REPUBLIQUE DU CAMEROUN
*Paix – Travail – Patrie*
********
UNIVERSITE DE YAOUNDE I
FACULTE DES SCIENCES
DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE ANIMALES
*********
LABORATOIRE D'HYDROBIOLOGIE ET ENVIRONNEMENT

REPUBLIC OF CAMEROUN
Peace – Work – Fatherland
*******
UNIVERSITY OF YAOUNDE I
FACULTY OF SCIENCE
DEPARTMENT OF ANIMAL BIOLOGY AND PHYSIOLOGY
*******
LABORATORY OF HYDROBIOLOGY AND ENVIRONMENT

# Impact of altitude and physicochemical parameters on groundwater quality and biodiversity in Fako Division, South West Region, Cameroon

Thesis
Presented in partial fulfilment of the requirements for the award of a Doctorate/Ph.D. in Biology of Animal Organisms

Par : **CHINCHE SYLVIE BELENGFE**
Master of Sciences

Sous la direction de
**ZEBAZE TOGOUET Serge Hubert**
**Professor**
**FOMENA Abraham**
**Professor**

**Année Académique : 2021**

**UNIVERSITE DE YAOUNDE I**
*UNIVERSITY OF YAOUNDE I*

**FACULTE DES SCIENCES**
*FACULTY OF SCIENCE*

**DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE ANIMALES**
*DEPARTMENT OF ANIMAL BIOLOGY AND PHYSIOLOGY*

# ATTESTATION DE CORRECTION

Nous soussignés, membres du jury de soutenance de la **Thèse de Doctorat/Ph.D** en Biologie des Organismes Animaux (Option : Hydrobiologie et Environnement) de Madame **CHINCHE Sylvie BELENGFE,** matricule 07Q159, soutenance autorisée par la correspondance N° 21-0563/UY1/VREPDTIC/DAAC/DEPE/SPD/CB-AP du Recteur de l'Université de Yaoundé I en date du 05 Mars 2021, attestons que les corrections exigées à la candidate lors de cette évaluation faite le 18 Mars 2021 ont réellement été effectuées et que le présent document peut être déposé sous sa forme actuelle.

En foi de quoi cette attestation lui est délivrée pour servir et valoir de ce que de droit.

Yaoundé, le 18 MAY 2021

**Président du Jury**

M. NOLA

**Examinateur**

Pr ASSAGAH

**Chef de Département**

UNIVERSITE DE YAOUNDE I
University of Yaounde I
DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE ANIMALES
Department of Animal Biology and Physiology
Le Chef de Département
The Head of Department
FACULTE DES SCIENCES
Faculty of Sciences

Charles Félix
Bilong Bilong
Professeur

**UNIVERSITY OF YAOUNDE I**

*UNIVERSITE DE YAOUNDE I*

**FACULTY OF SCIENCE**

*FACULTE DES SCIENCES*

**DEPARTMENT OF ANIMAL BIOLOGY AND PHYSIOLOGY**

*DEPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE ANIMALES*

**LABORATORY OF HYDROBIOLOGY AND ENVIRONMENT**

*LABORATOIRE D'HYDROBIOLOGIE ET ENVIRONNEMENT*

# Impact of altitude and physicochemical parameters on groundwater quality and biodiversity in Fako Division, South West Region, Cameroon

***Thesis***

***Presented in partial fulfilment of the requirements for the award of a Doctorate/Ph.D. in Biology of Animal Organisms***

**Option: Hydrobiology and Environment**

**By**

**CHINCHE SYLVIE BELENGFE**

**Matriculation number: 07Q159**

*Master of Sciences*

**Under the Co-supervision of:**

**ZEBAZE TOGOUET Serge Hubert**

*Professor*

**and**

**FOMENA Abraham**

*Professor*

**Year: 2021**

| UNIVERSITÉ DE YAOUNDÉ I<br>**Faculté des Sciences**<br>Division de la Programmation et du Suivi des Activités Académiques | | THE UNIVERSITY OF YAOUNDE I<br>**Faculty of Science**<br>Division of Programming and Follow-up of Academic Affaires |
|---|---|---|
| **LISTE DES ENSEIGNANTS PERMANENTS** | | **LIST OF PERMANENT TEACHING STAFF** |

**LISTE PROTOCOLAIRE DE LA FACULTÉ DES SCIENCES**

**ANNÉE ACADEMIQUE 2019/2020**

(Par Département et par Grade)

**DATE D'ACTUALISATION 19 Février 2020**

**ADMINISTRATION**

**DOYEN** : TCHOUANKEU Jean - Claude, Maitre de Conférences

**VICE-DOYEN / DPSAA** : Alex de Théodore ATCHADE, Maitre de Conférences

**VICE-DOYEN / DSSE** : AJEAGAH Gideon AGHAINDUM, Professeur

**VICE-DOYEN / DRC** : ABOSSOLO Monique, Maitre de Conférences

**Chef Division Administrative et Financière** : NDOYE FOE Marie C. F., Maitre de Conférences

**Chef Division des Affaires Académiques, de la Scolarité et de la Recherche DAASR** : MBAZE MEVA'A Luc Léonard, Professeur

| **1- DÉPARTEMENT DE BIOCHIMIE (BC) (38)** | | | |
|---|---|---|---|
| N° | Noms et PrÉnoms | Grade | Observations |
| 1 | BIGOGA DIAGA Jude | Professeur | En poste |
| 2 | FEKAM BOYOM Fabrice | Professeur | En poste |
| 3 | FOKOU Elie | Professeur | En poste |
| 4 | KANSCI Germain | Professeur | En poste |
| 5 | MBACHAM FON Wilfried | Professeur | En poste |
| 6 | MOUNDIPA FEWOU Paul | Professeur | Chef de Département |
| 7 | NINTCHOM PENLAP V. épse BENG | Professeur | En poste |
| 8 | OBEN Julius ENYONG | Professeur | En poste |
| 9 | ACHU Merci BIH | Maître de Conférences | En poste |
| 10 | ATOGHO Barbara Mma | Maître de Conférences | En poste |
| 11 | AZANTSA KINGUE GABIN BORIS | Maître de Conférences | En poste |
| 12 | BELINGA née NDOYE FOE M. C. F. | Maître de Conférences | Chef DAF / FS |
| 13 | BOUDJEKO Thaddée | Maître de Conférences | En poste |

| | | | |
|---|---|---|---|
| 14 | DJUIDJE NGOUNOUE Marcelline | Maître de Conférences | En poste |
| 15 | EFFA NNOMO Pierre | Maître de Conférences | En poste |
| 16 | NANA Louise épouse WAKAM | Maître de Conférences | En poste |
| 17 | NGONDI Judith Laure | Maître de Conférences | En poste |
| 18 | NGUEFACK Julienne | Maître de Conférences | En poste |
| 19 | NJAYOU Frédéric Nico | Maître de Conférences | En poste |
| 20 | MOFOR née TEUGWA Clotilde | Maître de Conférences | Inspecteur de Service MINESUP |
| 21 | TCHANA KOUATCHOUA Angèle | Maître de Conférences | En poste |
| 22 | AKINDEH MBUH NJI | Chargé de Cours | En poste |
| 23 | BEBOY EDZENGUELE Sara Nathalie | Chargée de Cours | En poste |
| 24 | DAKOLE DABOY Charles | Chargé de Cours | En poste |
| 25 | DJUIKWO NKONGA Ruth Viviane | Chargée de Cours | En poste |
| 26 | DONGMO LEKAGNE Joseph Blaise | Chargé de Cours | En poste |
| 27 | EWANE Cécile Anne | Chargée de Cours | En poste |
| 28 | FONKOUA Martin | Chargé de Cours | En poste |
| 29 | BEBEE Fadimatou | Chargée de Cours | En poste |
| 30 | KOTUE KAPTUE Charles | Chargé de Cours | En poste |
| 31 | LUNGA Paul KEILAH | Chargé de Cours | En poste |
| 32 | MANANGA Marlyse Joséphine | Chargée de Cours | En poste |
| 33 | MBONG ANGIE M. Mary Anne | Chargée de Cours | En poste |
| 34 | PECHANGOU NSANGOU Sylvain | Chargé de Cours | En poste |
| 35 | Palmer MASUMBE NETONGO | Chargé de Cours | En poste |
| 36 | MBOUCHE FANMOE Marceline Joëlle | Assistante | En poste |
| 37 | OWONA AYISSI Vincent Brice | Assistant | En poste |
| 38 | WILFRIED ANGIE Abia | Assistante | En poste |
| **2- DÉPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE ANIMALES (BPA) (46)** | | | |
| 1 | AJEAGAH Gideon AGHAINDUM | Professeur | VICE-DOYEN / DSSE |
| 2 | BILONG BILONG Charles-Félix | Professeur | Chef de Département |
| 3 | DIMO Théophile | Professeur | En Poste |
| 4 | DJIETO LORDON Champlain | Professeur | En Poste |
| 5 | ESSOMBA née NTSAMA MBALA | Professeur | Vice Doyen/FMSB/UYI |
| 6 | FOMENA Abraham | Professeur | En Poste |
| 7 | KAMTCHOUING Pierre | Professeur | En poste |
| 8 | KEKEUNOU Sévilor | Professeur | En poste |
| 9 | NJAMEN Dieudonné | Professeur | En poste |
| 10 | NJIOKOU Flobert | Professeur | En Poste |
| 11 | NOLA Moïse | Professeur | En poste |

| | | | |
|---|---|---|---|
| 12 | TAN Paul VERNYUY | Professeur | En poste |
| 13 | TCHUEM TCHUENTE Louis Albert | Professeur | Inspecteur de service Coord.Progr./MINSANTE |
| 14 | ZEBAZE TOGOUET Serge Hubert | Professeur | En poste |
| 15 | BILANDA Danielle Claude | Maître de Conférences | En poste |
| 16 | DJIOGUE Séfirin | Maître de Conférences | En poste |
| 17 | DZEUFIET DJOMENI Paul Désiré | Maître de Conférences | En poste |
| 18 | JATSA BOUKENG Hermine épse MEGAPTCHE | Maître de Conférences | En Poste |
| 19 | MEGNEKOU Rosette | Maître de Conférences | En poste |
| 20 | MONY Ruth épse NTONE | Maître de Conférences | En Poste |
| 21 | NGUEGUIM TSOFACK Florence | Maître de Conférences | En poste |
| 22 | TOMBI Jeannette | Maître de Conférences | En poste |
| 23 | ALENE Désirée Chantal | Chargée de Cours | En poste |
| 24 | ATSAMO Albert Donatien | Chargé de Cours | En poste |
| 25 | BELLET EDIMO Oscar Roger | Chargé de Cours | En poste |
| 26 | DONFACK Mireille | Chargée de Cours | En poste |
| 27 | ETEME ENAMA Serge | Chargé de Cours | En poste |
| 28 | GOUNOUE KAMKUMO Raceline | Chargée de Cours | En poste |
| 29 | KANDEDA KAVAYE Antoine | Chargé de Cours | En poste |
| 30 | LEKEUFACK FOLEFACK Guy B. | Chargé de Cours | En poste |
| 31 | MAHOB Raymond Joseph | Chargé de Cours | En poste |
| 32 | MBENOUN MASSE Paul Serge | Chargé de Cours | En poste |
| 33 | MOUNGANG Luciane Marlyse | Chargée de Cours | En poste |
| 34 | MVEYO NDANKEU Yves Patrick | Chargé de Cours | En poste |
| 35 | NGOUATEU KENFACK Omer Bébé | Chargé de Cours | En poste |
| 36 | NGUEMBOK | Chargé de Cours | En poste |
| 37 | NJUA Clarisse Yafi | Chargée de Cours | Chef Div. UBA |
| 38 | NOAH EWOTI Olive Vivien | Chargé de Cours | En poste |
| 39 | TADU Zephyrin | Chargé de Cours | En poste |
| 40 | TAMSA ARFAO Antoine | Chargé de Cours | En poste |
| 41 | YEDE | Chargé de Cours | En poste |
| 42 | BASSOCK BAYIHA Etienne Didier | Assistant | En poste |
| 43 | ESSAMA MBIDA Désirée Sandrine | Assistante | En poste |
| 44 | KOGA MANG DOBARA | Assistant | En poste |
| 45 | LEME BANOCK Lucie | Assistante | En poste |
| 46 | YOUNOUSSA LAME | Assistant | En poste |

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| **3- DÉPARTEMENT DE BIOLOGIE ET PHYSIOLOGIE VÉGÉTALES (BPV) (32)** | | | |
| 1 | AMBANG Zachée | Professeur | Chef Division/UYII |
| 2 | BELL Joseph Martin | Professeur | En poste |
| 3 | DJOCGOUE Pierre François | Professeur | En poste |
| 4 | MOSSEBO Dominique Claude | Professeur | En poste |
| 5 | YOUMBI Emmanuel | Professeur | Chef de Département |
| 6 | ZAPFACK Louis | Professeur | En poste |
| 7 | ANGONI Hyacinthe | Maître de Conférences | En poste |
| 8 | BIYE Elvire Hortense | Maître de Conférences | En poste |
| 9 | KENGNE NOUMSI Ives Magloire | Maître de Conférences | En poste |
| 10 | MALA Armand William | Maître de Conférences | En poste |
| 11 | MBARGA BINDZI Marie Alain | Maître de Conférences | CT/ MINESUP |
| 12 | MBOLO Marie | Maître de Conférences | En poste |
| 13 | NDONGO BEKOLO | Maître de Conférences | CE / MINRESI |
| 14 | NGONKEU MAGAPTCHE Eddy L. | Maître de Conférences | En poste |
| 15 | TSOATA Esaïe | Maître de Conférences | En poste |
| 16 | TONFACK Libert Brice | Maître de Conférences | En poste |
| 17 | DJEUANI Astride Carole | Chargée de Cours | En poste |
| 18 | GOMANDJE Christelle | Chargée de Cours | En poste |
| 19 | MAFFO MAFFO Nicole Liliane | Chargée de Cours | En poste |
| 20 | MAHBOU SOMO TOUKAM. Gabriel | Chargé de Cours | En poste |
| 21 | NGALLE Hermine BILLE | Chargée de Cours | En poste |
| 22 | NGOUO Lucas Vincent | Chargé de Cours | En poste |
| 23 | NNANGA MEBENGA Ruth Laure | Chargée de Cours | En poste |
| 24 | NOUKEU KOUAKAM Armelle | Chargée de Cours | En poste |
| 25 | ONANA JEAN MICHEL | Chargé de Cours | En poste |
| 26 | GODSWILL NTSOMBAH NTSEFONG | Assistant | En poste |
| 27 | KABELONG BANAHO Louis-Paul-Roger | Assistant | En poste |
| 28 | KONO Léon Dieudonné | Assistant | En poste |
| 29 | LIBALAH Moses BAKONCK | Assistant | En poste |
| 30 | LIKENG-LI-NGUE Benoit C | Assistant | En poste |
| 31 | TAEDOUNG Evariste Hermann | Assistant | En poste |
| 32 | TEMEGNE NONO Carine | Assistante | En poste |
| **4- DÉPARTEMENT DE CHIMIE INORGANIQUE (CI) (35)** | | | |
| 1 | AGWARA ONDOH Moïse | Professeur | Chef de Département |
| 2 | ELIMBI Antoine | Professeur | En poste |

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|---|---|---|---|
| 3 | Florence UFI CHINJE épouse MELO | Professeur | Recteur Univ.Ngaoundéré |
| 4 | GHOGOMU Paul MINGO | Professeur | Ministre Chargé deMiss.PR |
| 5 | NANSEU Njiki Charles Péguy | Professeur | En poste |
| 6 | NDIFON Peter TEKE | Professeur | CT MINRESI |
| 7 | NGOMO Horace MANGA | Professeur | Vice Chancelor/UB |
| 8 | NDIKONTAR Maurice KOR | Professeur | Vice-Doyen Univ. Bamenda |
| 9 | NENWA Justin | Professeur | En poste |
| 10 | NGAMENI Emmanuel | Professeur | DOYEN FS UDs |
| 11 | BABALE née DJAM DOUDOU | Maître de Conférences | Chargée Mission P.R. |
| 12 | DJOUFAC WOUMFO Emmanuel | Maître de Conférences | En poste |
| 13 | KAMGANG YOUBI Georges | Maître de Conférences | En poste |
| 14 | KEMMEGNE MBOUGUEM Jean C. | Maître de Conférences | En poste |
| 15 | KONG SAKEO | Maître de Conférences | En poste |
| 16 | NDI NSAMI Julius | Maître de Conférences | En poste |
| 17 | NJIOMOU C. épse DJANGANG | Maître de Conférences | En poste |
| 18 | NJOYA Dayirou | Maître de Conférences | En poste |
| 19 | YOUNANG Elie | Maître de Conférences | En poste |
| 20 | ACAYANKA Elie | Chargé de Cours | En poste |
| 21 | BELIBI BELIBI Placide Désiré | Chargé de Cours | CS/ ENS Bertoua |
| 22 | CHEUMANI YONA Arnaud M. | Chargé de Cours | En poste |
| 23 | EMADACK Alphonse | Chargé de Cours | En poste |
| 24 | KENNE DEDZO Gustave | Chargé de Cours | En poste |
| 25 | KOUOTOU Daouda | Chargé de Cours | En poste |
| 26 | MAKON Thomas Beauregard | Chargé de Cours | En poste |
| 27 | MBEY Jean Aime | Chargé de Cours | En poste |
| 28 | NCHIMI NONO Katia | Chargé de Cours | En poste |
| 29 | NEBA née NDOSIRI Bridget NDOYE | Chargée de Cours | CT/ MINFEM |
| 30 | NYAMEN Linda Dyorisse | Chargée de Cours | En poste |
| 31 | PABOUDAM GBAMBIE Awawou | Chargée de Cours | En poste |
| 32 | TCHAKOUTE KOUAMO Hervé | Chargé de Cours | En poste |
| 33 | NJANKWA NJABONG N. Eric | Assistant | En poste |
| 34 | PATOUOSSA Issofa | Assistant | En poste |
| 35 | SIEWE Jean Mermoz | Assistant | En Poste |
| **5- DÉPARTEMENT DE CHIMIE ORGANIQUE (CO) (35)** | | | |
| 1 | DONGO Etienne | Professeur | Vice-Doyen /DSSE/ FSE |
| 2 | GHOGOMU TIH Robert Ralph | Professeur | Dir. IBAF/UDA |
| 3 | NGOUELA Silvère Augustin | Professeur | Chef de Departement UDS |

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| 4 | NKENGFACK Augustin Ephrem | Professeur | Chef de Département |
| 5 | NYASSE Barthélemy | Professeur | En poste |
| 6 | PEGNYEMB Dieudonné Emmanuel | Professeur | Directeur/ MINESUP |
| 7 | WANDJI Jean | Professeur | En poste |
| 8 | ATCHADE Alex de Théodore | Maître de Conférences | VICE-DOYEN / DPSAA |
| 9 | EYONG Kenneth OBEN | Maître de Conférences | En poste |
| 10 | FOLEFOC Gabriel NGOSONG | Maître de Conférences | En poste |
| 11 | FOTSO WABO Ghislain | Maître de Conférences | En poste |
| 12 | KEUMEDJIO Félix | Maître de Conférences | En poste |
| 13 | KEUMOGNE Marguerite | Maître de Conférences | En poste |
| 14 | KOUAM Jacques | Maître de Conférences | En poste |
| 15 | MBAZOA née DJAMA Céline | Maître de Conférences | En poste |
| 16 | MKOUNGA Pierre | Maître de Conférences | En poste |
| 17 | NOTE LOUGBOT Olivier Placide | Maître de Conférences | Chef Service/MINESUP |
| 18 | NGO MBING Joséphine | Maître de Conférences | Sous/Direct. MINERESI |
| 19 | NGONO BIKOBO Dominique Serge | Maître de Conférences | En poste |
| 20 | NOUNGOUE TCHAMO Diderot | Maître de Conférences | En poste |
| 21 | TABOPDA KUATE Turibio | Maître de Conférences | En poste |
| 22 | TCHOUANKEU Jean-Claude | Maître de Conférences | Doyen /FS/ UYI |
| 23 | TIH née NGO BILONG E. Anastasie | Maître de Conférences | En poste |
| 24 | YANKEP Emmanuel | Maître de Conférences | En poste |
| 25 | AMBASSA Pantaléon | Chargé de Cours | En poste |
| 26 | KAMTO Eutrophe Le Doux | Chargé de Cours | En poste |
| 27 | MVOT AKAK Carine | Chargée de Cours | En poste |
| 28 | NGNINTEDO Dominique | Chargé de Cours | En poste |
| 29 | NGOMO Orléans | Chargée de Cours | En poste |
| 30 | OUAHOUO WACHE Blandine M. | Chargée de Cours | En poste |
| 31 | SIELINOU TEDJON Valérie | Chargé de Cours | En poste |
| 32 | TAGATSING FOTSING Maurice | Chargé de Cours | En poste |
| 33 | ZONDENDEGOUMBA Ernestine | Chargée de Cours | En poste |
| 34 | MESSI Angélique Nicolas | Assistant | En poste |
| 35 | TSEMEUGNE Joseph | Assistant | En poste |
| **6- DÉPARTEMENT D'INFORMATIQUE (IN) (27)** | | | |
| 1 | ATSA ETOUNDI Roger | Professeur | Chef Div.MINESUP |
| 2 | FOUDA NDJODO Marcel Laurent | Professeur | Chef Dpt ENS/Chef IGA.MINESUP |
| 3 | NDOUNDAM René | Maître de Conférences | En poste |

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| 4 | AMINOU Halidou | Chargé de Cours | Chef de Département |
| 5 | DJAM Xaviera YOUH - KIMBI | Chargé de Cours | En Poste |
| 6 | EBELE Serge Alain | Chargé de Cours | En poste |
| 7 | KOUOKAM KOUOKAM E. A. | Chargé de Cours | En poste |
| 8 | MELATAGIA YONTA Paulin | Chargé de Cours | En poste |
| 9 | MOTO MPONG Serge Alain | Chargé de Cours | En poste |
| 10 | TAPAMO Hyppolite | Chargé de Cours | En poste |
| 11 | ABESSOLO ALO'O Gislain | Chargé de Cours | En poste |
| 12 | KAMGUEU Patrick Olivier | Chargé de Cours | En poste |
| 13 | MONTHE DJIADEU Valery M. | Chargé de Cours | En poste |
| 14 | OLLE OLLE Daniel Claude Delort | Chargé de Cours | C/D Enset. Ebolowa |
| 15 | TINDO Gilbert | Chargé de Cours | En poste |
| 16 | TSOPZE Norbert | Chargé de Cours | En poste |
| 17 | WAKU KOUAMOU Jules | Chargé de Cours | En poste |
| 18 | BAYEM Jacques Narcisse | Assistant | En poste |
| 19 | DOMGA KOMGUEM Rodrigue | Assistant | En poste |
| 20 | EKODECK Stéphane Gaël Raymond | Assistant | En poste |
| 21 | HAMZA Adamou | Assistant | En poste |
| 22 | JIOMEKONG AZANZI Fidel | Assistant | En poste |
| 23 | MAKEMBE. S. Oswald | Assistant | En poste |
| 24 | MESSI NGUELE Thomas | Assistant | En poste |
| 25 | MEYEMDOU Nadège Sylvianne | Assistante | En poste |
| 26 | NKONDOCK. MI. BAHANACK.N. | Assistant | En poste |
| **7- DÉPARTEMENT DE MATHÉMATIQUES (MA) (30)** | | | |
| 1 | EMVUDU WONO Yves S. | Professeur | Inspecteur MINESUP |
| 2 | AYISSI Raoult Domingo | Maître de Conférences | Chef de Département |
| 3 | NKUIMI JUGNIA Célestin | Maître de Conférences | En poste |
| 4 | NOUNDJEU Pierre | Maître de Conférences | Chef Service Programme & Diplomes |
| 5 | MBEHOU Mohamed | Maître de Conférences | En poste |
| 6 | TCHAPNDA NJABO Sophonie B. | Maître de Conférences | Directeur/AIMS Rwanda |
| 7 | AGHOUKENG JIOFACK Jean Gérard | Chargé de Cours | Chef Cellule MINPLAMAT |
| 8 | CHENDJOU Gilbert | Chargé de Cours | En poste |
| 9 | DJIADEU NGAHA Michel | Chargé de Cours | En poste |
| 10 | DOUANLA YONTA Herman | Chargé de Cours | En poste |
| 11 | FOMEKONG Christophe | Chargé de Cours | En poste |
| 12 | KIANPI Maurice | Chargé de Cours | En poste |

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| 13 | KIKI Maxime Armand | Chargé de Cours | En poste |
| 14 | MBAKOP Guy Merlin | Chargé de Cours | En poste |
| 15 | MBANG Joseph | Chargé de Cours | En poste |
| 16 | MBELE BIDIMA Martin Ledoux | Chargé de Cours | En poste |
| 17 | MENGUE MENGUE David Joe | Chargé de Cours | En poste |
| 18 | NGUEFACK Bernard | Chargé de Cours | En poste |
| 19 | NIMPA PEFOUNKEU Romain | Chargé de Cours | En poste |
| 20 | POLA DOUNDOU Emmanuel | Chargé de Cours | En poste |
| 21 | TAKAM SOH Patrice | Chargé de Cours | En poste |
| 22 | TCHANGANG Roger Duclos | Chargé de Cours | En poste |
| 23 | TCHOUNDJA Edgar Landry | Chargé de Cours | En poste |
| 24 | TETSADJIO TCHILEPECK M. E. | Chargée de Cours | En poste |
| 25 | TIAYA TSAGUE N. Anne-Marie | Chargée de Cours | En poste |
| 26 | MBIAKOP Hilaire George | Assistant | En poste |
| 27 | BITYE MVONDO Esther Claudine | Assistante | En poste |
| 28 | MBATAKOU Salomon Joseph | Assistant | En poste |
| 29 | MEFENZA NOUNTU Thiery | Assistant | En poste |
| 30 | TCHEUTIA Daniel Duviol | Assistant | En poste |
| **8- DÉPARTEMENT DE MICROBIOLOGIE (MIB) (18)** | | | |
| 1 | ESSIA NGANG Jean Justin | Professeur | Chef de Dépt DRV/IMPM |
| 2 | BOYOMO ONANA | Maître de Conférences | En poste |
| 3 | NWAGA Dieudonné M. | Maître de Conférences | En poste |
| 4 | NYEGUE Maximilienne Ascension | Maître de Conférences | En poste |
| 5 | RIWOM Sara Honorine | Maître de Conférences | En poste |
| 6 | SADO KAMDEM Sylvain Leroy | Maître de Conférences | En poste |
| 7 | ASSAM ASSAM Jean Paul | Chargé de Cours | En poste |
| 8 | BODA Maurice | Chargé de Cours | En poste |
| 9 | BOUGNOM Blaise Pascal | Chargé de Cours | En poste |
| 10 | ESSONO OBOUGOU Germain G. | Chargé de Cours | En poste |
| 11 | NJIKI BIKOÏ Jacky | Chargée de Cours | En poste |
| 12 | TCHIKOUA Roger | Chargé de Cours | En poste |
| 13 | ESSONO Damien Marie | Assistante | En poste |
| 14 | LAMYE Glory MOH | Assistant | En poste |
| 15 | MEYIN A EBONG Solange | Assistante | En poste |
| 16 | NKOUDOU ZE Nardis | Assistant | En poste |
| 17 | SAKE NGANE Carole Stéphanie | Assistante | En poste |
| 18 | TOBOLBAÏ Richard | Assistant | En poste |

| 9. DEPARTEMENT DE PYSIQUE(PHY) (40) | | | |
|---|---|---|---|
| 1 | BEN- BOLIE Germain Hubert | Professeur | En poste |
| 2 | ESSIMBI ZOBO Bernard | Professeur | En poste |
| 3 | KOFANE Timoléon Crépin | Professeur | En poste |
| 4 | NANA ENGO Serge Guy | Professeur | En poste |
| 5 | NDJAKA Jean Marie Bienvenu | Professeur | Chef de Département |
| 6 | NOUAYOU Robert | Professeur | En poste |
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| 11 | WOAFO Paul | Professeur | En poste |
| 12 | BIYA MOTTO Frédéric | Maître de Conférences | DG/HYDRO Mekin |
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| 16 | EYEBE FOUDA Jean sire | Maître de Conférences | En poste |
| 17 | FEWO Serge Ibraïd | Maître de Conférences | En poste |
| 18 | HONA Jacques | Maître de Conférences | En poste |
| 19 | MBANE BIOUELE César | Maître de Conférences | En poste |
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| | | | |
|---|---|---|---|
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| 33 | MINYEM Dieudonné-Lucien | Chargé de Cours | CD/Uma |
| 34 | NGO BELNOUN Rose Noël | Chargée de Cours | En poste |
| 35 | NGO BIDJECK Louise Marie | Chargée de Cours | En poste |
| 36 | NOMO NEGUE Emmanuel | Chargé de Cours | En poste |
| 37 | NTSAMA ATANGANA Jacqueline | Chargée de Cours | En poste |
| 38 | TCHAKOUNTE J. épse NOUMBEM | Chargée de Cours | Chef.cell / MINRESI |
| 39 | TCHAPTCHET TCHATO De P. | Chargé de Cours | En poste |
| 40 | TEHNA Nathanaël | Chargé de Cours | En poste |
| 41 | TEMGA Jean Pierre | Chargé de Cours | En poste |
| 42 | FEUMBA Roger | Assistant | En poste |
| 43 | MBANGA NYOBE Jules | Assistant | En poste |

**Répartition chiffrée des Enseignants de la Faculté des Sciences de l'Université de Yaoundé I**

| | NOMBRE D'ENSEIGNANTS | | | | |
|---|---|---|---|---|---|
| **DÉPARTEMENT** | **Professeurs** | **Maîtres de Conférences** | **Chargés de Cours** | **Assistants** | **Total** |
| BCH | 8 (1) | 13 (08) | 14 (06) | 3 (2) | 38 (17) |
| BPA | 14 (1) | 08 (06) | 19 (05) | 05 (2) | 46 (14) |
| BPV | 06 (0) | 10 (02) | 9 (06) | 07 (01) | 32 (9) |
| CI | 10 (1) | 09 (02) | 13 (03) | 03 (0) | 35 (5) |
| CO | 7 (0) | 17 (04) | 09 (04) | 02 (0) | 35 (8) |
| IN | 2 (0) | 1 (0) | 14 (01) | 9 (01) | 26 (2) |
| MAT | 1 (0) | 5 (0) | 19 (02) | 05 (01) | 30 (3) |
| MIB | 1 (0) | 5 (02) | 06 (01) | 06 (03) | 18 (6) |
| PHY | 11 (0) | 16 (01) | 10 (03) | 03 (0) | 40 (4) |
| ST | 8 (1) | 14 (01) | 19 (05) | 02 (0) | 43 (7) |
| Total | 67 (4) | 99 (26) | 132 (36) | 45 (10) | 343 (76) |

Soit un total de 343 (76) dont :

Professeurs 67 (4)

Maîtres de Conférences 99 (26)

Chargés de Cours 132 (36)

Assistants 44 (10)

( ) = Nombre de Femmes

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# DEDICATION

To

My beloved and adorable mother CHINCHE Anna KWENWI, for bringing me into this world, for her unfailing love, her support, the advice she has always been given me since my childhood and for all the sacrifices she made for my education. May GOD continue to bless her with love, grace and long life so that she may reap and enjoy the fruit of her labour.

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I cannot forget thanking my classmates of the "Solidarity batch" with whom I share knowledge during the preparation of this thesis in the Laboratory and during our monthly meetings for the enthusiasm and the many enriching discussions we had during the scientific debates, meetings and seminars.

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# LIST OF ABBREVIATIONS AND ACRONYMS

**ACC:** Canonical Correspondence Analysis

**HCA:** Hierarchical Classification Analysis

**PCA:** Principal Components Analysis

**APHA:** American Public Health Association

**CDC:** Cameroon Development Cooperation

**NIC:** National Institute of Cartography

**DO:** Dissolved oxygen

**EC:** Electrical conductivity

**GPS:** Global Positioning System

**SS:** Suspended Solids

**FTU:** Ferometric Turbidity Units

**WHO:** World Health Organization

**TDS:** Total Dissolved Solids

**Inds** : Individuals

**GDE**: Groundwater Dependent Ecosystems

**PSU:** Practical Salinity Unit

**SPSS:** Statistical Packages for Social Sciences

**PASCALIS:** Protocols for the Assessment and Conservation of Aquatic Life in the Subsurface

**PL :** Piezometric level

**WC :** Water Column

**SODIS:** Solar Water Disinfection

**NIC:** National Institute of Cartography

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# ABSTRACT

In order to bring more light on the aquatic fauna of groundwater and its emergence, a study on the impact of altitude and physicochemical parameters on the biodiversity in some groundwater points in Fako division, South West Region of Cameroon was investigated. For this study, a total of 33 sampling points was investigated in the towns of Muyuka (average elevation 70 m), Limbe (33 m), Tiko (64), Owe (74 m), Ekona-Mautu (372 m) and Buea (900 m). The physico-chemical parameters of water were analysed using standard methods. Fauna was collected in wells using a phreatobiological net and in the springs by filtration. The physicochemical analyses showed that, the sampling points found at lower altitudes in Fako had high water temperatures (26.68 ± 1.32°C) slightly acidic pH (6.06 ± 0.76 CU), high level of turbidity (16.41 ± 9.80 FTU), high orthophosphate levels (1.18 ± 3.28 mg/L), good dissolved oxygen level (58.77 %), weakly mineralized (385.2 ± 313.7 µS/ cm). The sampling points found at high altitudes had very good oxygenation (67.05 ± 7.09 %), were highly turbid (13.96 ± 6.14 FTU), low temperatures (19.94 ± 14.00 °C), almost neutral pH (6.93 ± 0.52 CU), lowly mineralized (313.74 ± 344.25 µS/cm), higher levels of orthophosphates (8.23 ± 36.96 mg/L). The taxonomic richness was relatively higher at lower altitudes (10265 individuals (inds)) than at high altitudes (10749 inds). A total of 21014 organisms were collected during the study period, belonging to 04 phyla, 12 classes and 58 families and 62 genera/or sub families, dominated by insects (25 %) followed by arachnids (17.7 %) and the fewest families were the classes Hirudinea (0.3 %), Collembola (0.4 %) and Gastropoda (0.5 %). Groundwater was rich and diversified, made up abundantly of epigean families due to the poor management of the water points and their nearness to agricultural areas and also due to the relationship between ground-surface water. A positive correlation was observed between altitude and salinity ($p = 0.372$) and dissolved oxygen ($p = 0.580$). while a negative correlation was obtained between altitude and nitrate ($p = -0.525$), temperature ($p = -0.708$) and pH ($p = -0.266$). The stygobites collected belonged to the families Asellidae, Stenasellidae, Darwinulidae and Cirolanidae. No significant difference as observed between stygobites during the seasons, but a significant difference was observed between stygobites and sampling points (Asellidae $p = 0.002$, Stenasellidae $p= 0.006$, Cirolanidae $p= 0.002$ and Darwinulidae $p = 0.004$) and between stygobites and sampling sites ($p < 0.05$ for Asellidae, Stenasellidae, Cirolanidae and Darwinulidae).

**Keywords**: groundwater, biodiversity, altitude, stygobitic species, Fako division, water quality, physico-chemical parameters

# RESUME

Afin d'apporter plus de lumière sur la faune aquatique des eaux souterraines et ses emérgences, une étude sur l'impact de l'altitude et des paramètres physico-chimiques sur la biodiversité de certains points d'eau souterraine dans le Département de Fako, région du sud-ouest du Cameroun a été menée. Pour cette étude, 33 points d'échantillonnage ont été prélevés dans les villes de Muyuka (altitude moyenne de 70 m), Limbe (33 m), Tiko (64), Owe (74 m), Ekona-Mautu (372 m) et Buea (900 m). Les paramètres physico-chimiques de l'eau ont été analysés à l'aide de méthodes standards. La faune a été collectée dans des puits à l'aide d'un filet phréatobiologique et dans les sources par filtration. Les analyses physico-chimiques ont montré que, les points de prélèvement trouvés à des altitudes plus basses à Fako avaient des températures d'eau élevées (26,68 ± 1,32°C), un pH légèrement acide (6,06 ± 0,76 CU), une forte turbidité (16,41 ± 9,80 FTU), des teneurs élevées en orthophosphate (1,18 ± 3,28 mg/L), une bonne teneur en oxygène dissous (58,77 %), une faible minéralisation (385,2 ± 313,7 µS/ cm). Les points de prélèvement trouvés en haute altitude présentaient une très bonne oxygénation (67,05 ± 7,09 %), étaient très turbides (13,96 ± 6,14 FTU), des températures basses (19,94 ± 14,00 °C), un pH presque neutre (6,93 ± 0,52 CU), faiblement minéralisés (313,74 ± 344,25 µS/cm), des niveaux plus élevés d'orthophosphates (8,23 ± 36,96 mg/L). La richesse taxonomique était relativement plus élevée à basse altitude (10265 inds) qu'à haute altitude (10749 inds). Au total, 21014 organismes ont été collectés pendant la période d'étude, appartenant à 04 embranchements, 12 classes, 58 familles et 62 genres/sous-familles, dominés par les insectes (25 %) suivis par les arachnides (17,7 %). Les familles les moins nombreux étaient les classes des Hirudinea (0,3 %), Collembola (0,4 %) et Gastropoda (0,5 %). Les eaux souterraines étaient riches et diversifiées, composées en abondance de familles épigés en raison de la mauvaise gestion des points d'eau et de leur proximité avec les zones agricoles, mais aussi en raison de la relation entre les eaux souterraines et les eaux de surface. Une corrélation positive a été observée entre l'altitude et la salinité ($p = 0,372$) et l'oxygène dissous ($p = 0,580$). Tandis qu'une corrélation négative a été obtenue entre l'altitude et les nitrates ($p = -0,525$), la température ($p = -0,708$) et le pH ($p = -0,266$). Les stygobies recueillis appartenaient aux familles suivantes : Asellidae, Stenasellidae, Darwinulidae et Cirolanidae. Aucune différence significative n'a été observée entre les stygobies et la saison mais une différence significative a été observée entre les stygobies et les points d'échantillonnage (Asellidae $p = 0,002$, Stenasellidae $p= 0,006$, Cirolanidae $p= 0,002$ et Darwinulidae $p = 0,004$) et entre les stygobies et les sites d'échantillonnage ($p < 0,05$ pour Asellidae, Stenasellidae, Cirolanidae et

Darwinulidae). Les résultats obtenus ont montré que les points d'eau trouvés à haute altitude sont de bonnes qualités écologiques et bonnes pour la consommation de la population tandis que les points d'eau trouvés à basse altitude ne sont pas de bonne qualité écologique.

**Mots-clés :** eaux souterraines, biodiversité, altitude, espèces stygobies, Département du3 Fako, qualité de l'eau, paramètres physico-chimiques

# INTRODUCTION

Water is indispensable for life, but its availability at a sustainable quality and quantity is threatened by many factors, of which climate change and human activities play a leading role. Groundwater is characterised by its flows beneath the earth's surface, filling the porous spaces in soil, sediments and rocks (Lou and Bloomfield, 2012). It originates from rain and melting ice and it is the source of water for aquifers, springs and wells. It is the main source of drinking water reservoir on earth, but also a major ecosystem in terms of biological diversity (Leijs *et al*., 2009). Maintaining groundwater quality and conserving its biodiversity are converging goals because the healthy functioning of these systems is attested by their level of biodiversity (Botoseananu, 1986).

Groundwater ecosystems are the oldest on earth, and contain many endemic species adapted to live in an environment with no light and limited resources such as oxygen (Lou and Bloomfield, 2012). Ecological and microbiological exploration of groundwater over the past has identified a diverse range of organisms inhabiting groundwater systems, collectively called stygofauna (Danielopol *et al.,* 2003, Boulton *et al.,* 2008, Schulz *et al.,* 2013). Stygofauna are made up of many kinds of crustaceans and other invertebrates (Humphreys, 2006) which are typically well adapted for the subterranean environment. Tomlinson and Boulton (2008) indicated that stygofauna are valued as a biodiversity resource, as indicators of groundwater ecosystem health, and potential providers of ecosystem goods and services. Such ecosystem goods and services may include nutrient cycling and storage (Danielopol *et al.,* 2003, Murray *et al.,* 2006, Schulz *et al.,* 2013, Asmyhr *et al.,* 2014), organic matter cycling and redistribution (Danielopol *et al.,* 2003), water treatment (Danielopol *et al.,* 2003, Murray *et al.,* 2006, Boulton *et al,* 2008, Leijs *et al.,* 2009, Schulz *et al.,* 2013, Asmyhr *et al.,* 2014), water regulation (Hancock *et al.,* 2005, Murray *et al.,* 2006, Boulton *et al.,* 2008, Majer 2009, Nwankwoala 2012, Schulz *et al.,* 2013), and mineral weathering and formation (Danielopol *et al.,* 2003). Stygofauna might be used to manage groundwater resources and more specially to monitor the effect of pollution sources.

The major pressures on groundwater systems are from anthropogenic activities that modify aspects of the groundwater regime, including flow, flux, level and quality (Eamus *et al.,* 2006), and the transport of nutrients and organic matter (Menció *et al.,* 2014). Activities such as agriculture, industrial production and domestic water supply result in a depletion in groundwater quantity and may introduce pollutants that impact groundwater quality (Danielopol *et al.,* 2003), potentially altering ecosystem function (Danielopol *et al.,* 2003) and driving changes in stygofauna distribution and composition (Menció *et al.,* 2014). The pressures on groundwater ecosystems are cumulative (Danielopol *et al,* 2003) and their impacts

may be observed earlier on the stygofauna communities of the hyporheic zone or in shallow, dynamic groundwater systems (Nwankwoala, 2012). Biological inventories have been used extensively to support management and conservation activities including development of conservation goals and identification (Glanville *et al.*, 2016). It has become increasingly obvious that groundwater (GW) should not only be viewed as drinking water reservoir but also as part of strategic aquatic ecosystems. There is a need to search for appropriate groundwater management procedures of stygoxene species.

The supply of potable water remains a problem in Cameroon due to the unequal distribution of this resource on the earth's surface, fast and anarchistic urbanization, various pollutions that denature the quality of the continental hydro systems and the high poverty level of Cameroon. The population are not able to access potable pipe borne water and therefore, many households depend entirely on groundwater for their water supply (Zebaze Togouet *et al.*, 2009). In Cameroon and especially in rural areas, water quality is a call for concern due to higher poverty levels and large disregard towards the environment. Consequences of inadequate supply of water and sanitation are very evident especially with the outbreak of diseases and illnesses related to water quality (Gorham et al., 2017). Septic tanks and pit latrines are overloading irreversibly subterranean water with bacteria and nitrate. Since there is no required license and standards to drill a well, the final responsibility for constructing a well correctly and maintaining it falls on the well owner. As a result, householders drill wells in many cases that is not far from where they dispose their wastes, with latrines just beside these wells and they use the wells as drinking water and for all household activities that require the use of water (Yongsi, 2010). If there is no political will to tackle such a problem in these rural areas, then there will be no immediate solution.

In Cameroon, previous work has been done in this domain in the Centre, Littoral and West regions. The results of the physico-chemical parameters of the different stations studied showed that these regions have a high level of organic and chemical pollution and the groundwater habours Stygobites of the genus *Metastenasellus* (Zebaze Togouet, 2006, Zebaze Togouet *et al.*, 2011, Tuekam Kayo, 2013, Nana Nkengmeni *et al.*, 2015), and a rich and diversified micro flora made up of harmful bacteria, protozoa and other germs which endanger the health of the consumers (Nola *et al.*, 1999, Zebaze Togouet, 2006). The previous results also showed that, morphometric parameters like piezometric level, water depth, diameter of well and water column influence the distribution of stygofauna and groundwater quality (Nana Nkengmeni *et al.*, 2015). The respect for elementary hygiene rules, the treatment of water

before its use, the protection of groundwater points, can possibly avoid health risk problems due to water quality.

The main objective of this study is to determine if altitude and physicochemical parameters have an influence on the distribution of groundwater organisms in selected areas in Fako division of the South West region of Cameroon, since these are the main source of potable water in this region. This study will add to already existing knowledge based on other studies carried out in this domain in different regions in order to reinforce public awareness of the necessity to conserve the quality and quantity of groundwater and its biodiversity by emphasising on its economic, social, and scientific value together with its detriment on the health of the population when it's quality is bad or not good for consumption.

The specific objectives are to;

-Characterise the seasonal variation of the physico-chemical quality of the groundwater points, located at different altitudes in Fako division, South West region of Cameroon;

-Determine the community structure of groundwater biodiversity;

- Evaluate the influence of altitude and physicochemical parameters on the distribution of groundwater organisms and on water quality;

-Deduce the impact of environmental factors on stygofauna and on water quality.

# CHAPTER I

# LITERATURE REVIEW

## I.1. GROUNDWATER ENVIRONMENT

### I.1.1. Definition and origin of groundwater

Groundwater is water which is under the surface of the ground, in the saturation zone and in direct contact with the ground. Groundwater comes from the infiltration of rainwater in the permeable rocks where they form aquifer systems stored in the cracks of compact rocks (limestones, schists, or granites) and the interstices of porous movable rocks (sands or sandstone) (Boutin, 1997). Therefore, water present in a zone of saturation is called groundwater (Stanley, 2005). A cavity of any size is a potential habitat for underground terrestrial, freshwater or marine species, if food resources reach the cavity from the surface and if it has the characteristics of the groundwater milieu (Juberthie, 1995). Underground habitats are very favourable ecosystems for scientific studies as they are generally delimited and contain relatively immense biotopes for many animal species (Boutin, 1997, Ferreira, 2005, Boutin and Coineau, 2004). Groundwater media are differentiated by the nature of the parent rock, the physico-chemical characteristics of the surrounding water and the climatic conditions (Juberthie, 2000).

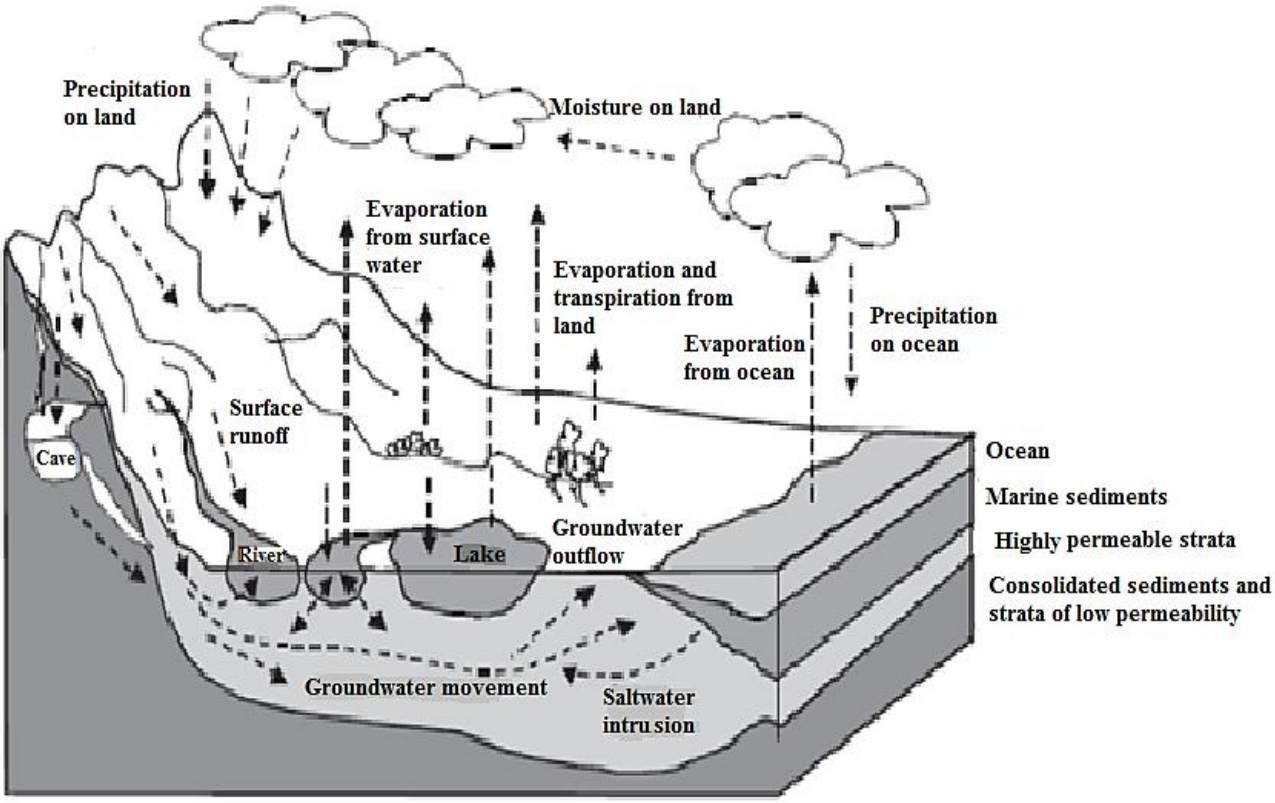



**Figure 1:** The hydrological cycle (Adapted from Danielopol et *al.*, 2003)

The hydrological cycle (Figure 1) illustrates linkages and flows between atmospheric, surface, ground and marine water bodies. The resulting water balance determines the volume and quality of fresh water available to support groundwater dependent ecosystems. With respect to the available (liquid) fresh water, terrestrial ground water contributes 94%. Hydrological recharge of aquifers is geographically very variable and strongly dependent on climate, geology, soil type, vegetation, and land use, among other factors. Groundwater recharge through precipitation is complemented by naturally infiltrating surface water or by artificial recharge. In the opposite direction, ground water leaves the subsurface via springs and wetlands enters surface or is being exploited for different types of usage (Scanlon *et al.*, 2002).

### I.1.2. Classification of underground ecosystems

The underground ecosystem can be divided into the terrestrial and the aquatic underground ecosystems (Boutin and Coineau, 2004),

#### I.1.2.1. Terrestrial underground milieu

Terrestrial underground milieu consists of karst and caves, sub-soil and terrestrial interstitial habitats.

##### I.1.2.1.1. Karsts and caves

A karst refers to any limestone formation eroded by water on and below the surface, whose formation contain underground network of fissures, cavities, galleries and caves (Juberthie, 1995). It is under the direct influence of microclimates and absolute darkness leads to the rarity of photosynthetic green plants (Camacho, 1992). Consequently, primary consumers are also very rare and almost all of the food resources come from the epigeal environment making the fauna generally predators and preys (Juberthie and Decou, 2003). Karsts receive an energy which reduces progressively as it is transmitted to the deepest parts by conduction of rocks, therefore, water and air enter due to the presence of fissures. In the opposite direction, karsts receive energy from the depth of the sub-soil in the form of geothermal transmission (Andrieux, 1971).

A cave constitutes only a small portion of the underground ecosystem which is the portion that consists of cavities and galleries of large size penetrable by man (Juberthie, 1995).

##### I.1.2.1.2. Sub-soil

This environment is made up of piles of limestone fields or not, covered by a layer of sufficient soil which offers a determined protection in the interstices of the sub-soil. The microclimatic conditions inside are comparable to those that prevail in caves.

#### I.1.2.1.3 Terrestrial interstitial habitat

Terrestrial interstitial habitat has been described as the Mesovoid Shallow Substratum (MSS) which is the compartment of terrestrial subterranean biome located between the base of the mineral soil and the bed rock. It is also referred to as the superficial underground environment and it is that portion of the underground ecosystem which is directly in contact with the lowest horizon of the soil (Juberthie *et al*., 1980, Howarth, 1981).

Two faunal communities inhabit the MSS, the first consists of groups inhabiting only the MSS (troglobitic) and the second community is composed of soil dwellers that actively enter the MSS for food and humidity, or drift in with the flow of meteoritic water (troglophilic species). Some are food supply for zoophagous species, while others are predators or parasites. The MSS evolves cyclically with three stages which are;

A juvenile stage, colonized by soil- or cave-dwellers, a mature stage with an equilibrium community and the old stage characterized by the collapse of voids and the disappearance of fauna. This cycle takes an average time of ten thousand to perhaps a hundred thousand years (Juberthie and Decou, 2003).

### I.1.2.2. Aquatic underground environment

Groundwater is found in two zones. The unsaturated zone immediately below the land surface, which contains water and air in the open spaces or pores and the saturated zone where all pores and rock fractures are filled with water and which underlines the unsaturated zone (Juberthie, 1995). Underground water comes from water vapour and gaseous emanations liberated from magma from the depths of the earth (Banton and Bangoy, 1997). The water can be stagnant, can displace laterally following the slope of the impermeable layer or at times, at the origin of a stream, but their displacement is determined by the regional geomorphology (Nola *et al.,* 1998).

#### I.1.2.2.1. Phreatic layer

The phreatic zone constitutes a part of the interstitial aquatic environment and it is the deep portion of the aquifer that does not experience exchange with the stream water (Gibert *et al*., 1994; Malard *et al*., 2000 and Ward *et al*., 2000). The sediment layer is filled with water and just below, there is a mixture of both surface and groundwater. Light is attenuated rapidly with depth in unconsolidated sediments (Albuquerque and Coineau, 2003). The stability of other environmental variables (temperature, water flow, dissolved oxygen and organic matter) increases with depth from the river bed. Grain size is an important factor because most of the other factors depend on the size of the granules present.

The phreatic zone is located below the water table and is permanently water logged. It is extremely porous and consists of drains with extremely jagged edges resulting from the dissolution of rocks by corrosion, leaving the least soluble elements exposed while creating voids connecting the micro-fissures with the large cavities (Juberthie, 1995). The phreatic layer is at times more or less polluted by septic tanks, pesticides, fertilizers and other agents located at the surface (Vilaginès, 2003). It therefore provides water that is not always of good drinking quality (Tuekam Kayo, 2007).

**I.1.2.2.2. Interstitial habitats**

The aquatic interstitial habitats constitute groundwater that is filled with porous spaces between unconsolidated and saturated sediments (Albuquerque and Coineau, 2003). Such sandy biotopes occur in littoral sandy or gravelly sea bottoms and beaches within freshwater, lakes, river margins, alluvial plains, river banks and river beds. This layer has been described as the hyporheic zone where surface water and shallow groundwater mix (Juberthie, 1995). This habitat contains pebbles, gravel, sand and clayey minerals that are deposited on the beds of waterways. The hyporheic zone of rivers is viewed as a dynamic interface with surface and ground water interactions whereby, there is high bio-production and energetic transformations (Albuquerque and Coineau, 2003).

**I.1.2.2.3. Underground thermal water**

Many hot springs do not support life owing to their extremely high temperatures, the presence of toxic chemical compounds, their depths and the absence of nutritional organic matter though other thermal springs may mix with phreatic waters and become habitats of interesting stygobiotic species (Juberthie, 1995).

**I.1.3. Emergence of groundwater to the surface**

Any type of groundwater present on the earth's surface is given the general name of emergence. There are three types of underground water emergence that exist, some of which are better presented for biological studies which are springs, wells and boreholes (Ginet and Decou, 1977).

**I.1.3.1. Springs**

A spring can be limnocrene, rheocrene or holocrine, depending on the mode of appearance of water on the surface (Vilaginès, 2003).

Limnocrene springs emerge as groundwater flows from confined or unconfined aquifers into one or more pools. It initially forms a pond in a depression and when it is overflown, it forms a brook;

Rheocrene spring: it is a spring which literally flows directly out of the soil where water is often released under pressure where it directly forms a brook. Spring-fed streams are also referred to as spring brooks or spring runs. They are areas with relatively uniform temperature and the de-oxygenated groundwater contribution to the stream and they form a continuum between channels that are springs discharge dominated and those dominated by surface runoff. Runoff-dominated springs are influenced by flood-related disturbance, whereas spring flow-dominated springs tend to provide stable habitat that allows for evolutionary micro-adaptation (Hynes, 1970, Springer and Stevens, 2008);

Helocrene spring is a marshy spring whose water flows across a zone of the soil and/or a permeable rock and which eventually forms a relatively large marshy zone. The feature of this spring is a part of the land surface characterized by a local weakness of limited extent underlain by a mixture of sand, silt, clay, and water. Groundwater discharge from these helocrenes is typically saline while others may have freshwater, but low oxygen concentrations, yet still support many wetland species. Hot water emerges from some helocrenes where they support primarily bacteria, while hypersaline helocrenes can support marine relict taxa (Toth, 2003).

Due to their relatively uniform temperature and chemistry, the sources of these springs may support aquatic species that are different from surrounding habitat influenced by surface water (Hynes, 1970).

#### I.1.3.2. Wells

A well is a deep hole drilled into the soil right down to the underground water. Wells are often polluted by pollutants situated up stream and less often by those situated downstream. Diverse geological formations require different types of wells for tapping groundwater for irrigation and water supply. There are two broad classes of wells; tube wells and hand dug or open wells. Wells vary in depth and volume of water present and occasionally wells serve other purposes, such as for subsurface exploration and observation, artificial recharge, and disposal of waste waters (Vilaginès, 2003).

#### I.1.3.3. Boreholes

These are shafts of a few centimetres diameter drilled into the ground typically for the extraction of drinking water or observation of groundwater (Smart and Worthington, 2003). Boreholes are of great depths situated at alluvial layers. They do not face the risks of pollution and can reach layers that have a relatively high output (Vilagines, 2003).

## I.2. CHARACTERISTICS OF UNDERGROUND ENVIRONMENTS

The characteristics of underground environments include darkness and photoperiod, trophic level which is limited and the physicochemical aspects.

### I.2.1. Darkness and photoperiod

Darkness which is simply the absence of light is a major factor of the underground world where it is continuous. As a direct or indirect consequence of this darkness, the eyes of underground species have degenerated and eyes are totally lacking in some species and these species have also lost all pigmentation that serves as protection against ultraviolet rays (Juberthie, 1995). Darkness of these underground milieus has rendered them poor in oxygen due to very little photosynthetic activity. Its functioning is determined by hydrological exchange processes between soil and surface water (Ward *et al.*, 2000).

Underground environments are also characterized by the absence of photoperiod which is accompanied by periods of activity that is pread at random throughout the twenty-four hours in a day (Juberthie, 1995).

### I.2.2. Limited trophic resources

Food resources in underground water are largely based on low energy organic matter coming from the surface which is transferred underground (Juberthie, 1995). Another source of organic enrichment of groundwater is the washing away by rainwater from the superficial soil before sinking it underground (Nola *et al.*, 1998), the absence of vegetation and the low animal density cause a low concentration of organic matter from native origin (Ginet and Decou, 1977).

### 1.2.3. Absence of extreme temperatures, cold or hot and physico-chemical characteristics of groundwater

Lack of adaptation contributes to confining these species to the underground environment. There, the temperature remains favourable to their development and reproduction during the entire year (Juberthie, 1995).

#### I.2.3.1. Physical variables that can influence underground water quality

The most important physical variables that could bring positive or negative changes to groundwater environments and groundwater organisms are Temperature, Suspended Solids, Turbidity, Colour and Total Dissolved Solids.

##### I.2.3.1.1. Temperature (ºC)

Temperatures affect the density and viscosity of water, the solubility of gases; particularly oxygen and the rate of chemicals and biochemical reactions. The temperatures of underground environments depend on many factors, the most significant being latitude and

altitude (Camacho, 1992). In deep underground environments, there are generally constant temperatures or little temperature variations and the average value depends on the global geographical situation of the region (Andrieux, 1971).

**I.2.3.1.2. Suspended Solids (SS) (mg/L)**

Suspended Solids represent the non-soluble matter found in suspension in water and can slow down photosynthetic phenomena which contribute to the aeration of water. In groundwater, SS are made up of algae, bacteria, decomposing dead organisms, detritus of exogenic origin which is used as food by underground organisms (Ginet and Decou, 1977). SS also includes the organic and mineral particles transported in the water column. Increase in the level of SS in water leads to the reduction of luminosity and can be disadvantageous to underground organisms, causing their death by asphyxia or by clumping their respiratory organs.

**I.2.3.1.3. Turbidity (FTU)**

The measurement of turbidity makes it possible to specify the visual information on water. Turbidity is due to the presence of different types of suspended particles and it translates the presence of suspended particles in water (organic debris, colloids, plankton and microorganisms) (Devendra *et al.*, 2014). However, a strong turbidity can permit the fixation of micro-organisms on suspended particles (Derwich *et al.*, 2010).

**I.2.3.1.4. Total Dissolved Solids (TDS) (mg/L)**

Total Dissolved Solids are the sum of the cations and anions concentration present in water and they might impact on water quality adversely in many ways. TDS is directly associated with the purity of water and also the quality of water (Devendra *et al.*, 2014, Sajitha and Smitha, 2016).

**I.2.3.2. Chemical variables that can influence underground water quality**

The most important chemical variables that affect groundwater are electrical conductivity, pH, dissolved gases ($CO_2$ and $O_2$), nitrogen compounds, orthophosphate and salinity.

**I.2.2.2.1. Electrical Conductivity (µS/cm)**

Electric conductivity is the ability of an aqueous solution to take away the electric charges. The purity of water is evaluated by electrical conductivity and therefore it is a useful tool to check the purity of water (Sajitha and Smitha, 2016). The measurement of electric conductivity makes it possible to appreciate the quantity of dissolved salts in water, because majority of the dissolved matter found in water are present in the form of electrically charged

ions (Table I). Consequently, it is a variable which gives information on the level of mineralization of water (Derwich *et al.*, 2010). The pollution of well water is translated by an increase in conductivity and hence an increase in the level of dissolved salts (Zebaze Togouet, 2004; Pandey and Tiwara, 2008).

**Table I: Relation between conductivity and mineralization of water meant for consumption (Detay, 1993)**

| **Electric conductivity (µS/cm)** | **Mineralisation** |
|---|---|
| <100 | Very low |
| 100 - 200 | Low |
| 200 - 400 | A little strong |
| 400 - 600 | Medium |
| 600 - 1000 | Important |
| >1000 | Excessive |

**I.2.3.2.2. pH (CU)**

The pH value is the negative log of hydrogen ion concentration whose values usually ranges from zero to fourteen. It indicates the acidity or basicity of the water intervening in complex phenomena such as hardness, dissolved $CO_2$, alkalinity and temperature. 6.5 to 8.5 is the limit of pH value for drinking water (Namita and Alka, 2017). Its value depends on the nature of the field but it is generally near neutrality in groundwater (WHO, 2011). A little increase in pH level may decrease the effectiveness of disinfectants like chlorine thereby requiring an additional quantity (Pandey and Tiwara, 2008).

**I.2.3.2.3. Dissolved oxygen (% Saturation)**

The concentration of dissolved oxygen conditions the life of aquatic organisms (Tuekam Kayo, 2013). The quantity of dissolved oxygen in underground water is a result of fluctuation between extreme water input enriched with this gas, and its use for respiration by aquatic organisms and also by the oxidation of organic substances (Gibert *et al.*, 1994). The major source of hypogeal oxygen is due to the effect of passive diffusion from the surface in contact with air since there are no photosynthetic plants and this process is very slow (Ginet and Decou, 1977).

**I.2.3.2.4. Orthophosphates (mg/L)**

Phosphorous is one of the biological elements responsible for the growth of aquatic organisms in water (Tuékam Kayo, 2013). An increase in the phosphate level is linked to the degradation in the quantity of underground water since orthophosphate ions ($PO^{3-}_4$) represent

only a small portion of the total phosphorous in the underground water; the major part being associated to suspended material and to dissolved organic matter (Ginet and Decou, 1977). According to these authors, orthophosphates form the phosphorous that is directly available for organisms, permitting the appreciation of the degree of water pollution. Its origin in water is usually urban such as the use of phosphate fertilizers and the washing of soils that contains these fertilizers and also the use of detergents.

**I.2.3.2.5. Nitrates, nitrite and Ammonium ions (mg/L)**

Ammonium compounds are present in water due to incomplete degradation of organic matter because of lack of oxygen. It is an index of human and industrial pollution (Rodier *et al.*, 2009). Nitrates in underground environments come from the degradation and oxidation of organic matter, synthesis from atmospheric nitrogen and nitrogen fertilizers. The quantity of dissolved nitrogen varies from 0.1 mg/L to more than 10 mg/L depending on the environment (Camacho, 1992). Nitrates ($NO_3^-$) dominate in well oxygenated water while ammonium compounds are abundant in less oxygenated zones. High values of nitrates indicate rejections of waste water in superficial and underground aquatic milieu and excessive use of nitrate fertilizers (Chapman and Kimstach, 1996). Ammonia levels in excess of the recommended limits may harm aquatic life. Although the ammonia molecule is a nutrient required for life, excess ammonia may accumulate in the organism and cause alteration of metabolism or increases in the amount of pH in the body. It is an indicator of pollution from the excessive usage of ammonia rich fertilizers (Agarwal and Saxena, 2011).

**I.2.3.2.6. Total Alkalinity (mg/L)**

Alkalinity of water is its capacity to neutralise an acid. Hydroxide, carbonate and bicarbonate ions and their salts in water are the principal cause of the alkalinity in natural water which may affect the bioavailability and toxicity of several metallic environmental contaminants and pesticides to non-target and target organisms. Water with low alkalinity trap carbon dioxide and increases the concentration available for photosynthesis. If alkalinity is too low, the water may not contain sufficient carbon dioxide or dissolved carbonates for photosynthesis to occur, thus restricting phytoplankton growth. Excess alkalinity in an aquatic ecosystem can reduce that ecosystem's ability to sustain life (Namita abd Alka, 2017).

**I.2.3.2.7. Salinity (PSU)**

Salinity is the total quantity of dissolved elements present in water. Salinity of water can change the relative proportions of cations and anions of water, that which influence the chemical equilibrium and solubility of certain minerals. It also increases osmotic pressure and

strong concentrations of ions ($Cl^-$, $Na^+$ and $K^+$) which are toxic to many living organisms (Piscart *et al.*, 2011).

**I.2.3.2.8. Total hardness (mg/L)**

Hardness of water is mainly due to the presence of salts of calcium and magnesium and this reduces lather formation and also increases the boiling point of the water. The users of hard water tend to use a lot of soaps for washing. Hardness of water also leads to the formation of scales in sinks, pipe fittings and cooking utensils. According to (Durvey *et al.*, 1991) there is some suggestive evidence that long term consumption of extremely hard water might lead to increase urolithiasis, ancephaly, parental mortality and some kind of cancer and cardiovascular disorders (Table II). On the other hand, water softness (low in $Ca^{++}$ and $Mg^{++}$) could be a health problem since soft water has been linked to cardiovascular ailments (Mafany and Fantong, 2006).

**Table II: Classification of water in function of total hardness (Devendra *et al.*, 2014).**

| **Category of water** | **Amount in $CaCO_3$ (mg/L)** |
|---|---|
| Soft | 0-60 mg/l |
| Medium | 60-120 |
| Hard | 120-180 |
| Very hard | > 180 |

## I.3. CLASSIFICATION AND ADAPTATION OF ORGANISMS IN UNDERGROUND AQUATIC ENVIRONMENTS

### I.3.1. Derivation of underground aquatic organisms

Groundwater water is colonized by a relatively rich community of species made principally of invertebrates, micro-organisms and a few vertebrates (Weber, 2000). These organisms reach underground water by vertical infiltration from streams and by vertical and lateral infiltration from surface water (Gounot, 1994; Boutin and Coineau, 1990, 2004). Micro-organisms penetrate into sediments first of all temporarily and then progressively, thereby increasing vital life activities and hence permitting a better vertical migration (Boutin and Coineau, 1990). These migrations are controlled by diverse transportation processes such as (advection, dispersion, adsorption and desorption) depending on the trajectory of water flow (Gounot, 1994).

### I.3.2. Classification of underground aquatic organisms

Several different classifications have been proposed for underground organisms although they cannot easily be compared because the authors frequently use similar names but employ different definitions (Boutin, 2004). There is presently no term referring to the whole terrestrial subterranean fauna but there is the introduction of the prefix stygo for aquatic subterranean species and the prefix troglo is used specifically for terrestrial cave fauna (Botosaneanu, 1986; Galassi, 2001; Boutin, 2004). Stygofauna in this case includes all subterranean aquatic fauna, whether continental or marine, living in open water, in caves and crevices, or in interstitial water within sediments (Boutin, 2004). Aquatic underground organisms are classified into three principal groups namely stygoxens, stygophiles (epigean species) and stygobites (hypogean species), as represented in figure 2.

#### I.3.2.1. Stygoxens

These are exclusively surface-dwelling species that are occasionally transported into the groundwater and have no affinity to aquatic underground milieu but may be accidentally found there (Boutin, 2004). A majority of accidental hypogean stygoxens die and disappear locally or succeed to return to the surface. There exist among the stygoxens organisms, a certain number of species that are common to a broad ecological valence, for which environmental factors and underground trophic resources are favourable (Figure 2).

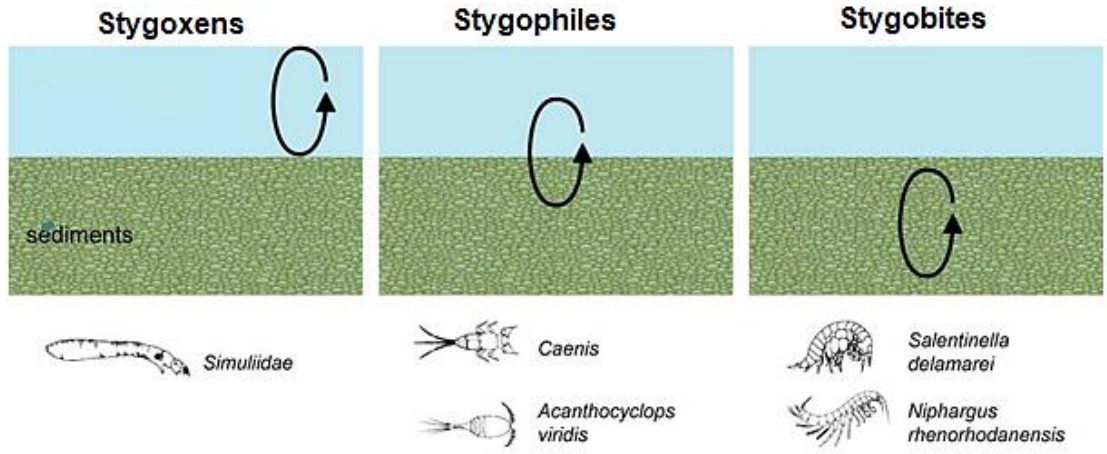



**Figure 2:** Ecological classification of stygofauna (Marmonier *et al*., 1993)

These stygoxens are more sensitive to scarcity of food and oxygen. Their occurrence is correlated with the availability of sufficient organic matter and oxygen. Most of them are pigmented and have more or less well-developed eyes. Their rate of reproduction is much higher and they compete for food i.e. stygoxens have not adapted to groundwater as a living space in general (Griebler and Mösslacher, 2003).

### I.3.2.2. Stygophiles

Stygophiles are surface-dwelling species that have an affinity to underground aquatic environments and exploit resources there to partially or totally complete their life cycle (Sket, 2004). Stygophilous organisms do not generally present morphological characteristic of underground adaptations found in stygobites (Hamilton-Smith, 1971). Stygophilous and ubiquistic species colonise habitats both in groundwater and in surface waters (Figure 2). According to Hamilton-Smith (1971), these species are therefore adapted physiologically and ecologically but not morphologically. Stygophiles belong to taxa of nematodes, oligochaetes, copepods, ostracods, Cladocera and tardigrades. If surface water together with nutrients and oxygen infiltrates into groundwater, food and oxygen will be available. As a consequence, living conditions for stygophilous and stygoxenous species improve. Stygophiles may pass all their life cycle in underground environments and are largely distributed in underground aquatic environments and sometimes are found in the superficial layer (Griebler and Mösslacher 2003).

### I.3.2.3. Stygobites or Stygobionts

These are species which are morphologically, physiologically and ecologically adapted to underground water and where they complete all their biological cycle (Boutin, 2004) as shown in figure 2. Real groundwater fauna consists of organisms, adapted to life in groundwater which means adapting to scarceness. Adapting to scarceness is their evolutionary advantage over their surface-dwelling relatives (Remane, 1952). Stygobites are blind and whitish or translucent (as an adaptation to darkness). In addition, they are elongated (as an adaptation to the narrow habitat), but most important, their metabolism is reduced. Stygobionts are tolerant to very long periods without food and low oxygen concentrations and can survive even temporary anoxic conditions. Their life span is long and the reproduction rate low. They are considered to be very poor in interspecific competition, therefore competition is not considered to be an important issue in groundwater. These special adaptations enable them to colonise nearly every groundwater, if the poor size of the matrix is wide enough and a minimum of organic matter and oxygen is available (Griebler and Mösslacher 2003). Improvement of the environmental conditions in the groundwater in the sense of increased nutrient and oxygen supply means a shift of the communities from stygobiotic to stygophilous and ubiquistic, or even stygoxenous species.

### I.3.2.4. Adaptation of organisms to underground aquatic environment

Depending on the zoological groups, the skin which envelops the body of the animals has varied structures. It forms a kind of rigid but articulated box (exoskeleton) in arthropods.

One of its layers (the cuticle) is impregnated by a resistant substance called chitin which is a universal constituent of the tegument of arthropods (Peck, 1973). Whatever the structure, the envelop covering the body of stygofauna especially stygobites is void of pigmentation (Vandel, 1964; Juberthie, 1995).

The lack of light especially sunlight is a powerful feature of most cave environments and undoubtedly, has led to the reduction and even disappearance of eyes and their constituent element in many cavernous vertebrates as well as invertebrate species (Culver *et al.*, 1995). Underground organisms, be them aquatic or terrestrial, they lack functional eyes (Vandel, 1964). Different species compensate this loss of eyes with different adaptations such as the enhancement of the lateral line organs and taste buds in cave fish, elongated limbs, antenna and body hairs in cave arthropods to detect tactile stimuli, water or air currents (Meyer-Rochow, 2004). Generally, in underground species which lack eyes, other sensory organs for equilibrium, tactile sensitivity, chemical and metabolic receptors are more organized.

The size of the organisms is another adaptive character of underground organisms. Underground species are smaller than epigeal species of the same zoological group. This small size is logically explained in the case of phreatic or interstitial animals given the characters to filter in areas where small size and elongated body form are convergently developed (Boutin and Coineau, 2000). Ginet and Decou (1977) have shown that species of large size are excluded from underground milieus because they are incapable of actively digging a gallery of sufficient dimension.

In many underground species the absence of hormonal incitation resulting from their blind state and the absence of light hinder them from carrying out their normal biochemical reactions which usually lead to the formation of melanin pigments; individuals therefor have a clear colour. Adaptations to life in absolute darkness are identical to all these cases; but some differ. This is the case of certain bacteria and fish of marine milieus which are endowed with bioluminescence hence they fabricate their own light (Ginet and Decou, 1977).

In subterranean environments, food input is not uniformly distributed in space or time and the primary adaptation of organisms living in hypogeal habitats is the improved ability to accumulate and store large quantity of energy reserve (Oana, 2003). According to this author, the lipids of underground species contain twice the energy per unit weight compared to protein and carbohydrates. The adipose tissues can increase through excessive feeding, increased efficient feeding and improved metabolic pathways favouring lipid deposition during food-rich periods (Hüppop, 2000).

During the colonization of the hypogeal environment, the ancestral species have gradually evolved into being underground forms. This evolution, due to the selective abiotic and biotic parameters of the medium, involves many adaptive changes from the morphological and metabolic point of view than the ecological point of view. Thus, the absence of light, periods of hypoxia and limited trophic resources represent environmental constraints to which the underground organisms had to adapt. These constraints and the resulting adaptations are often closely related and convergent. For example, the slowed metabolism is considered an adaptation to hypoxia or fasting, because in both cases it allows the organisms concerned to increase their survival time. This could also explain the depigmentation and anophthalmia found in both vertebrates and hypogeal invertebrates (Christiansen *et al.*, 1996).

Underground organisms are adapted to resources and the resources are fully exploited. This exploitative ability is seen in small energy investment in reproduction (low fertility and egg laying distributed throughout the year), low energy used for cellular functioning, seen in very low respiratory metabolic level and retardation in all developmental activities and reduced activity and decreased metabolic rates are all responses to a selective pressure in order to economize the use of energy because food and oxygen are in limited supply (Malard and Hervant, 1999).

#### I.3.2.4.1. Morphological changes

The absence of light radiation results in the appearance of modifications particularly convergent morphological patterns, among which the most widespread are:

**- The general depigmentation of the body of variable intensity**

In epigeal animals, pigmentation protects the body from sunlight, and especially ultraviolet radiations. In underground environments, sunlight energy is absent.

**- Ocular regression ranging from microphthalmia to anophthalmia**

The adaption of groundwater organisms to anophthalmia is highly debated. Some specialists see it as a result of an accumulation of neutral mutation of the genes encoding the eye development (Culver and Wilkens, 2000). It is the neutralist theory that natural selection has no influence on the functional role of the eye, since darkness is total, mutation accumulate without being pre-selected (Hervant and Renault, 2002). The adaptive character of anophthalmia would then be due to the fact that the energy used in the development, maintenance and the use of the eye would be allocated to other processes, including the compensatory development of other sensory organs such as longer antennae (Culver and Wilkens, 2000).

### I.3.2.4.2. Longevity and reproduction

Unlike their superficial counterparts, underground organisms do not have any periodicity during their lifetime. The fact that underground organisms are not being subjected to day / night alternation, they do not show a daily variation of activity or metabolism (Hervant *et al.*, 2000). Similarly, reproduction which is usually cyclical in many epigeal species is relatively constant in hypogeal species when the environmental conditions are conducive (Ginet and Decou 1977; Mathieu and Turquin 1992). Underground aquatic animal's diet is directly related to the scarcity of food and probability of external contributions. Hypogeal organisms are therefore mainly scavengers (with a low proportion of predators) and thus optimize food intake. Underground organisms are also distinguished from epigeal organisms by their long life. For example, the stygobite Amphipod *Niphargus rhenorhodanensis* lives for about ten years while its superficial counterpart *Gammarus fossarum* only lives for two years (Mathieu and Turquin, 1992). The Urodela *Proteus anguinus* and the cavernicolous fish of the genus *Amblyopsid* can reach record longevities of 90 and 150 years respectively (Hervant *et al.*, 2000). There are many models explaining the longevity of living organisms among which two theories seem to work particularly well for underground organisms: the radical theory and evolutionary theory of aging.

According to the radical theory, longevity could be explained by the very high metabolism characterizing these organisms and according to this theory, the metabolism creates by-products (including free radicals) capable of damaging cells and which represent one of the most important mechanisms of aging (Finkel and Holbrook, 2000). The slower the metabolism, as is the case in underground organisms, the lower the production of by-products and the longer the life span (Speakman *et al.*, 2002). However, many examples diminish the veracity of this hypothesis for example bats live for approximately 20 years but maintain a high metabolism (Brunet-Rossinni and Austad, 2004).

According to the evolutionary theory of aging, underground organisms undergo predation age slower than those living under heavy pressure of predation (Brunet-Rossinni and Austad, 2004). This phenomenon could be explained by the use of energy (principle of resource allocation) whereby, underground organisms would invest their energy in protection mechanisms rather than those aimed at combating predators. Underground animals such as macro crustaceans are at the top of the trophic pyramid; they have no predators and therefore no longer have a reason to develop protective mechanisms against predators. The energy initially allocated could therefore be used to extend longevity. Organisms with such longevity would maximize their reproductive success. Individuals who live longer increase their

reproductive success since they can reproduce many times and increase the number of their descendants.

**I.3.2.4.3. Adaptations to the lack of food**

The scarcity of food is one of the parameters considered to be at the origin of the adaptations of groundwater animals in their environment (Ginet and Mathieu, 1968; Hüppop, 1986; Hervant *et al.*, 1997). Plants are usually found at the base of the food chain on land ecosystems, but in the absence of light, plants development is impossible. The underground ecosystems are therefore different from land ecosystems by the absence of photosynthetic activities. Subterranean ecosystems are entirely heterotrophic depending for food resources from the surface (Creuzé des Chatelliers *et al.*, 1991b). Trophic contribution is ensured only by the infiltration of water from lotic or meteoric origin, draining the dissolved organic matter into the hypogean environment (Ginet and Decou, 1977; Juberthie and Decu, 1994; Gibert *et al.*, 1994). The fungal and bacterial flora that make up the underground biofilm represent an alternative source of nutrients for hypogean macro-organisms. The response to a long-term fast among surface or epigean aquatic invertebrates is usually monophasic, showing an immediate reduction of all types of energy reserves (Hervant *et al.*, 1999). In the epigean crustacean *Niphargus rhenorhodanensis* and *Niphargus virei*, one observes a sequential use of energy reserves, with a dominant carbohydrate catabolism during the first days of fasting (which represents only 5% of the energy supply during a period of 180 days of fasting), then lipids (representing 51% of the energy consumed during the same period) and finally proteolipid (44% of mobilized energy) during the last phase of fasting (Hervant *et al.*, 1999; 2001). The best food fast survival observed in these organisms was also related to higher energy reserves (arginine, phosphate, triglycerides, glycogen), and at a much lower metabolite utilization rate than in epitope that are morphologically close (Hervant *et al.*, 2001). This allows them to feed their body with energy during a longer period of fasting. Finally, underground organisms assimilate more quickly the foods present in the environment during the post-fasting recovery period (refeeding), allowing them to better prepare for a new phase of food stress (Hervant *et al.*, 1999; 2001).

**I.3.2.4.4. Adaptations to hypoxia**

Dissolved oxygen gets into groundwater through diffusion along the unsaturated zone of the aquifer or by recharge with rainwater that is poor in oxygen or superficial streams (Malard and Hervant, 1999). In experimental anoxic condition, hyperactivity has been observed in many epigean aquatic crustaceans (just like during a food deficiency) probably

corresponding to the flight to a more oxygenated habitat (Hervant and Malard, 2005). This behavioural adaptation has the effect of reducing energy costs during periods of low oxygen (by decreasing oxygen requirements) and therefore, increase the survival time in hypoxic groundwater.

Many aquatic crustaceans can maintain oxygen consumption which is independent of the partial pressure of oxygen in the environment up to a certain critical value of the molecular oxygen pressure from which this independence is lost. This critical value of partial pressure of oxygen is significantly lower in subterranean animals, thus translating greater ability to maintain aerobic metabolism when oxygen content falls (Hervant *et al.*, 1995). Most underground animals have many adaptations metabolites classically found in hypoxia-tolerant organisms to optimize their anaerobic metabolism by increasing their yield in terms of ATP production (Hervant *et al.*, 1999). During the re-oxygenation, groundwater animals resynthesize their glycogen stock more rapidly from a terminal product known as lactate during gluconeogenesis that accumulated during hypoxic stress while epigeal organisms tend to excrete it, which is more expensive for the body (Hervant *et al.*, 1996, 1999).

### 1.3.3. Importance of underground aquatic ecosystems

Considered as an essential component of the water cycle, underground water ensures many important hydrological functions such as, the regulation of water courses and the maintenance of humid zones; it acts as a buffer in periods of dryness and ensures the basic flow of the surface hydrographic networks (Degremont, 2005). The ecosystem-services framework relates ecosystem functions and environmental health to human health, security and the material goods necessary for well-being (Brauman *et al.*, 2007). Groundwater is a supporting service because most terrestrial and surface aquatic ecosystems depend on its availability in good quality and sufficient quantity. Regulating services include purification of water and, particularly, in situ bio- degradation of contaminants and elimination of pathogenic microorganisms and viruses, which in turn, contributes to disease control (Figure 3). Also, cultural services include large water bodies in caves that constitute tourist attractions and hot springs that are used for recreation. Underground aquatic environment services can be summarized in two main roles: the role of water reservoir and the role of biodiversity reservoir.

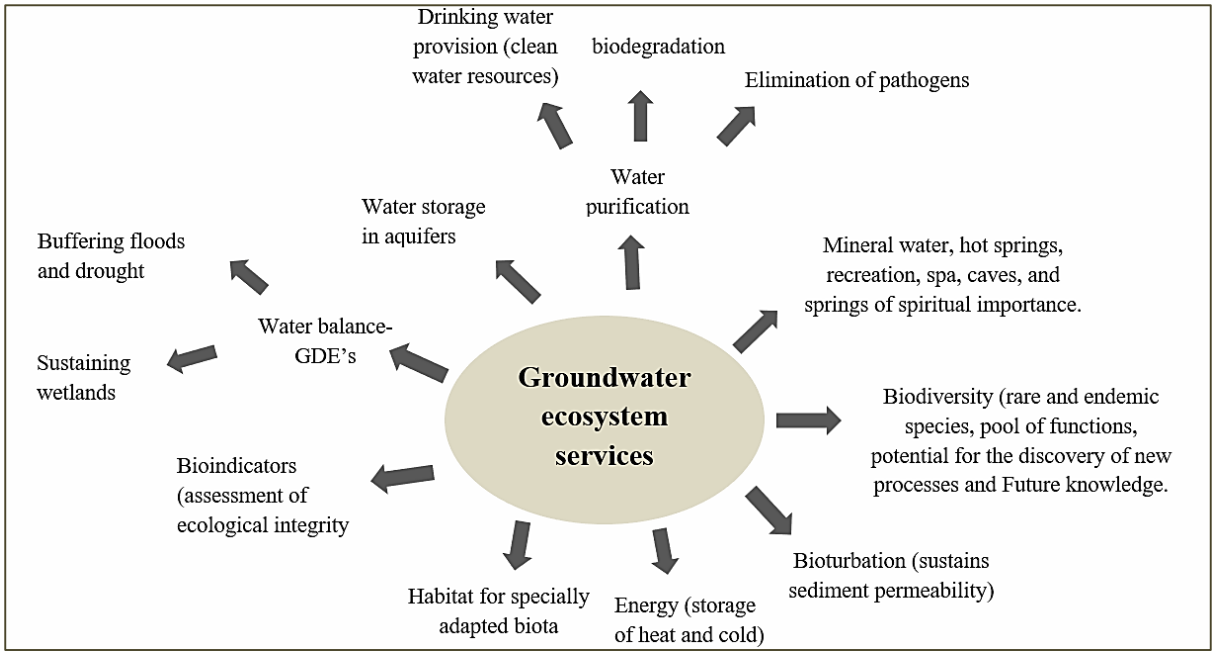



**Figure 3:** Services provided by groundwater ecosystems (Griebler and Avramov, 2015)

### I.3.3.1. Water reservoir

Groundwater with a more effective level of protection compared to surface water, offer a varied range of services starting from the simple supply drinking water to their use for recreational activities and sources of income (Margat, 2008; Mace *et al.*, 2012; Margat and Vazken, 2014; Griebler and Avramov, 2015).

Underground water whose volume is higher than that of surface freshwater (BRGM, 2006), presents a significant socio-economic value, as a priceless natural resource for domestic, agricultural and industrial needs (Aït Boughrous, 2007). Groundwater accounts for about 97% of continental freshwater liquids (Bosca, 2002). The presence of Man and his possibilities of survival depend on the existence and quality of this resource which in many parts of the world is limited and fragile. About 75 to 90% of the world's population depend on groundwater which shows how important the study of groundwater and its components is for a better knowledge of these ecosystems and to introduce new scientific concepts for its management, planning, monitoring, protection and conservation (Danielopol *et al.*, 2004).

Groundwater is an essential component of the water cycle (Castany, 1998). It constitutes the vertical dimension of river hydro systems (Amoras and Petts, 1993); it ensures many important hydrological functions (regulation of hydrological regimes rivers) and ecological functions (exchange of matter, energies and organisms) needed for the proper functioning of aquatic ecosystems (Gibert *et al.*, 1994; Ward, 1998; Malard *et al.*, 2003). It also

offers properties of quality and protection often superior to surface water that are generally more polluted (Figure 3).

Groundwater has an important socio-economic value as an invaluable natural resource for agricultural, industrial and domestic uses in both developed and developing countries (Danielopol *et al.*, 2003; Gibert and Culver, 2004). Compared to surface waters, groundwater has some advantages in terms of coverage of needs since they play an important role in the development of irrigation and domestic and industrial supplies (Danielopol 1980, Gibert *et al.*, 2004).

**I.3.3.2. Biodiversity reservoir**

Groundwater remains an essential good as long as its quality is preserved, for the health of the consumers as well as it maintains the survival of the organisms which live there (Margat, 2008; Griebler and Avramov, 2015). Regarded for a long time as primarily mineral and particularly unfavourable media for life, the recognition of the ecological importance of groundwater has been accepted for the last thirty years (Gibert and Culver, 2009). Groundwater shelters an unequal, relic, original and adapted biodiversity, compared to those of surface ecosystems and able to colonize a wide range of habitats on a continental scale (Piscart *et al.*, 2008, 2011; Dole-Olivier *et al.*, 2009b; Griebler and Avramov, 2015). It represents a significant part of the world's biodiversity and includes all the great zoological groups, certain lineage being old with several tens of million years (Figure 3).

Some lineages of ancient groundwater organisms have existed for tens or even hundreds of millions of years (Boutin, 1997; Danielopol *et al.*, 2000; Humphreys, 2000a). Indeed, all the big phyla of the animal kingdom, from Protozoa to Vertebrates, through the various groups of worms, molluscs and especially arthropods, have representatives in groundwater. This fauna can be sampled by different adapted techniques in wells, boreholes, springs, alluvial streams and in caves (Ginet and Decou, 1977). These ecosystems serve as a habitat to an extremely diverse aquatic fauna, which harbours many endemic species whose origin is often related to the geological history of the region and the possibilities of colonization offered by this environment (Juberthie, 1984). Groundwater also constitutes an ecological milieu; it acts as an original biodiversity reservoir, composed of organisms whose majority do not present an equivalence in the surface water ecosystems and certain organisms whose descendants are several million years old (Humphreys, 2000b).

Groundwater organisms live in an energy-limited habitat with comparably predictable environmental conditions. Thus, they may be very sensitive to anthropogenic impacts and

environmental changes. This sensitivity would make them potential candidates as bioindicators that could provide decision makers and groundwater managers with useful information on ecosystem status (Griebler *et al.,* 2010), an important cultural ecosystem service (Figure 3).

### I.3.3.3. Importance of stygofauna

Scientifically, stygofauna are extremely valuable as they have linkages to species with no or very few surface-dwelling representatives. Many stygofauna evolved from surface-dwelling ancestors; therefore, it is very important to improve the understanding of evolution and they can be used to help understand the aridification of some countries (Humphreys, 2008). Stygofauna play an essential role in ecosystem processes, by breaking down nutrients and recycling them through the food web. They may also play an important role in maintaining water quality through bioturbation, in almost the same manner like how earthworms contribute to the health of the soil (Figure 3). Stygofauna may be valuable indicators of threats to the integrity and sustainability of the groundwater system (Humphreys, 2000a).

Owing to their requirement for permanent groundwater and their ancient origins, the presence of stygofauna may indicate the long-term presence of suitable groundwater. This is because many species belong to lineages that are entirely confined to groundwater and so their presence there is considered to predate the breakup of the super continents and to indicate the continuous presence of groundwater throughout the subsequent climatic oscillations (Humphreys 2000a). Even the more recent colonisers of groundwater, such as subterranean diving beetles invaded the groundwater 85 million years ago (Leys *et al.,* 2003). Thus, their loss will serve to indicate that groundwater conditions have changed more or faster than in previous epochs.

#### 1.3.3.3.1. Stygofauna ecological requirements

Compared to surface environments, groundwater fluctuates less in level and in physico-chemical variables such as electrical conductivity, temperature, and pH (Hancock *et al.,* 2005). Groundwater is also generally lower in dissolved oxygen and has less readily available organic matter than surface water environments (Humphreys, 2002). As there is no direct photosynthesis in aquifers, stygofauna rely on connections to the land surface to provide them with food. These connections may be hydrological, with infiltrating water bringing dissolved or particulate organic matter to form the basis of subterranean food webs, or it may be more direct, with tree roots that extend below the water table providing leachates or organic carbon or fine rootlets for food (Hancock *et al.,* 2005). Generally, stygofauna biodiversity is highest near the water table and declines with depth (Datry *et al.,* 2005). Stygofauna biodiversity is

also higher in areas of recharge where the water table is close (< 10 m) to the land surface (Humphreys, 2000; Hancock and Boulton, 2008). This is because the water table is likely to have the highest concentration of oxygen and organic matter. Stygofauna still occur at considerable depth below the water table, but are fewer in number, have lower diversity, and may be different species (Datry *et al.,* 2005). In some karstic aquifers, where there is relatively high vertical exchange, or flow does not come into contact with large microbial surface areas (such as occurs in sedimentary aquifers), stygofaunal communities can occur at depths exceeding 100 m (Humphreys, 2000b).

**1.3.4. Origin of groundwater fauna**

The marine origin of all living organisms that occupy the continents was discovered a very long time ago (Stock, 1980). Thereafter, many stygobiologists considered that, there was the colonization of continental waters by marine organisms. Several models were therefore elaborated to account for the relatively complex mechanisms of changes of the medium and the correlative evolution of the animals concerned. One can with this effect quote the Zonation Model (Iliffe, 1986), Regression Model (Boutin and Coineau, 2004), Model of active colonization (Rouch and Danielopol, 1987), Two-step model (Notemboom, 1991), the three step model (Holsinger, 1994), adaptive model (Stoch, 1995) and the Two-phase Model (Boutin an Coineau, 1990; Coineau and Boutin, 1992). Coineau and Boutin (1992) synthesised that, the stygobites living in inland subterranean waters belong to two groups: limnocoid and thalassoid. Thus, the colonization of underground medium by fauna can be explained, according to Coineau and Boutin (1992) in the Two-phase model by two ways of colonization (Figure 6) in two successive stages:

The first stage is by surface water whereby, the organisms pass by streams, rivers or lakes and sometimes by ground water of the continental caves which were first colonized initially. The passage in the interstitial biotopes of the phreatic nappe, or of groundwater in general, is a secondary phenomenon which subsequently leads to an active dispersion of animals in surface fresh waters. In this way, one can distinguish a horizontal transition (active or passive colonization of the continental interstitial groundwater) and a vertical transition (active colonization of the littoral interstitial environment). The organisms that fall under this group are the limnocoid stygobites (the marine ancestors of which lived in surface freshwaters before groundwater colonization).

The second stage consists of the colonization of biotopes which differ from the preceding one. Freshwater stygobites of marine origin had first undergone the adaptive evolution necessary for vertical transition (passage towards the interstices or burrows). The

horizontal transition took place a second time, and each time phreatobite organisms of marine origin had to move long marine distances from the shores. This phenomenon can be active or passive (Boutin, 2004). They are thalassoid stygobites (species which colonised continental groundwater from the marine environment through the littoral interstitial zone during a marine regression). During their evolutionary history, the vertical transition (which allowed the population of marine sediments or the marine caves) preceded horizontal transition (usually passive when the sea was withdrawn) which allowed the population of underground fresh water in continental areas. It is understood that these thalassoid stygobites can be used like indicators of paleogeographical changes. The most recent studies show that diversity and even sometimes the presence of ground water fauna vary according to the quality of water (Lafont *et al.*, 1992; El Adnani *et al.*, 2007; Aït Boughrous, 2007), conditions of the medium (Gibert and Deharveng, 2002) or sources of food available.

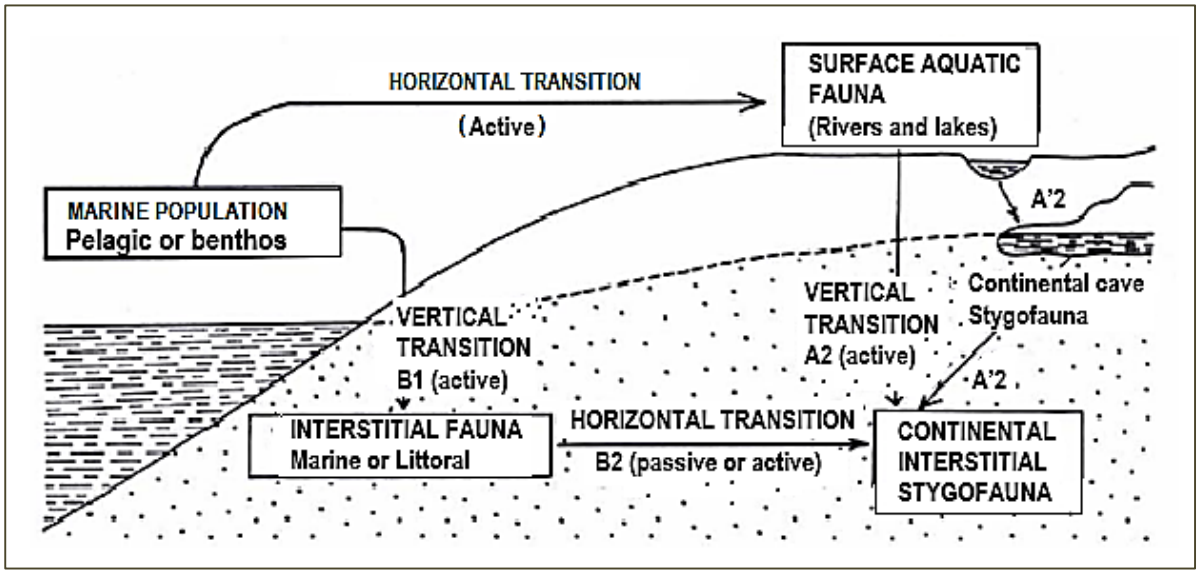



**Figure 4:** The two-way colonisation of continental groundwater according to the two-step model; A: transition via surface freshwaters; B: transition via littoral interstitial waters (Boutin and Coineau, 1990)

### 1.4. POLLUTION OF GROUNDWATER ENVIRONMENTS

Growing industrialization, waste deposition, and the exponentially increasing production and use of synthetic chemicals, which are often released into the environment, put groundwater resources under growing pressure (Figure 4). Today, groundwater quality is poor in many areas of the world as a result of pollution (Danielopol *et al.*, 2003).

### 1.4.1. Impact of pollution on stygofauna

Stygofauna are potentially threatened by activities that change the quality or quantity of groundwater, disrupt connectivity between the surface and aquifer, or remove living space. This has become a particular issue for mining proponents over the last decade or so, principally because of the perceived biodiversity value of stygofauna and the fact that little is known on their environmental water requirements (Avramov *et al.*, 2010).

Water abstraction, artificial filling and contamination of aquifers (including the clogging of pore spaces by the mobilisation of fine sediments) are threats to stygofauna (Hancock *et al.*, 2005), especially where groundwater may affect the entire distribution of short-range endemics.

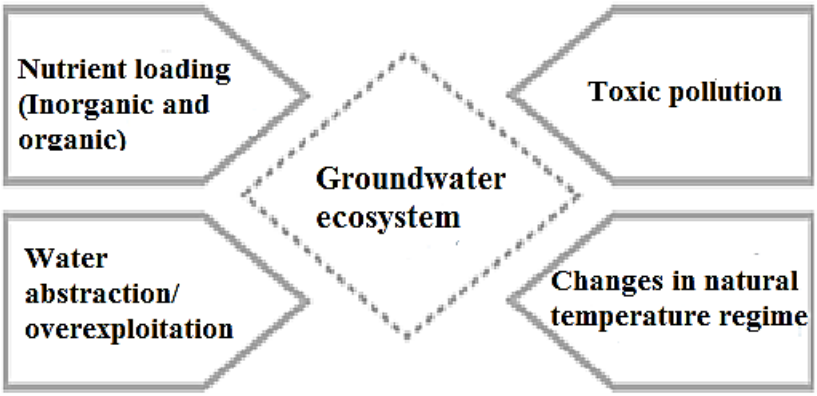



**Figure 5:** Anthropogenic stressors affecting groundwater ecosystems and their functioning (Avramov *et al.*, 2010)

Many species need stable conditions. However, rapid decrease in groundwater level or the creation of too much separation between the land surface and the water table, could lead to loss of biodiversity.

Another critical factor that makes stygofauna vulnerable to human activity is their high degree of endemism (Humphreys, 2008). This comes about because, unlike many surface-dwelling aquatic invertebrates, stygofauna do not have aerially dispersing life stages. To migrate between areas, stygofauna must be able to swim or crawl, and any barriers to this, such as an area of lower porosity, sections of poor water quality, or other disruptions, prevent natural species migration (Humphreys, 2002). This also means that stygofauna are poorly equipped to re-colonise an area once it has been disturbed. Many species of stygofauna are restricted to small geographical areas (Humphreys, 2002). This means that any process that threatens the aquifer, potentially threatens an entire species. There is also a high degree of endemism in alluvial aquifers, even between adjacent systems (Hancock and Boulton, 2008).

### 1.4.2. Impact of pollution on water quality

The impact of pollution on water quality has been explained by the conceptual model on driving forces and their outcomes on groundwater pollution (Kristensen, 2004) adapted from Drivers Pressures State Impact and Responses (DPSIR) model in connection to water problems (Figure 5). The model explains the reasons of demeaning groundwater quality and the unevenness comes as an outcome of driving forces such as increase abstraction rates, increased population, urbanization and pressure like chemical intrusion, poor waste disposal.

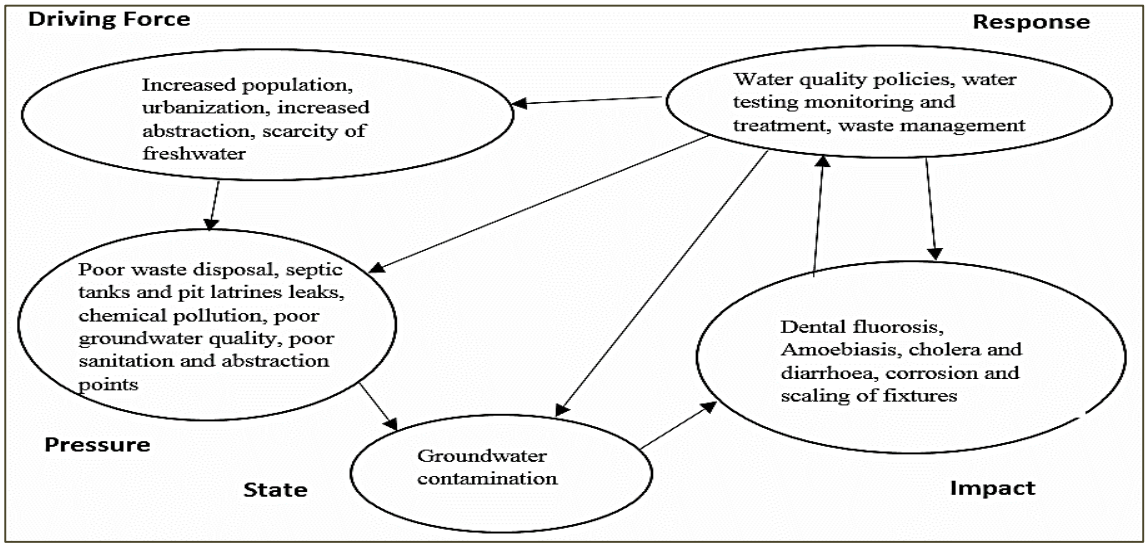



**Figure 6:** Conceptual model on driving forces and outcomes of groundwater pollution (Kristensen, 2004).

The increase in population, urbanization and abstraction reduce hygienic sewage structures thereby, compromising the excellence of septic tanks, pit latrines and sanitation as a whole. When these pressures are exerted on groundwater sources, their levels reduce, their quality decrease and this may cause dental fluorosis in case of high fluoride levels, amoebiasis, cholera and diarrhoea when the water has faecal coliforms (Yongsi, 2010). These pressures also cause corrosion and scale forming in boilers and water fixtures due to too much calcium and iron in the groundwater. Change in the colour of groundwater from crystal clear to whitish or brown and suspended solids or dissolved solids as well as alkalinity or acidity will also appear due to increase pollution of groundwater. When these happen, the responses may include formulation of groundwater testing, monitoring and management programs, permission on abstraction and waste management policies to reduce contamination of groundwater.

## 1.5. GROUNDWATER AND CLIMATE CHANGE

### 1.5.1. Impact of climate change on the variability of groundwater quantity and quality

Climate change and variability directly and indirectly affect groundwater quantity and quality in many complex and unprecedented ways (Holman, 2006; Dettinger and Earman, 2007; Earman and Dettinger, 2011; Treidel *et al*., 2012; Taylor *et al.*, 2012). Besides the direct effects of climate changes impacts on surface water availability and its suitability for utilization, the assessment of climate variability consequences on groundwater resources is still more complicated (Younes *et al.*, 2018). Potential impacts of the drought trend on subterranean hydrogeologic systems are often evaluated in terms of quantity and quality deterioration depending on both natural and anthropogenic effects.

Direct effects are related to the infiltration of rainfall water, changing in recharge conditions, and interaction with surface water while indirect effects are attributed to removing water from storage and increasing pumping, which may affect hydraulic conductivity, storage capacity and compaction acceleration of the aquifer (Younes *et al.*, 2018).

Increasing abstraction with reduced recharge can reduce groundwater levels significantly. Groundwater recharge depends on the distribution, amount and timing of precipitation, evapotranspiration, snow cover thickness and snow melt characteristics, and land use/land cover. Recharge to an aquifer depends on the groundwater level, with lower positions normally increasing the capture zone and recharge. The properties of the aquifer are also essential; small, shallow unconfined aquifers respond more rapidly to climate change, whereas larger and confined systems show a slower response. Unconfined aquifers, especially surficial and shallow aquifers, are more likely to have renewable groundwater on meaningful time scales and will be particularly sensitive to changes in variability and climatic conditions (Winter, 1999; Healy and Cook, 2002; Lee *et al.*, 2006). Confined and deeper aquifers are more likely to have non-renewable groundwater and will be less sensitive to the direct effects of climate variability and change. Non-renewable groundwater is vulnerable to the indirect effects of increased human abstraction to meet current water requirements (Wada *et al*., 2012) and future water demand under a changing climate (Treidel *et al*., 2012).

Predicting spatiotemporal changes in the magnitude, timing and mechanism of recharge is complex in most climate regions. For example, in semi-arid regions, only heavy rainfall events result in groundwater recharge, whereas in humid regions an increase in heavy rainfall events can reduce recharge rates because most water may be lost through runoff (Bates *et al*., 2008).

In cold climates, seasonal variations in water level are common where a permanent snow cover hinders groundwater recharge in winter, while snow melt water replenishes aquifers in spring (Kuusisto, 1984; Rutulis, 1989; Van der Kamp and Maathuis, 1991). Groundwater quality changes will be a consequence of changed recharge patterns and land-use (Klove *et al.*, 2013). Reduced soil frost result in more recharge and less overland flow (Okkonen and Klove, 2011). This can increase groundwater availability (Jyrkama and Sykes, 2007) but also increase risk of leaching of contaminants during winter (Okkonen *et al*., 2010). Warmer climate increase might influence pesticide leaching to groundwater, but the processes are complex and mainly related to land use changes driven by changes in climate (Bloomfield *et al.,* 2006). Reduced groundwater level increases the risk of contamination mainly from sea water intrusion in coastal aquifers (Werner *et al.*, 2013).

Changes to both groundwater and surface water levels may ultimately alter the interaction between groundwater and surface water, as well as the interaction between natural and societal water supply and demand (Hanson *et al*., 2012). Groundwater storage acts as a moderator of surface water response and climate feedback (Maxwell and Kollet, 2008).

### 1.5.2. Impacts of climate and groundwater availability on ecosystems

Groundwater ecology as a scientific discipline is in its infancy (Larned, 2012), and little is known about how climate change will affect groundwater dependent ecosystems (GDE) and their biota. Considering the importance of the ecosystem good and services provided by GDE to humankind, this lack of knowledge is unfortunate, as it hinders the adaptive management of GDE in the face of global environmental change (Klove *et al.*, 2013). Many GDE support surprisingly high biodiversity and levels of endemism (Goldscheider *et al*., 2006; Boulton *et al*., 2008), thus being of considerable conservation value. However, as they have suffered from human disturbance around the world, their unique biota is rapidly becoming threatened (Heino *et al*., 2006; Barquin and Scarsbrook, 2008; Boulton, 2009).

Changes in groundwater input can influence water quality in ecosystems in several, partly unknown, ways. A reduction in the average groundwater level tends to enhance soil aeration and thus organic matter oxidation. This can lead to nutritive enrichment, mostly through production of $NO_3$ and $PO_4$, which are generally the limiting nutrients in GDE (Wassen *et al*., 2005).

In Cameroon, the deterioration of ecosystems and their unsustainable exploitation are the main threats to biodiversity. The main indirect drivers of biodiversity loss are, among others, socio-cultural environment, namely demographic pressure, increasing urbanization and poverty, which will lead to food insecurity and the tendency of overexploitation of available

resources (Reid and Swiderska, 2008). Majority of Cameroonians currently live in cities (52.1%), with an annual rate of urbanization of 3.23% between 2010 and 2015, higher than the growth rate of the entire population (2.04%) (Reid and Swiderska, 2008). The impact of climate change on ecosystems poses a real risk to livelihoods, food security and the health of the most vulnerable individuals. To address the root causes of biodiversity loss by reducing pressures, at least 80% of the entire population must be aware of the importance of biodiversity with the link and impact of human activities on major ecosystems (Reid and Swiderska, 2008).

## 1.6. IMPACT OF ALTITUDE ON GROUNDWATER SYSTEMS

The distribution of organisms along altitudinal gradients has been studied for many groups of plants and animals. Although the general pattern is a decrease in taxon richness at higher altitudes, the decrease is not necessarily uniform nor similar for all groups of organisms (Rahbek 1995). Hydrobiologists have also studied altitudinal gradients in richness of macro invertebrates in tropical (Illies, 1964; Hynes, 1970) and temperate water bodies (Allan, 1975; Ward 1986) which demonstrated clear changes in faunal structure and taxon richness with altitude. However, these early longitudinal zonation studies were not very appropriate to examine the effect of altitude. Studies following the same water bodies from mountain areas to lowland water bodies obscure the effect of altitude because small water bodies and large water bodies, even at the same altitude, are two different habitat types with different faunal assemblages (Vannote *et al.,* 1980), and the size of the water body itself has an effect on species richness (Brönmark *et al.,* 1984; Jacobsen, 1999; Malmqvist and Hoffsten, 2000). Multi-locality studies on faunal structure and richness in water bodies of similar size at different altitudes are more appropriate for studying the effect of altitude. During the last decade, such studies have begun to appear (Ormerod *et al.,* 1994; Brewin *et al.,* 1995; Monaghan *et al.,* 2000). Most of these studies have however, included a wide range of water types, and thus did not show very clear patterns in richness with altitude. In addition, the effect of human disturbance through pollution and land use, especially at lower altitudes, has also influenced observed patterns. Hence, the specific influence of altitude on faunal composition and richness still is somewhat unclear. Patterns in taxon richness and community structure of macroinvertebrates in groundwater are dependent on the spatial scale of the study (Downes *et al.,* 1993; Carter *et al.,* 1996). However, despite the general interest in the relationship between local and regional taxon richness (Connell and Lawton, 1992; Caley and Schluter, 1997; Huston, 1999), the relationships between local and regional richness of aquatic organisms along an altitudinal gradient has been explained (Jacobsen *et al.,* 1997). They found that local

richness decreased more than regional richness with increasing altitude, and that taxon diversity increased at higher altitudes. Another study to examine relationships between local taxon richness, regional taxon richness and regional taxon turnover along an altitudinal gradient, to quantify the variance components of taxon richness at three spatial scales, to examine overall changes in community diversity of fauna and to compare the influence of altitude on taxon richness with other environmental parameters was carried out (Dean Jacob, 2003). He found out that, the invertebrate fauna was dominated by insects, mainly Ephemeroptera, Trichoptera and Diptera at all three altitudes.

## 1.7. STYGOFAUNA SAMPLING TECHNIQUES

There are several methods in sampling stygofauna among which are the use of haul nets, stygofauna traps and drift nets. These methods are used together in order to maximize the chances for trapping most of the stygofauna in the milieu.

### 1.7.1. Haul nets

A haul net is a weighted plankton net, which is lowered into the bottom of the bore or well, bounced up and down to agitate sediments at the base of the bore or well, and then slowly retrieved, filtering stygofauna out of the water column on the upward haul (Eberhard *et al.*, 2007). Net hauling requires relatively little equipment, can be done quickly and works equally well for all depths of bore or well. However, it can only be used in vertical bores and is a relatively inefficient method of sampling since several hauls must be made to obtain a sample of the stygofauna present at the time of sampling. It is recommended that the net is lowered and retrieved six times, with the operator being aware that, in most cases, the majority of animals will be near, or in, the sediments at the base of the well, so that the yield will increase if the sediments are vigorously agitated. Many stygofauna are less than 0.5 mm in length and have elongated body forms (Hancock and Boulton, 2007). A small mesh size (about 50 μm) is required for reliable collection of the smaller species of stygofauna. However, small mesh sizes tend to become clogged with sediment and also create a pressure wave in front of the net as it is retrieved, which may cause animals to be pushed away from the net. The use of a larger meshed net (about 150 μm) on some hauls is likely to improve capture rates of larger animals. Thus, it is recommended that three hauls are made with a 150 μm net, then three with a 50 μm net (Eberhard *et al.*, 2007). The contents of the net should be emptied after each haul because any animals present are likely to swim free as the net is dropped back down the bore or well. Emptying the contents into a sample jar is easier if the bottom of the net consists of a removable

vial that can be unscrewed and tipped straight into the sample jar. Cutting off the base of this vial and replacing with 50 μm mesh improves flow through the net. Animals that may be adhering to the mesh of the net should be washed into the vial before it is removed from the net (Dole-Olivier and Marmonier, 1992).

### 1.7.2. Stygofauna traps

Traps are not often used to catch stygofauna, partly because they require setting one day and pulling up a few days later. Designs are based on a suitable weighted, baited container or substrate being placed within a plankton net and lowered into the bore. Any animals washed out of the container or substrate as the trap is retrieved are caught by the net. The principal drawbacks with traps are expense (both in terms of the number of nets required and the field-time needed to set and then re-visit them) and taxonomic bias. They preferentially capture large animals and tend to miss taxa that occur in sediments (Culver *et al.,* 2004).

### 1.7.3. Drift net

The placement of drift nets at the point of issue can be effective in sampling springs. These simply consist of a net fixed in place and left to capture fauna as it is washed out of the ground. A method that consists of combining drift nets and the aid of cave divers for springs and resurgences that are accessible by humans. As the divers enter the spring the drift nets are anchored in place and removed when the divers exit. As the divers advance up the flooded gallery, they agitate the silt on the bottom and walls of the gallery, dislodging fauna that are then washed out and into the nets (Camacho, 1992). A double funnel of bronze wire netting, fixed to a glass flask and sealed with a rubber ring was developed. The device is dug into the mound of the spring's issue point and removed after several hours (Pospisil, 1994, Dole-Olivier *et al.,* 2009b).

## 1.8. STYGOFAUNAL SAMPLING AND PRESERVING TECHNIQUES

### 1.8.1. Preserving samples

Whatever sampling method is adopted, samples should be preserved in the field and returned to a laboratory for sorting under a dissecting microscope. The best most efficient preservative is 70 % ethanol but 96 % analytical grade ethanol should be used if DNA is likely to be extracted from animals (Dumas and Fontanini, 2001). Ensure that animals for DNA studies are placed in 96 % ethanol while still alive and that there is full contact with the preservative. A weak solution of buffered formalin (5 %) gives crisper fixation of crustaceans for morphological studies but it must be replaced after a couple of weeks with 70 % alcohol

(Eberhard *et al.*, 2007). Formalin is difficult to transport, needs to be handled with great care and prevents later extraction of DNA.

### 1.8.2. Sorting samples

Accumulating live samples each day and sorting them in the evening under a microscope is sub-optimal. The number of species recovered from a sample is related to the number of animals seen and it is unlikely that all species will be recovered unless the whole sample is examined carefully. This rarely occurs in field sorting, which tends to be rushed and often occurs with poor lighting and difficult working conditions. Preserved invertebrates may be sorted using a range of techniques in the laboratory. Separating a sample to get rid of as much sediment as possible and sieving the sample into size fractions assists this process. A common strategy is to use three sieves (250, 90 and 53 μm mesh size) to separate the sample into > 250, 250-90, and 9-53 μm categories (Eberhard *et al.*, 2007). Even after elutriation and sieving, sediment will be present and the volume of sample added to a sorting tray should be small enough that sediment is not more than one particle thick across the bottom of the tray.

# CHAPTER II

# MATERIAL AND METHODS

## II.1. DESCRIPTION OF STUDY SITES

### II.1.1. General presentation of the study area

Fako division has the mountain with the highest peak in West Africa, the Mount Cameroon. The division experiences all the major terrestrial ecosystems which includes rain forest, mountain forest, cold humid and dry savanna and fresh water ecosystems with their associated biodiversity. It also has marine and brackish water ecosystems with their associated biodiversity, considering the fact that it is found at the coast of the Atlantic whereby, some of the sites are relatively undisturbed and are a heaven to biodiversity. The Mount Cameroon area, most of which is found in Fako Division, is home to many endemic terrestrial species of both plants and animals with many of them threatened and critically endangered species (Folack and Gabche, 2000). Besides the natural sites, Fako Division is also home to most of the plantations of the Cameroon Development Corporation (CDC) which grows a variety of agricultural biodiversity, with the excessive use of agricultural fertilizers and pesticides.

The vegetation shows that, eighty percent (80%) of the forest land of Fako has been converted to oil palm, rubber and banana plantations by CDC and only few patches of secondary forests exist (Ngwa *et al.*, 2001). The creeks of Limbe and Tiko harbor large areas of mangrove forest which is intensively exploited for firewood. These mangrove swamps form important breeding sites for fish, shrimp and other important aquatic wildlife. It is also characterized by irregular relief made of lowlands and the surface area is confined between the surrounding hills and the Atlantic Ocean (Folack and Gabche, 2000). The vegetation of Fako is made up of low altitude mountain forest. It is characterized by lava flows due to the presence of the Cameroon mountain which is above 4000 m high. Mount Cameroon is an active Hawaiian type volcano with relatively fertile soils. It is the highest mountain in an isolated chain of volcanic uplands (Ngwa *et al.*, 2001).

This study was carried out in Fako division, South West region of Cameroon. Six towns of this division were chosen based on differences in altitude for sampling. They were; Tiko (elevation of 64 m) where 10 water points were chosen, Limbe (33 m) where 05 water points were sampled, Muyuka (average elevation 41 m) with 05 points, Owe (74 m) with 03 water points, Ekona/ Mautu (372 m) with 04 water points and Buea (870 m) with 06 water points, giving a total of 33 sampling points. The unequal distribution of the sampling points in different towns was due to the unavailability of sufficient and equal distribution in most of the towns. Example is the fact that, Tiko had a lot of wells but no springs while buea had just springs and no wells. All the springs in Owe and Ekona were sampled and these towns lack wells. Limbe and Muyuka lack springs but have wells that are also limited.

### II.1.2. Geographic situation of the study area

The towns that were sampled for this study were Limbe, Tiko, Muyuka, Owe, Ekona/Mautu and Buea (Figure 7). Tiko town is situated between latitude 44° 4’ 18" and 4° 5' 46" N and longitude 9° 20' 11’’ and 9° 22' 23 "E, along the Douala highway. Most of the town is covered with the CDC rubber and banana plantation. There is also the presence of the CDC rubber factory where rubber is being processed before exportation. Muyuka is located between latitude 4°16' 00" and 4°18' 00" and longitude 9° 22' 00" 9° 25' 50" E about 31 km from Buea, the Regional capital. It also contains the CDC rubber plantation and most of the activity carried out in this town if farming. Ekona/ Mautu is situated between latitude 4 °12' 09" and 4° 15' 54" N, and longitude 9 °19' 12" and 9° 22' 12" E. It has a stretch of the CDC banana plantation and also the palm plantation, which produces palm oil for both exportation and local use.

Limbe town is a subdivision in Fako division of the South-west region of Cameroon, located between latitude 3° 58′ 54″ to 4° 01′ 27″ N and longitude 9°11′44″ E to 9°14′25″ E. This is a coastal region that has approximately 50.5 km of Atlantic Ocean coastline to the southwest. The subdivision consists of more than 25 villages with an estimated population of 224,418 (Buh Wung, 2009) having a surface area of about 674 square kilometres with the city of Limbe as capital. It is bordered to the North and North-East by the Buea subdivisions and Tiko subdivisions respectively. It shares boundary to the west with the Idenau subdivision (Buh Wung, 2009). The main activities in Limbe are small scale fishing along the Atlantic Ocean coastline and farming especially in the CDC plantations. Buea is a center of trade, education and tourism, with a few old historic buildings, monuments and Mount Cameroon. The geographical coordinates for Buea are Latitude 4° 6' 20"  and 4° 10’ 50" N and longitude 9° 13’ 01" and 9°17' 49"E. The geographical coordinates for Owe is between latitude 4° 17' 13" and 4° 18' 20" N and longitude 9° 22' 03" and 9° 23' 32" E and it is a town in which farming is the main activity of the inhabitants.

### II.1.3. Hydrographic networks

The main water courses in Tiko include river Mungo, the Ombe river, Ndongo and Benyo streams. Many smaller streams feed the main rivers and streams. These rivers and streams empty into the Atlantic Ocean (Figure 7).

The hydrographic network of Limbe is made up of the Limbe river and the Djenguele river. The latter rises from four springs in the steep thick soil-colonized hills to the northeast and crosses the entire city of Limbe. It then enters the Atlantic Ocean to the western part of the villages of Ngeme, Isokolo and Krater which are drained by a series of Streams and rivers which get their rise from Mount Etindi (Buh Wung, 2009).

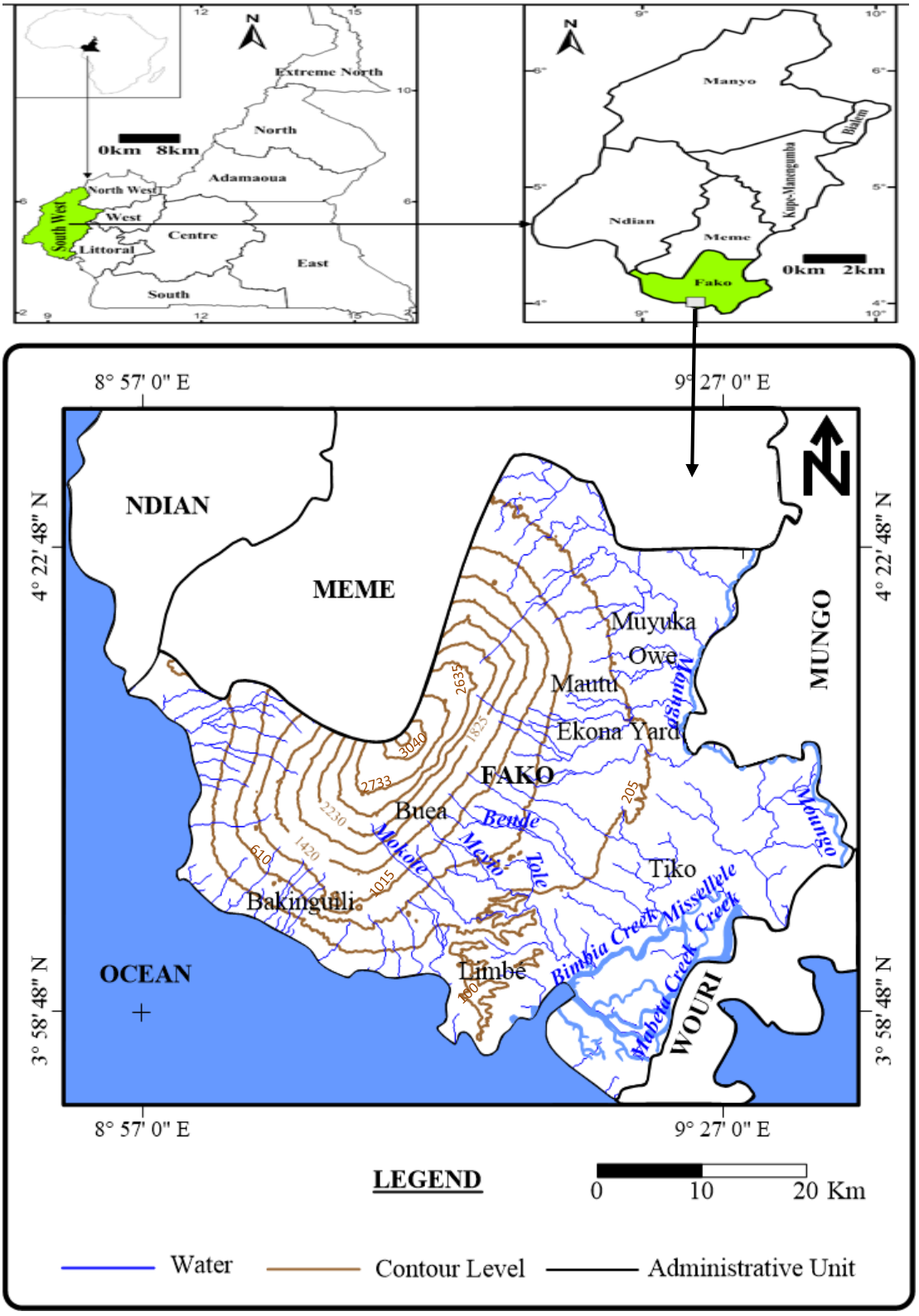



**Figure 7:** Map of Fako division showing the geographical situation of the sampling towns and the hydrographic network (NIC, 1972 modified)

The major water bodies in Muyuka and Owe are the Yoke river found in Yoke, the Mungo river that flows across Mpondu village and Lake Mboudong in Masoni village and other small streams in various villages. The water in the town of Muyuka, Owe and Ekona

empty their contents in the Moungo drainage basin while Limbe empties its water in the Bimbia creek and Tiko empties its water in the, Mabeta and Missellele creeks (Figure 7).

### II.1.4. Pedology

The soil type of Fako is characterized by old volcanic soils which is reddish and reddish brown in colour. The soil is deep, clayey and poor in plant nutrients but with very good physical properties (Buh Wung, 2009). The volcanic soils are highly exploited for plantation agriculture and that is why Fako division is dominated with the CDC plantation which deals in rubber, palm and banana cultivation. Due to poor farming techniques in the area, there is gradual decline in soil fertility. Ecologically, since Fako is found in an active volcanic area, the soil is of rich volcanic nature (black), because most of the towns in Fako are located at the foot of Mount Cameroon, known for its volcanic nature (Buh Wung, 2009).

### II.1.5. Relief

Analysis of orographic/relief map displays three principal geomorphological units classified as Units I, II and III in Fako division. The first unit is marked by altitudes that are less than 500 m and this is visible at the East region of the map. The second unit, visible mainly at the foot of Mount Cameroon is characterized by altitudes between 500 m and 1300 m. The third unit is marked by altitudes above 1300 m and they are found in the NNW of the study area. Mount Cameroon belongs to this unit, which peaks at more than 4000 m (Figure 8).

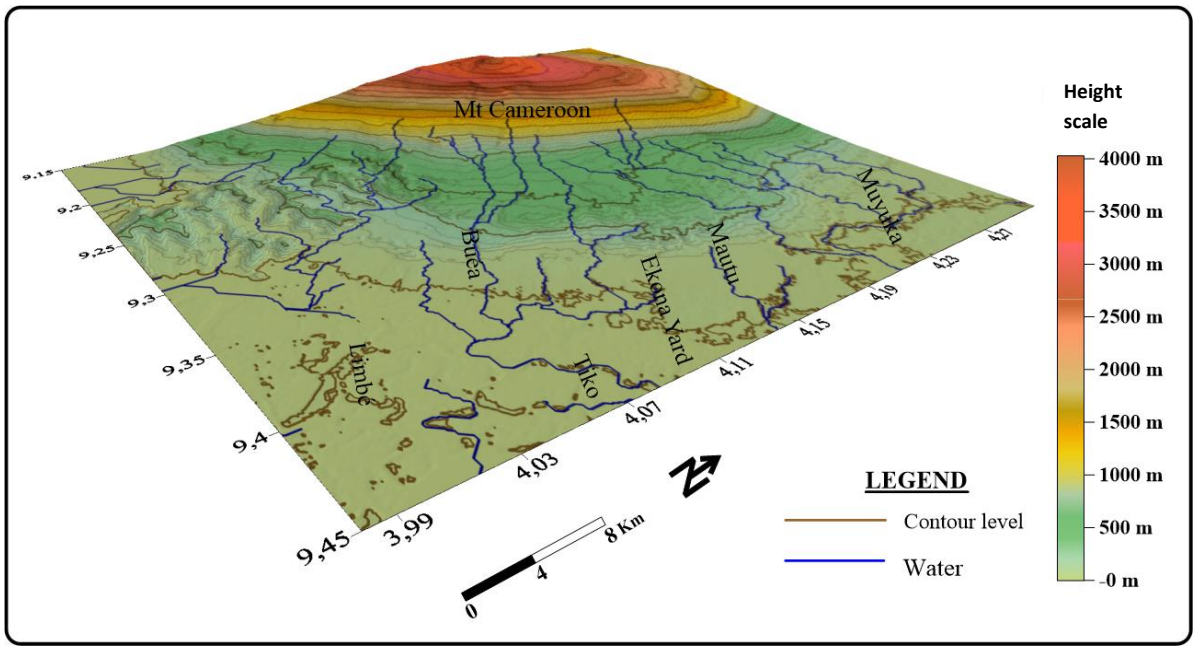



**Figure 8:** A map of relief/orography study area (NIC, 1972 modified)

### II.1.6. Climate of Fako division

Fako division experiences the subequatorial climate which is hot and humid throughout with two distinct seasons: four months of dry season from November to mid-March and eight

months of rainy season that runs from mid-March to October with a mean annual rainfall of about 3.100 mm (Che *et al.,* 2012). Annual rainfall in Fako is thus high, with yearly precipitations varying from 1.500 to 6.000 mm in the last 18 years for different stations (CDC, 2017). Peak rainfall is recorded from June to August and at times in September. June and July are characterised by intense and short-lived rainfall usually lasting less than five hours a day whereas, August and September tend to experience less intense but more prolonged rainfalls that can last for four to five days in a row (Che *et al.,* 2012). Monthly rainfall totals frequently attain over 500 mm and sometimes up to 1.000 mm in June, July and August. The mean annual temperature is approximately 26 °C and shows only limited variations of approximately 4°C throughout the year (Peel *et al.,* 2007). Humidity is generally above 85% (CDC, 2017). These characteristics correspond to the Tropical Monsoon Climate according to the Koppen climate classification scheme (Peel *et al.,* 2007; Che *et al.,* 2012).

The rainfall pattern provides suitable conditions for both perennial and annual crops to grow; thus, providing ideal conditions for two cropping seasons a year. The rainfall is one of the most important climatic factors influencing agriculture, having the highest effect in determining the potential of the area, the crops grown, the farming system and the sequence and timing of farming operations. The atmospheric humidity varies with the absolute value and the seasonal distribution of rainfall, being uniformly high throughout the wet season, and falling to lower levels during the dry season.

The variation of rainfall, temperature and relative humidity in the town of Limbe plotted for a period of eighteen years (2000 to 2017) showed that, the highest mean precipitation was recorded in the year 2010 (760.1 mm), followed by the year 2009 (541.1 mm) and the lowest value was obtained in the year 2016 (164.2). The values for yearly mean temperature show that the highest values were obtained from the years 2000 to 2007 (26.5 °C) and the lowest mean temperatures were obtained in the years 2010, 2011 and 2013(24.5 °C). Relative humidity showed high values in 2014 and 2017 (91 %) while lower values of 85 % in the year 2000 as shown on figure 9A. The ombrothermic diagram for the year 2017 is represented on Figure 9 B.

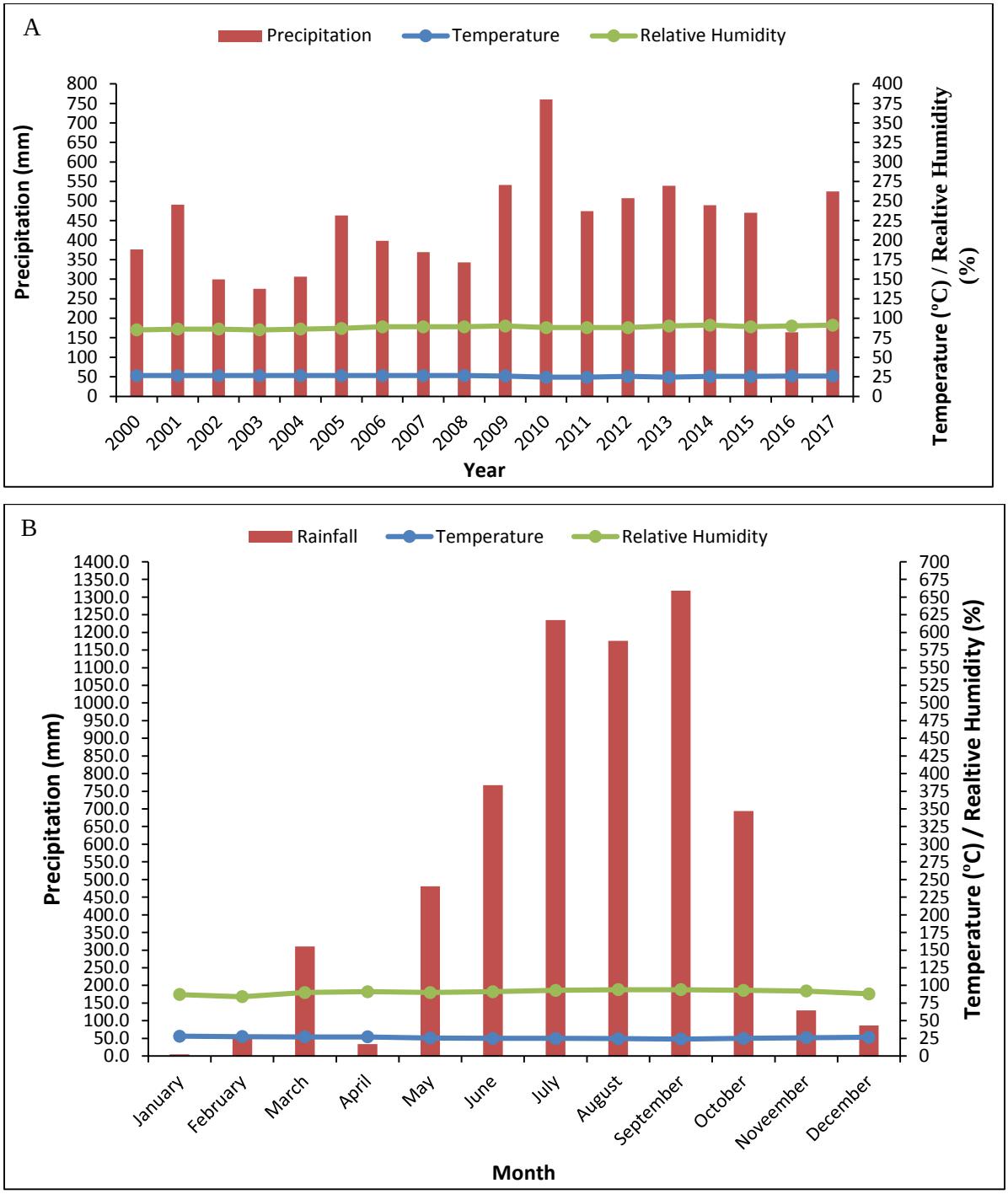



**Figure 9:** Mean yearly variation of precipitation, temperature and relative humidity from 2000 to 2017 (A) and ombrothermic diagram for the year 2017(B) Limbe

The variation of rainfall, temperature and relative humidity in the town of Muyuka, Owe and Ekona from the year 2000 to 2017 showed that, the highest mean precipitation was recorded in the year 2010 (190 mm), followed by the year 2001 (168 mm) and the lowest value was obtained in the year 2002 (109 mm). The values for yearly mean temperature showed that the highest values were obtained from the year 2004 and 2016 (27.5 °C) and the lowest mean

temperatures were obtained in the year 2010 and 2011 (26.5 °C). The highest value for relative humidity was 86 % in the year 2000 and the lowest was 78 % in 2004 as shown on figure 10A. The ombrothermic diagram for the year 2017 for Muyuka, Owe and Ekona represented on Figure 10 B.

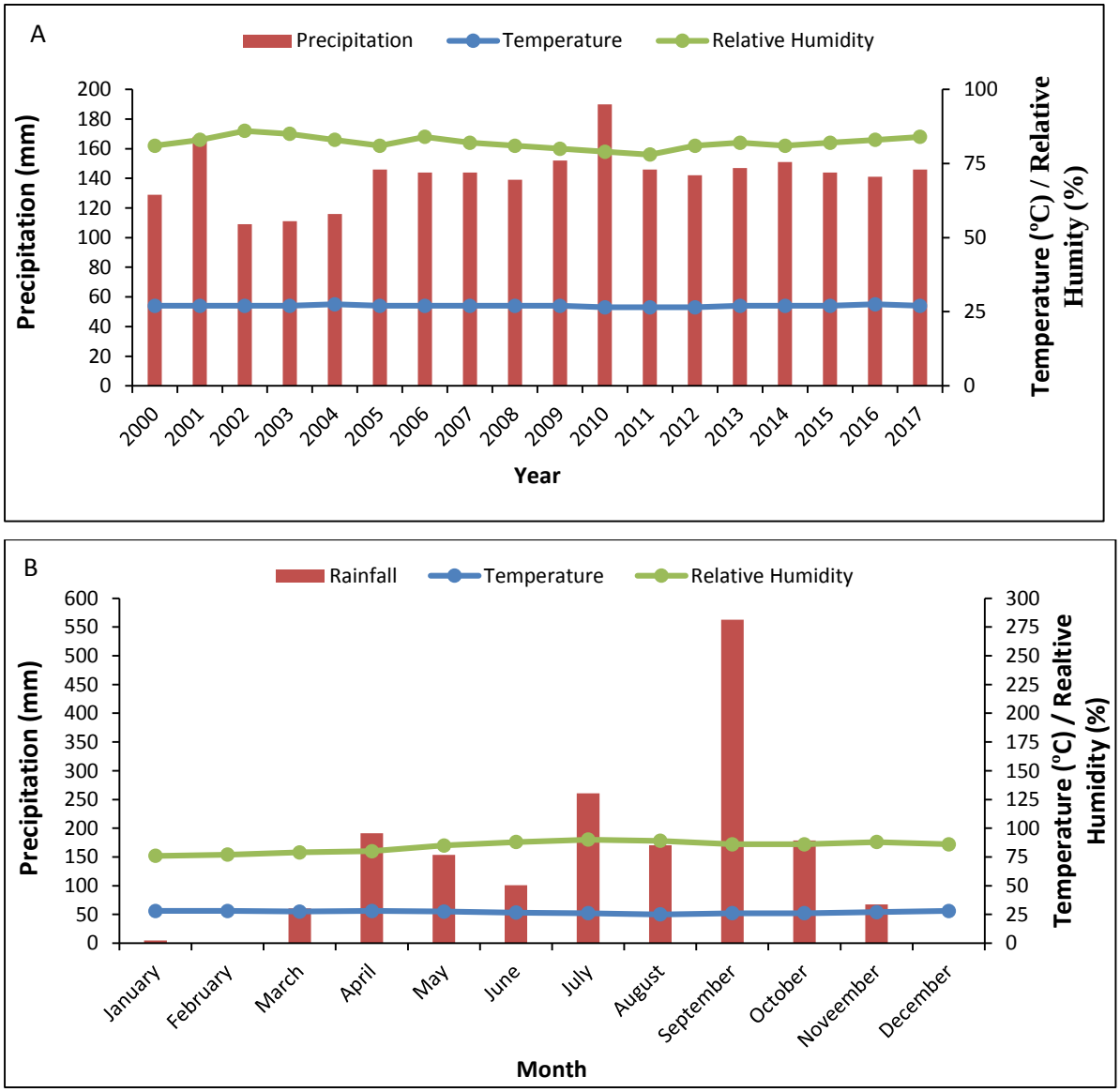



**Figure 10:** Mean yearly variation of precipitation, temperature and relative humidity from 2000 to 2017 (A) and ombrothermic diagram for the year 2017 (B) for Muyuka, Owe and Ekona

The variation of climate variables for the town of Tiko showed that, the highest values were recorded in the year 2003, 2004 and 2016 (28 °C) and the lowest mean temperatures were obtained in the year 2001, 2002, 2006, 2011, 2014, 2015 and 2017 (27 °C). The highest mean precipitation was recorded in the year 2017 (276 mm), followed by the year 2013 (261 mm)

and the lowest values were recorded in the year 2004 (40 mm) and 2003 (41 mm). Relative humidity varied from 81 % in 2015 to 86 % in 2013 as shown in figure 11 A. The ombrothermic diagram for 2017 is represented on figure 11 B.

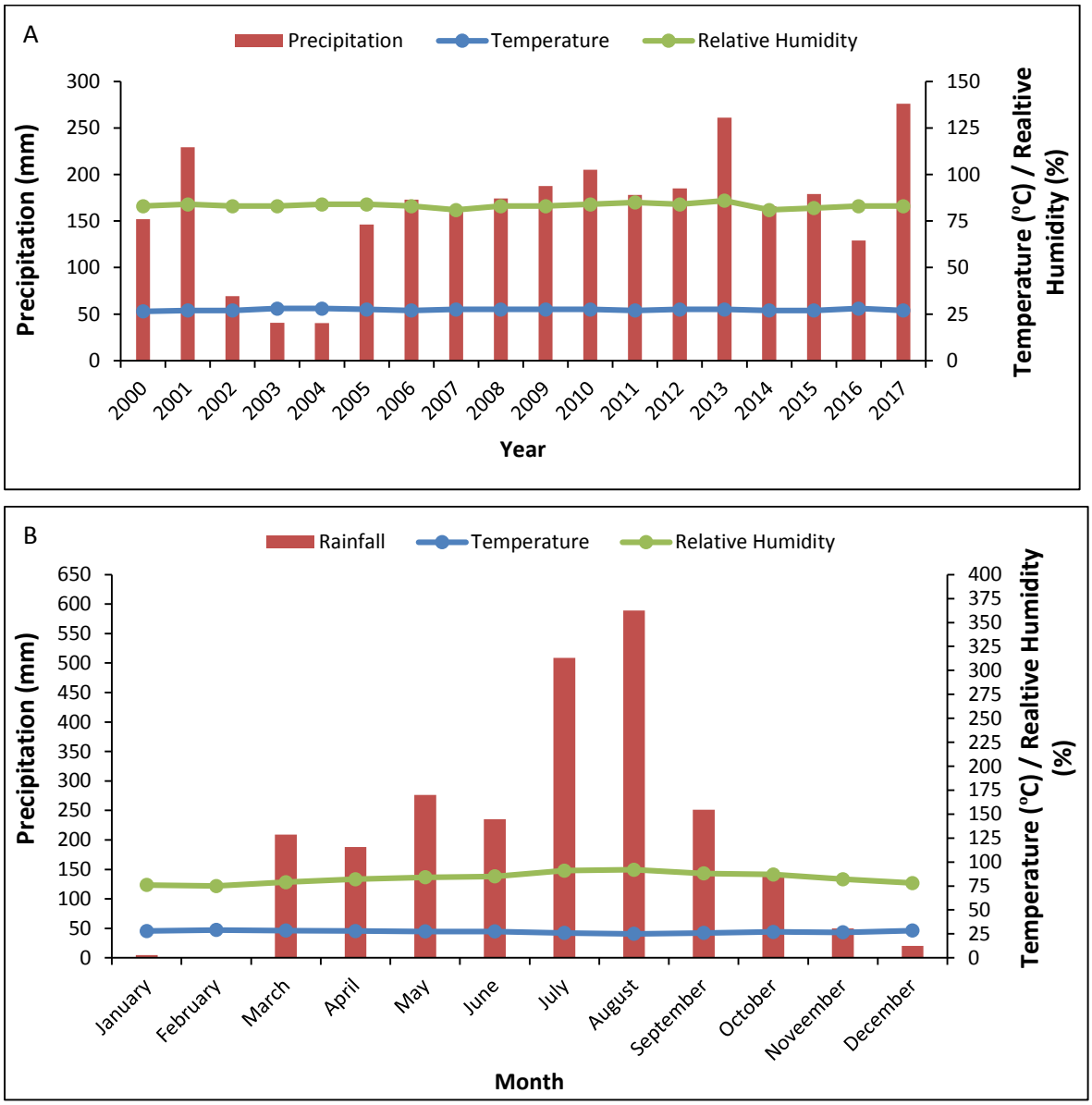



**Figure 11:** Mean yearly variation of precipitation, temperature and relative humidity from 2000 to 2017 (A) and ombrothermic diagram for the year 2017 (B) in Tiko

## II.2. METHODS

### II.2.1. Choice and description of sampling points

#### II.2.1.1. Choice of the sampling sites

The sampling towns were chosen based on the following criteria:

-The altitude or elevation above sea level of the towns;

-The accessibility of the different towns; the availability of important water points.

The water points for sampling were chosen based on the following criteria:

-The importance of the water points to the population for example most of them are used as the main drinking water sources;

-The level of protection of the water points;

Based on these criteria, 33 water points were chosen which are; five in Muyuka, ten in Tiko, five in Limbe, four in Ekona/Mautu, three in Owe and six in Buea. This gives us a total of twenty wells and thirteen springs that were sampled during the study period.

**II.2.1.2. Description of sampling points**

The altitude and the coordinate points of the different sampling points were measured using a GPS of the mark Garmin. The W and S on the sampling points refer to wells and springs respectively.

**II.2.1.2.1. Sampling points in Tiko**

The sampling point TW1 is located in Longstreet quarter. The coordinate points are 04$^{o}$ 04' 33.8" N and 009$^{o}$ 21' 44.4" E (Figure 12). It is located at approximately 10 m from a minor road. The elevation is made in square, with concrete and it is well protected with a cover (figure 13). It is covered, located at 56 m altitude and has a depth of 9 m. The piezometric level of this well is 6.8 m, with an average water column of 2.2 m (Table III). This well is surrounded by houses that are occupied by people and has about five houses that directly depend on this water points.

The well TW2 is also located in Longstreet quarter. The coordinate points for well TW2 is 04$^{o}$4' 34.5" N and 009$^{o}$ 21' 32.1" E and is built attached to the wall of the owner's house, around many houses (Figure 13). Its elevation is built with brick blocks, covered with a zinc sheet and its altitude is 61 m. This well has a depth of 45m, piezometric level of 3.4 m and a water column of 1.6 m.

The well TW3 is found in a residential area and it is well protected with a lid that is always present. At about 50 m, there is the palm plantation of the CDC in hectares of land. It is approximately 50 m from a CDC palm tree plantation and is located at approximately 180 m behind the city council. The coordinates of TW3 is 04°4' 54.3" N and 009°21' 07.3" E and the altitude is 71 m. The depth is 3.7 m, with a piezometric level of 2 m and a water column of 1.7 m (Table III).

The sampling point TW4 is a well situated behind the Tiko city council. Its coordinate point is 04°4' 53.9" N and 00921' 19.3" E and its altitude is 67 m with the presence of a small

farm land in the neighbourhood (Figure 13). It is surmounted by a curb stone made in blocks, does not have a lid and is found in an area with about six houses. The well has a depth of 3.8 m, a water column of 1.6 m and a piezometric level of 2.2 m.

The well TW5 is located in Chombes quarter, at 50 m from the principal road. The coordinate points are 04°5' 01.9’ ' N and 009°21' 19.5" E, located at an altitude of 68 m. There is the presence of banana/ plantain farm, with a pear tree acting as a canopy, blocking the sun rays from directly heating the water in this well. The well is occasionally protected, with a depth of 15 m, a piezometric level of 7.8 m and the water column was 7.2 m (Table III).

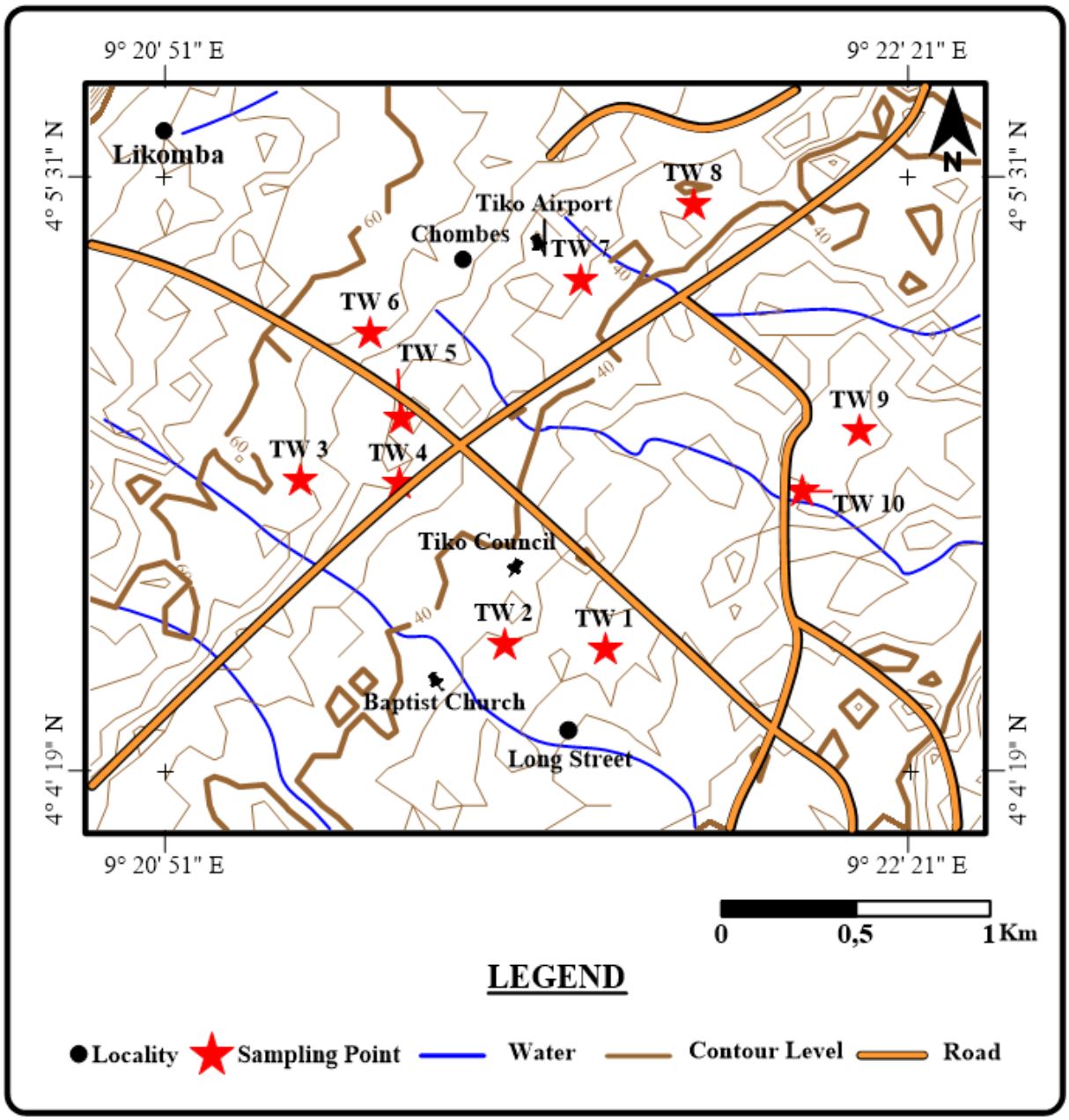



**Figure 12:** Map of Tiko showing sampling points (NIC, 1972 modified)

The well TW6 is located in Chombes quarter near a small field of plantains, just 2 m away from a community dustbin at 78 m of altitude. The coordinate points are 04°5' 12.2" N and 009°21' 15.9' ' E. The depth of this well was 12.1 m, the piezometric level was 9.3 m and the water column was 2.8 m.

The sampling point TW7 is situated at approximately 30 m from the principal highway road linking Tiko to Douala, with a banana farm upstream and in the neighbourhoods. It has coordinates as 04°5' 18.6" N and 09°21' 41.4" E. This well is partially protected and is located at an altitude of 56 m (Figure 13). The well has a depth of 2.8 m, with a piezometric level of 1.7 m and a water column of 1.1 m.

TW8 is a well that is protected with a lid and it is found close to the kitchen of the owner and just downstream there is a plantain farm. There is also a stream present at about 3 m from this water point where the plantains are found. It is surmounted by a concrete made in blocks and it is well protected and covered. The altitude is 66 m and the coordinates are 04°5' 27.8" N and 009°21' 55.0" E and it is situated in Tiko-Douala road quarter (Figure 1 and 13). This well has a depth of 10.05 m, a piezometric level of 7.5 m and a water column of 2.55 m (Table III).

The sampling point TW9 is located in the Tiko hospital new layout area. It is located at approximately 25 m from a CDC rubber plantation (Hevea) situated at approximately 100 m which is about eight hectares. There is the presence of a plantain farm in the neighbourhood and this point is near houses with inhabitants and it is protected by a lid made of roofing sheets. The coordinates are 04°5' 00.3 " N and 009°22' 15.2" E, situated at an altitude of 49 m. The well has a depth of 9.3 m, a piezometric level of 6.7 m and the water column is 2.6 m (Table III).

Well TW10 is located in the Tiko hospital new layout area. The coordinates are 04°4' 53.1" N and 009°22' 08.1" E and the altitude is 53 m. It is located at approximately 200 m away from the Tiko airport. It has a vegetation around it and is located under a pear tree (Figure 13). It has no lid and therefore, it is not protected. The well has a depth of 6.6 m, a piezometric level of 5.3 m and the water column is 1.3 m.

**Table III: Morphometric and hydrological characteristics of the sampled groundwater points in Tiko.**

| Quarters | Sampling point codes | Coordinate points | | Alt (m) | P(m) | Depth (m) | W. C (m) | PL (m) | D (m) | Lev. pro | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Latitude | Longitude | | | | | | | | |
| Long street 1 | TW1 | 04º 04' 33.8" N | 009º 21' 44.3" E | 61 | 0.7 | 9 | 2.2 | 6.8 | 0.7 | Fully protected | All uses |
| Long street 2 | TW2 | 04º 04' 34.5" N | 009º 21' 32.1" E | 56 | 0.95 | 5 | 1.6 | 3.4 | 1.1 | Not protected | All uses |
| Behind council 1 | TW3 | 04º 04' 54.3" N | 009º 21' 07.3" E | 71 | 0.5 | 3.7 | 1.7 | 2 | 1.25 | Fully protected | Periodic usage |
| Behind council 2 | TW4 | 04º 04' 53.9" N | 009º 21' 19.3" E | 67 | 0.8 | 3.8 | 1.6 | 2.2 | 1.5 | Not protected | All uses |
| Chombes 1 | TW5 | 04º 05' 01.9" N | 009º 21' 19.5" E | 68 | 0.5 | 15 | 7.2 | 7.8 | 115 | Partially protected | All uses |
| Chombes 2 | TW6 | 04º 05' 12.2" N | 009º 21' 15.9" E | 78 | 0.8 | 12.1 | 2.8 | 9.3 | 1 | Poorly protected | All uses |
| Tiko-Douala road 1 | TW7 | 04º 05' 18.6" N | 009º 21' 41.4" E | 56 | 0.6 | 2.8 | 1.1 | 1.7 | 0.8 | Poorly protected with wood | Periodic usage |
| Tiko-Douala road 2 | TW8 | 04º 05' 27.8" N | 009º 21' 55.0" E | 66 | 0.6 | 10.05 | 2.55 | 7.5 | 1 | Well protected | All uses |
| Hospital layout 1 | TW9 | 04º 05' 00.3" N | 009º 22' 15.2" E | 49 | 1 | 9.3 | 2.6 | 6.7 | 0.5 | Well protected | All uses |
| Hospital layout 2 | TW10 | 04º 04' 53.1" N | 009º 22' 08.1" E | 53 | 0.5 | 6.6 | 1.3 | 5.3 | 1 | Not protected | Periodic usage |

**Legend:** Alt=Altitude, P= Protection height above the ground, WC=Water column, PL=Piezometric layer, D=Diameter, Lev.pro=Level of protection

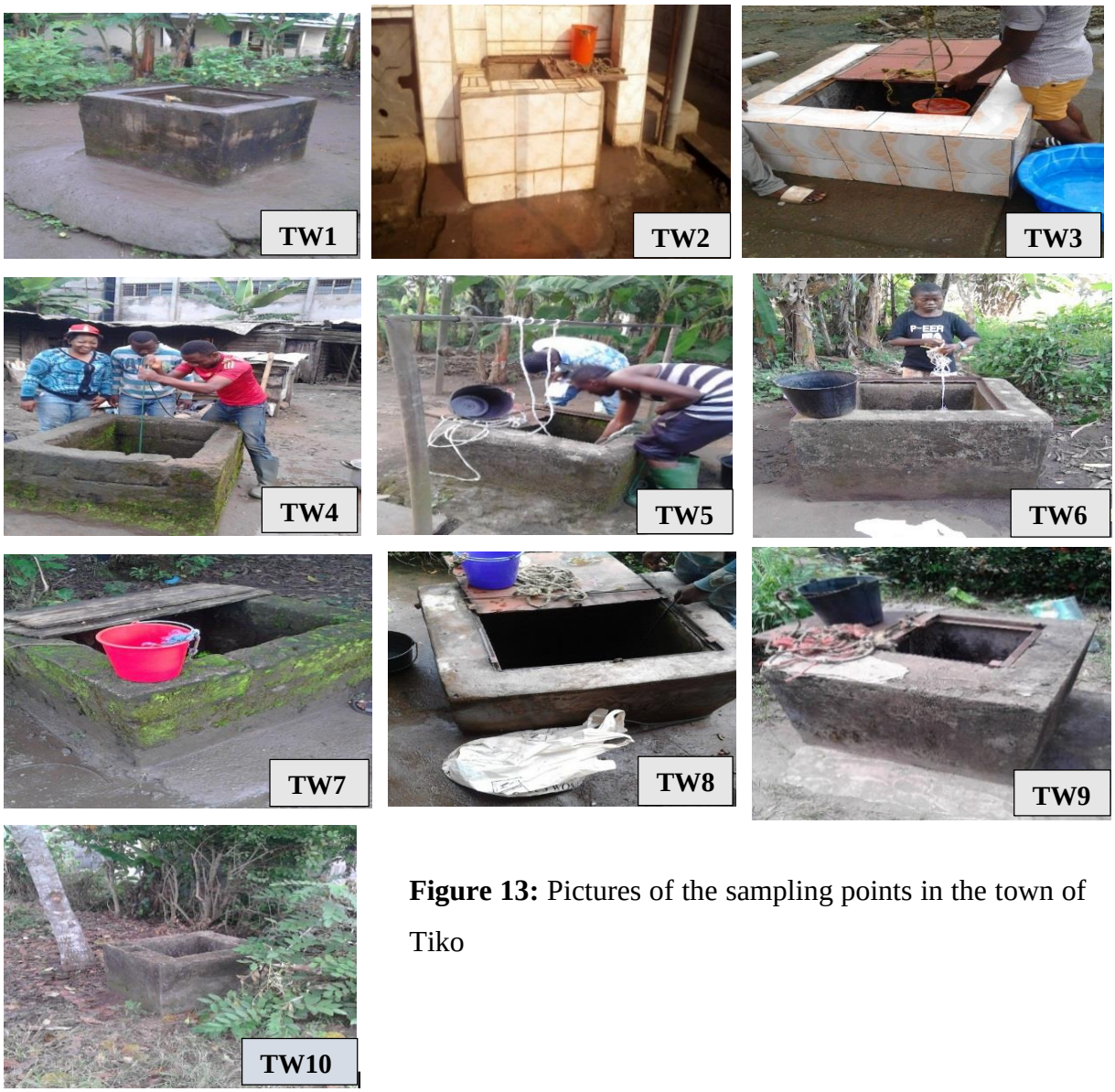



**Figure 13:** Pictures of the sampling points in the town of Tiko

### I.2.1.2.2. Sampling points of Limbe

The well LW1 is found in Dog yard quarter in Down Deach around the sea area about 30 m from the sea. Its elevation is made with a plastic barrel with the lid of the barrel used to partially cover it. The depth of this well is 2.8 m, the piezometric level is 1.7 m and the water column is 1.1 m (Table IV). The water from this well is used by the owners to clean fish, bath and to wash household utensils. Its coordinate is latitude 04° 00’ 03.6” N and longitude 009° 12’ 43.4” E, located at an altitude of 07 m.

The sampling point LW2 has an altitude of 08 m and is situated at about 50 m from the sea. Its coordinate is latitude 03°59’ 59.7” N and longitude 009° 12’ 45.1” E (Figure 14). This well is found in an area surrounded by houses of inhabitants. It is made with plastic barrel which is semi protected with a lid and is used principally to clean fish, bath and for other domestic activities like cooking and washing. The depth of the well is 3.1 m, with a piezometric level of 1.7 m and a water column of 1.4 m.

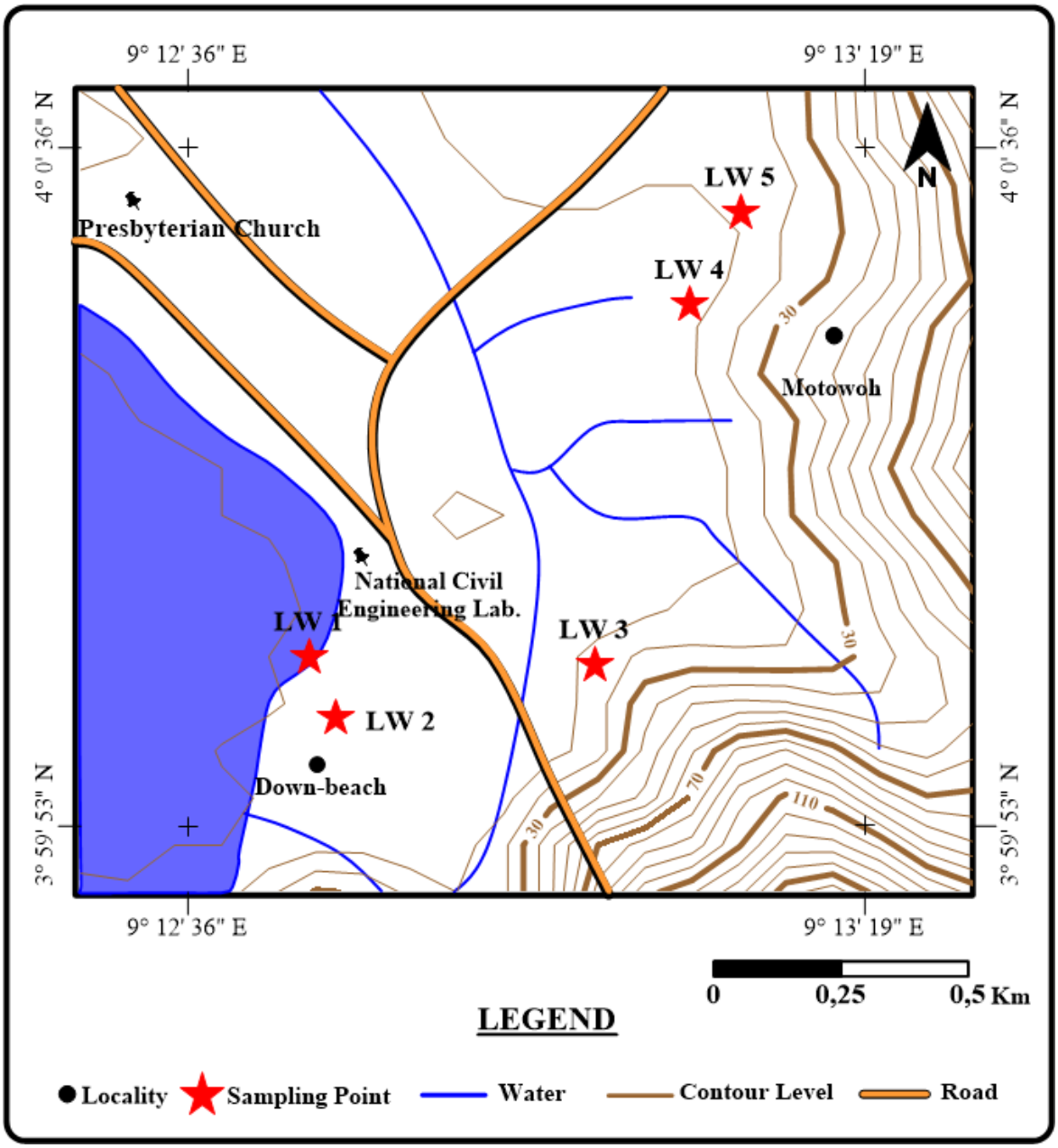



**Figure 14:** Map of Limbe showing sampling points (NIC, 1972 modified)

The well LW3 is situated in Lower Motowoh quarter, it is semi-protected with a lid and is found in an area that is swampy and flooded with water during the rainy season. There is a natural canopy created by mango trees that protect the water point from direct sunlight. It is used by the owner for cooking and washing. Its coordinate is latitude 04° 00' 03.1" N and longitude 009° 13' 01.6" E and it is found at an altitude of 25 m. It has a depth of 2.1 m, a piezometric layer of 0.1 m and a water column of 2 m.

**Table IV: Morphometric and hydrological characteristics of the sampled groundwater points in Limbe**

| Quarters | Sampling point codes | Coordinate points | | Alt (m) | P (m) | Depth (m) | W. C (m) | PL (m) | D (m) | Lev. pro | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Latitude | Longitude | | | | | | | | |
| Dog yard 1 | LW1 | 04º 00' 3.6" N | 009º 12' 43.4" E | 07 | 01 | 2.8 | 1.1 | 1.7 | 0.5 | Partially protected. | All uses |
| Dog yard 2 | LW2 | 03º 59' 59.7" N | 009º 12' 45.1" E | 08 | 1.1 | 3.1 | 1.4 | 1.7 | 0.5 | Made with rubber barrel and semi protected | All uses |
| Lower Motowoh | LW3 | 04º 00' 03.1" N | 009º 13' .6" E | 25 | 0.3 | 2.1 | 2 | 0.1 | 0.7 | Poorly protected | All uses |
| Upper Motowoh | LW4 | 04º 00' 26.0" N | 009º 13' 7.7" E | 33 | 0.8 | 6 | 1.5 | 4.5 | 1.3 | Fully protected | All uses |
| Mawoh | LW5 | 04º 00' 31.9" N | 009º 13' 10.9" E | 38 | 0.45 | 4 | 1.2 | 1.7 | 1 | Poorly protected | All uses |

**Legend:** Alt = Altitude, P = Protection height above the ground, WC = Water column, D = Diameter, Lev. Pro = Level of protection, PL = Piezometric Level.

LW4 Is a well that is surrounded by many houses and inhabitants who depend on it for water to carry out different activities like washing of dresses, dishes, cleaning the house and for cooking. It is found in upper Motowoh quarter at an altitude of 33 m, having coordinate point as latitude 04° 00' 26.0" N and longitude 009°13' 07.7" E. it is well protected with a lid and has a well-built elevation. The depth of this well is 6 m, the piezometric level is 4.5 m and the water column was 1.5 m.

LW5 is situated in Mawoh quarter and there is a stream at about 1.5 m from this point, which is protected with a lid that has many holes around it and will allow rain water and surface organisms to get into the water easily (Figure 15). It is used by the owner for all their household chores. It is situated at an altitude of 38 m and its coordinate point is latitude 04°00' 31.9" N and longitude 009°13' 10.9" E (Figure 14). It has a depth of 4 m, a piezometric level of 1.7 m and a water column of 1.2 m.

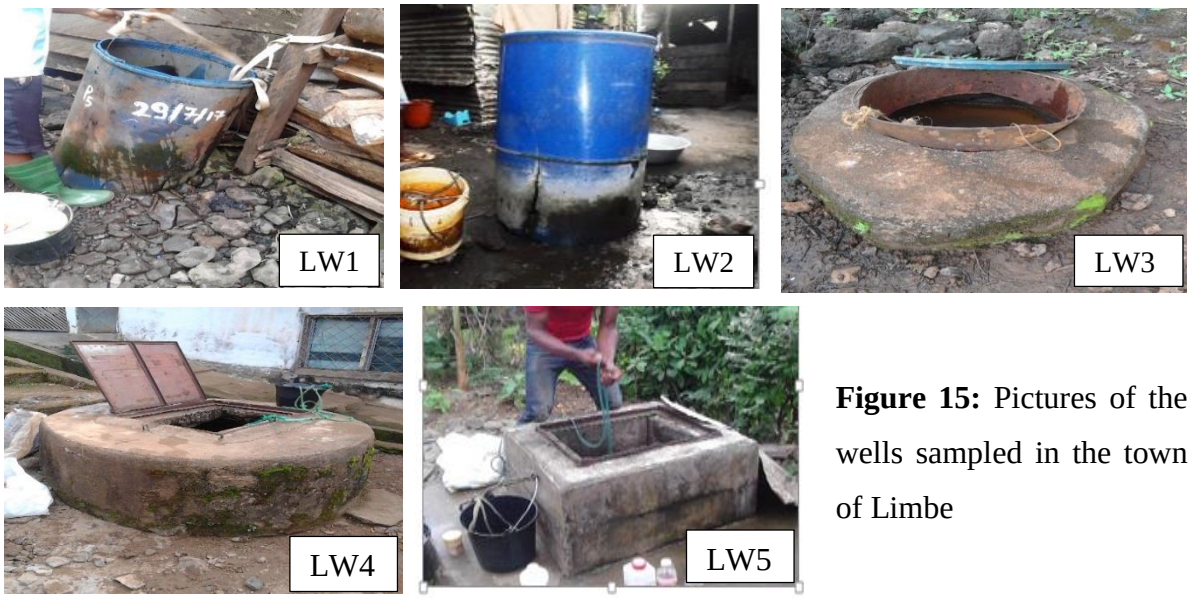



**Figure 15:** Pictures of the wells sampled in the town of Limbe

**II.2.1.2.3. Sampling points of Muyuka**

The sampling point MW1 is a well that is situated in a rural area. There are houses around this water point with people living there. The water is used to wash dresses, clothes, floor and for other domestic uses and it is situated in Owe road. It is semi protected with a roofing sheet cover. The coordinate point is latitude 04° 17’ 25.5” N and longitude 009° 24’ 13.3” E, with an altitude of 63 m (Figure 16 and 17). The depth of this well is 11 m, the piezometric level is 9 m and the water column was 2 m.

The well MW2 is found in an urban zone in stranger quarters around houses and it is protected with a covering. It was drained and cleaned by the owners about one week before the first sampling campaign. The sampling point has an altitude of 63 m, with coordinate points of 04° 17’ 31.7” N latitude and 009°24’ 44.5” E longitude and a depth of 4.2 m.

MW3 is found in sand quarter, with many houses whereby, the inhabitants of these houses depend on the water from this well. The soil is clayish with mud present all around the area and it is semi protected with a covering and found in an area where sunlight is prevented from reaching it due to the fact that it is found attached to the houses, getting canopy from the roofing sheets of the houses (Figure 16). It is situated at an altitude of 70 m and its coordinate points are latitude 04° 17’ 25.2” N and longitude 009° 24’ 37.2” E, with a depth of 5.1 m.

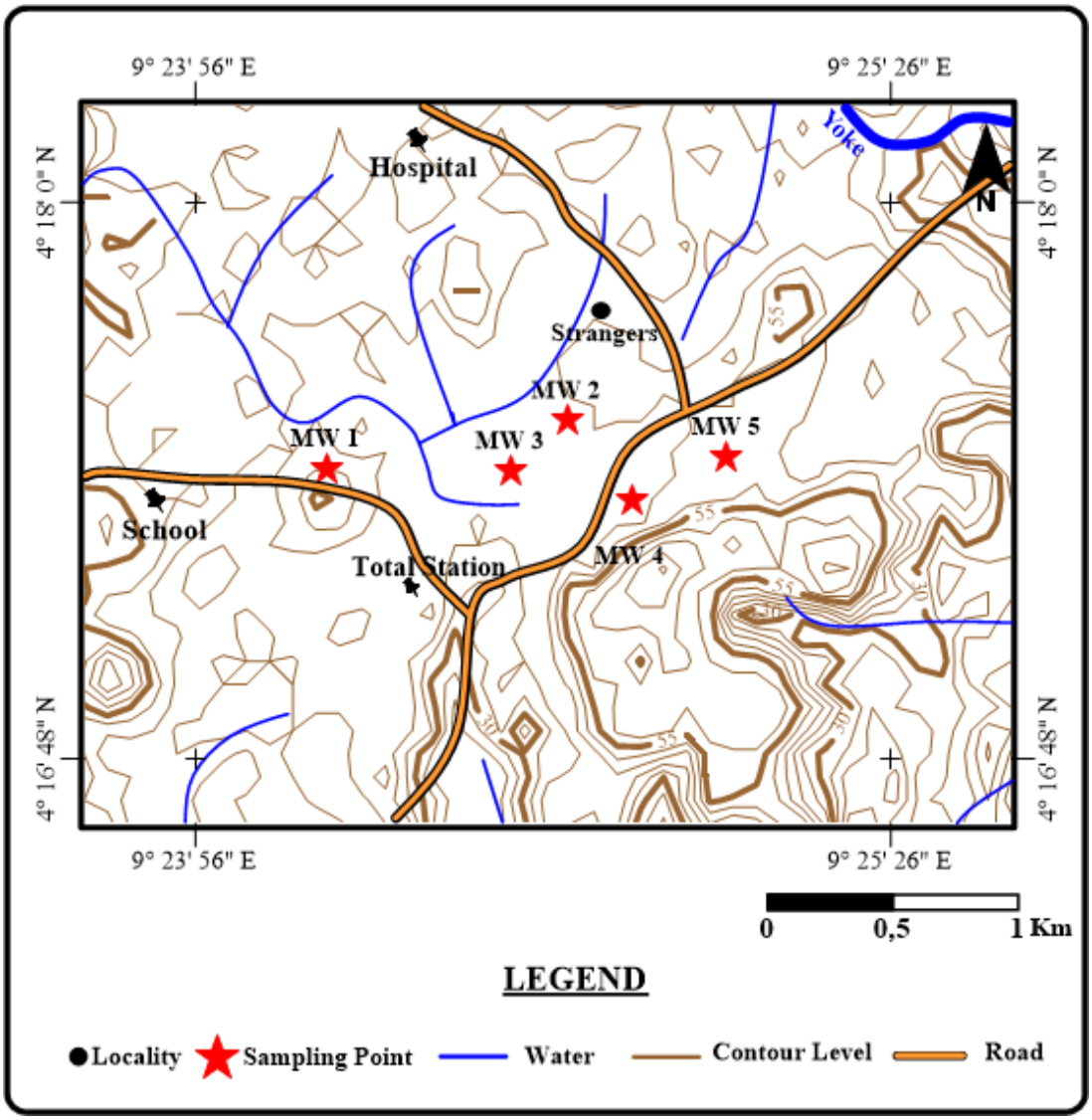



**Figure 16:** Map of Muyuka showing sampling points (NIC, 1972 modified)

MW4 has an elevation which has been built with an iron barrel and the well has a lid which is has holes. It is used for domestic activities such as drinking, bathing, washing of plates and dresses. The coordinate points are latitude 04° 17’ 21.5’’N and longitude 009° 24’ 53.0” E and has an altitude of 66 m, surrounded by a plantain farm and there are two toilets around this point situated at about 50 m from it. The well has a depth of 6 m, a piezometric level of 3.6 m and a water column of 2 m (Table V).

MW5 is found in stadium quarter with an altitude of 71 m. It is semi protected with a lid and the water from this point is used for cooking, washing household utensils and to bath. The coordinate point is latitude 04° 17’ 27.0” N and longitude 009° 25’ 05.2” E (Figure 17). The depth of this well is10.8 m, the piezometric level is 6.3 m and the water column is 4.5 m.

**Table V: Morphometric and hydrological characteristics of the sampled groundwater points in Muyuka**

| Quarters | Sampling point codes | Coordinate points | | Alt (m) | P (m) | Depth (m) | W. C (m) | PL (m) | D (m) | Lev. pro | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Latitude | Longitude | | | | | | | | |
| Muyuka 1 | MW1 | 04º 17' 25.5" N | 009º 24' 13.3" E | 63 | 0.70 | 11 | 2 | 9 | 1 | Fully Protected | All uses |
| Strangers quarter | MW2 | 04º 17' 31.7" N | 009º 24' 44.5" E | 63 | 0.3 | 4.2 | 1 | 3.2 | 0.8 | Fully protected | All uses |
| Sand sand quarter | MW3 | 04º 17' 25.2" N | 009º 24' 37.2" E | 70 | 0.5 | 5.1 | 0.75 | 4.35 | 1.3 | Partially protected | All uses |
| Bitter leaf quarter | MW4 | 04º 17' 21.5''N | 009º 24' 53.0" E | 66 | 0.8 | 6 | 2.4 | 3.6 | 1.1 | Partially protected | All uses |
| Stadium quarter | MW5 | 04º 17' 27.0" N | 009º 25' 05.2" E | 71 | 0.8 | 10.8 | 4.5 | 6.3 | 0.9 | Fully protected | All uses |

**Legend:** Alt = Altitude, P = Protection height above the ground, WC = Water column, D = Diameter, Lev. Pro = Level of protection, PL = Piezometric Level.

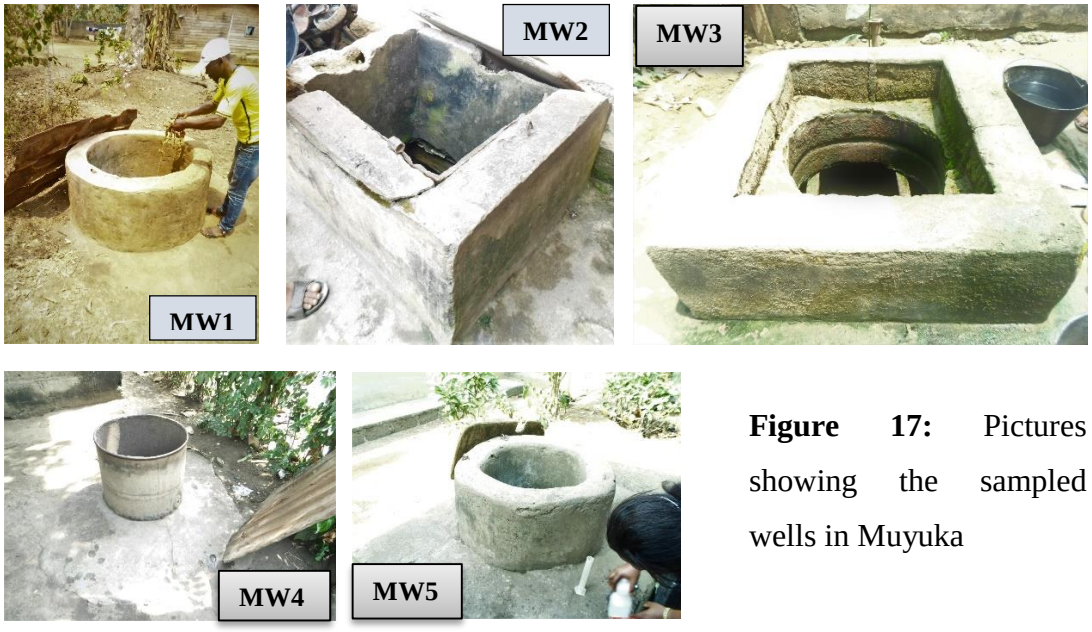



**Figure 17:** Pictures showing the sampled wells in Muyuka

**II.2.1.2.4. Sampling points of Buea (Springs)**

BS8 is called "Mile 18 spring" because it is found in mile 18 quarter. It is canalized but not maintained, with a large water bed towards the point of the canalisation and a major bed downstream (Figures 18 and 19). It is the main source of potable drinking water to the

population of mile 18 in Buea. The water is also used for other daily activities like bathing, cooking, washing. It is surrounded by houses and is situated at altitude 569 m, with coordinate points as latitude 04°09’ 41.9’’N and longitude 009° 17’ 56.7’’E.

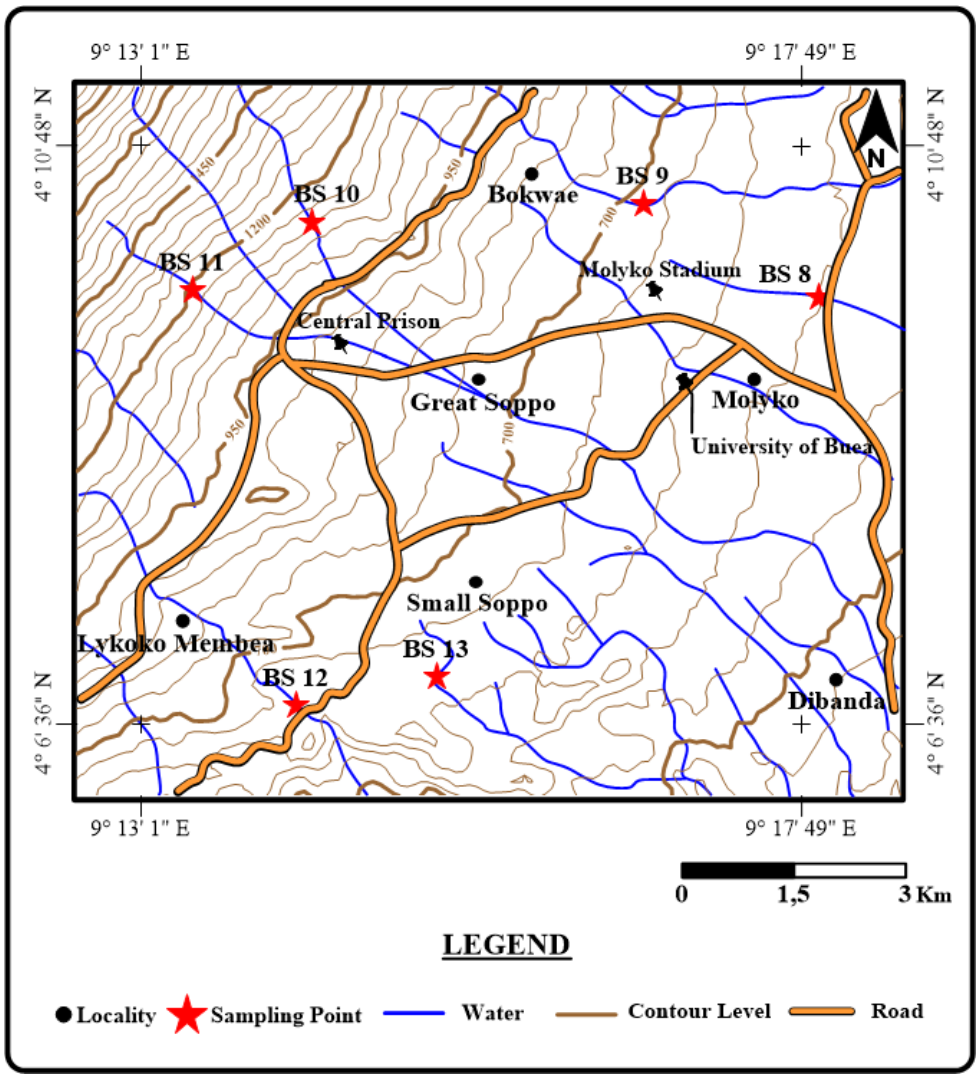



**Figure 18:** Map of Buea, showing sampling points (NIC, 1972 modified)

BS9 is located in Bonakanda village, with an altitude of 686 m and coordinate points of latitude 04°10’ 22.5’’N and longitude 009° 16’ 40.1’’E. It has been arranged and canalized by a non-governmental organization to supply the population with potable pipe borne water. The flow of the water is good and it is very much used for consumption and for all house chores.

BS10 is situated in a village called Liangamene-Wongongo at an altitude of 1016 m and coordinate points of latitude 04º 10’ 14.1’’N and longitude 009º 14’ 15.7’’E (Figure 19). Water from this sampling points comes out directly from the large rocks that surround the area and during the dry season, small iron sheets are used to channel the water into the containers of the villagers (Figure 19). A water tank has been built below the water point where water seeps and

is stored. It is then canalized to supply the population of this village where potable water flows continuously during the rainy season. This spring is situated in the forest, surrounded by very tall trees and very large rocks. It does not have a water bed during the dry season due to decrease in water level while the water bed reappears in the rainy season.


**Figure 19:** Pictures showing sampling points in Buea

BS11 is a spring that is located in upper farms. It is situated at the foot of Mount Cameroon and found in the forest zone where the water comes out directly from rocks. The flow velocity is very strong and it is this water that supplies the population of Buea and some villages around Buea with potable drinking pipe borne water (Figure 18 and 19). Just below the water point is a reservoir that has been built which is linked to very large pipes, used to channel the water to the town. Its altitude is 1189 m and the coordinate points are latitude 04$^{o}$ 09’ 44.9’’N and longitude 009$^{o}$ 13’ 23.6’’N (Table VI).

BS12 is found a village called Mevio at the outskirt of Buea town, precisely just after Tole. It has been built with concrete to capture water but it is not being maintained. The water is used to water the crops found in the farm around the it during the dry season and for consumption by farmers during both the rainy season and the dry season (Figure 18 and 19). This farm consists of crops like tomato, cabbage and pepper. This water is also used for bathing. The coordinate point is latitude 04$^{o}$ 06’ 44.0’’N and longitude 009$^{o}$ 14’ 08.9’’E and the altitude is 636 m.

**Table VI: Morphometric and hydrological characteristics of the sampled groundwater points in Buea.**

| Quarters | Sampling point codes | Coordinate points | | Altitude (m) | Uses |
|---|---|---|---|---|---|
| | | Latitude | Longitude | | |
| Mile 18 | BS8 | 04$^{o}$ 09’ 41.9’’N | 009$^{o}$ 17’ 56.7’’E | 569 | Consumption, washing of dresses, cooking and bathing. |
| Bonakanda | BS9 | 04$^{o}$ 10’ 22.5’’N | 009$^{o}$ 16’ 40.1’’E | 686 | Consumption and cooking |
| Liangamene-Wongongo | BS10 | 04$^{o}$ 10’ 14.1’’N | 009$^{o}$ 14’ 15.7’’E | 1016 | Consumption as it is canalized to supply the population with potable water, washing of dresses and bathing. |
| Upper farms | BS11 | 04$^{o}$ 09’ 44.9’’N | 009$^{o}$ 13’ 23.6’’N | 1189 | Consumption as it is canalized to supply the population with potable water, washing of dresses and bathing |
| Mevio | BS12 | 04$^{o}$ 06’ 44.0’’N | 009$^{o}$ 14’ 08.9’’E | 636 | Consumption, watering of crops, washing of dresses and bathing. |
| Tole weeding | BS13 | 04$^{o}$ 06’ 56.4’’N | 009$^{o}$ 15’ 10.0’’E | 638 | Consumption, washing of dresses and bathing. |

The spring BS13 is situated in the heart of Tole village, in a rural zone and is called “Tole weeding”. There are palm trees, potatoes and rocks that are found downstream. It is used by the people for drinking and bathing. The coordinate points are latitude 04$^{o}$ 06’ 56.4’’N and longitude 009$^{o}$ 15’ 10.0’’E and it is found at 638 m altitude (Figure 18 and 19).

**II.2.1.2.5. Sampling point of Ekona/Mautu (Springs)**

MS4 is known by the indigenes as “Papa James spring”. There is a large cocoa farm found upstream together with a palm farm around this water point. All these farms are found above the sampling point on a hill. There are many rocks found around this area and the speed at which its water flows very high (Figure 20). The population uses it for drinking, bathing and for other household activities. The coordinate points are latitude 04° 15’ 31.9’’N and longitude 009° 21’ 55.2’’E and it is found at an altitude of 160 m (Figures 20 and 21).

The sampling point MS5 also known as “Mbanga water” is found in a rural village setting. The coordinate points are Latitude 04° 15’ 37.6’’N and longitude 009° 22’ 02.2’’E.

The water is used for bathing, cooking, drinking and washing of dresses and household utensils. It is situated in a rocky area. It is situated at an altitude of 133 m (Figure 20).

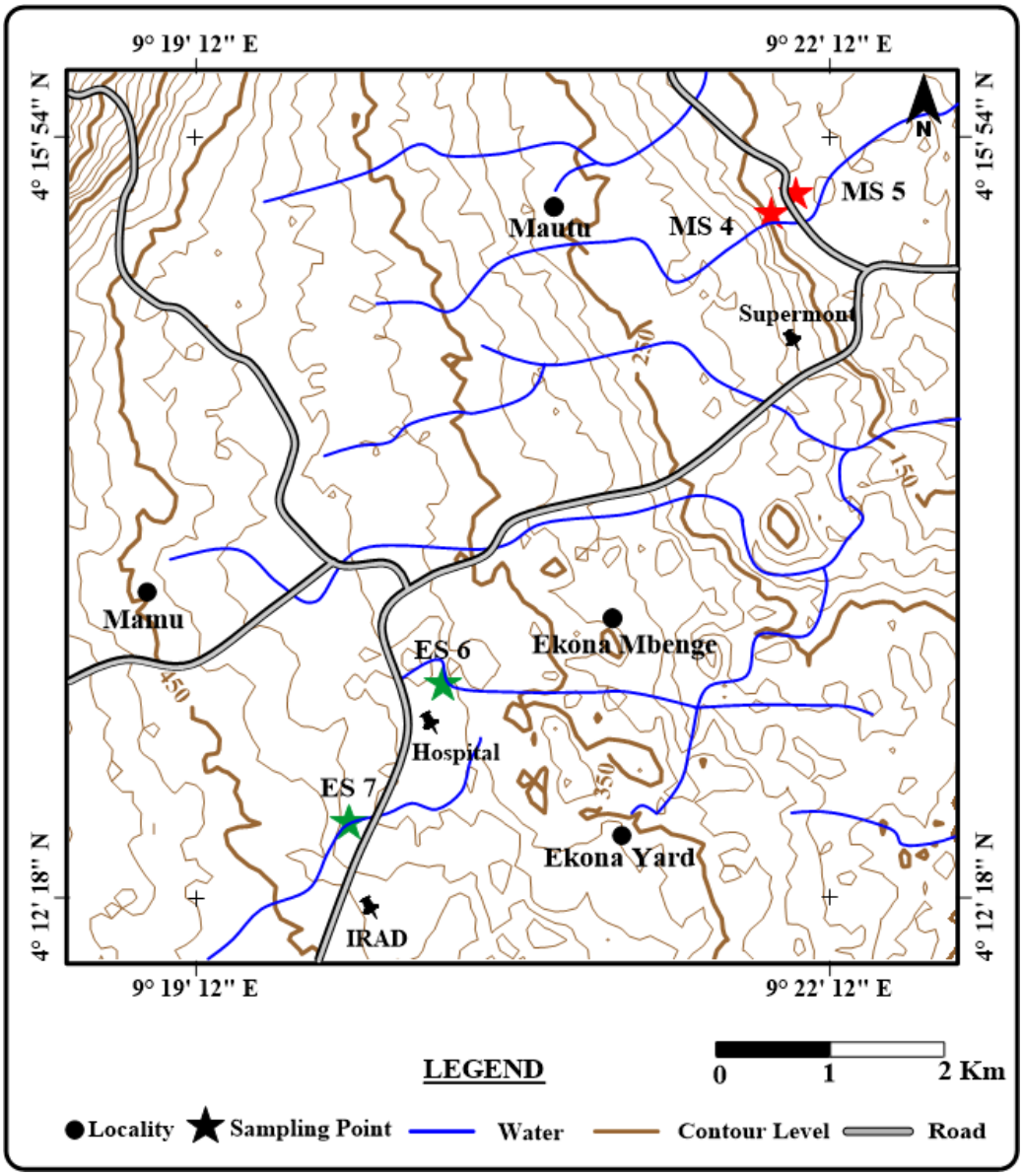



**Figure 20:** Map of Ekona/Mautu showing sampling points (NIC, 1972 modified)

ES6 is found in a rural zone and is called "Pindi", found at 386 m altitude. It is surrounded by a cocoa farm downstream and upstream by a palm plantation which belongs to the Cameroon Development Corporation (CDC). The soil around the water is rocky and the water is used for consumption by the local population and also to spray their crops. Its coordinate points are latitude 04°13' 18.4''N and longitude 009° 20' 22.2''E (Figure 20).

ES7 is situated at about 100 m from the main road linking Buea and Muyuka. It is found in a rural zone in a cocoa farm of an indigenous farmer. It is known as "Ekona yard water" has a very small bed and is used mainly by farmers to spray their cocoa and to drink (Figure 21).

**Table VII: Morphometric and hydrological characteristics of the sampled groundwater points in Ekona/Mautu.**

| Quarters | Sampling point codes | Coordinate points | | Altitude (m) | Uses |
|---|---|---|---|---|---|
| | | Latitude | Longitude | | |
| Papa James | MS4 | 04$^{o}$ 15’ 31.9’’N | 009$^{o}$ 21’ 55.2’’E | 160 | Consumption, washing of dresses and bathing. |
| Banga water | MS5 | 04$^{o}$ 15’ 37.6’’N | 009$^{o}$ 22’ 02.2’’E | 133 | Consumption, washing of dresses, cooking and bathing. |
| Pindi 2 | ES6 | 04$^{o}$ 13’ 18.4’’N | 009$^{o}$ 20’ 22.2’’E | 386 | Consumption, bathing and watering of crops. |
| Ekona yard | ES7 | 04$^{o}$ 12’ 39.3’’N | 009$^{o}$ 19’ 55.5’’e | 419 | Consumption and spraying of crops. |

The altitude of this spring is 419 m and the coordinate points are latitude 04°12’ 39.3’’N and longitude 009° 19’ 55.5’’E. Table VII shows the morphometric and hydrological characteristics of the groundwater in Ekona/Mautu.

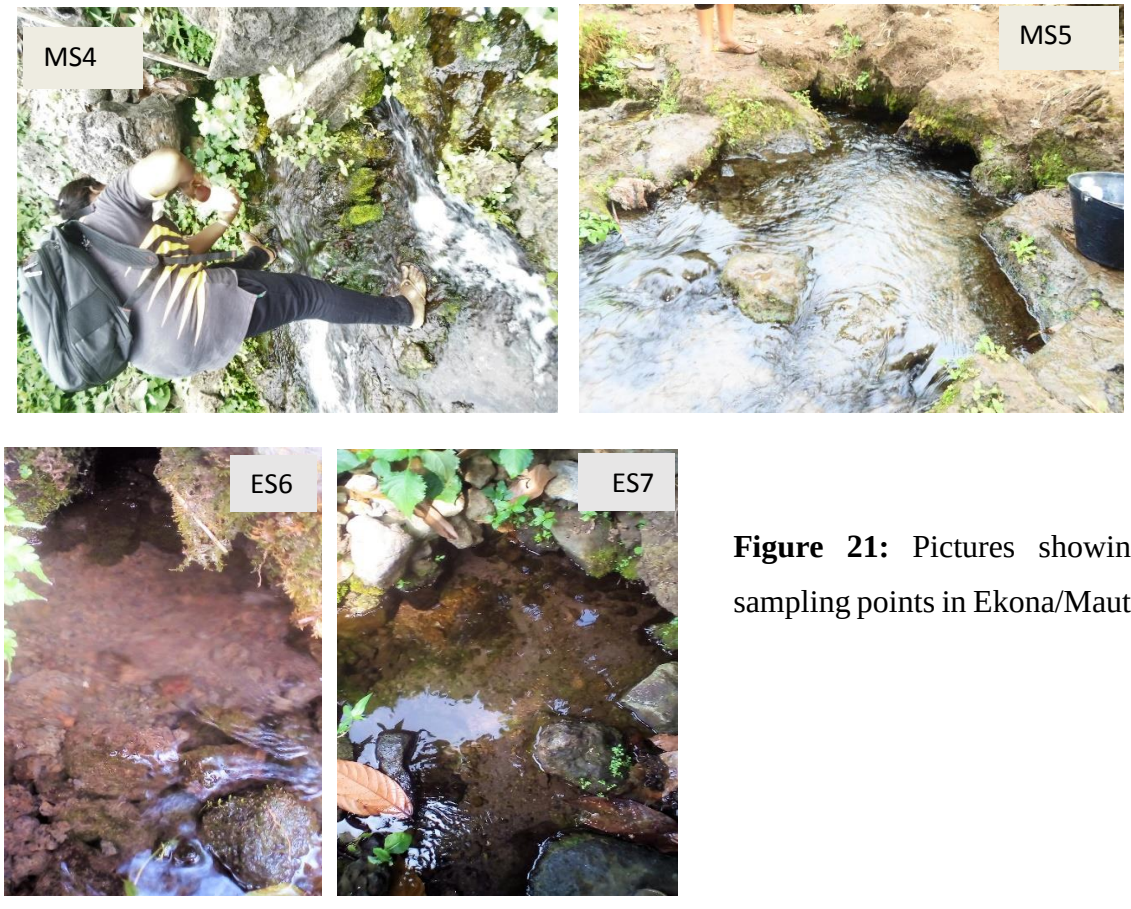



**Figure 21:** Pictures showing sampling points in Ekona/Mautu

### II.2.1.2.6. Sampling points of Owe (springs)

The spring OS1 is situated in Owe III quarters in Owe village. The water at the source of this sampling point is supplied by two springs from the upstream lying side by side and it is an open spring that has formed a stream which empties itself in Balung River in Muyuka (Figures 22 and 23). It is used by the population basically for consumption as a source of potable water. It is also used for household activities like cooking, bathing, washing. The coordinate points are 04° 17’ 57.7’’N latitude and 009° 22’ 40.9’’E longitude and its altitude is 94 m.

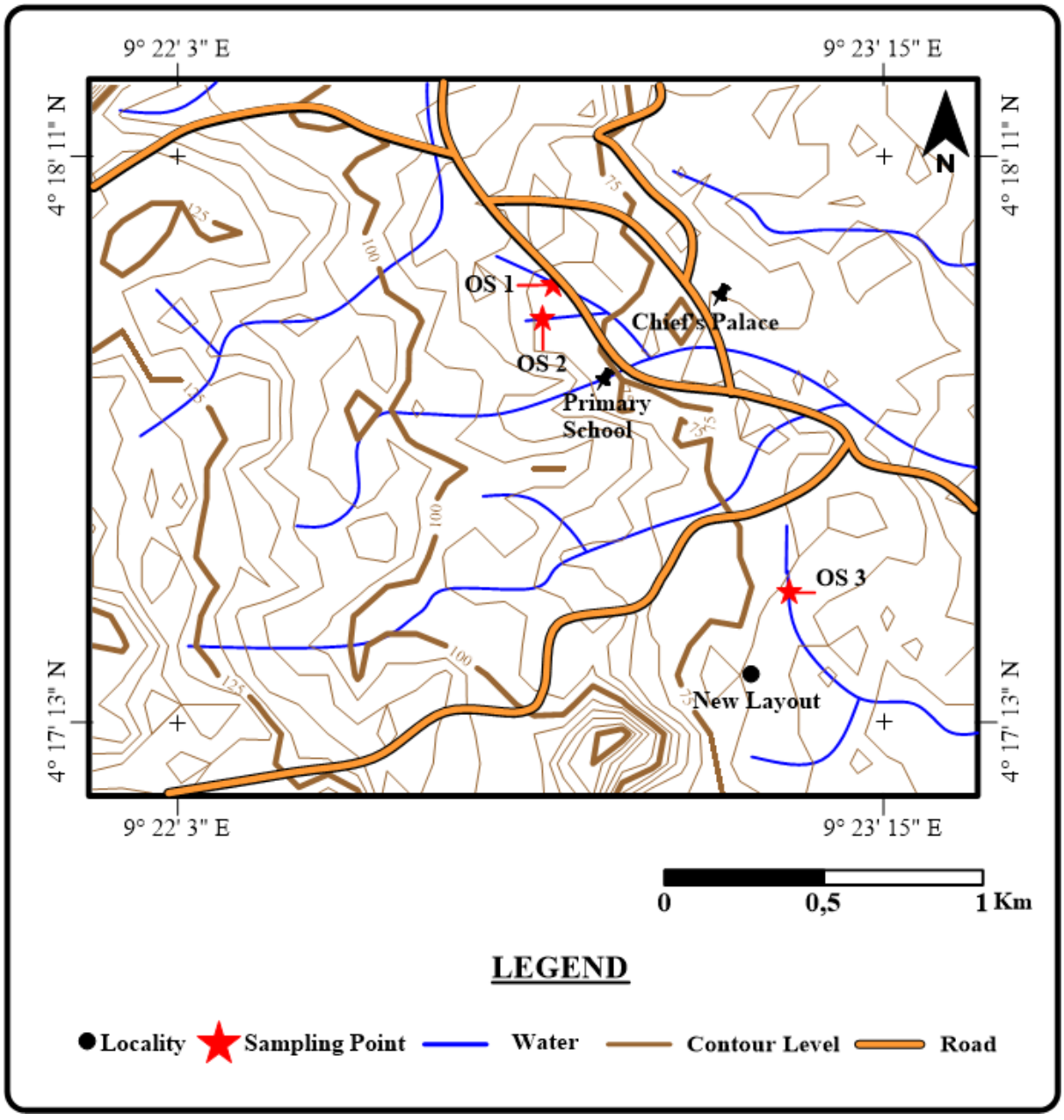



**Figure 22:** Map of Owe showing sampling points (NIC, 1972 modified

OS2 is situated in Owe III quarters and it is used by the population basically for consumption as a source of potable water. It is also used for household activities like cooking, bathing, washing. The stream formed from this spring meets with that of OS1 downstream where they empty in the Balung River in Muyuka. This sampling point is surrounded by a large cocoa farm upstream, situated in a rural area with the soil rich in black rocks. The coordinate points of spring OS2 are latitude 04°17’ 54.2’’N and longitude 009° 22’ 39.9’’E, situated at altitude 96 m (Table VIII).

**Table VIII: Morphometric and hydrological characteristics of the sampled groundwater points in Owe.**

| Quarters | Sampling point codes | Coordinate points | | Altitude (m) | Uses |
|---|---|---|---|---|---|
| | | Latitude | Longitude | | |
| Owe III a | OS1 | 04º 17’ 57.7’’N | 009º 22’ 40.9’’E | 94 | Consumption, washing of dresses and bathing. |
| Owe III b | OS2 | 04º 17’ 54.2’’N | 009º 22’ 39.9’’E | 96 | Consumption, washing of dresses and bathing. |
| New layout | OS3 | 04º 17’ 26.4’’N | 009º 23’ 05.0’’E | 82 | Consumption, washing of dresses and bathing. |

Spring OS3 is situated in a rural area, shaded by farm with stones found downstream and a potatoes farm and many bananas around the spring. Upstream, there is a big cocoa farm. The water is used for drinking, bathing, washing of dresses and spraying of cocoa farm (Figure 23). The altitude is 82 m and the coordinate points are latitude 04° 17’ 26.4’’N and longitude 009° 23’ 05.0’’E.


**Figure 23:** Pictures of sampling points in Owe

### II.2.2. Sampling

The sampling was carried out from January to December 2017 in two campaigns per season separated in intervals of three months in each of the sampling points and twice per season. The various groundwater points were sampled using the most adapted and feasible methods.

#### II.2.2.1. Sampling of water for physicochemical analyses

In the wells the sampling for physicochemical analysis of water was done before collection of the fauna. A 5 L bucket that was normally used by the well owners was used to carry water, which was then carefully transferred without producing bubbles into 250 mL and 1000 mL polyethylene bottles with double corks.

In the springs, the water was directly sampled using a 250 mL and a1000 mL polyethylene bottles, without producing bubbles. All water samples collected was transported to the Hydrobiology laboratory at the University of Yaounde I in a cooler containing ice for analyses using standard methods described by PASCALIS (2009).

#### II.2.2.2. Sampling of fauna in the wells

Organisms were collected from the bottom of the wells using a Phreatobiological net sampler that was conceived by Cvetcov (Cvetkov, 1968) and modified by Boutin (1984). Successive upward and downward movement was done using the net that captured swimming animals in the well water. The net of 150 µm mesh size was drawn ten to fifteen times through the entire water column (Dumas and Fontanini, 2001). The ascending movement of water dislodges the sediments and associated animals present at the bottom of the well. The lower end of the net consists of a container closed with a valve that prevents the animals from escaping. The net is then removed from the well to obtain a sample of the fauna collected. The samples containing the organisms were immediately fixed with 96 ° alcohol and carried to the laboratory for identification and counting. The collection of organisms was done only after the water samples to be used for physicochemical analysis had been collected following the protocol described by PASCALIS (2009).

#### II.2.2.3. Sampling of fauna in the springs

In the springs, the organisms were collected by passive direct filtration using a mesh of 150 µm mesh size, 5 to 8 cm in diameter for 30 minutes to 1 hour. Filtration of the water taken from the spring is done after washing off all stones and pipes around that could have trapped some of the groundwater organisms in order to detach and capture organisms that may be

attached to the walls of the pipe and stones. Samples containing organisms were directly fixed in 96 ° alcohol and brought back to the laboratory for identification and counting.

**II.2.3. Physicochemical analyis of groundwater samples**

Two types of analysis were done; physico-chemical and faunistic analysis.

The physicochemical variables were measured following the techniques described by APHA (1998) and Rodier *et al.,* (2009).

**II.2.3.1. Physical analysis**

Temperature was measured on the field using a mercury thermometer, graduated in $1/10^0$C and the results expressed in degree Celsius (°C). To get the temperature, 2/3 of the thermometer was dipped in the sampled water in a bucket for wells for 2 to 3 minutes while in the springs, temperature was directly measured and the corresponding values noted. Suspended Solids was measured on the field using a spectrophotometer HACH DR/2010 and the results are expressed in mg/L, read at 810 nm wavelength. Turbidity was measured on the field using a spectrophotometer of the mark HACH DR/2010, read at 450 nm wavelength and the results expressed in FTU (Formazine Turbidity Unit).

**II.2.3.2. Chemical analysis**

pH was measured *in situ* using a pH meter of the mark HACH HQ11d by dipping 2/3 of the electrode into the sample water and the results gotten. Electric conductivity was measured on the field using a portable conductimeter of the mark HACH HQ 14d and the results expressed in microsiemens per centimeter (µS/cm). Dissolved oxygen was measured on the field using a portable multimeter of the HACH HQ 30d Flexi brand. The results were expressed in percentage saturation of oxygen.

Dissolved carbon dioxide was measured in two steps: On the field, 20 mL of NaOH N/20 was measured using a graduating funnel and poured into a 200 mL volumetric flask. 2 to 3 drops of phenolphthalein indicator was added producing a pink colour and the sample was added in the volumetric flask until it reached the mark on the flask, (fixation of $CO_2$). In the laboratory, 50 mL of the sample was titrated with HCl N/20 till discoloration. The amount of $CO_2$ was obtained by the formula:

| CO2 (mg/L) = (burette decrease of control test - burette decrease of sample) x 17.6 |
|---|

The control test burette decrease was gotten by titrating distilled water.

Alkalinity was determined by volumetric analysis in the laboratory whereby in the laboratory, 50 mL of the sample was poured in a beaker. 2 to 3 drops of red green methyl

bromocresol (blue colour) indicator was added and titrated with $H_2SO_4$ N/50 and a magnetic bar was placed inside the beaker while the beaker was placed on a magnetic agitator. It was then titrated and the value of the result expressed in mg/L of $HCO_3$ was obtained by multiplying the value of the burette decrease by 20.

| Alkalinity (mg/l) = burette decrease of sample x 20 |
|---|

Oxidability was measured by volumetric analysis. Into a 500 ml volumetric flask, 200 ml of water sample was introduced with 2 ml of monosodic carbonate and boiled using a Bunsen burner. Once boiling started, 20 ml of $KMnO_4$ (N/80) was added. Ten minutes after the boiling began, the volumetric was cooled with running tap water, and then 5 ml of 25% $H_2SO_4$ and 20 ml of Mohr salt were added successively. The discoloured sample was then titrated with $KMnO_4$ (N/80) until a persistent pink colour was obtained. The control sample is prepared under the same conditions, but with distilled water. Oxidability was expressed in mg/L O2 and was obtained by the formula;

$$\text{Oxidability (mg/L of } O_2) = \frac{q - q_o}{2} \times 3.95$$

Where

q = burette decrease of sample
$q_o$= burette decrease of control

Nitrate ions was measured using a HACH DR/2010 spectrophotometer and Nitraver V gel in the laboratory. The results were read at wavelength 400 nm and expressed in mg/L of $NO^-_3$. Ammonium ions were measured using a HACH DR/2010 spectrophotometer in the laboratory. The results read at wavelength 425 nm were expressed in mg/L of $NH^+_4$. Orthophosphate was measured using a spectrophotometer HACH DR/2010 at 890 nm wavelength by filling the spectrophotometric cell with 25 mL of distilled water and a phosver III gel for the control. Same quantity of the sample was measured and phosver III gel was used for the test experiment in the laboratory and the results were expressed in mg/L of $PO^{3-}$.

Salinity was measured *in situ* using a potable conductimeter HANNA HI 9829, whereby the electrode was dipped inside the sample in a bucket for about 2 to 3 minutes. The results were expressed in Practical Salinity Unit (PSU). Total hardness is defined as the sum of calcium and magnesium concentrations, both expressed as CaCO3 in mg/L. It is calculated by summing up the calcium and magnesium concentrations. It was gotten by using the formula; $2.497(Ca^{2+}) + 4.118(Mg^{2+})$ (ISO standard, 1984). Calcium was measured using a spectrophotometer HACH DR/2010 at 220 nm wavelength whereby, sodium hydroxide,

potassium cyanide, HH-S-NN (indicator) and EDTA were used. The correction factor used was; A*18.41 while magnesium was read at 225 nm wavelength where a coloured indicator called eriochrome black T was used, together with EDTA and potassium cyanide. The values were corrected using the formula; B*20.13 (ISO standard, 1984).

**II.2.4. Faunal analysis (Sorting and counting)**

In the laboratory, the fauna was rinsed using tap water and passed through a net of 150 µm mesh size, and transferred into Petri dishes of 8 to 12 cm diameter for sorting, identification and counting. The sorting and the counting of the organisms were carried out in a meticulous way using a binocular magnifying loupe of the Wild M5 brand and an optical microscope of the brand IVymen R system. The organisms of the same taxa were grouped together in small storage bottles, labeled and conserved in 96° alcohol for future use. The taxonomic identification was done with the help of identification keys published by Magniez (1976; 1979, 1999), Coineau *et al*., (1994), Tachet *et al*., (2000, 2002, 2006, 2009 and 2010), Durand and Levêque (1980), Zebaze Togouet *et al.* (2013). Argano (1994), Chappuis (1942, 1951, 1952), Lincoln (1972) Delvare and Aberlenc (1989), Moisan (2006, 2010).

**II.2.5. Data analysis**

The analysis of groundwater biodiversity integrates at the same time the diversity, the abundance and the dynamics of the population of invertebrates. Therefore, it is important to analyse this diversity of the milieu and examine how physicochemical factors and altitude influence them in order to be able to answer some important questions as far as dynamics and abundance are concerned. The physico-chemical and biological data will be tested for normality and in the case where the distribution is normal, the parametric test will be used for the data analyses. On the contrary, if the distribution of the data does not follow the normal law, the nonparametric tests will be used for the data analyses. In the case of this study, the physicochemical and biological data did not follow the normal distribution and the non-parametric tests were used to analyse the data.

Histograms of distribution of values and box plots helped in the representation of the measurements observed on a spatiotemporal scale in order to emphasize the season effect. These treatments were carried out using the Microsoft-Excel 2016 program and SPSS 20.0.

**II.2.5.1. Indices**

Taxonomic richness, diversity index of Shannon and Weaver (Shannon and Weaver 1949) and evenness were calculated using the list of fauna of each site and for each sampling date in order to study the effect of site and season

**II.2.5.1.1. Taxonomic richness (T), Relative abundance (Nr) and Frequency (F) or Occurrence**

The general structure of the population collected were evaluated from the taxonomic richness and abundance of each taxa. It was essentially carried out by comparing the means of abundances, detection of the tendencies and analyses of the variance of the population. The relative abundance is expressed as

$$\mathbf{Nr} = \frac{\mathbf{ni}}{\mathbf{N}}\mathbf{x100}$$

Where:

ni = absolute abundance of taxon i (total number of individuals sampled, belonging to taxon i),

N = total number of individuals collected, belonging to the whole of taxa present in point

The frequency measures the regularity of each taxon. It is measured with the following formula

$$F = \frac{\mathbf{Pi}}{\mathbf{P}}\mathbf{x\ 100}$$

Where:

Pi = number of taxa i present

P = total number of taxa

**II.2.5.1.2. Diversity Index (H') of Shannon and Weaver (1949)**

This index establishes a link between the number of species and the number of individuals of the same ecosystem. It takes into account the size of the sample and the relative proportion of the species. It considers at the same time the specific richness and the relative abundance. This index helps to estimate the taxonomic diversity of the organisms which make up the population of the studied groundwater. It makes it possible to have quick figure evaluation of the biodiversity of the population. The index of Shannon and Weaver (1949) is expressed using the following formula;

$$H' = -\sum_{I=1}^{S}\left(\frac{n}{N}\log_2\frac{n}{N}\right)$$

Where;

- n is the number of the species i in the sample;
- N is the total number of individuals in the sample;
- $Log_2$ is the logarithm of base 2;
- s is the number of species.

NB:

- H' is Minimal (H' min = 0) if all the individuals of the population belong to a single taxon or if, in a population, each taxon is represented by only one individual, except a taxon which is represented by all the other individuals of the population;
- H' is Maximal (H' max = log2 S) when all the individuals are divided in an equal manner in all the taxa (Fontier *et al.*, 2001).

**II.2.5.1.3. Evenness index (J') of Pielou**

It is calculated at each site to determine the degree of dominance of taxon from one site to another or equilibrium in each taxon. It is calculated using the formula:

$$\mathbf{J'} = \frac{H'}{H'max}$$

Where:

- J' is the Equitability index;
- H' is the Shannon and Weaver index;
- Hmax is ln S.

**II.2.5.2. Correlations**

The nonparametric test of Kruskal-Wallis (test H) was used to check on the spatiotemporal distribution, the significance of the differences (or similarities) in variances of the abiotic parameters and the densities of the biological variables, relating to the distribution of the collected organisms. The test H was also used to compare, using the physicochemical parameters measured, water of the studied groundwater stations. Two hypotheses were put forth which are, a null hypothesis whereby the medians of the samples to be compared do not differ significantly and a second alternative hypothesis whereby there is a significant difference between the medians of the samples to be compared.

The analysis was carried out using the program SPSS, 20.0 version which gives the value of p (p-value). If this value is lower than 0.05 ($p < 0.05$), the null hypothesis is rejected. On the contrary if $p > 0.05$, it is verified. The variables being quantitative, this rank test is measured with at least an ordinal scale (rank). The test is based on the hypothesis that the various samples to be compared follow the same distribution or that they have distributions around a median (StatSoft France, 2005). Each time the test of Kruskal-Wallis showed a significant difference between the variances of the compared samples, the multiple test of

comparison of ranks or the U test of Mann-Whitney was used for a two by two, in order to isolate the samples which differ significantly.

### II.2.5.3. Multivariate analyses

#### II.2.5.3.1. Principal Component Analysis (PCA)

The Principal Component Analysis (PCA) consists of seeking correspondences or correlations between elements of a matrix of data. PCA permits the description in a simplified way, the tables of quantitative data of the type "N observations p variable". PCA permits the discovery of existing structures before seeking explanatory hypothesis (Fontier *et al.*, 2001).

In this study, the PCA was used to establish the physicochemical, altitudinal and biodiversity typology of the sampling stations on the basis of the environmental variables measured at each station throughout the study period. This method of statistical factorial descriptive aims to present in a graphic form, the maximum information contained in a table of figures of significant size (Philippeau, 1992).The matrix of data is made up of samples "N" in rows on which are measured quantitative variables "p" laid out in columns. The matrix used in this study is a base that has undergone a logarithmic transformation curve "Log (X + 1)" to have an approximate normality then standardized to obtain a comparable scale of variables (Michael *et al.*, 2004) thus giving importance to the rare species. The table of figures "N" × "p" thus form a cloud of "N" points in a space with "p" dimensions. Each principal component (dimension) explains a more or less significant quantity of the starting information. The principal components are classified by descending order of the quantity of information which they explain.

In general, first three principal components are enough to explain 60 to70% of the information contained in the starting matrix (Ouro-Boya, 2004). The principal components are obtained by the diagonalisation of a matrix which, according to the nature of the initial variables, is either the matrix of the correlations, or the matrix of covariance (Legendre and Legendre, 1979). In the case of this study, the individuals are the sampling points or altitude, and the variables are the taxa or the average values with the physicochemical descriptors of water. The final phase of the PCA consists of a chart which then makes it possible to have an outline of the results. There are two types of representations that were used for the analyses of these data which are the scatter chart of the variables which is a circle of correlation and the scatter chart of the sites. The percentage of initial information explained by each principal component is illustrated in the form of a histogram. The PCA was carried out using the software XLSTAT, 2016 version. The data of the matrix will be able to undergo a transformation log

or double square root in order to stabilize the variances thereby giving importance to the rare species.

**II.2.5.3.2. Hierarchical Classification Analysis (HCA)**

The objective of the Hierarchical Classification Analysis of (HCA) is to constitute the averages of variables in larger classes, on the basis of certain measurement of distances similarity which is the Euclidean distance. The results of this type of classification are usually represented in the form of dendrogram. This method is distinguished from all the others by the fact that it uses an analysis of the approximate variance in order to evaluate the distances between the classes (Ward, 1963). In this work, the HCA was used to gather the stations according to their physicochemical similarities, and the similarity of the organisms collected on the basis of average density. The Euclidean distance employed in this analysis of ascending classification is an ordinal scale from 0 to 10 (Williams *et al.*, 1971) and the method of Ward was used as criterion of aggregation. The HCA was carried out using the software XLSTAT, 2016 version.

**II.2.5.4. Analysis of the impact of altitude**

The altitudes of the different sampling stations were recorded using a GPS of the mark Garmin. The sampling points were chosen based on altitude and almost all the main towns of Fako division were sampled for representativity of the altitudes of Fako division. The analysis for altitude was carried out from the level of the ocean in the town of Limbe at 7m from sea level to Buea at1189 m, under the foot of Mount Cameroon which has an altitude of 4000 m at its peak.

The samples for physicochemical analysis were analysed based on the sampling towns and based on altitude to evaluate how altitude affects the results of physicochemistry. The sampling points were divided into groups in order to better characterise the effects of altitude. Organisms were also separated based on altitude to have an idea on the distribution of biodiversity based on altitude for better conclusions. Multivariate analyses were carried out to evaluate the effect of altitude and physicochemical parameters on biodiversity so as to identify which parameter mostly affect the distribution of organisms on the different groups of altitudes. It is worth noting that the grouping of the sampling points into different groups of altitude did not consider the sampling points as different (wells or springs) but the sampling points were all considered as groundwater. This grouping was to help evaluate the general trend of distribution of groundwater organisms from lower altitudes to higher altitudes and to see the general trend of the physicochemical parameters across different altitudes.

# CHAPTER III

# RESULTS AND DISCUSSION

## III. 1. RESULTS

### III.1.1. Distribution of the physicochemical variables of groundwater in Fako

#### III.1.1.1. Variation of physicochemical variables of the sampled groundwater in Tiko

The lowest mean seasonal value of temperature was obtained in the rainy season in TW7 (25 °C) and the highest value was obtained in the dry season (28.4 °C) in TW3 (Table IX) with a mean seasonal value of 27 ± 0.83 °C (Figure 24 A). No significant difference was observed between the rainy season and dry season for temperature ($p>0.05$). The highest value of Suspended Solids (SS) was obtained in the dry season in TW1 (18.5mg/L) while the lowest mean seasonal value of 2.5 mg/L was obtained in the rainy season in TW5 (Figure 24 B). The U test of Mann Whitney showed a significant difference for Suspended Solids from one season to another ($p=0.002$). Turbidity oscillated between 3.00 FTU in the rainy season in TW3 and 29.00 FTU in the dry season in well TW5 and TW8. The U test on Mann Whitney showed a significant difference between the rainy and the dry season ($p<0.05$) but no significant difference was obtained from one sampling point to another (Figure 24 C).

**Table IX:** Seasonal variation of physicochemical variables during the sampling period in Tiko

| Para | Temp (ºC) | | SS (mg/L) | | Tur (FTU) | | EC (µS/cm) | | Sal (PSU) | | pH (CU) | | Oxyd (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S. P | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS |
| TW1 | 26.05 | 27.15 | 18.50 | 7.50 | 24.00 | 10.50 | 362.5 | 233.00 | 0.12 | 0.13 | 7.12 | 6.26 | 1.98 | 1.97 |
| TW2 | 26.80 | 27.05 | 15.00 | 5.00 | 22.00 | 5.00 | 331.00 | 391.00 | 0.12 | 0.19 | 7.21 | 6.12 | 3.16 | 1.97 |
| TW3 | 28.40 | 27.55 | 6.00 | 7.00 | 10.00 | 3.00 | 368.00 | 271.00 | 0.18 | 0.11 | 6.34 | 6.22 | 3.56 | 1.78 |
| TW4 | 27.65 | 26.80 | 16.00 | 4.50 | 23.50 | 9.00 | 231.00 | 304.50 | 0.11 | 0.13 | 6.55 | 6.13 | 3.46 | 2.17 |
| TW5 | 27.20 | 26.75 | 15.00 | 2.50 | 29.00 | 6.50 | 398.50 | 245.00 | 0.19 | 0.11 | 7.15 | 6.13 | 4.84 | 2.96 |
| TW6 | 25.80 | 27.60 | 11.50 | 4.00 | 19.50 | 6.50 | 268.00 | 200.50 | 0.13 | 0.09 | 6.23 | 5.63 | 2.77 | 2.76 |
| TW7 | 27.50 | 25.00 | 8.50 | 8.00 | 23.50 | 10.00 | 172.00 | 149.00 | 0.09 | 0.07 | 6.19 | 6.09 | 2.27 | 1.97 |
| TW8 | 25.60 | 27.65 | 14.00 | 4.50 | 29.00 | 10.50 | 416.00 | 340.50 | 0.11 | 0.16 | 6.97 | 6.51 | 2.77 | 3.75 |
| TW9 | 27.25 | 27.90 | 4.50 | 4.00 | 11.00 | 4.50 | 127.50 | 98.50 | 0.03 | 0.04 | 6.93 | 6.05 | 3.75 | 1.18 |
| TW10 | 26.95 | 27.40 | 6.00 | 3.50 | 10.5 | 3.50 | 132.50 | 99.00 | 0.06 | 0.03 | 6.58 | 5.93 | 6.02 | 2.56 |

| Para | $DO_2$ (% sat) | | $DCO_2$ (mg/L) | | Phos (mg/L) | | Amm (mg/L) | | Nitra (mg/L) | | Alkal (mg/L) | | T hard(mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| S. P | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS |
| TW1 | 52.60 | 59.40 | 2.71 | 0.47 | 0.59 | 0.17 | 0.01 | 0.00 | 1.23 | 0.950 | 5.00 | 6.00 | 78.18 | 113.63 |
| TW2 | 70.45 | 55.75 | 4.145 | 0.52 | 0.43 | 0.33 | 0.01 | 0.01 | 0.20 | 0.95 | 5.00 | 5.00 | 54.48 | 30.79 |
| TW3 | 61.15 | 54.80 | 6.03 | 0.45 | 0.32 | 0.70 | 0.51 | 0.01 | 1.65 | 1.95 | 6.00 | 7.00 | 59.16 | 165.06 |
| TW4 | 61.9 | 58.05 | 3.29 | 0.4 | 0.55 | 0.38 | 0.36 | 0.001 | 1.15 | 1.20 | 4.00 | 4.00 | 50.05 | 66.34 |
| TW5 | 58.20 | 59.85 | 2.51 | 0.35 | 0.76 | 0.31 | 0.55 | 0.002 | 0.31 | 1.10 | 4.00 | 8.00 | 54.14 | 104.98 |
| TW6 | 49.40 | 56.05 | 5.35 | 0.55 | 0.63 | 0.34 | 0.05 | 0.002 | 1.10 | 1.70 | 6.00 | 12.00 | 32.28 | 22.72 |
| TW7 | 47.70 | 58.80 | 2.36 | 0.42 | 0.46 | 0.22 | 0.75 | 0.003 | 0.90 | 2.15 | 5.00 | 14.00 | 59.99 | 139.25 |
| TW8 | 64.40 | 60.65 | 4.25 | 0.37 | 0.47 | 0.53 | 0.30 | 0.002 | 1.05 | 0.55 | 6.00 | 8.00 | 37.24 | 57.32 |
| TW9 | 75.75 | 60.65 | 1.48 | 0.47 | 0.24 | 0.27 | 0.02 | 0.003 | 0.55 | 1.20 | 6.00 | 10.00 | 65.74 | 93.46 |
| TW10 | 65.75 | 60.15 | 2.29 | 0.35 | 0.66 | 0.23 | 0.05 | 0.002 | 2.75 | 1.20 | 7.00 | 8.00 | 94.92 | 133.10 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

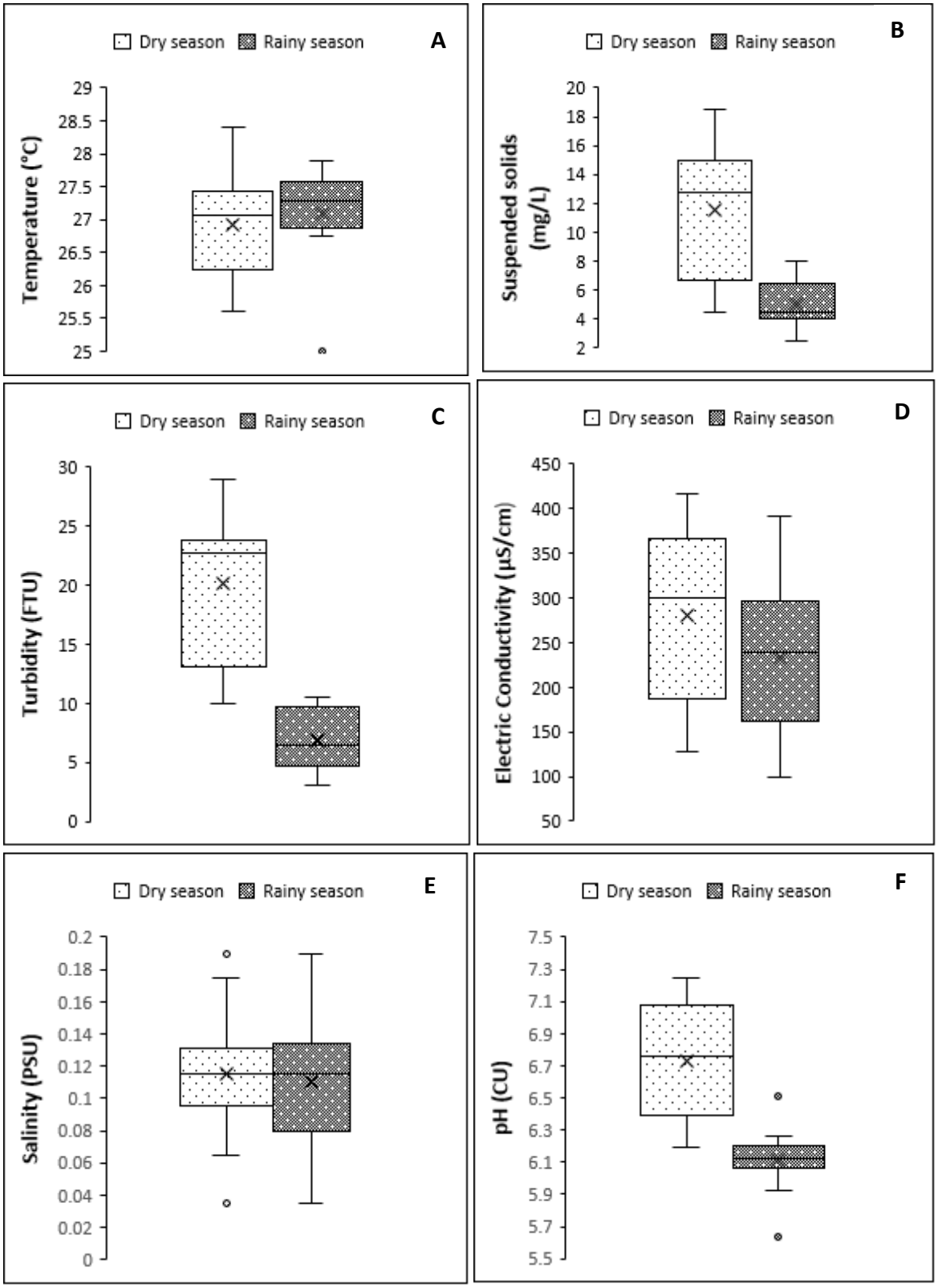



**Figure 24:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), electric conductivity (D) , salinity (E) and pH (F) obtained in Tiko.

The value of Electric Conductivity (EC) in the town of Tiko varied from 99 µS/cm in TW10 in the rainy season and 416 µS/cm in the dry season in well TW8. The mean seasonal value was 256.95 ± 104.52 µS/cm and no significant difference was observed for this parameter during the study period (Figure 24 D). The mean seasonal value of salinity was distributed between 0.04 PSU in TW9 in the rainy season and 0.19 PSU in TW2, obtained in the rainy season and TW5, obtained during the dry season, with a mean value of 0.11 ± 0.04 PSU (Figure 24 E). pH values varied significantly during the study period. The lowest value was 5.63, obtained during the rainy season in station TW6 while the highest value recorded in TW2 was 7.21, during the dry season (Figure 24 F). A significant difference was observed between the dry season and the rainy season as shown by the U test of Mann Whitney ($p<0.05$).

The values of oxidability oscillated between 1.18 mg/L of $KMnO_4$, recorded in TW9 during the rainy season and 6.02 mg/L during the dry season, recorded in TW10. The U test of Mann Whitney showed a significant difference between the rainy and dry season ($p = 0.09$). However, no significant difference was observed from one sampling point to another (Figure 25 A). Dissolved oxygen was distributed between 47.70 % (lowest value), obtained in TW7 and 75.75 % (highest value), recorded in TW9 all in the dry season with a mean of 59.57± 6.48 %. The U test of Mann Whitney did not show any significant difference neither from one sampling point to the other nor from one season to another (Figure 25 B). The mean seasonal value of dissolved carbon dioxide varied from 0.35 mg/L in the rainy season which was recorded in sampling points TW5 and TW 10 to 6.03 mg/L (TW3) during the dry season. The U test of Mann Whitney showed a significant difference between the rainy and dry season with a p value of 0.001 (Figure 25 C).

The values of orthophosphates fluctuated between 0.17 mg/L (TW1) in the rainy season and 0.76 mg/L, obtained in TW5 in the dry season. The U test of Mann Whitney showed a significant difference from one season to another ($p = 0.007$) but no significant difference was obtained from one sampling point to another for orthophosphates (Figure 25 D). The mean seasonal value of ammonium ions was distributed between 0.00 mg/L in the rainy season (TW1) and 0.75 mg/L in the dry season (TW7), with a mean value of 0.13 ± 0.22 mg/L. The U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another for ammonium ions (Figure 25 E). The mean seasonal value of nitrate ions varied between 0.20 mg/L in the dry season and 2.75 mg/L in the dry season, with a mean value of 1.19 ± 0.61 mg/L. The lowest and highest values were all obtained in the dry season at sampling points TW2 and TW10 respectively during the study period. The

U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another for nitrate (Figure 25F).

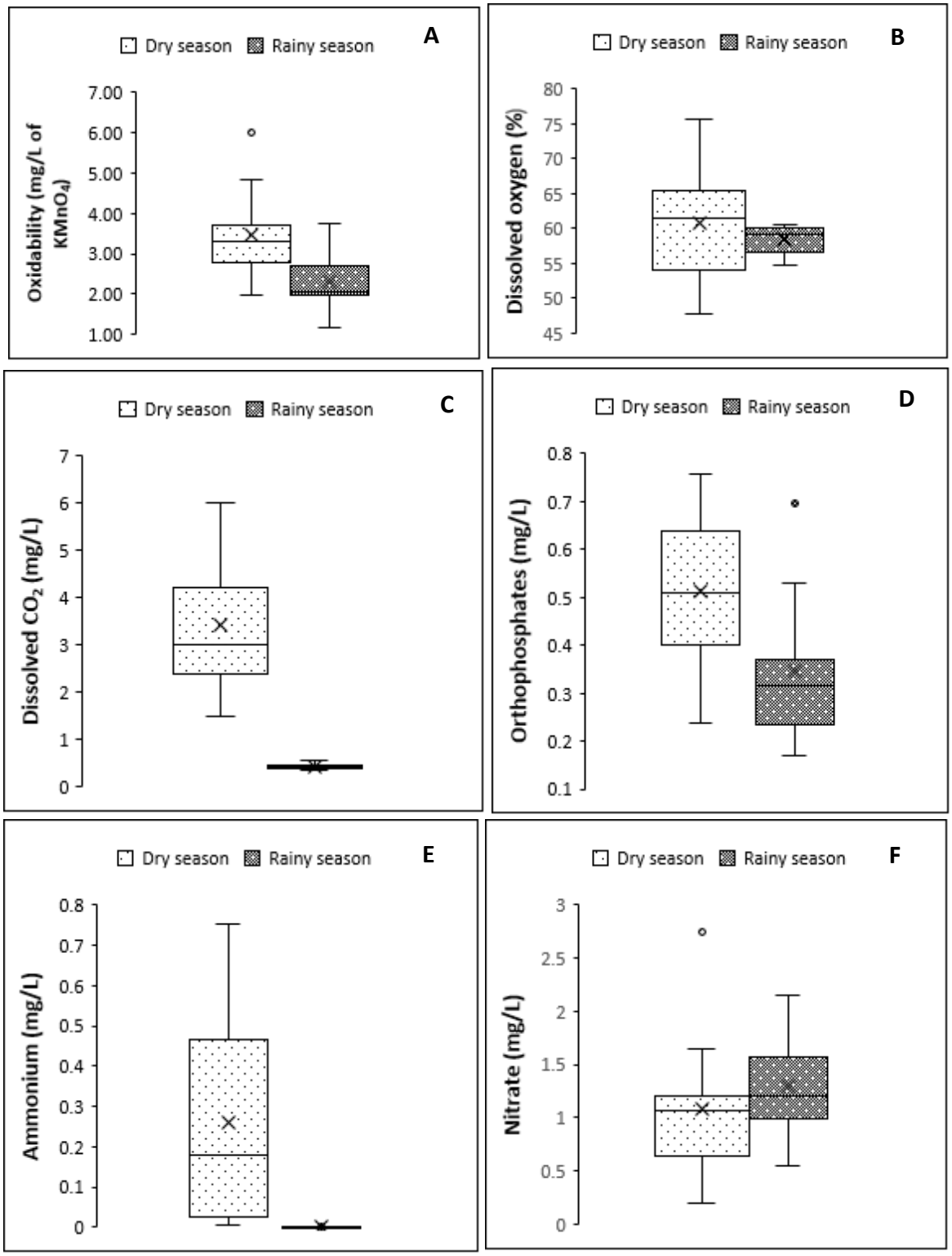



**Figure 25:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B), dissolved carbon dioxide (C), orthophosphate (D), ammonium ions (E) and nitrate ions(F) obtained during the sampling period in Tiko.

The value of alkalinity varied significantly from one season to another as showed by the U test of Mann Whitney (p = 0.19) but no significant difference was observed from one sampling point to another. The lowest value was 4.00 mg/L of $CaCO_3$, obtained in TW 4 in both the rainy and dry seasons and in TW5 in the rainy season. The highest value was 14.00 mg/L of $CaCO_3$, obtained in the rainy season in sampling point TW7 (Figure 26 A). The values of total hardness varied between 22.72 mg/L of $CaCO_3$ in the rainy season (TW6) and 165.06 mg/L of $CaCO_3$in the rainy season (TW3), with a mean value of 75.64 ± 39.14 mg/L. The U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another (Figure 26 B).

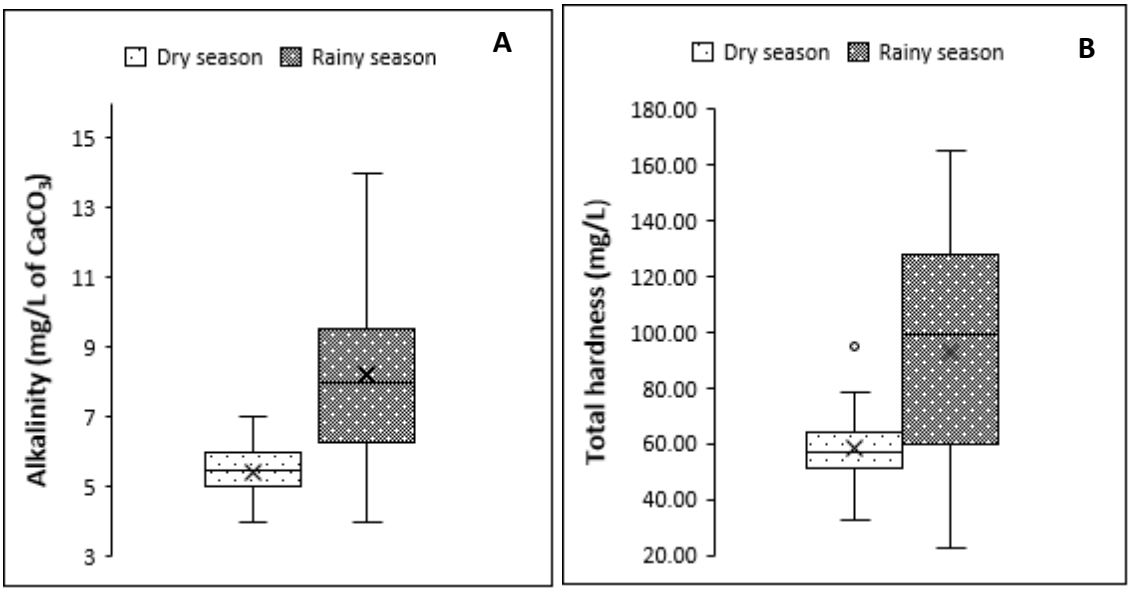



**Figure 26:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness (B) in the sampled points in the town of Tiko.

### III.1.1.3. Distribution of physicochemical variables of groundwater studied in the town of Limbe

The lowest mean seasonal value for temperature was obtained in the dry season (26 °C) in LW3 while the highest value was obtained in LW2 in the dry season (27.70 °C) with a mean value of 26.76 ± 0.57 °C. (Figure 27 A). The highest mean seasonal value of suspended solids was obtained in the dry season (25.00 mg/L) in LW3 while the lowest mean seasonal value (0.50 mg/L) was obtained in the rainy season in LW4 (Figure 27 B). Turbidity values oscillated between 5.00 FTU as highest value recorded in LW4 and 33.5 FTU recorded in LW5 in the dry season and the mean value was 18.75 ± 11.39 FTU (Figure 27 C). The U test on Mann Whitney did not show any significant difference for temperature, SS and turbidity during the study period in Limbe.

The mean seasonal value of electric conductivity varied from 99.0 µS/cm (LW3) in the rainy season to 2720 µS/cm (LW5) in the dry season (Table X). The mean value was 725.25 ± 600.23 µS/cm and no significant difference was observed for this parameter (Figure 27 D). The mean seasonal value of salinity was distributed from 0.04 PSU in LW3 as lowest value in the dry season and 2.51 PSU in LW2 as highest value in the dry season, with a mean value of 0.68 ± 0.42 PSU (Figure 27 E). The mean seasonal value of pH fluctuated between 5.66 as lowest value obtained in LW4 in the rainy season and 7.48, recorded in LW2 in the dry season with a mean value of 6.40 ± 0.55. No significant difference was observed between seasons and between sampling points for EC, salinity and pH during the sampling period in Limbe (Figure 27 F).

**Table X:** Seasonal variation of the physicochemical variables recorded during the sampling period in Limbe

| Para | Temp (°C) | | SS (mg/L) | | Tur (FTU) | | EC (µS/cm) | | Sal (PSU) | | pH (CU) | | Oxyd (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **LW1** | 26.05 | 26.30 | 16.50 | 5.00 | 29.00 | 8.50 | 627.50 | 425.00 | 2.41 | 0.21 | 6.70 | 6.56 | 5.04 | 2.37 |
| **LW2** | 27.70 | 26.55 | 14.50 | 4.50 | 31.00 | 10.50 | 1250.00 | 1062.00 | 2.51 | 0.52 | 7.48 | 6.85 | 4.54 | 1.58 |
| **LW3** | 26.00 | 26.80 | 16.50 | 25.00 | 21.00 | 30.50 | 100.00 | 99.00 | 0.04 | 0.09 | 6.19 | 6.06 | 3.75 | 2.96 |
| **LW4** | 26.85 | 27.15 | 0.50 | 5.50 | 5.00 | 11.50 | 223.50 | 261.00 | 0.36 | 0.12 | 5.98 | 5.66 | 4.94 | 2.17 |
| **LW5** | 27.50 | 26.75 | 16.5 | 3.50 | 33.50 | 7.00 | 2720.50 | 484.00 | 0.28 | 0.29 | 6.71 | 5.88 | 5.04 | 2.17 |

| Para | $DO_2$ (% sat) | | $DCO_2$ (mg/L) | | Phos (mg/L) | | Amm (mg/L) | | Nitra (mg/L) | | Alkal (mg/L) | | T hard(mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **LW1** | 55.50 | 55.75 | 8.57 | 0.275 | 0.53 | 1.56 | 0.03 | 0.002 | 1.05 | 1.00 | 11.00 | 11.00 | 56.64 | 97.66 |
| **LW2** | 56.40 | 56.15 | 9.78 | 0.40 | 2.69 | 1.21 | 0.01 | 0.01 | 1.20 | 1.05 | 10.00 | 11.00 | 23.83 | 30.71 |
| **LW3** | 56.75 | 53.00 | 1.53 | 0.40 | 0.27 | 0.23 | 0.02 | 0.009 | 0.41 | 1.30 | 3.50 | 10.00 | 46.53 | 86.61 |
| **LW4** | 52.65 | 55.35 | 2.36 | 0.57 | 21.08 | 0.64 | 0.009 | 0.003 | 1.15 | 1.85 | 3.00 | 6.00 | 51.87 | 61.24 |
| **LW5** | 56.30 | 54.15 | 11.26 | 0.65 | 2.37 | 0.12 | 0.01 | 0.001 | 0.90 | 3.20 | 11.00 | 4.00 | 22.17 | 129.80 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

The mean seasonal values of oxidability oscillated between 1.58 mg/L, recorded in LW2 during the rainy season and 5.04 mg/L, recorded in LW1 and LW4 during the dry season. The U test of Mann Whitney showed a significant difference between the rainy and dry season ($p = 0.008$). However, no significant difference was observed from one sampling point to another (Figure 28 A). Dissolved oxygen values were generally higher in the dry season than in the rainy season. The lowest value was 53 %, obtained in the rainy season in the sampling point LW3 and the highest value was 56.75 %, obtained in the dry season in station LW3, with a mean value of 55.2 ± 1.44 % (Figure 28 B). The mean seasonal value of dissolved carbon dioxide was distributed between 0.28 mg/L in LW1 in the rainy season and 11.26 mg/L in LW5

during the dry season, with a mean value of 3.57 ± 2.43 mg/L (Figure 28 C). The U test of Mann Whitney showed a significant difference between the rainy and dry season (p = 0.08).

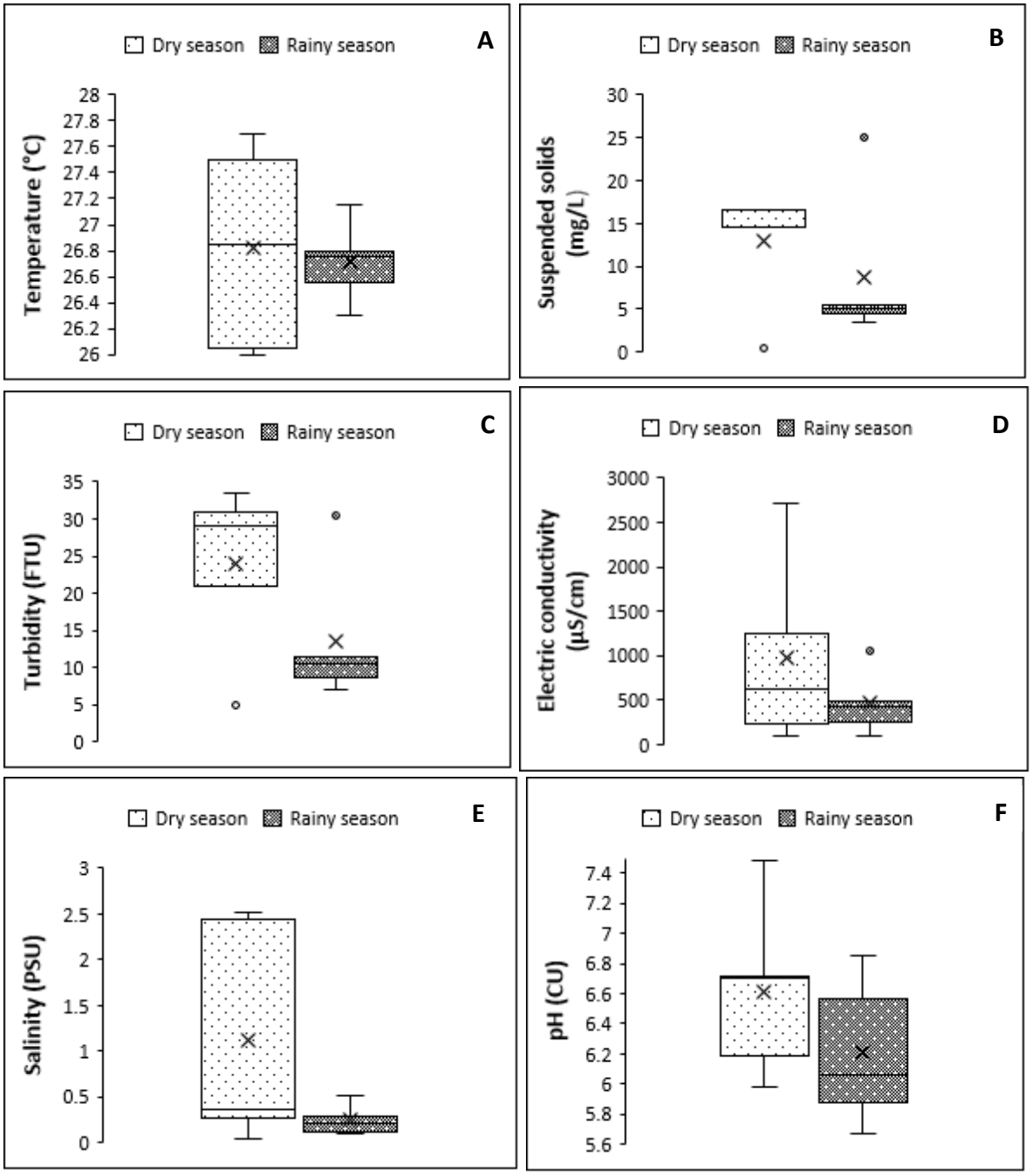



**Figure 27:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), electric conductivity (D), salinity (E) and pH (F) in the sampled points in Limbe.

The values of orthophosphates fluctuated between 0.12 mg/L in the rainy season in LW5 and 21.08 mg/Lin LW4 in the dry season. The mean value was 3.06 ± 2.39 mg/L. The U test of Mann Whitney did not show any significant difference from one season to another and from

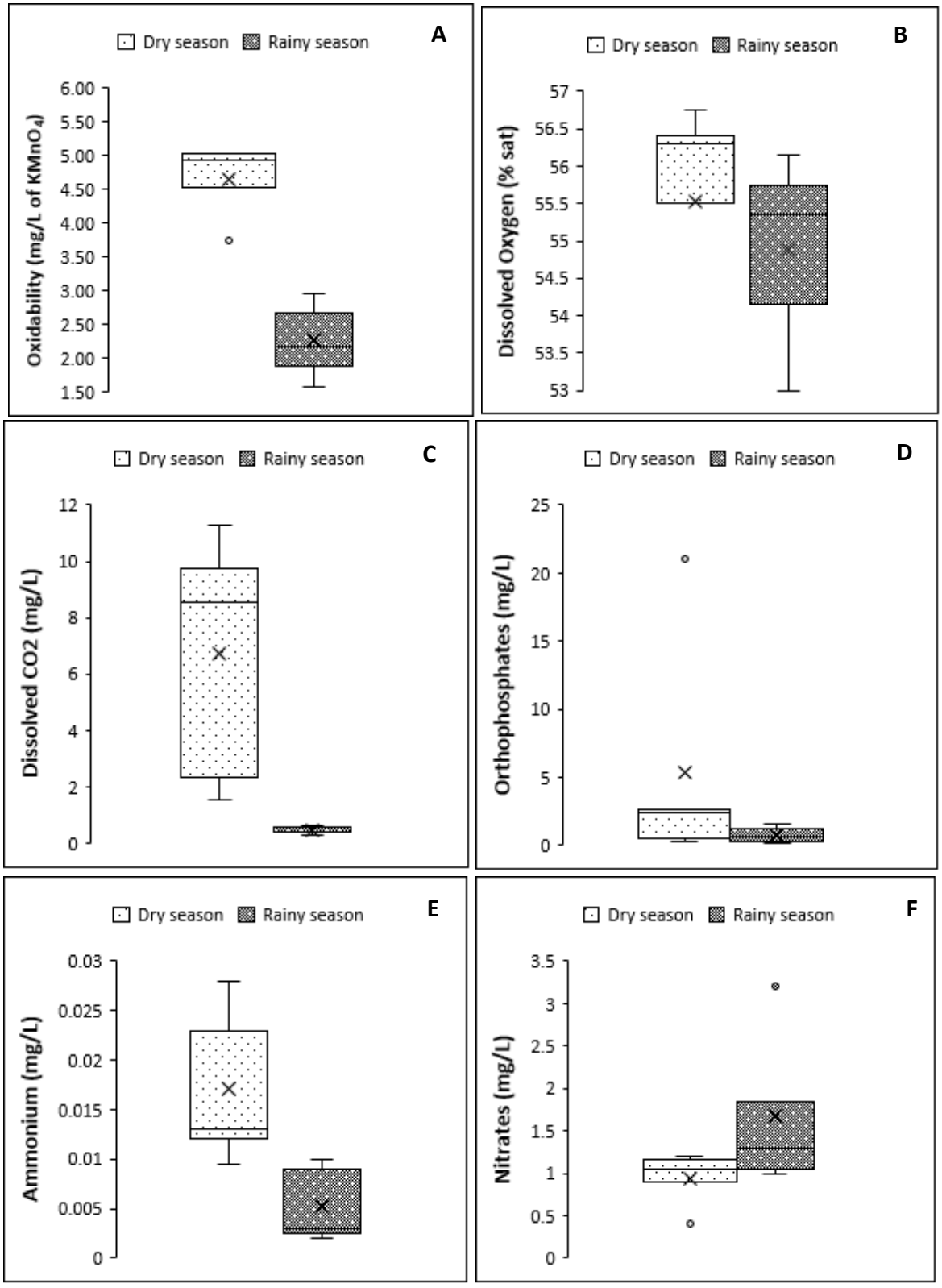



**Figure 28:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B) and dissolved carbon dioxide (C), orthophosphate (D), ammonium (E) and nitrate (F) in the sampled stations in Limbe.

one sampling point to another for orthophosphates (Figure 28 D). The mean seasonal value of ammonium was distributed between 0.0025 mg/L in LW5 in the rainy season and 0.03 mg/L in LW1 in the dry season, with a mean value of 0.012 ± .0085 mg/L. The U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another for ammonium (Figure 28 E). The mean seasonal value of nitrate varied between 0.41 mg/L in LW3 in the dry season and 3.20 mg/L in LW5 in the rainy season, with a mean value of 1.31 ± 0.75 mg/L. The U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another for nitrate (Figure 28 F).

The value of alkalinity varied with the lowest value of 3 mg/L recorded in the dry season in LW3 and a highest value of 11 mg/L recorded in LW1 in the rainy season and in LW5 in the dry season with a mean value of 8.05 ± 3.48 mg/L (Figure 29 A). The values of total hardness varied between 22.17 mg/L in station LW5in the dry season and 129.8 mg/L in station LW5 in the rainy season with a mean value of 60.71 ± 34.72 mg/L. The U test of Mann Whitney did not show any significant difference from one sampling point to another nor from one season to another for alkalinity and total hardness throughout the study period (Figure 29 B).

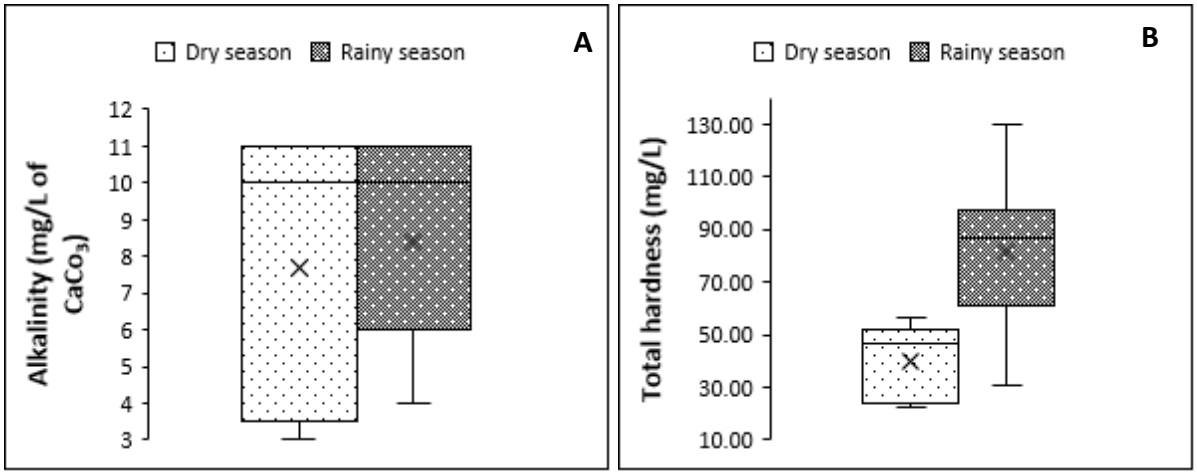



**Figure 29:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness (B) in the sampled stations in the town of Limbe

### III.1.1.4. Variation of physicochemical variables of the groundwater studied in Muyuka

The seasonal distribution of temperature was significantly higher in the dry season than in the rainy season in Muyuka (Table XI). The highest value was 28.40 °C recorded in the dry season in station MW1 and MW4 while the lowest value was obtained during the rainy season (22.90 °C) in station MW4 (Figure 30 A). The U test on Mann Whitney showed a significant difference between the rainy and the dry season (p=0.008). Suspended solids (SS) showed high

distribution in the rainy season generally than in the dry season, when outliers are considered. The lowest seasonal value was 5.5 mg/L, obtained in the rainy season in station MW3 with a mean rainy season value of 12.6 ± 5.3 mg/L while the highest value was 20.5 mg/L obtained still in the rainy season in station MW5. The mean dry season value was 9.4 ± 3.69 mg/L and the mean seasonal value for suspended solids was 11.00 ± 4.64 mg/L (Figure 30 B). The pattern of distribution of turbidity showed high values in the rainy season than in the dry season. The values ranged from 9.00 FTU in station in MW3 in the dry season (mean value of 22.8 ± 8.53 FTU) to 38.50 FTU in the rainy season, recorded in MW4 (mean value of 22.8 ± 10.35 FTU) and the mean seasonal value was 19.80 ± 9.46 FTU (Figure 30 C). No significant difference however, was obtained for SS and turbidity throughout the study period in Muyuka.

The mean seasonal distribution of salinity values did not vary much during the study period. The highest value was recorded MW3 in the rainy season (0.22 PSU) while the lowest value was recorded in the dry season in MW5 (0.04 PSU). The mean value in the rainy season was 0.13 ± 0.07 PSU and in the dry season, it was 0.10 ± 0.07 PSU while the mean seasonal value of salinity obtained during the study period was 0.12 ± 0.68 PSU (Figure 30 D). Electric conductivity values showed a high magnitude in the dry season than in the rainy season. The values ranged from 118.0 µS/cm in, recorded in station MW5 in the rainy season (260.7 ± 164.1 µS/cm) to 536.0 µS/cm, recorded in MW3 in the dry season (342.3 ± 189.4 µS/cm). The mean seasonal value was 301.5 ± 172.5 µS/cm (Figure 30 E). The seasonal value of pH varied less during the study period. The lowest value was 4.28 recorded in the dry season in MW3 (mean dry season value 4.90 ± 0.51) while the highest value was 5.65, recorded in the rainy season in station MW5 (mean rainy season value 5.15 ± 0.41). The mean seasonal value was 5.02 ± 0.45 (Figure 30 F). No significant difference however, was obtained for salinity, EC and pH during the study period in Muyuka.

The distribution of the seasonal values of oxidability was higher in the dry season than in the rainy season and it ranged between 1.98 mg/L in rainy season in MW4 and 3.16 mg/L in the dry season, recorded in MW1 with a mean seasonal value of 2.63 ± 0.38 mg/L. The mean value in the rainy season was 2.40 ± 0.35 mg/L and for the dry season 2.86 ± 0.28 mg/L (Figure 31 A). Dissolved Oxygen distribution ranged from 55.10 % to 65.75 % with both lowest and highest values recorded in the dry season, recorded in MW4 and MW2 respectively with a mean seasonal value of 60.74 ± 3.43 % (Figure 31 B).

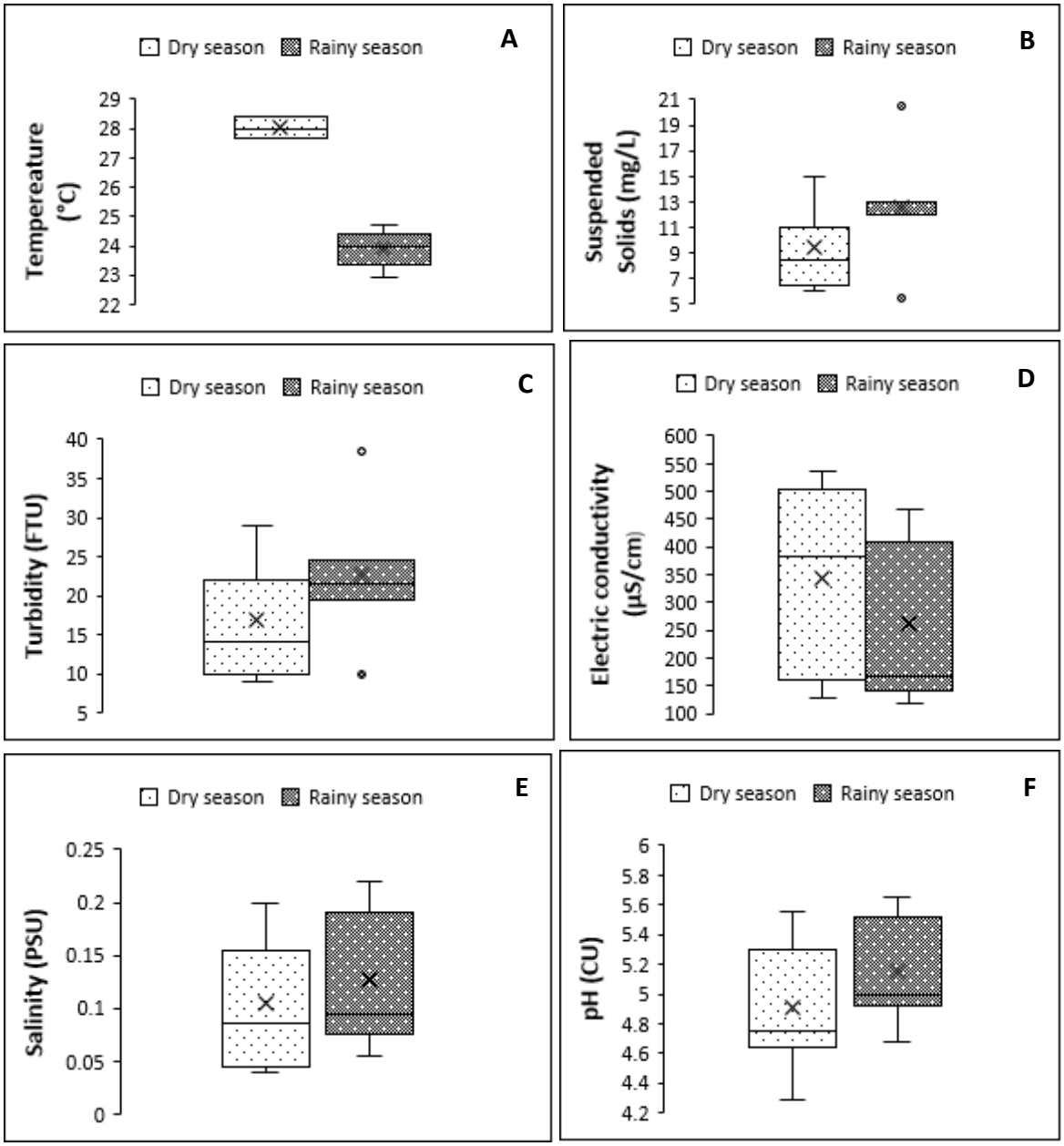



**Figure 30:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), electric conductivity (D), salinity (E) and pH (F) in the sampled points in Muyuka.

No significant difference from one season to another or from one station to another for oxidability and dissolved oxygen was obtained during the study period in Muyuka. The distribution of the mean seasonal value of dissolved carbon dioxide varied between the rainy and dry season, with higher values recorded in the dry season. The lowest value was obtained in the rainy season (0.23 mg/L) in MW5 while the highest value was 19.01 mg/L, recorded in

the dry season in station MW5. The U test of Mann Whitney showed a significant difference between the rainy and dry season with a p value of 0.008 (Figure 31 C).

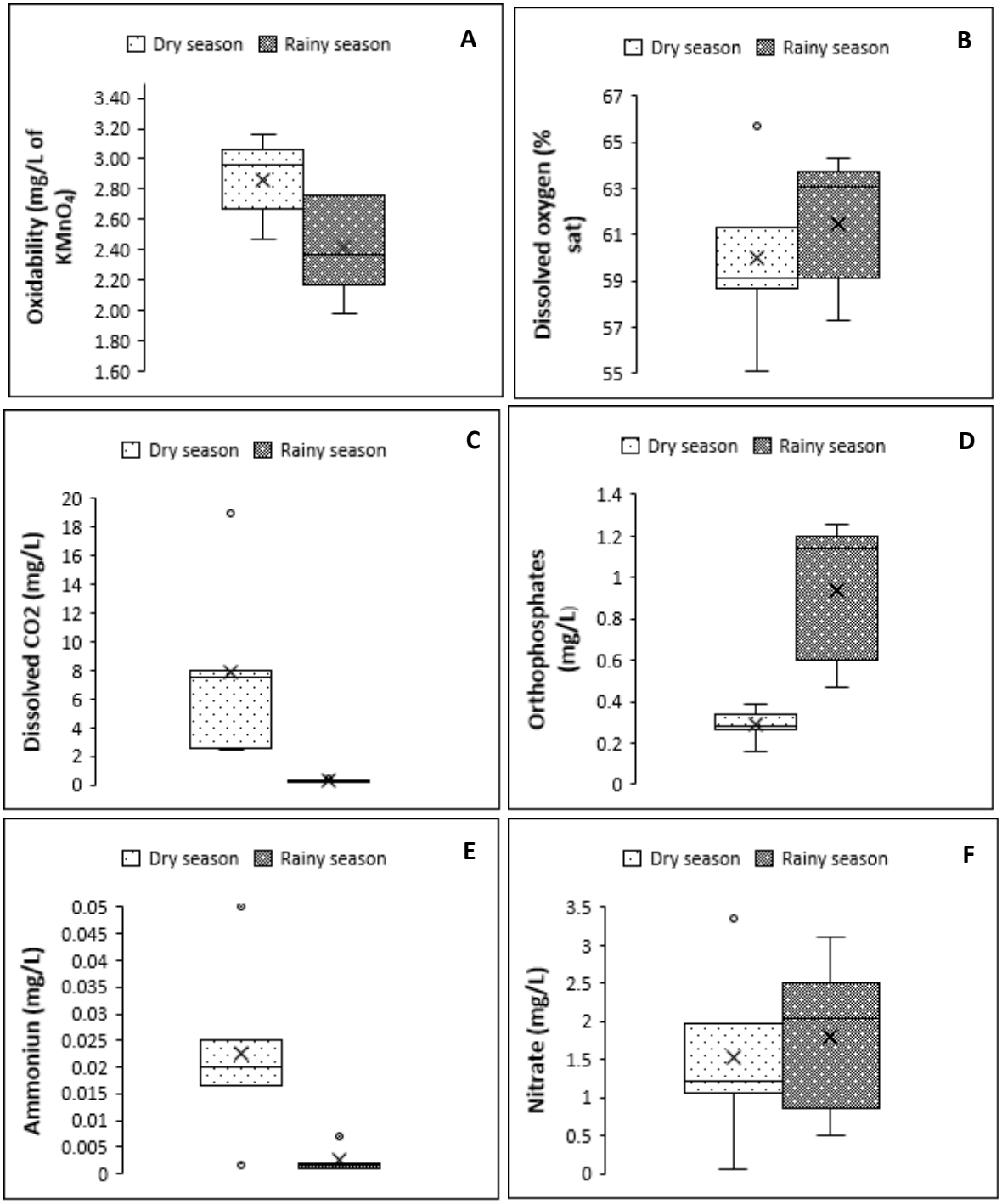



**Figure 31:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B) and dissolved carbon dioxide (C), orthophosphate (D), ammonium (E) and nitrate (F) in the sampled points in Muyuka.

**Table XI:** Seasonal variation of physicochemical variables recorded in Muyuka during the sampling period

| Para | Temp (°C) | | SS (mg/L) | | Tur (FTU) | | EC (µS/cm) | | Sal (PSU) | | pH (CU) | | Oxyd (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **MW1** | 28.40 | 23.95 | 6.50 | 12.00 | 14.00 | 24.50 | 129.50 | 142.50 | 0.08 | 0.07 | 5.55 | 5.65 | 3.16 | 2.76 |
| **MW2** | 27.65 | 24.7 | 6.00 | 12.00 | 10.00 | 10.00 | 503.00 | 408.50 | 0.20 | 0.19 | 4.64 | 4.66 | 2.67 | 2.76 |
| **MW3** | 27.65 | 24.15 | 8.50 | 5.50 | 9.00 | 21.50 | 536.00 | 467.50 | 0.15 | 0.22 | 4.28 | 5.00 | 2.96 | 2.37 |
| **MW4** | 28.40 | 22.90 | 11.00 | 13.00 | 22.00 | 38.50 | 160.00 | 167.00 | 0.04 | 0.09 | 5.30 | 5.51 | 3.06 | 1.97 |
| **MW5** | 28.00 | 23.80 | 15.00 | 20.50 | 29.00 | 19.50 | 383.00 | 118.00 | 0.04 | 0.05 | 4.75 | 4.92 | 2.47 | 2.17 |

| Para | $DO_2$ (% sat) | | $DCO_2$ (mg/L) | | Phos (mg/L) | | Amm (mg/L) | | Nitra (mg/L) | | Alkal (mg/L) | | T hard(mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **MW1** | 58.70 | 64.35 | 2.53 | 0.32 | 0.34 | 1.2 | 0.02 | 0.002 | 1.205 | 2.50 | 3.00 | 5.00 | 40.84 | 103.01 |
| **MW2** | 65.75 | 57.25 | 19.01 | 0.27 | 0.27 | 1.26 | 0.03 | 0.001 | 1.06 | 0.50 | 5.00 | 1.01 | 55.07 | 169.46 |
| **MW3** | 61.30 | 63.75 | 7.56 | 0.45 | 0.16 | 0.6 | 0.001 | 0.001 | 3.36 | 3.10 | 6.00 | 2.02 | 58.93 | 24.08 |
| **MW4** | 55.10 | 59.10 | 2.38 | 0.32 | 0.28 | 1.15 | 0.02 | 0.001 | 1.97 | 2.05 | 2.00 | 2.02 | 27.74 | 47.01 |
| **MW5** | 59.10 | 63.05 | 7.96 | 0.22 | 0.39 | 0.47 | 0.05 | 0.007 | 0.06 | 0.85 | 4.00 | 3.02 | 70.03 | 62.29 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

The values of orthophosphates fluctuated greatly between the rainy and the dry season during the study period in Muyuka. The lowest value was 0.16 mg/L, obtained in station MW3 in the dry season while the highest value recorded was 1.26 in MW2 in the rainy season. The U test of Mann Whitney showed a significant difference between the seasons ($p = 0.008$) (Figure 31 D). The mean seasonal value of ammonium ions distribution ranged from 0.001 mg/L in the rainy season (MW3) to 0.05 mg/L (MW5) in the dry season (Figure 31 E). The U test of Mann Whitney showed a significant difference from one season to another ($p = 0.008$). The values of nitrate ions ranged from 0.05 mg/L in the dry season in MW5 (mean dry season value 1.52 ±1.2 mg/L) to 3.35 mg/L in the dry season in MW3, with a mean seasonal value of 1.66 ± 1.11 mg/L (mean rainy season value 1.80 ± 1.09 mg/L). The U test of Mann Whitney did not show any significant difference from one season to another for nitrate (Figure 31 F).

Alkalinity values varied from one season to the other as seen on figure 32 A. The values ranged from 1.03 mg/L as smallest value (MW2) to 6.00 mg/L (MW3) as highest value in the rainy and dry season respectively and had a mean seasonal value of 3.31 ± 1.63 mg/L. The values of total hardness varied between 24.08 mg/L in the rainy season in MW3 and 169.46 mg/L in the rainy season in station MW2, with a mean seasonal value of 65.84 ± 42.80 mg/L. The U test of Mann Whitney did not show any significant difference for alkalinity and total hardness throughout the study period in Muyuka (Figure 32 B).

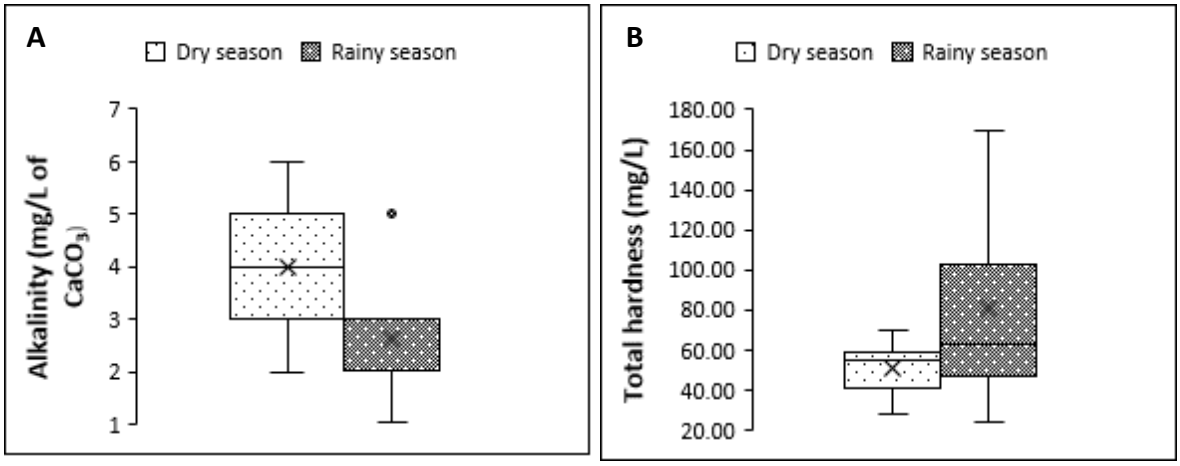



**Figure 32:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness (B) in the sampled points in the town of Muyuka.

### III.1.1.5. Variation of physicochemical variables of the sampled groundwater in Buea

The seasonal distribution of temperature was significantly higher in the dry season than in the rainy season (Table XII). The highest value was obtained in BS8 (23.25 °C) in the dry season while the lowest value was recorded during the rainy season in BS11 (12.60 °C). The H test of Kruskal Wallis showed a significant difference between the rainy and the dry season ($p=0.037$) but no significant difference was obtained from one sampling point to another (Figure 33 A). The distribution of suspended solids (SS) did not vary much during the study period in the town of Buea. The lowest seasonal value was 3.5 mg/L, obtained in BS11 in the dry season (mean dry season value of 7.25 ± 2.42 mg/L) while the highest value was 22.0 mg/L obtained in the rainy season in BS9 (mean rainy season value of 10.58 ± 5.78 mg/L). The mean seasonal value for suspended solids was 8.92 ± 4.57 mg/L (Figure 33 B). The distribution pattern of Turbidity showed high values in the rainy season than in the dry season. The values ranged from 1.5 FTU (BS11) in the dry season (mean dry season value of 9.75 ± 4.89 FTU) to 31.50 FTU (BS9) in the rainy season (mean rainy season value of 16.25 ± 7.99 FTU). The mean seasonal value was 13.0 ± 7.17 FTU. The H test of Kruskal Wallis did not show any significant difference from one sampling point to another and from one season to another for SS and turbidity during the study period in Buea (Figure 33 C).

Electric conductivity values showed almost the same magnitude in both the dry season and the rainy season, but the difference was the high value of 1833 µS/cm that was recorded in the rainy season in BS9 which is an outlier (mean rainy season value 455.67 ± 678.02 µS/cm). The lowest value was 79 µS/cm, recorded in BS10 in the rainy season (mean dry season value 194.25 ± 76.87 µS/cm). The mean seasonal value was 324.95 ± 479.88 µS/cm (Figure 33 D).

**Table XII:** Seasonal variation of physicochemical variables during the study period in Buea

| Para | Temp (°C) | | SS (mg/L) | | Tur (FTU) | | EC (µS/cm) | | Sal (PSU) | | pH (CU) | | Oxyd (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **BS8** | 23.25 | 20.90 | 10.00 | 7.00 | 15.00 | 12.00 | 250.00 | 258.50 | 0.07 | 0.12 | 7.21 | 6.29 | 3.46 | 2.37 |
| **BS9** | 21.80 | 19.55 | 5.50 | 22.00 | 6.50 | 31.50 | 285.00 | 1833.00 | 0.09 | 0.16 | 7.17 | 6.49 | 2.77 | 1.58 |
| **BS10** | 20.05 | 16.30 | 9.00 | 11.00 | 11.50 | 9.50 | 80.00 | 79.00 | 0.03 | 0.04 | 7.72 | 6.8 | 3.46 | 1.58 |
| **BS11** | 18.75 | 12.60 | 3.50 | 8.50 | 1.50 | 11.50 | 152.50 | 140.00 | 0.06 | 0.06 | 7.73 | 6.82 | 2.86 | 2.56 |
| **BS12** | 21.35 | 20.15 | 8.50 | 7.00 | 12.00 | 17.00 | 240.00 | 244.50 | 0.09 | 0.13 | 7.49 | 6.52 | 2.86 | 1.78 |
| **BS13** | 21.75 | 17.60 | 7.00 | 8.00 | 12.00 | 16.00 | 158.00 | 179.00 | 0.05 | 0.09 | 7.88 | 6.59 | 3.65 | 2.17 |

| Para | $DO_2$ (% sat) | | $DCO_2$ (mg/L) | | Phos (mg/L) | | Amm (mg/L) | | Nitra (mg/L) | | Alkal (mg/L) | | T hard(mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **BS8** | 66.20 | 59.10 | 1.61 | 0.45 | 0.39 | 1.87 | 0.01 | 0.00 | 0.05 | 0.35 | 8.00 | 5.00 | 34.58 | 70.82 |
| **BS9** | 82.75 | 61.75 | 3.29 | 0.28 | 0.59 | 0.97 | 0.005 | 0.003 | 0.25 | 1.15 | 7.00 | 5.00 | 44.42 | 103.56 |
| **BS10** | 77.15 | 60.10 | 6.56 | 0.30 | 0.69 | 0.59 | 0.006 | 0.007 | 0.41 | 0.00 | 6.00 | 4.00 | 59.48 | 28.46 |
| **BS11** | 71.20 | 63.10 | 5.01 | 0.27 | 0.69 | 1.17 | 0.00 | 0.002 | 0.15 | 0.30 | 2.50 | 4.00 | 25.12 | 54.33 |
| **BS12** | 77.70 | 61.70 | 4.22 | 0.33 | 0.77 | 0.47 | 0.006 | 0.001 | 0.35 | 0.90 | 7.00 | 6.00 | 40.18 | 21.27 |
| **BS13** | 71.8 | 63.90 | 1.48 | 0.33 | 0.278 | 1.52 | 0.009 | 0.005 | 0.55 | 0.20 | 4.00 | 7.00 | 43.15 | 151.39 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

The mean seasonal distribution of salinity value did not vary much during the study period in Buea. The highest value was recorded in the rainy season (0.15 PSU) in BS9 while the lowest value was recorded in the dry season (0.025 PSU) in BS10. The mean value in the rainy season was 0.10 ± 0.05 and in the dry season, it was 0.07 ± 0.03 while the mean seasonal value of salinity obtained during the study period was 0.08 ± 0.03. No significant difference was observed for Electric conductivity and salinity during the study period (Figure 33 E). The seasonal value of pH varied greatly during the study period. The values in the dry season varied from 7.17 to 7.88 in BS9 and BS13 respectively (mean dry season value 7.53 ± 0.29) while in the rainy season, pH varied from 6.29 to 6.82 in BS8 and BS11 respectively (mean rainy season value 6.52 ± 0.20) as shown on figure 33 F. The H test of Kruskal Wallis showed a significant difference from one season to another for pH ($p = 0.004$).

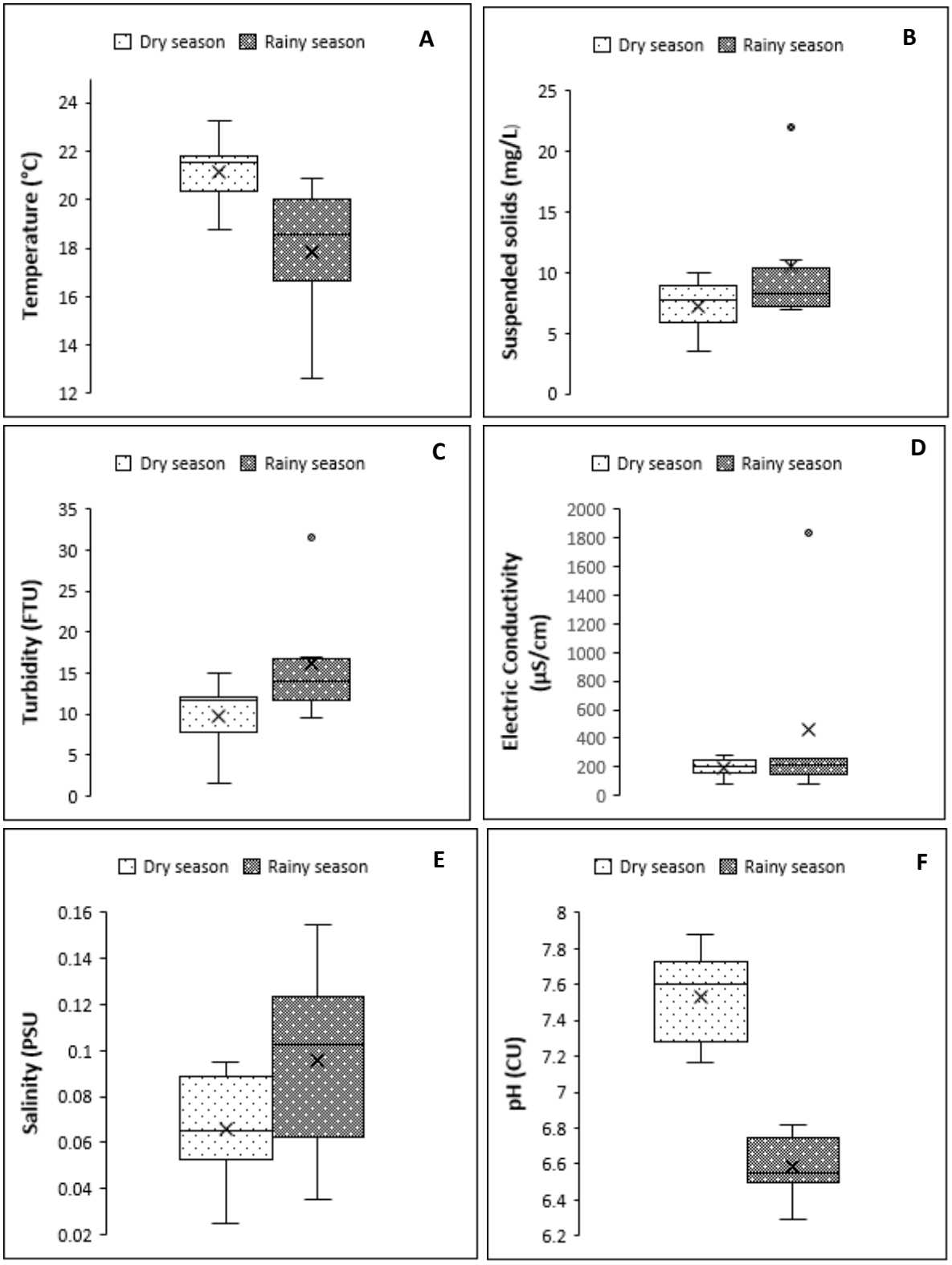



**Figure 33:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), electric conductivity (D), salinity (E) and pH (F) in the sampled points in Buea

The distribution of the seasonal values of oxidability was much higher in the dry season than in the rainy season and it ranged from 1.58 to 2.56 mg/L in the rainy season in BS10 and BS11 respectively and from 2.77 to 3.65 mg/L in the dry season in BS9 and BS13 respectively (Figure 34 A). The H test of Kruskal Wallis showed a significant difference from one season to another in the town of Buea ($p = 0.004$). Dissolved oxygen distribution varied significantly between the rainy and the dry season. The value ranged from 66.2 % (BS8) to 82.75 % (BS9) in the dry season and in the rainy season, the value of dissolved oxygen varied from 59.1% (BS8) to 63.9 % in BS13 (Figure 34 B). The H test of Kruskal Wallis showed a significant difference from one season to another ($p = 0.004$). The distribution of the mean seasonal value of dissolved carbon dioxide varied between the rainy and dry season and the H test of Kruskal Wallis showed a significant difference between the rainy and dry season, with a "p" value of 0.004. The highest value was 6.56 mg/L recorded in the dry season in BS10 and the lowest value was 0.27 mg/L, obtained in the rainy season in BS11 (Figure 34 C).

The values of orthophosphates fluctuated greatly between the rainy and the dry season during the study period in Buea. The values of orthophosphate ranged from 0.278 mg/L (BS13) to 0.77 mg/L in BS12 in the dry season with a mean of $0.57 \pm 0.20$ mg/L and from 0.47 mg/L in BS12 to 1.87 mg/L in BS8 during the rainy season with a mean of $1.10 \pm 0.54$ mg/L. The mean seasonal value was $0.83 \pm 0.47$ mg/L (Figure 34 D). The mean seasonal value of ammonium ions ranged from 0 mg/L (BS8) to 0.007 mg/L (BS10) in the rainy season and from 0 mg/L (BS11) to 0.01 mg/L (BS8) in the dry season. The mean seasonal value for ammonium ions was $0.004 \pm 0.003$ (Figure 34 E). The mean seasonal value of nitrate ions ranged between 0.05 mg/L in BS8 and 0.55 mg/L in BS13 in the dry season (mean dry season value $0.3 \pm 0.18$ mg/L) and between 0 mg/L (BS10) and 1.15 mg/L (BS9) in the rainy season (mean rainy season value $0.48 \pm 0.44$ mg/L) as observed on figure 34 F. The H test of Kruskal Wallis did not show any significant difference between the rainy and the dry season for orthophosphates, ammonium ions and nitrate ions in the town of Buea during the study period.

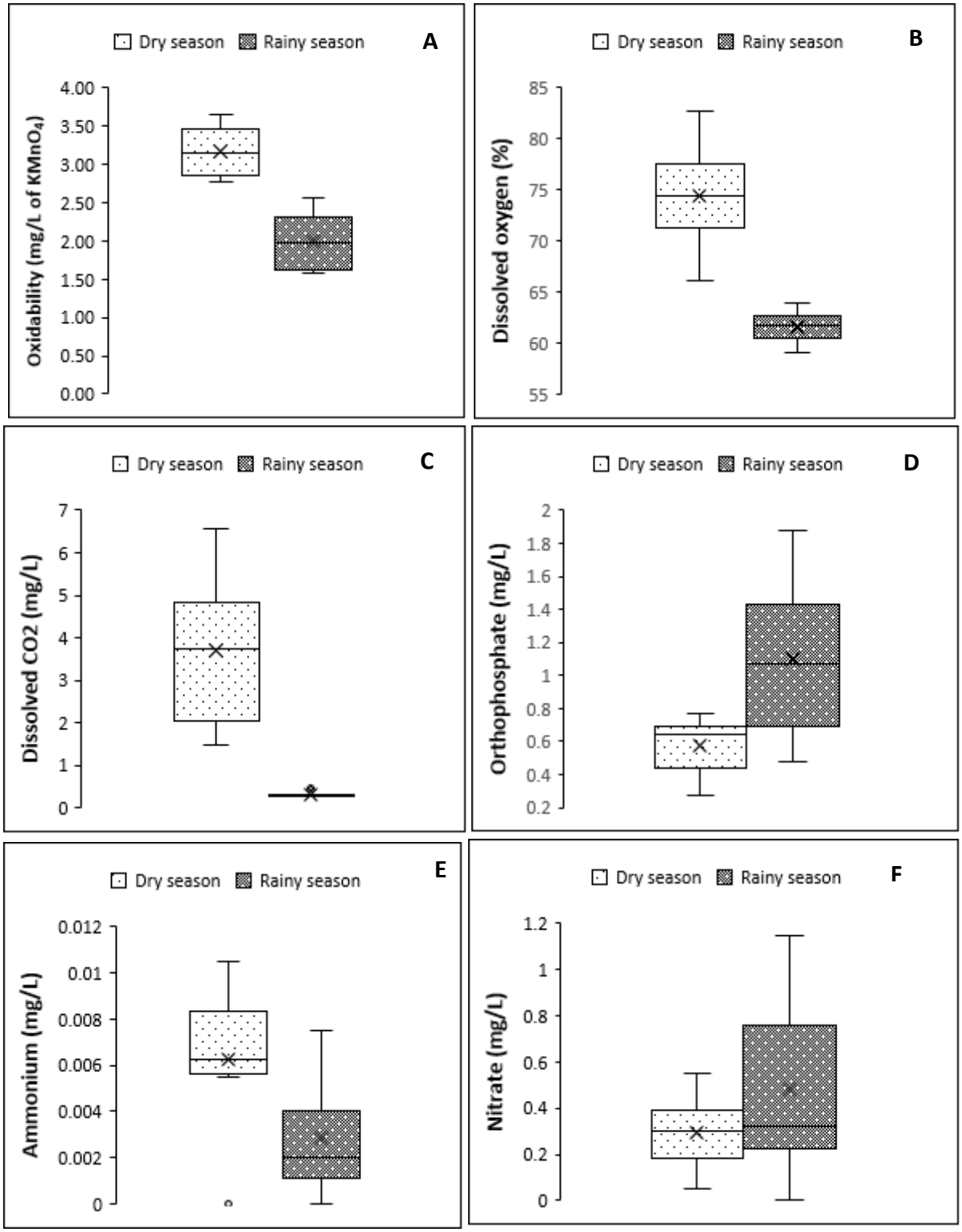



**Figure 34:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B) and dissolved carbon dioxide (C), orthophosphate (D), ammonium (E) and nitrate (F), in the sampled points in Buea.

The mean seasonal value of alkalinity ranged from 2.5 mg/L (BS11) as smallest value to 8.00 mg/L (BS8) as highest value, both obtained in the dry season, with a mean value of 5.45 ± 1.64 mg/L (Figure 35 A). The mean seasonal value of total hardness varied from 21.27 mg/L (BS12) to 151.39 mg/L (BS13) in the rainy season (71.64 ± 49.16 mg/L) and from 25.12 mg/L to 59.48 mg/L in the dry season in BS11 and BS1o respectively (41.16 ± 11.42 mg/L) and the mean seasonal value was 56.39 ± 37.56 mg/L. No significant difference was observed for alkalinity and for total hardness throughout the study period in Buea (Figure 35 B).

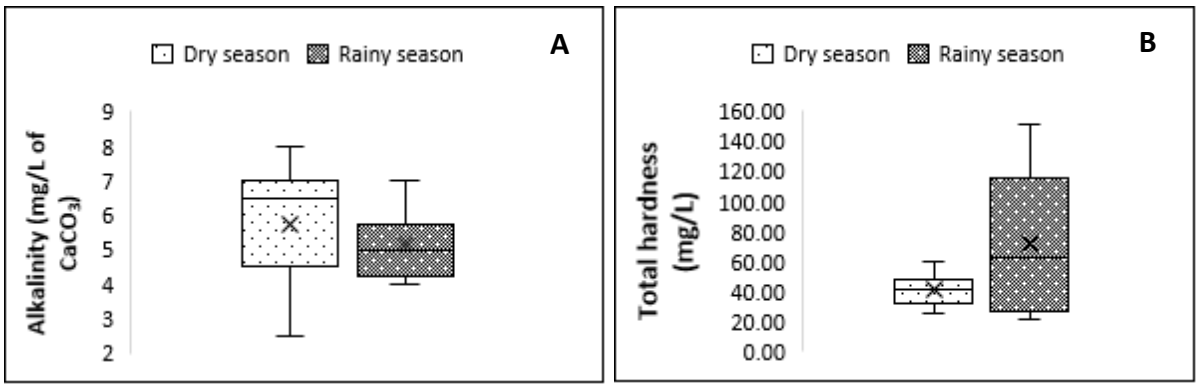



**Figure 35:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness (B) in the sampled points in the town of Buea

### III.1.1.6. Distribution of physicochemical variables of the sampled groundwater of Ekona/Mautu

The mean seasonal distribution of temperature was significantly higher in the dry season than in the rainy season (Table XIII). In the dry season, the highest value was 22.9 °, recorded in MS4 while the lowest value was 22 °C, obtained in ES6 with a mean of 22.48 ± 0.41 °C and in the rainy season, the lowest value was 18.8 mg/L, obtained in MS5 and the highest value was 22.7 °C in MS4 with a mean value of 20.10 ± 1.78 mg/L. The mean seasonal value was 21.29 ± 1.75 mg/L and no significant difference was observed (Figure 36 A). The distribution of suspended solids (SS) varied from 5.5 mg/L (ES6) to 16 mg/L (MS4) in the dry season and the mean dry season value was 9.63 ± 4.77 mg/L. In the rainy season, the value of SS varied from 7 mg/L in station ES7 to 18.5 in station ES6 mg/L with a mean rainy season value of 12.75 ± 5.20 mg/L (Figure 36 B). No significant difference was observed for SS during the sampling period. The values of turbidity ranged from 10.5 FTU in MS5 to 23.5 FTU in the dry season in station ES6 (mean value of 15.13 ± 5.91 FTU) and from 8 FTU (ES7) to 22.5 FTU (MS5) in the rainy season (mean value of 16.88 ± 6.33 FTU) and the mean seasonal value

was 16.0 ± 5.7 FTU. No significant difference was obtained for turbidity during the study period (Figure 36 C).

**Table XIII: Seasonal variation of physicochemical variables recorded in Ekona/Mautu during the sampling period**

| Para | Temp (°C) | | SS (mg/L) | | Tur (FTU) | | EC (µS/cm) | | Sal (PSU) | | pH (CU) | | Oxyd (mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **MS4** | 22.75 | 18.80 | 6.50 | 15.50 | 10.50 | 22.50 | 312.00 | 309.50 | 0.145 | 0.15 | 7.32 | 6.32 | 4.94 | 2.76 |
| **MS5** | 22.90 | 22.70 | 16.00 | 10.00 | 15.00 | 20.00 | 320.00 | 320.00 | 0.16 | 0.15 | 6.49 | 6.40 | 3.06 | 3.35 |
| **ES6** | 22.00 | 19.10 | 10.5 | 7.00 | 23.50 | 8.00 | 274.00 | 302.00 | 0.14 | 0.14 | 7.06 | 6.49 | 2.67 | 2.96 |
| **ES7** | 22.30 | 19.80 | 5.50 | 18.50 | 11.50 | 17.00 | 295.5 | 269.50 | 0.14 | 0.14 | 7.08 | 6.15 | 2.86 | 2.56 |

| Para | $DO_2$ (% sat) | | $DCO_2$ (mg/L) | | Phos (mg/L) | | Amm (mg/L) | | Nitra (mg/L) | | Alkal (mg/L) | | T hard(mg/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **MS4** | 79.9 | 64.35 | 6.98 | 0.35 | 0.52 | 1.65 | 0.55 | 0.001 | 0.80 | 2.25 | 7.00 | 7.00 | 27.19 | 328.19 |
| **MS5** | 67.00 | 56.70 | 5.07 | 0.25 | 0.42 | 1.93 | 0.01 | 0.002 | 0.3 | 0.35 | 4.00 | 5.00 | 16.53 | 103.69 |
| **ES6** | 60.60 | 62.40 | 16.5 | 0.58 | 2.25 | 1.48 | 0.00 | 0.004 | 0.29 | 0.40 | 4.00 | 15.00 | 36.31 | 48.23 |
| **ES7** | 74.70 | 61.40 | 13.57 | 0.38 | 2.03 | 2.35 | 0.0005 | 0.007 | 0.21 | 0.85 | 5.00 | 3.00 | 58.04 | 171.34 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

The value of electric conductivity showed almost the same magnitude in both the dry and the rainy season. The values in the dry season varied from 274.0 to 320.0 µS/cm. In the rainy season, the lowest recorded value was 269.5 µS/cm, obtained in ES6 while the highest value was 320.0 µS/cm, obtained in MS4 in both the rainy and dry seasons. The mean seasonal value for turbidity was 300.31 ± 19.50 µS/cm. No significant difference for salinity and electric conductivity was observed (Figure 36 D). The lowest value of salinity recorded in the rainy season was 0.14 PSU in ES7 and ES6 in the dry season and rainy season while the highest value was 0.16 PSU, recorded in MS4 with a mean dry season value of 0.15 ± 0.00 PSU. The mean seasonal value of salinity obtained during the study period was 0.15 ± 0.06 (Figure 36 E). The mean seasonal value of pH varied during the study period. The values in the dry season varied from 6.49 (MS44) to 7.32 (MS5) while in the rainy season, it varied from 6.15 (ES6) to 6.49 (ES7). The mean seasonal value of pH was 6.66 ± 0.42 (Figure 36 F) and the U test of Mann Whitney showed a significant difference between the rainy and the dry season ($p = 0.029$).

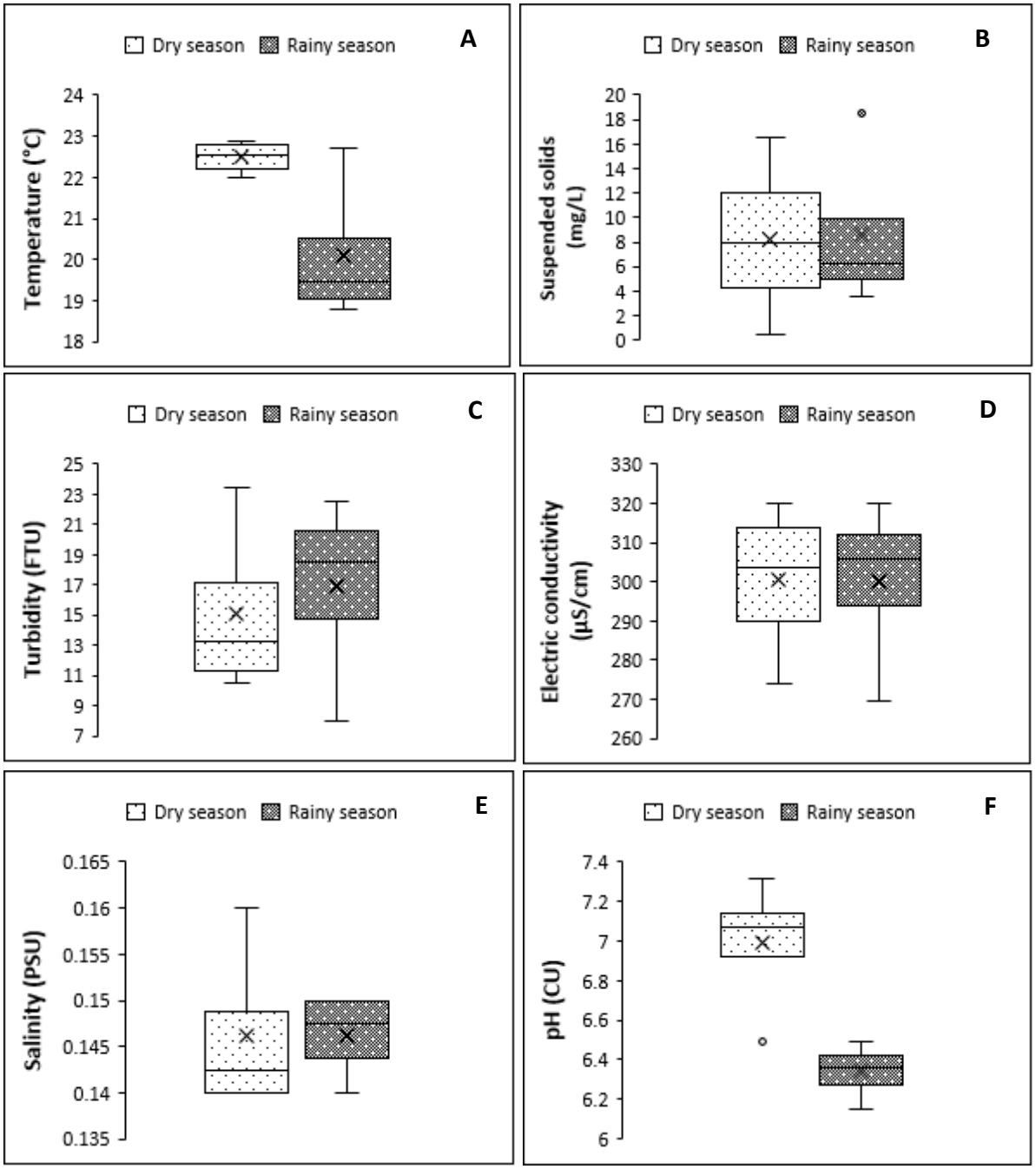



**Figure 36:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), electric conductivity (D), salinity (E) and pH (F) in the sampled groundwater in Ekona /Mautu.

The distribution of the seasonal values of oxidability was much higher in the dry season than in the rainy season but however, no significant difference was observed. The values ranged between 2.56 (ES6) and 3.35 mg/L (MS4) in the rainy season and between 2.67(ES7) and 4.94 mg/L (MS5) in the dry season. The mean seasonal value for oxidability was 3.14 ± 0.76 mg/L (Figure 37 A). The distribution of dissolved oxygen varied from 60.6 % in ES7 to 79.9 %,

observed in MS5 in the dry season with a mean dry season value of 70.55 ± 8.49 %. In the rainy season, the value of dissolved oxygen varied from 56.7 in MS4 to 64.35 % in MS5. The mean seasonal value of dissolved oxygen was 65.88 ± 7.76 % and no significant difference was seen between the rainy and dry season for oxidability and dissolved oxygen (Figure 37 B). The distribution of the mean seasonal value of dissolved carbon dioxide varied between the rainy and dry season and the U test of Mann Whitney showed a significant difference between the rainy and dry season, with a "p" value of 0.029. The highest value of dissolved carbon dioxide in the dry season was 16.5 mg/L, recorded in ES7 while the lowest value was 5.07 mg/L, recorded in MS4. In the rainy season, the highest value was 0.57 mg/L, recorded in ES7 and the lowest value was 0.25 mg/L, recorded in sampling point MS5 (Figure 37 C).

The values of orthophosphates fluctuated between the rainy and the dry season during the study period, however, the U test of Mann Whitney did not show any significant difference between the rainy and dry seasons. The values of orthophosphate ranged from 0.42 mg/L, obtained in station MS4 in the dry season to 2.34 mg/L, obtained in ES6 in the rainy season, with a mean seasonal value of 1.57 ± 0.74 mg/L (Figure 37 D). The mean seasonal value distribution of ammonium ions ranged from 0.00 mg/L, recorded in station ES7 in the dry season to 0.55 mg/L, recorded in station MS5 in the dry season and the mean seasonal value for ammonium ions was 0.072 ± 0.19 mg/L. The U test of Mann Whitney did not show any significant difference from one season to another for ammonium ions (Figure 37 E). The seasonal values of nitrate ions ranged from 0.20 mg/L (ES6) to 0.8 mg/L in the dry season to 2.25 mg/L (MS5) in the rainy season. The mean seasonal value for nitrate ions was 0.68 ± 0.67 mg/L and no significant difference was observed (Figure 37 F).

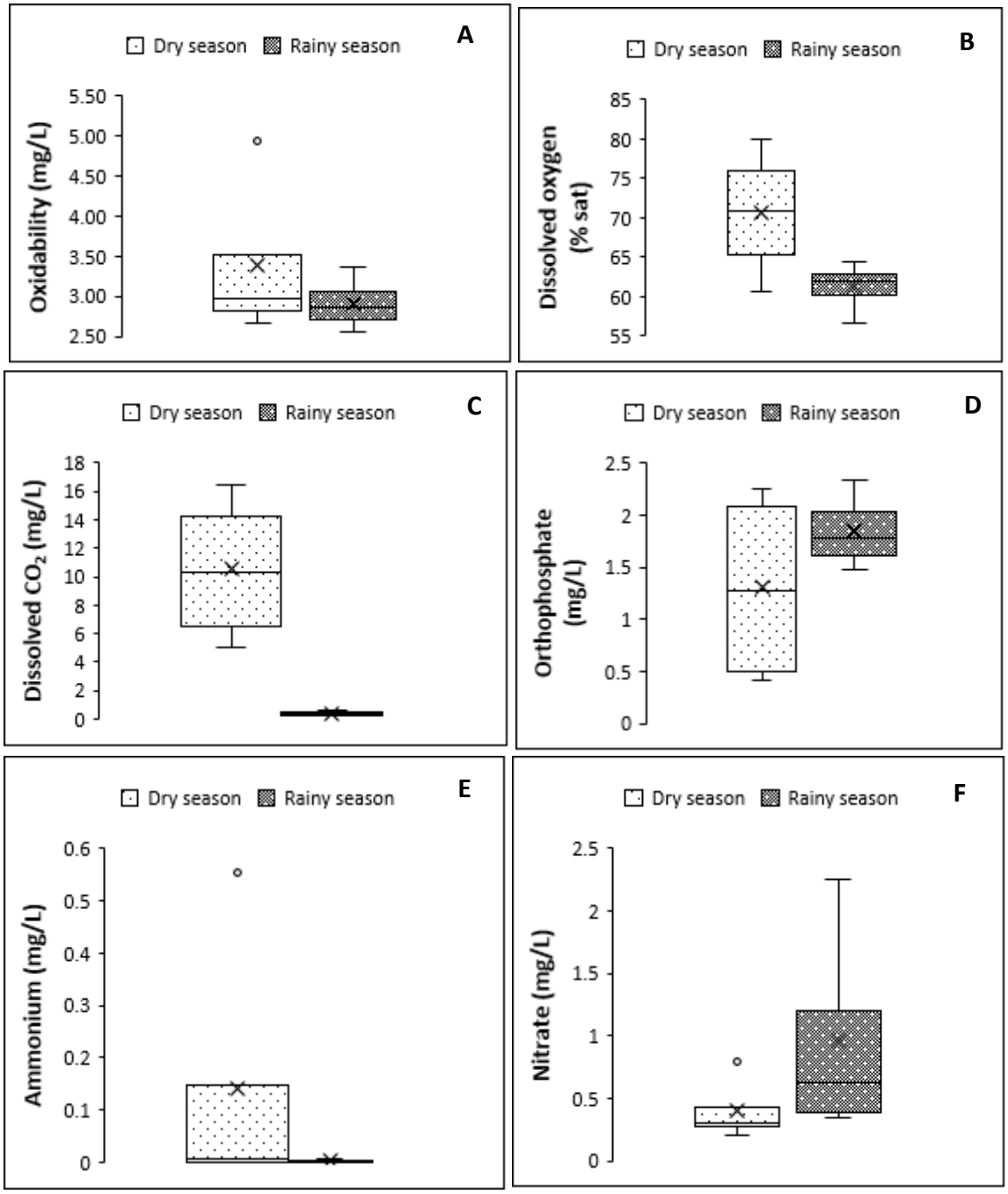



**Figure 37:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B), dissolved carbon dioxide (C), orthophosphate (D), ammonium ions (E) and nitrate ions (F) in the sampled groundwater in Ekona/Mautu.

The value of alkalinity ranged from 3 mg/L which was the smallest value, recorded in ES6 in the rainy season to 15 mg/L, which was the highest value, recorded in ES7 with a mean seasonal value of 6.25 ± 3.81 mg/L (Figure 38 A). The values of total hardness varied from 16.53 mg/L (MS4) in the dry season and from to 328.19 mg/L (MS5) in the rainy season and the mean seasonal value was 98.69 ± 105.5 mg/L. The Mann Whitney test did not show any

significant difference for alkalinity and total hardness throughout the study period (Figure 38 B).

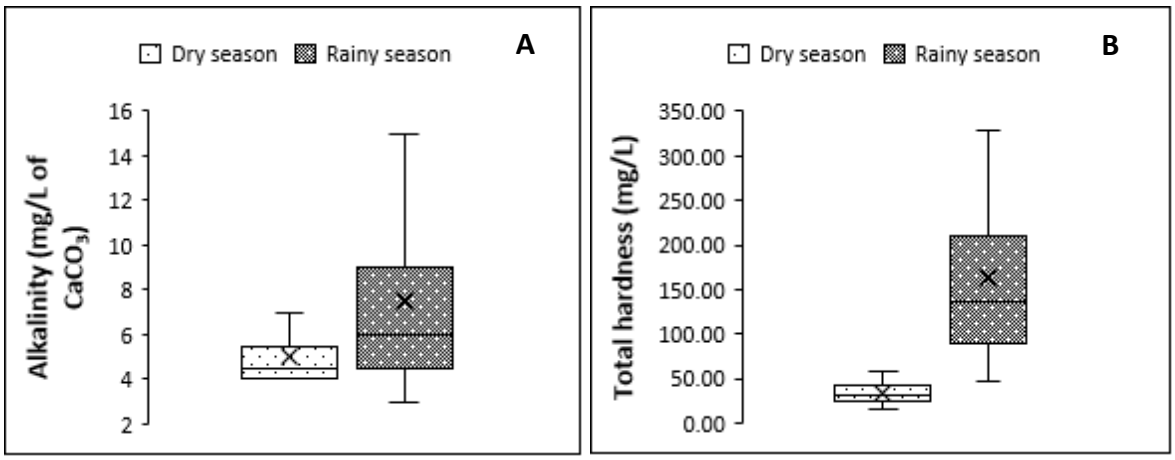



**Figure 38:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness (B) in the sampled groundwater in Ekona/Mautu.

### III.1.1.7. Distribution of the physicochemical variables of the groundwater sampled in Owe

Temperature values were significantly higher in the dry season than in the rainy season and the H test of Kruskal Wallis showed a significant difference between the rainy and the dry season (p=0.046). The highest value of temperature recorded in the dry season was 23.35 °C in station OS3 while the lowest value was 22.27 °C, recorded in station OS1 (mean value of 22.9 ± 0.39 °C) (Table XIV). In the rainy season, the highest value was 15.28 °C, recorded in station OS3 and the lowest value was 15.1 °C, recorded in stations OS1 and OS2 (mean value of 15.15 ± 0.08 °C). The mean temperature value throughout the study period was 19.01 ± 4.23 ° C (Figure 39 A). The distribution of suspended solids (SS) ranged from 4 mg/L, obtained in OS3 to 14 mg/L, recorded in OS1 in the dry season. The mean seasonal value for suspended solids was 9.75 ± 4.36 mg/L (Figure 39 B). The lowest value for turbidity was 8.5 FTU, recorded in the rainy season in OS2 (mean rainy season value of 11.67 ± 3.25 FTU) while the highest value was 20.5 FTU, recorded in OS1 in the dry season (mean dry season value of 14.67 ± 5.75 FTU). The mean seasonal value was 13.16 ± 4.49 FTU (Figure 39 C). The H test of Kruskal Wallis did not show any significant difference for SS and turbidity throughout the study period in Owe.

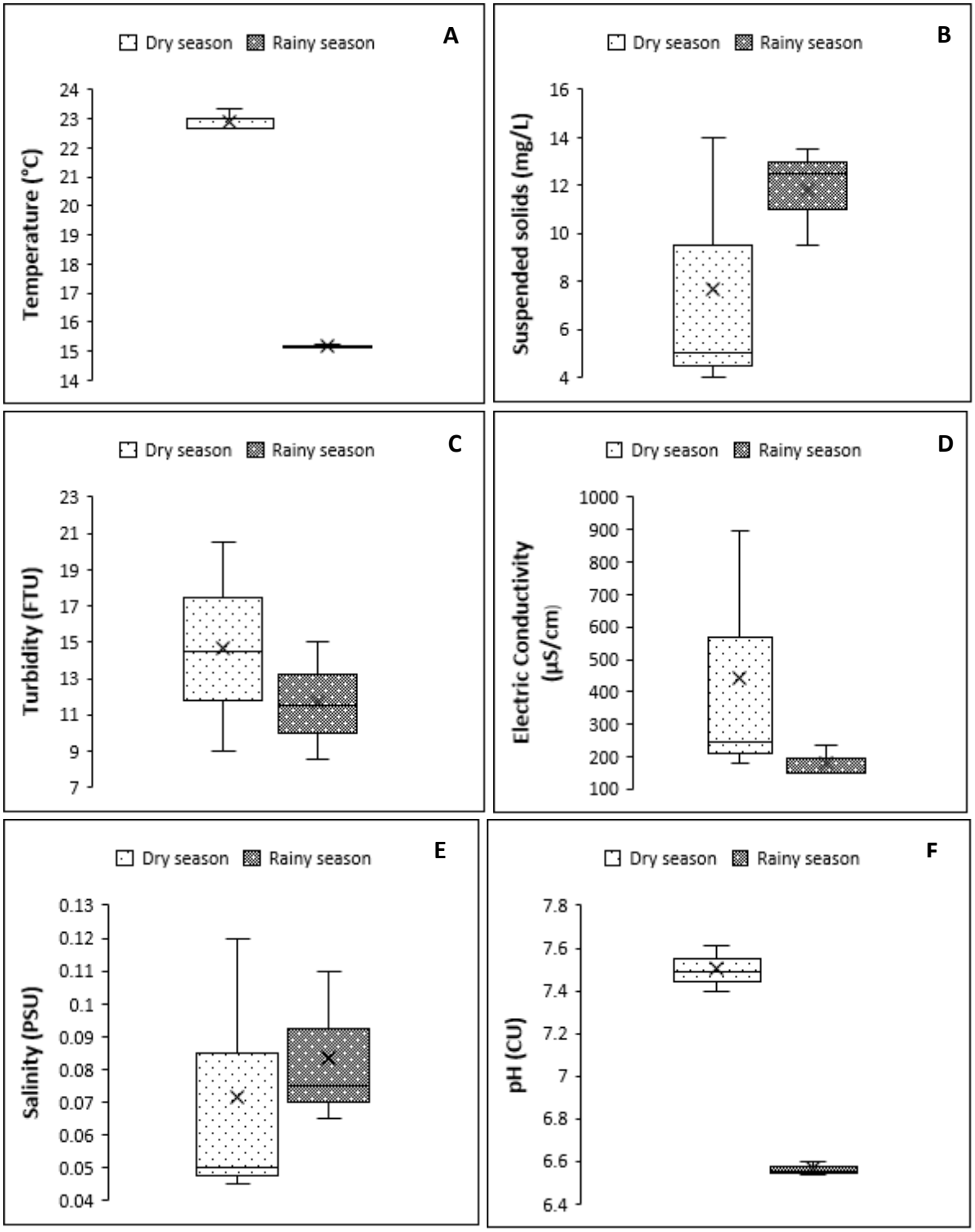



**Figure 39:** Boxplots showing the seasonal distribution of temperature (A), Suspended solids (B), Turbidity (C), salinity (D), electric conductivity (E) and pH (F) of the sampled groundwater points in Owe.

The values of electric conductivity were generally higher in the dry season than in the rainy season. The highest value was recorded in the dry season recorded (898 µS/cm) in station

OS1 while the lowest value was recorded in the rainy season (151.5 µS/cm) in station OS1. The mean seasonal value for EC was 309.24 ± 291.17 µS/cm (Figure 39 D). The mean seasonal distribution of salinity value did not fluctuate much during the study period. The values recorded in the rainy season fluctuated from 0.06 PSU (station OS2) to 0.11 PSU in station OS3 (mean dry season value of 0.08 ± 0.02 PSU) while in the dry season, the values of salinity varied from 0.04 PSU in OS2 to 0.12 PSU in OS3 (mean rainy season value of 0.07 ± 0.04 PSU). The mean seasonal value of salinity obtained during the study period was 0.08 ± 0.03 PSU (Figure 39 E). The H test of Kruskal Wallis did not show any significant difference for EC and salinity throughout the study period in Owe. The seasonal value of pH greatly fluctuated between the seasons during the study period and were higher in the dry season than in the rainy season. The values in the dry season varied from 7.4 in OS1 to 7.62 in OS3 while in the rainy season, it varied from 6.54 in OS1 to 6.6 in OS3 and the H test of Kruskal Wallis showed a significant difference between the rainy and the dry season (p = 0.050) (Figure 39 F).

**Table XIV:** Seasonal variation of physicochemical variables recorded in Owe during the sampling period

| **Para** | **Temp (°C)** | | **SS (mg/L)** | | **Tur (FTU)** | | **EC (µS/cm)** | | **Sal (PSU)** | | **pH (CU)** | | **Oxyd (mg/L)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **OS1** | 22.7 | 15.1 | 14.00 | 9.50 | 20.50 | 11.50 | 898.00 | 151.00 | 0.05 | 0.07 | 7.40 | 6.54 | 2.96 | 3.16 |
| **OS2** | 22.65 | 15.1 | 5.00 | 13.50 | 9.00 | 8.50 | 177.45 | 151.5 | 0.05 | 0.06 | 7.49 | 6.55 | 2.57 | 4.54 |
| **OS3** | 23.35 | 15.25 | 4.00 | 12.50 | 14.50 | 15.00 | 243.00 | 234.50 | 0.12 | 0.11 | 7.61 | 6.60 | 2.37 | 2.76 |

| **Para** | **$DO_2$ (% sat)** | | **$DCO_2$ (mg/L)** | | **Phos (mg/L)** | | **Amm (mg/L)** | | **Nitra (mg/L)** | | **Alkal (mg/L)** | | **T hard(mg/L)** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **S. P** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** | **DS** | **RS** |
| **OS1** | 66.20 | 61.5 | 22.65 | 0.20 | 0.47 | 0.55 | 0.005 | 0.007 | 0.5 | 1.10 | 4.00 | 5.00 | 57.21 | 10.54 |
| **OS2** | 72.80 | 64.90 | 1.53 | 0.30 | 0.35 | 0.34 | 0.65 | 0.005 | 0.35 | 1.00 | 3.00 | 4.00 | 72.79 | 70.59 |
| **OS3** | 72.70 | 61.75 | 3.72 | 0.07 | 0.41 | 0.61 | 0.00 | 0.001 | 0.35 | 0.40 | 7.00 | 10.00 | 61.95 | 154.59 |

**Legend:** DS = Dry season, RS = Rainy season, Para = Parameters, S.P = Sampling points

The distribution of the seasonal values of oxidability was much higher in the rainy season than in the dry season and it ranged from 2.76 in station OS3 to 4.54 mg/L in station OS2 in rainy season and from 2.37, recorded in OS3 to 2.96 mg/L, recorded in OS1 in the dry season. The mean seasonal value for oxidability throughout the study period was 3.06 ± 0.77 mg/L (Figure 40 A). The H test of Kruskal Wallis did not show any significant difference between seasons. Dissolved oxygen distribution varied significantly between the rainy and the dry season and the H test of Kruskal Wallis showed a significant difference between the dry season

and the rainy season (p = 0.050). The value varied in the dry season from 66.2 % in OS1 to 72.8 %, obtained in station OS2 and in the rainy season, the value of dissolved oxygen varied from 61.62 in OS1 to 64.9 % in OS2 (Figure 40 B). The distribution of the mean seasonal value of dissolved carbon dioxide varied between the rainy and dry season but however, the H test of Kruskal Wallis did not show any significant difference between the rainy and dry season (p > 0.05). The highest value of dissolved carbon dioxide in the dry season was 22.26 mg/L, obtained in station OS1 and the lowest value was 1.53 mg/L, recorded in OS2 (mean dry season value of 9.30 ± 11.61 mg/L). The lowest value in the rainy season was 0.007 mg/L in OS3 while the highest value was 0.3 mg/L (mean rainy season value of 0.19 ± 0.11 mg/L) (Figure 40 C).

The mean seasonal values of orthophosphates fluctuated less between the rainy and the dry season during the study period in Owe. The values of orthophosphate ranged from 0.35 mg/L recorded in sampling point OS2 to 0.60 mg/L, recorded in station OS3, all in the rainy season with a mean seasonal value was 0.45 ± 0.12 mg/L (Figure 40 D). No significant difference was obtained for orthophosphates. The mean seasonal value of ammonium ions distribution ranged from 0 mg/L in OS3 to 0.65 mg/L in OS2 and all these values were recorded in the dry season. The mean seasonal value of ammonium ions was 0.11 ± 0.26 mg/L and no significant difference was observed for this parameter during the study period in Owe (Figure 40 E). The values of nitrate ions ranged from 0.35 mg/L in the dry season in OS3 (mean dry season value 0.41 ± 0.08 mg/L) to 1.10 mg/L, obtained in OS1 in the rainy season (mean rainy season value 0.83 ± 0.38 mg/L). The mean seasonal value recorded in Owe was 0.62 ± 0.33 mg/L and no significant difference was observed (Figure 40 F).

The value of alkalinity ranged from 3.00 mg/L as smallest value, recorded in the dry season in station OS2 to 10.00 mg/L as highest value, recorded in the rainy season in station OS3, with a mean seasonal value of 5.50 ± 2.58 mg/L (Figure 41 A). No significant difference was observed for alkalinity. The values of total hardness varied from 10.54 mg/L in station OS to 154.59 mg/L in station OS3, recorded in the rainy season, with a mean seasonal value of 71.27 ± 46.72 mg/L. The H test of Kruskal Wallis did not show any significant difference for total hardness throughout the study period in Owe (Figure 41 B).

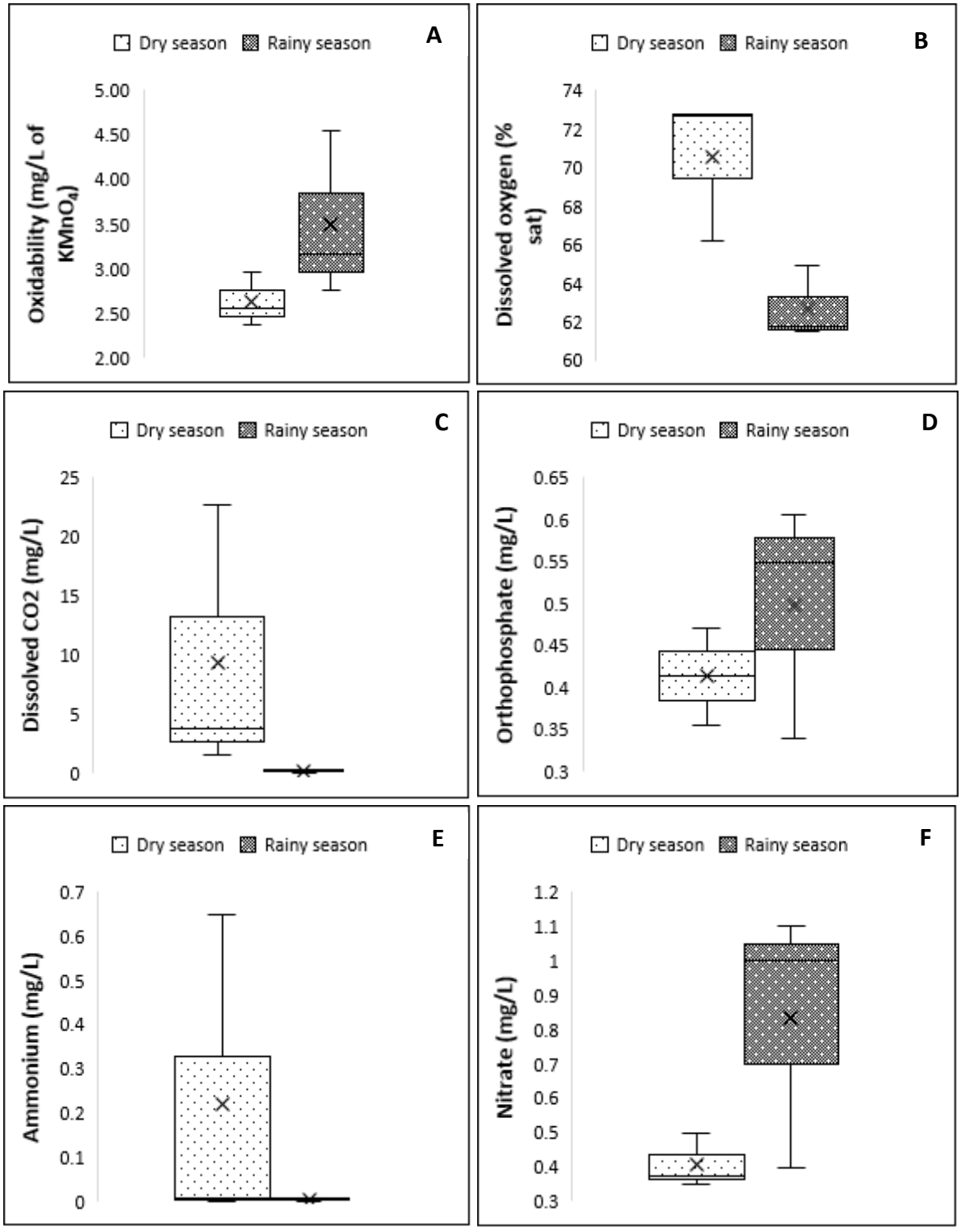



**Figure 40:** Boxplots showing the seasonal distribution of oxidability (A), dissolved oxygen (B) and dissolved carbon dioxide (C), orthophosphate (D), ammonium (E) and nitrate (F) in the groundwater sampled in Owe.

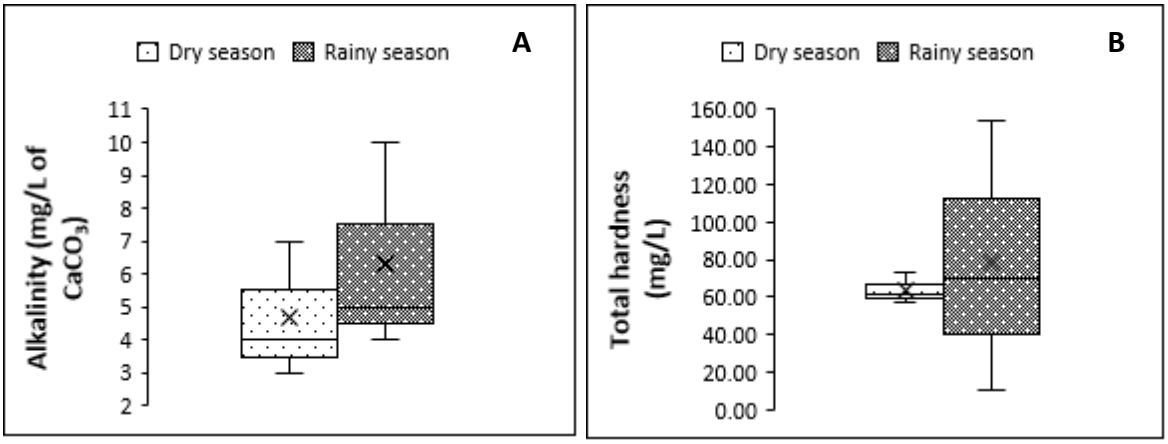



**Figure 41:** Boxplots showing the seasonal distribution of alkalinity (A) and total hardness in the sampled groundwater in Owe.

Generally, the analysis of physicochemical variables showed that groundwater in Fako from both the wells and springs generally has a high turbidity (≥13 FTU). The groundwater in Tiko has a high temperature (27 ± 0.84 °C), slightly acidic pH (6.42 ± 0.45 CU), highly turbid (13.55 ± 8.7 FTU), high orthophosphate levels (0.53 ± 0.45 mg/L), good dissolved oxygen level (59.57 ± 6.48 %) and weak mineralization (256.75 ± 104.52 µS/ cm). Groundwater in Limbe has a high temperature (26.76 ± 0.57 °C), acidic pH (6.4 ± 0.55), average oxygenation (55.20 ± 1.44 %), high phosphate ions level (3.06 ± 2.39 mg/L) and an important level of mineralization (725 ± 710 µS/cm) due to the presence of the sea in this town. In Muyuka, the temperatures are high (25.96 ± 2.28 °C), with good oxygenation (60.74 ± 3.43 %), acidic pH (5.02 ± 0.45), and not very accentuated mineralization (301.5 ± 172.5 µS/cm). The groundwater in Buea has a low temperature (19.50 ± 14 ºC), neutral pH (7.05 ± 0.54), good oxygenation (68.03 ± 7.88 %) and an acceptable mineralization (324.95 ± 260.0 µS/cm) where the Mount Cameroon is found. Mautu/Ekona is characterized by slightly high temperatures (21.29 ± 1.75 °C), acidic pH (6.66 ± 0.42), good oxygenation (65.88 ± 7.76) and a mineralization that is not very accentuated (300.31 ± 19.50 µS/cm) while Owe was characterized by low temperatures (19.00 ± 4.23 °C), neutral pH (7.03 ± 0.51), good oxygenation (66.64 ± 5.06 %), with a mineralization that is not very pronounced (309.24 ± 291.17 µS/cm).

### III.1.2. Abiotic characterization of the sampling towns

#### III.1.2.1. Spearman correlation between physicochemical variables and between physicochemical and morphometric variables and fauna with morphometric variables

Table XV shows the Spearman correlation between physicochemical parameters obtained during the study period in all the sampling points. The Spearman correlation showed

a positive correlation at a threshold of 0.01 between suspended solids and turbidity, between conductivity and salinity, between nitrates and temperature, between ammonium with temperature, oxidability and dissolved $CO_2$, between phosphate with pH and salinity, between dissolved oxygen and pH, between temperature and dissolved $CO_2$ and between oxidability and $CO_2$. This means that, higher values in these variables corresponded to higher values in the variables that they are positively correlated to at the threshold value of 0.01. Other variables were negatively correlated at a threshold of 0.01, which implies that, an increase in these variables, led to a decrease in the correlated parameters. They include nitrates with dissolved oxygen and pH, dissolved oxygen with salinity, dissolved carbon dioxide with total hardness.

At threshold value of 0.05, a positive correlation was recorded between the following parameters; suspended solids with ammonium ion, turbidity with phosphate, conductivity with phosphate, phosphate with pH, pH with $CO_2$ and oxidability. A negative correlation is observed between the following at 0.05 threshold, nitrates with phosphate, ammonium with total hardness, oxidability and total hardness. A negative correlation at a threshold of 0.05 was recorded between ammonium and total hardness, pH and total hardness, oxidability and total hardness.

**Table XV: Spearman correlation between physicochemical parameters obtained for all sampling points during the study period.**

| | SS (mg/L) | Turb (FTU) | Cond (µS/Cm | Nitra (mg/L) | Amm (mg/L) | Phos (mg/L) | $O_2$ (% sat) | pH (CU) | Sal (PSU) | Temp (ºC) | Alka (mg/L) | Oxyd (mg/L) | $CO_2$ (mg/L) | Hard (mg/ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS (mg/L | 1.00 | | | | | | | | | | | | | |
| Turb (FTU) | .774** | 1.0 | | | | | | | | | | | | |
| Cond (µS/cm) | .117 | .191 | 1.0 | | | | | | | | | | | |
| Nitra (mg/L | -.099 | -.035 | .031 | 1.00 | | | | | | | | | | |
| Amm (mg/L) | .268* | .219 | .035 | .035 | 1.00 | | | | | | | | | |
| Phos (mg/L) | .197 | .264* | .246* | -.233 | -.175 | 1.00 | | | | | | | | |
| $O_2$ (% sat) | -.059 | -.075 | -.154 | -.427** | -.090 | -.014 | 1.00 | | | | | | | |
| pH (CU) | .048 | .102 | .053 | -.561** | .116 | .269* | .498** | 1.00 | | | | | | |
| Sal (PSU) | -.033 | .063 | .796** | .200 | -.082 | .352** | -.326** | -.104 | 1.00 | | | | | |
| Temp (ºC) | -.180 | -.029 | .174 | .454** | .379** | -.399** | -.470** | -.428** | .176 | 1.0 | | | | |
| Alka (mg/L) | -.170 | -.142 | .119 | .117 | -.034 | -.016 | -.052 | .187 | .161 | .129 | 1.0 | | | |
| Oxida (mg/L) | .154 | .141 | .019 | -.111 | .400** | .041 | .214 | .300* | .042 | .118 | .037 | 1.00 | | |
| $CO_2$ (mg/L) | .035 | .160 | .322** | -.124 | .410** | -.082 | .155 | .299* | .133 | .349** | .006 | .407** | 1.00 | |
| Hard (mg/L) | .002 | -.133 | -.094 | .175 | -.254* | -.046 | -.088 | -.246* | -.085 | -.014 | .106 | -.283* | -.407** | 1.00 |

** Correlation is significant at threshold 0.01: *Correlation is significant at threshold 0.05

Total number of samples = 66

SS=Suspended solids, Turd=Turbidity, Cond=Electric conductivity, Nitra=Nitrate ions, Amm=Ammonium ions, Phos=Phosphate ions, O2=dissolved oxygen, pH=Hydrogen potential, Sal=Salinity, Temp=Temperature, Alka=Alkalinity, Oxyd=Oxidability, CO2=dissolved carbon dioxide, Hard=Total hardness

The Spearman correlation between physicochemical parameters obtained during the study period in wells showed a positive correlation at a threshold of 0.01 between suspended solids and turbidity, between conductivity and $CO_2$, between nitrates and temperature, between ammonium with temperature, oxidability and dissolved $CO_2$, and between pH and alkalinity. This means that, higher values in these variables corresponded to higher values in the variables that they are positively correlated to at the threshold value of 0.01. A negative correlated at a threshold of 0.01 was onserved between salinity and conductivity, $CO_2$ and hardness and between temperature and $CO_2$. This means that, an increase in these variables, led to a decrease in the correlated parameters (Table XVI).

At threshold value of 0.05, a positive correlation was recorded between suspended solids with ammonium ion and $CO_2$, turbidity with ammonium ions, oxidability and $CO_2$, between ammonium ions and oxidability with $CO_2$, phosphate ions and pH with salinity. A negative correlation was observed between the following at 0.05 threshold, nitrates and pH, hardness and turbidity, ammonium ions and oxidability.

**Table XVI: Spearman correlation between physicochemical parameters obtained in the wells during the study period.**

| | SS (mg/L | Turb (FTU) | Cond (µS/cm) | Nitra (mg/L | Amm (mg/L) | Phos (mg/L) | pH (CU) | Sal (PSU) | Temp (ºC) | Alka (mg/L) | Oxida (mg/L) | $CO_2$ (mg/L) | Hard (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SS** | 1.000 | | | | | | | | | | | | |
| **Turb** | .795** | 1.000 | | | | | | | | | | | |
| **Cond** | .061 | .120 | 1.000 | | | | | | | | | | |
| **Nitra** | -.242 | -.184 | -.121 | 1.000 | | | | | | | | | |
| **Amm** | .376* | .389* | .040 | -.255 | 1.000 | | | | | | | | |
| **Phos** | .111 | .307 | .255 | -.197 | .151 | 1.000 | | | | | | | |
| **pH** | .174 | .263 | .225 | -.337* | .394* | .370* | 1.000 | | | | | | |
| **Sal** | -.108 | -.028 | .843** | -.022 | -.087 | .319* | .233 | 1.000 | | | | | |
| **Temp** | -.236 | -.174 | -.174 | .031 | -.242 | .243 | -.012 | .013 | 1.000 | | | | |
| **Alka** | -.173 | -.170 | .114 | .061 | -.033 | -.037 | .425** | .110 | -.099 | 1.000 | | | |
| **Oxida** | .214 | .320* | .065 | -.192 | .419** | .253 | .293 | .098 | -.203 | .001 | 1.000 | | |
| **$CO_2$** | .324* | .352* | .401* | -.090 | .673** | -.019 | .263 | .217 | -.505** | .008 | .465** | 1.000 | |
| **Hard** | -.167 | -.396* | -.286 | .107 | -.320* | -.231 | -.135 | -.278 | .116 | .112 | -.327* | -.472** | 1.000 |

** Correlation is significant at threshold 0.01: *Correlation is significant at threshold 0.05

Total number of samples = 40

The Spearman correlation between physicochemical parameters obtained during the study period in the springs showed a positive correlation at a threshold of 0.01 between suspended solids and turbidity, between conductivity and salinity with temperature, between oxygen and pH and $CO_2$ and between $CO_2$ and pH. This means that, higher values in these variables corresponded to higher values in the variables that they are positively correlated to at the threshold value of 0.01. A negative correlated at a threshold of 0.01 was onserved between

salinity and pH, SS and pH and between Ammonium and phosphate ions. This means that, an increase in these variables, led to a decrease in the correlated parameters (Table XVII).

At threshold value of 0.05, a positive correlation was obtained between turbidity and salinity with temperature, ammonium ions and oxidability, phosphate ions and salinity, oxygen and oxidability and between salinity and temperature. A negative correlation was observed at 0.05 threshold between oxygen and SS, turbidity phosphate ions, pH and phosphate ions and between pH and temperature.

**Table XVII: Spearman correlation between physicochemical parameters obtained in the springs during the study period.**

| | SS | Turb | Cond | Nitra | Amm | Phos | $O_2$ | pH | Sal | Temp | Alka | Oxida | $CO_2$ | Hard |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SS (mg/L** | 1.000 | | | | | | | | | | | | | |
| **Turb (FTU)** | .601** | 1.000 | | | | | | | | | | | | |
| **Cond (µS/cm)** | .250 | .500** | 1.000 | | | | | | | | | | | |
| **Nitra (mg/L** | .345 | .263 | .180 | 1.000 | | | | | | | | | | |
| **Amm (mg/L)** | .161 | -.228 | -.097 | .093 | 1.000 | | | | | | | | | |
| **Phos (mg/L)** | .142 | .291 | .268 | -.126 | -.513** | 1.000 | | | | | | | | |
| **$O_2$ (% sat)** | -.471* | -.431* | -.021 | -.098 | .314 | -.419* | 1.000 | | | | | | | |
| **pH (CU)** | -.527** | -.370 | -.376 | -.293 | .161 | -.478* | .713** | 1.000 | | | | | | |
| **Sal (PSU)** | .237 | .449* | .780** | .227 | -.260 | .449* | -.224 | -.623** | 1.000 | | | | | |
| **Temp (ºC)** | .125 | .475* | .585** | .026 | -.092 | .182 | -.211 | -.420* | .444* | 1.000 | | | | |
| **Alka (mg/L)** | -.125 | .066 | .206 | .035 | -.098 | .046 | .169 | -.062 | .295 | .103 | 1.000 | | | |
| **Oxida (mg/L)** | .005 | -.262 | .049 | .163 | .394* | -.326 | .389* | .269 | -.073 | -.365 | .079 | 1.000 | | |
| **$CO_2$ (mg/L)** | -.305 | -.094 | .274 | -.282 | .059 | -.071 | .616** | .543** | -.035 | .058 | -.090 | .284 | 1.000 | |
| **Hard (mg/L)** | .251 | .337 | .160 | .248 | -.261 | .387 | -.177 | -.322 | .144 | .385 | .103 | -.268 | -.321 | 1.000 |

** Correlation is significant at threshold 0.01: *Correlation is significant at threshold 0.05

Total number of samples = 26

The Spearman correlation between physicochemical and morphometric parameters obtained during the study period in the wells showed that altitude was negatively and significantly corelated to pH and alkalinity, and diameter with alkalinity at a threshold value of 0.05. a positive correlation was obtained between protection height above the ground and

phosphate ions ar 0.05 threshold. At threshold of 0.01, a negative and significant correlation was onserved between water column and electric conductivity with salinity (Table XVIII).

**Table XVIII: Spearman correlation between physicochemical parameters and morphometric parameters in the wells during the study period.**

| | Altitude | Protection height above the ground | Water column | Piezometric Level | Diameter | Depth |
|---|---|---|---|---|---|---|
| **Cond (µS/cm)** | -.029 | .005 | -.417** | -.265 | .044 | -.238 |
| **Phos (mg/L)** | -.157 | .326* | -.035 | .036 | -.030 | .041 |
| **$O_2$ (% sat)** | .254 | -.067 | .075 | .303 | .108 | .303 |
| **pH (CU)** | -.335* | .265 | .108 | -.123 | -.195 | -.162 |
| **Sal (PSU)** | -.197 | .033 | -.459** | -.296 | .077 | -.302 |
| **Alka (mg/L)** | -.319* | .154 | -.083 | -.135 | -.381* | -.177 |

The Spearman correlation between fauna and morphometric parameters obtained during the study period in the wells showed that altitude was positively and significantly corelated to Cyclopidae at 0.01 threshold value while protection height above the ground was positively correlated to Cyprididae at 0.05 threshold value. Water column was negatively correlated to Chironomidae and positively correlated to Cyprididae and Cyclopidae at threshold value of 0.05. Piezometric level was positively corelated to Cytherididae and Cyclopidae while it was negatively correlated to Naididae at a threshold value of 0.05. Diameter was negatively correlated to Darwinulidae. The water depth was negatively correlatged to Naididae and Tetragnathidae while it was positively correlated to Cytherididae and Cyclopidae (Table XIX).

**Table XIX: Spearman correlation between fauna and morphometric parameters in the wells during the study period.**

| | Naidi | Tetrag | Cythe | Cypri | Darwin | Cyclo | Chiro |
|---|---|---|---|---|---|---|---|
| Altitude | -.127 | -.080 | -.009 | .001 | -.096 | .455** | -.103 |
| Protection height above the ground | .206 | -.081 | .033 | .369* | .165 | .151 | -.159 |
| Water column | -.124 | -.279 | .259 | .322* | .165 | .348* | -.356* |
| Piezometric Level | -.394* | -.279 | .363* | .226 | .002 | .402* | -.276 |
| Diameter | -.062 | -.161 | -.054 | -.180 | -.365* | .188 | -.044 |
| Depth | -.323* | -.318* | .321* | .179 | -.020 | .325* | -.310 |

### III.1.2.2. Multivariate Analyses: Agglomerative Hierachical Clustering and Principal Component Analysis of Physicochemical characteristics of sampled points in various towns.

#### III.1.2.2.1. Sampling points in the town of Tiko

The characterization of the sampled groundwater in function of the physicochemical parameters in Tiko on an Agglomerative Hierarchy Clustering, permitted the obtention of a

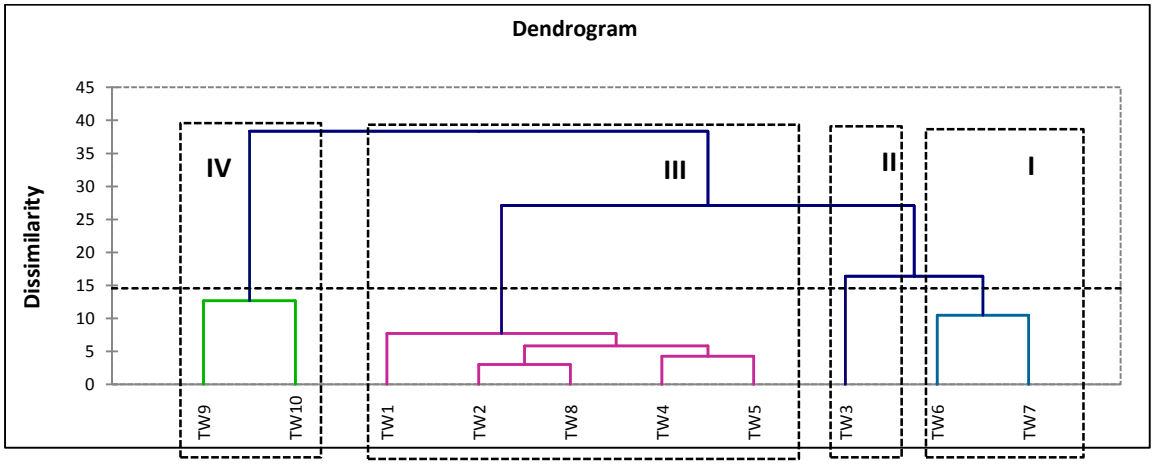



**Figure 42:** Agglomerative Hierarchical Clustering (AHC) for physicochemical parameters obtained during the sampling period in Tiko.

four-class hierarchy of the sampling points from right to left at 15 % of dissimilarity. Class I joins class II at 18 % and they both join to the third class at 28 % and class III joins class IV at 39 % (Figure 42). Class I regroups the sampling points TW6 and TW7, characterised by low amounts of ammonium ions, equal amounts of alkalinity and high amounts of nitrate ions while class II was made up of TW3 only, which was characterised by low amounts of turbidity and fairly moderate oxygenation. Class III regroups the sampling points TW1, TW2, TW8, TW4, TW5, characterised by low acidic pH and class IV englobes sampling points TW9 and TW10 which both have same amounts of SS and TDS.

The PCA for the physicochemical parameters studied was analysed for their characterisation in function of the sampling points. The two first factorial axes explained 54.31 % of the total variance (F1 = 35.91% and F2=18.40 %). The circle of correlation (Figure 43 A) showed that EC, salinity, dissolved carbon dioxide and pH were positively and significantly correlated to the F1 axis while turbidity and SS were positively correlated to the F1 axis and contributed less to the total inertia. Oxidability, phosphate ions, dissolved oxygen and temperature were positively correlated to the F2 axis. Total hardness, nitrate ions, alkalinity and ammonium ions were negatively and significantly correlated to the F1 axis.

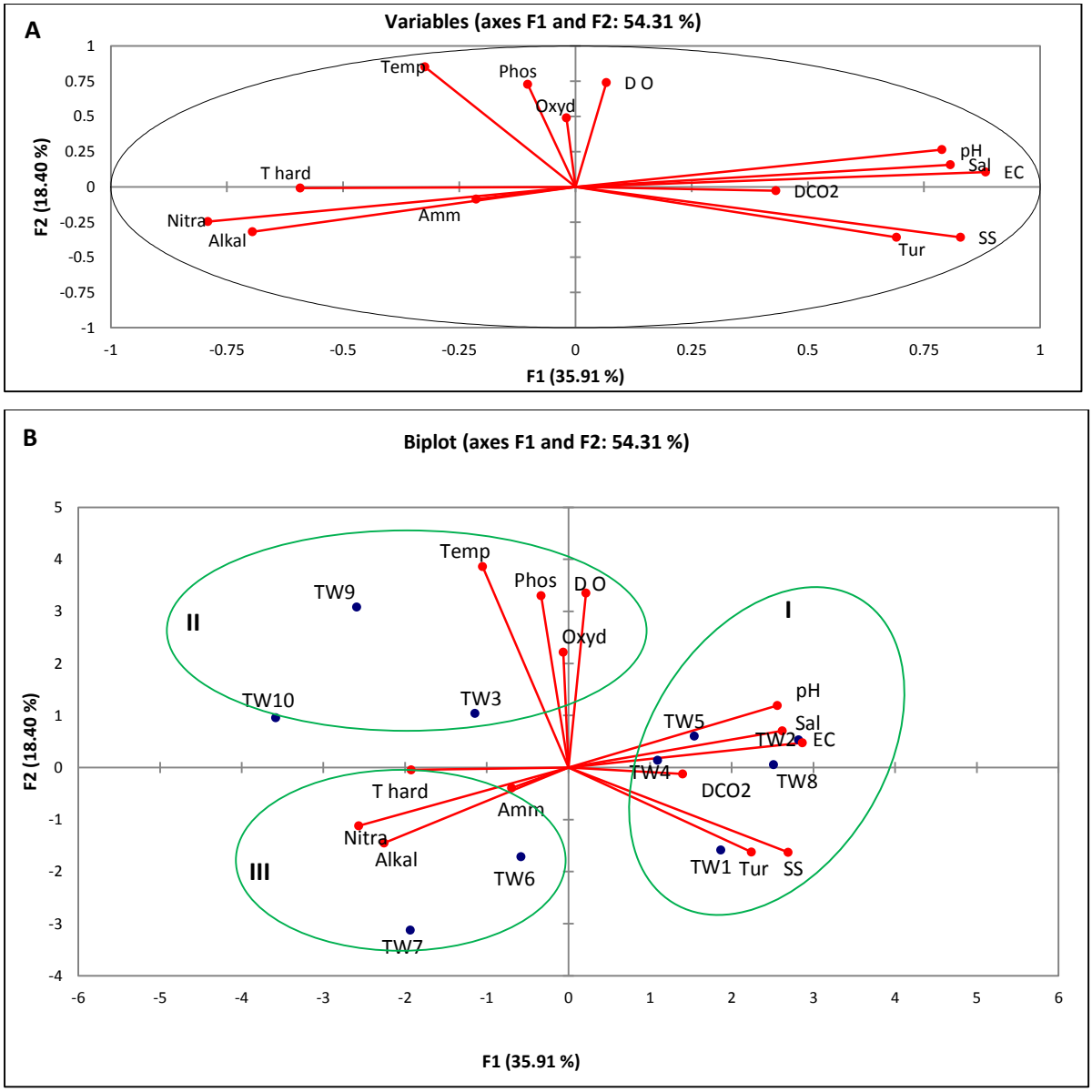



**Figure 43:** Principal Component analysis (PCA) of physicochemical parameters of the different sampling points during the study period in Tiko. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

Legend: (TW1=Tiko 1, TW2=Tiko 2, TW3=Tiko 3, TW4= Tiko 4, TW5= Tiko 5, TW6 = Tiko 6, TW7= Tiko 7, TW8= Tiko 8, TW9= Tiko 9, TW10= Tiko 10). DO= Dissolved oxygen, Phos= Orthophosphates, Thard=Total hardness, Akal=Alkalinity, DCO2=Dissolved Carbon dioxide, Tur=Turbidity, SS=Suspended solids, EC=Electric conductivity, Nitra= Nitrates, Oxyd=Oxidability, pH=Hydrogen potential, Amm=Ammonium ions, Temp=Temperature, Sal=Salinity.

Transposing the physicochemical parameters with the sampling stations, regrouped the sampling stations into three groups: I, II and III (Figure 43 B). Axis F1 discriminated in the positive coordinate in group I five of the sampling points in Tiko (TW1, TW2, TW4, TW5 and TW8). The samples of group I were characterized by dissolved carbon dioxide, EC, salinity,

turbidity, SS and pH. Group II which positively discriminated the F2 axis was made up of 03 sampling points which included (TW3, TW9 and TW10). These sampling points are characterized by high levels of temperature, highly influenced by nitrates ions content, dissolved oxygen and oxidability. Group III constituted of 02 sampling points; (TW6 and TW7). These sampling points discriminated F1 and F2 on the negative axis and were characterized by high levels of total hardness, alkalinity, nitrate and ammonium ion.

### III.1.2.2.2. Sampling points in the town of Buea

The Agglomerative Hierarchical Clustering (AHC) of the physicochemical parameters measured during the sampling period gave three classes from right to left. The first class regrouped the sampling points BS10 and BS11, characterized by high levels of dissolved oxygen, pH, $CO_2$. Class two constituted of BS8 and BS13 while the third class was composed of BS9 and BS12 (Figure 44). These stations had a dissimilarity level of 14 % and group I linked to group II at 20 % which then was linked to group III at 25 %.

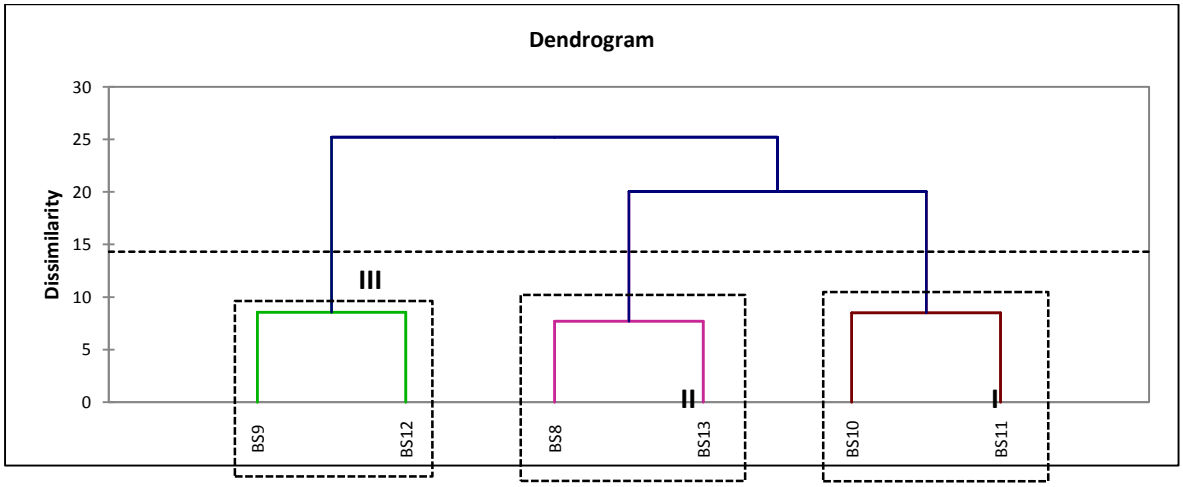



**Figure 44:** Agglomerative Hierarchical Clustering (AHC) for physicochemical parameters obtained during the sampling period in Buea.

The PCA for the 14 physicochemical parameters studied was analysed for their characterisation in function of the sampling points. The first two factorial axes explained 70.93 % of the total variance (F1 = 41.10 % and F2 = 25.83 %). The circle of correlation (Figure 45 A) showed that, salinity, alkalinity, EC, turbidity, SS and temperature were positively and significantly correlated to the F1 axis while dissolved carbon dixide and pH were negatively correlated to the F1 axis. Oxidability, phosphate, ammonium ions and total hardness were positively correlated to the F2 axis while dissolved oxygen was negatively correlated to the F2 axis.

When the physicochemical parameters were transposed with the sampling stations, the sampling stations were regrouped into three groups: I, II and III (Figure 45 B). Axis F1 discriminated in the positive coordinate and F2 discriminated in the negative axis in group I, two of the sampling points in Buea (BS9 and BS12). The samples of group I were characterized by temperature, EC, salinity, turbidity, alkalinity, nitrate ions, dissolved oxygen and SS. Group II which positively discriminated the F2 axis was made up of 02 sampling points (BS8 and BS13). These sampling points were characterized by high levels of phosphate ions, ammonium ions, total hardness and oxidability. Group III negatively discriminated the F1 and the F2 axes and was made up of 02 sampling points (BS10 and BS11). These sampling points were characterized by pH and dissolved carbon dioxide.

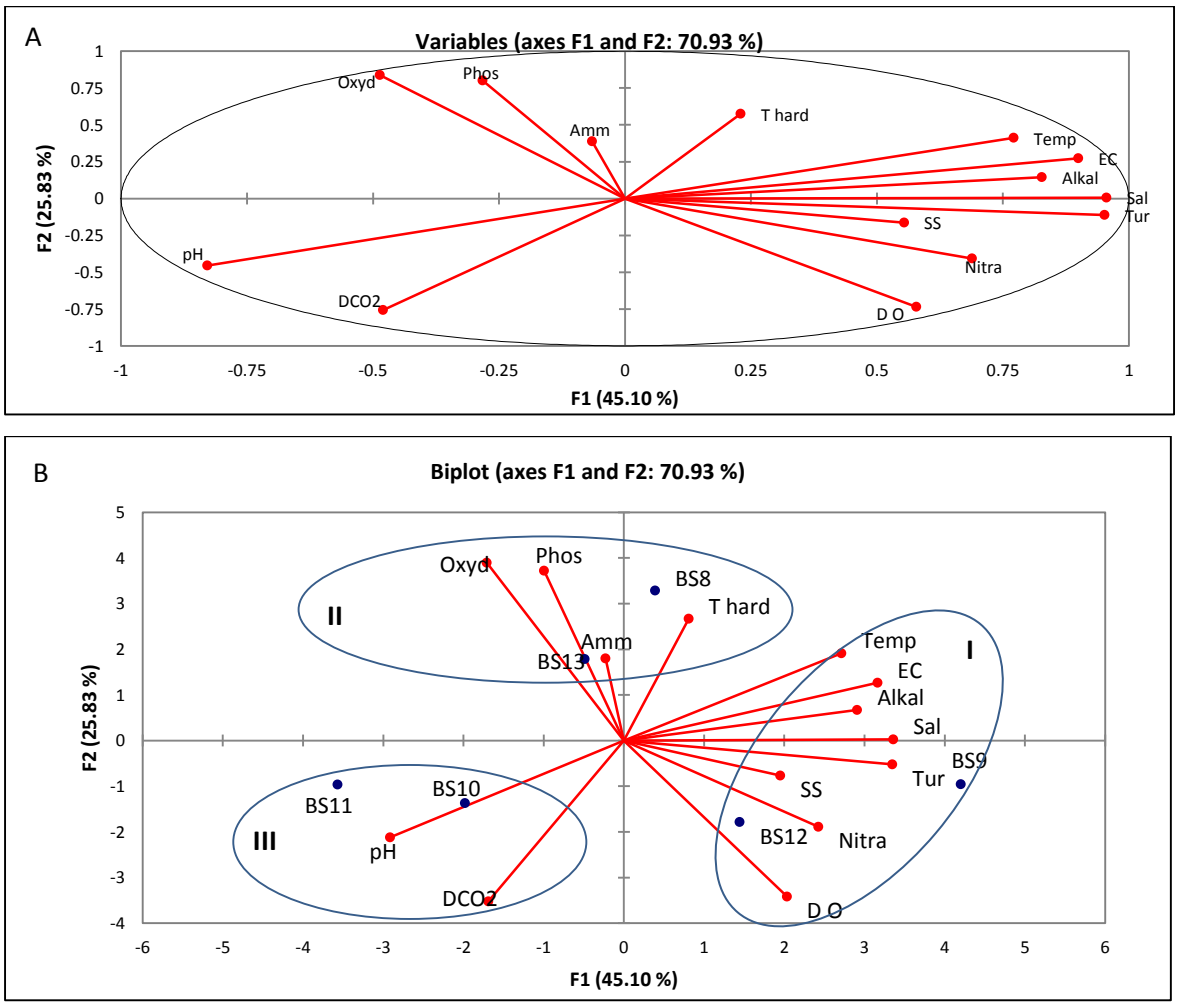



**Figure 45:** Principal Component analysis (PCA) of physicochemical parameters of the different sampling points during the study period in Buea. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.2.2.3. Sampling points in the town of Limbe

The Agglomerative Hierarchy Clustering in the town of Limbe of the sampling points and physicochemical parameters permitted the obtention of three classes from right to left at 11 % of dissimilarity. Class I connected to class II at 18 % and they both were connected to the third class at 21 % (Figure 46). Class I regrouped stations LW2 and LW5 while class II regrouped LW3 and LW1and class III was made up of station LW4 only. Class I was characterised by stations that had almost same contents of TDS, EC, temperature and dissolved carbon dioxide while class II was characterised by stations having high amounts of turbidity, SS and ammonium ions.

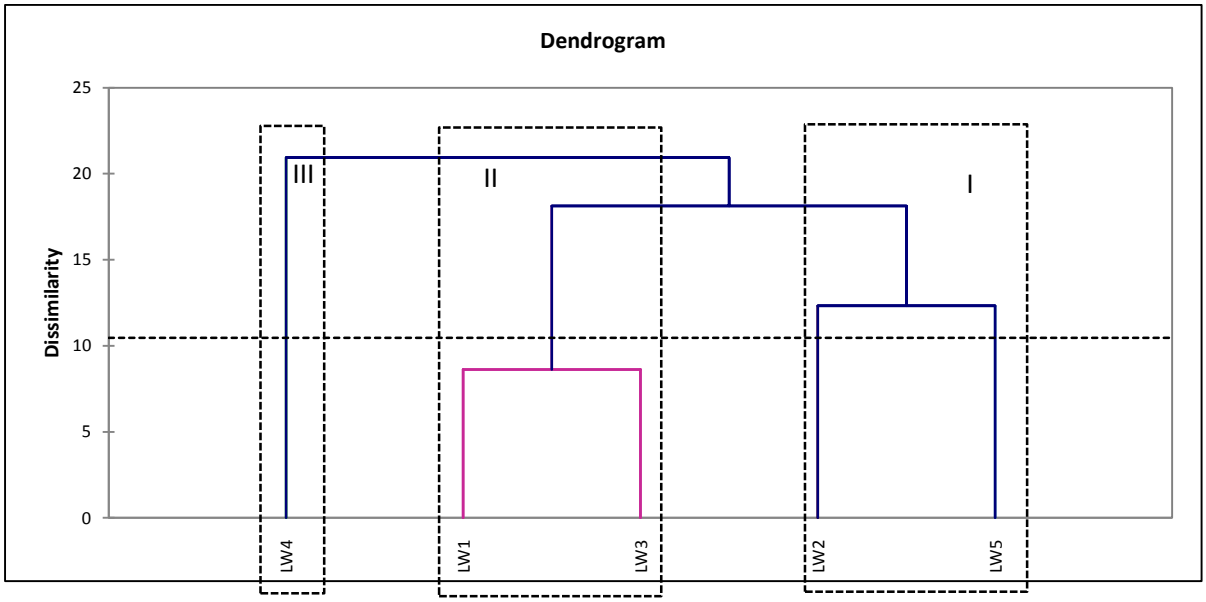



**Figure 46:** Agglomerative Hierarchical Clustering (AHC) for physicochemical parameters obtained during the sampling period in Limbe.

The PCA for the physicochemical parameters studied was analysed for their characterisation in function of the sampling points in the town of Limbe. The first two factorial axes explained 73.38 % of the total variance (F1 = 41.86 % and F2 = 31.51 %). The circle of correlation (Figure 47 A) showed that TDS, dissolved carbon dioxide, EC, temperature and salinity were positively and significantly correlated to the F1 axis and contributed more to the total inertia while dissolved oxygen, pH, nitrate ions and alkalinity were positively correlated to the F1 axis and contributed less of the total inertia. Oxidability, total hardness and turbidity were positively and significantly correlated to the F2 axis while ammonium ion and SS were positively correlated to the F2 axis and contributed less to the total inertia. Phosphate ions was negatively correlated to the F2 axis.

Transposing the physicochemical parameters with the sampling stations, regrouped the sampling stations into two groups that is group I and II (Figure 47 B). Axis F1 discriminated in the positive coordinate in group I station LW2 and LW5, characterised by dissolved $CO_2$, EC, TDS, salinity, temperature, nitrate ions and phosphate ions. Group II which positively discriminated the F2 axis was made up of stations LW1 and LW3 which were characterized by high values of total hardness, turbidity, SS and ammonium ions.

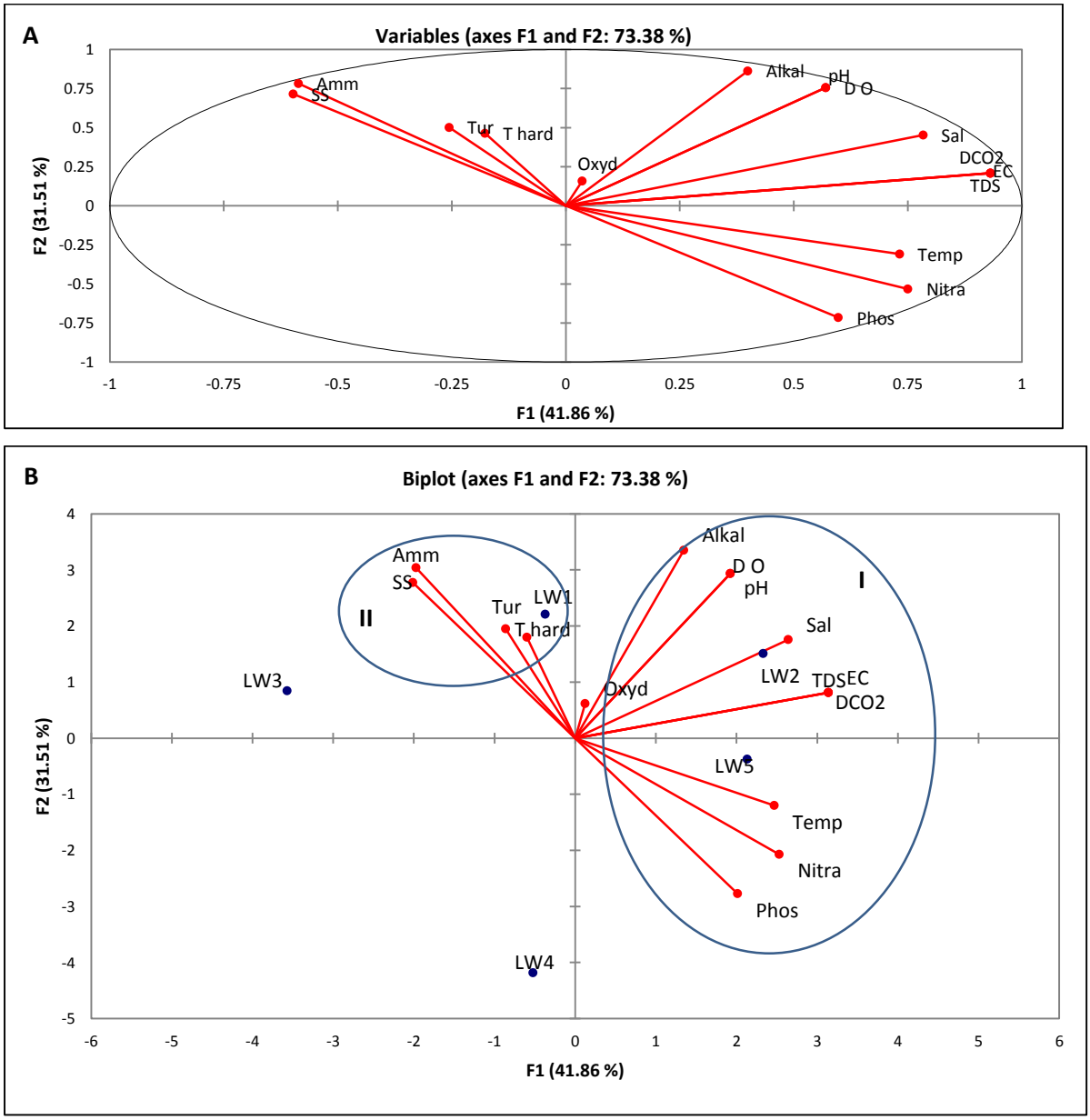



**Figure 47:** PCA of physicochemical parameters of the different sampling points during the study period in Limbe. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.I.2.2.4. Sampling points in the town of Muyuka

The characterization of the sampled groundwater in function of the physicochemical parameters in Muyuka on an AHC, permitted the obtention of a three-class hierarchy of the sampling points from right to left at 11.8 % of dissimilarity. Class I joined class II at 11 % and class II connected to the third class at 21 % (Figure 48). Class I regrouped sampling points MW3 and MW2, characterised by low amounts of salinity, dissolved oxygen and high amounts of oxidability while class II was made up of MW1 only, which was characterised by high amounts of phosphate ions and total hardness. Class III regrouped the sampling point MW4 and MW5, characterised by high SS, turbidity and low pH.

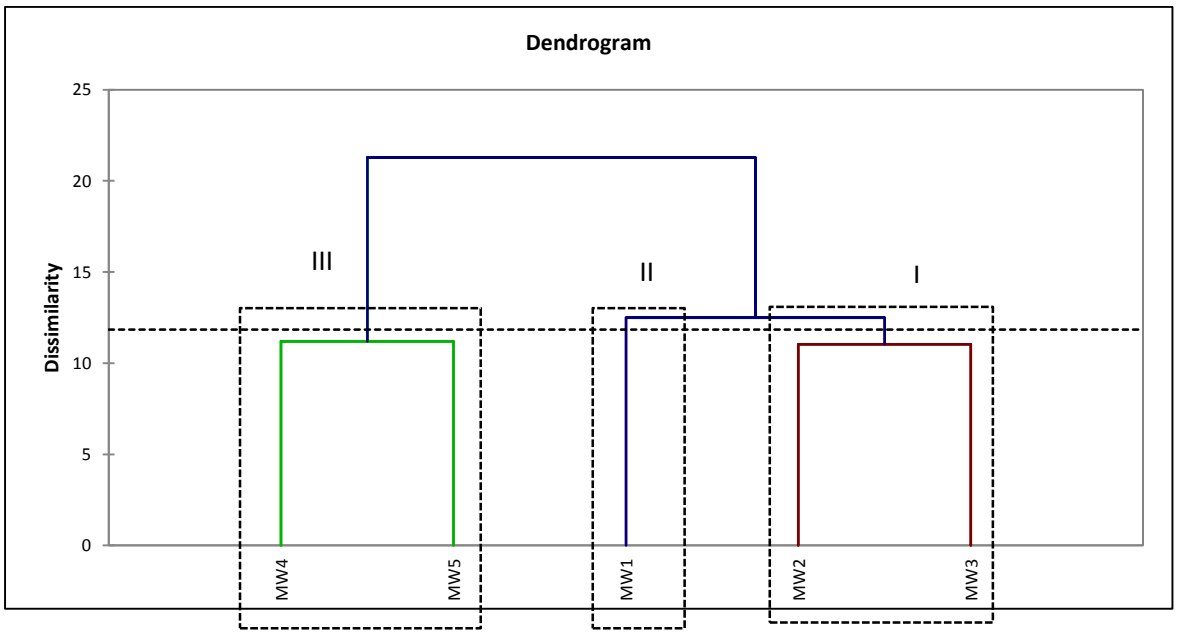



**Figure 48:** Agglomerative Hierarchical Clustering (AHC) for physicochemical parameters obtained during the sampling period in Muyuka.

The PCA for the 14 physicochemical parameters studied was analysed for their characterisation in function of the sampling points in Muyuka. The two first factorial axes explained 68.80 % of the total variance (F1 = 41.96 % and F2 = 26.84 %). The circle of correlation (Figure 49 A) showed that SS, ammonium ions and turbidity were positively and significantly correlated to the F1 axis and contributed more to the total variance. Dissolved oxygen, dissolved carbon dioxide and alklinity were negatively and significantly correlated to the F1 axis.Phosphate ions was significantly and positively correlated to the F2 axis while total hardness, temperature, salinity and oxidability were positively correlated to the F2 axis and contributed less to the total inertia. Nitrate ions and EC were negatively correltaed to the F2 axis.

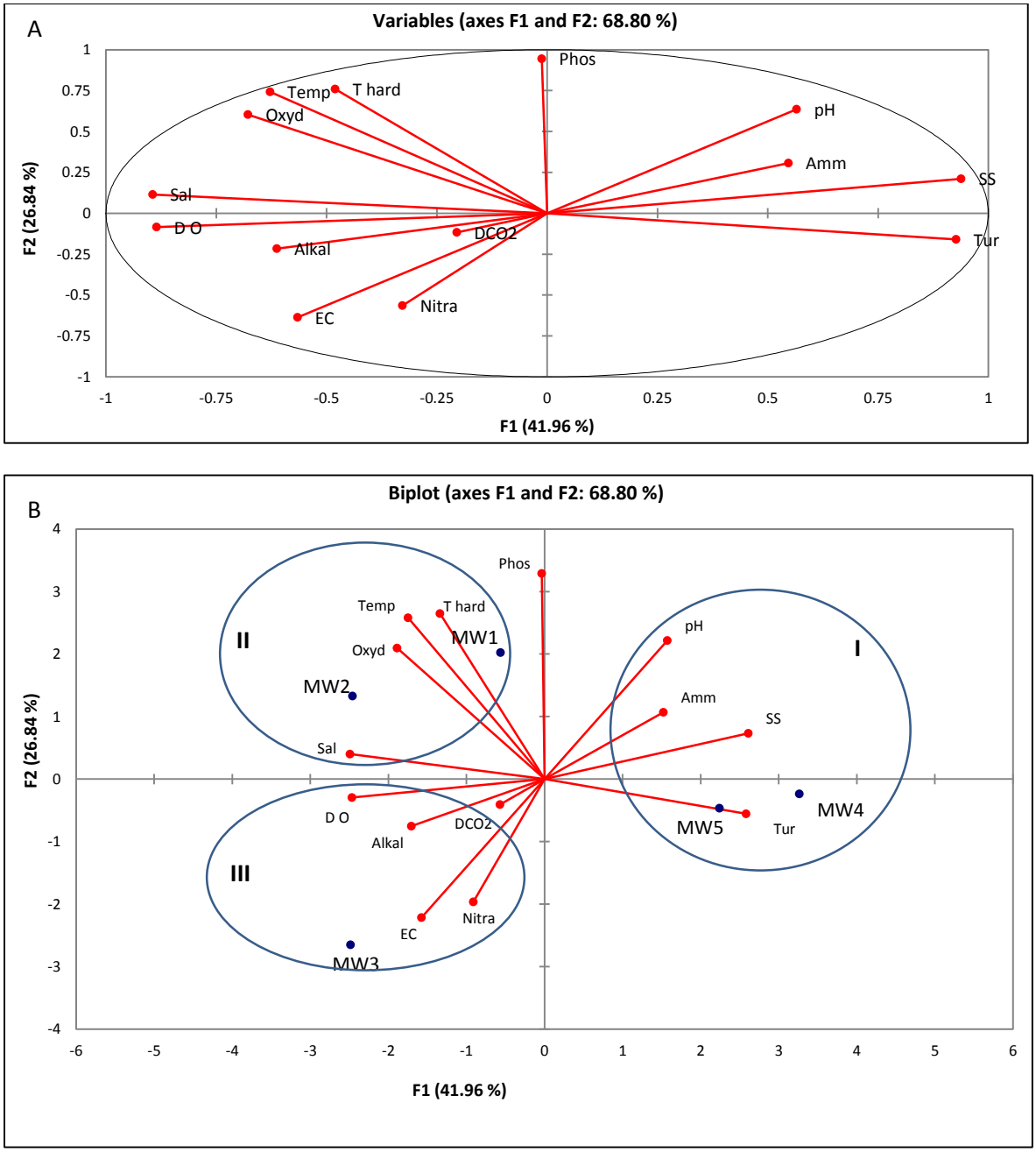



**Figure 49:** PCA of physicochemical parameters of the different sampling points during the study period in Muyuka. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

When the physicochemical parameters were transposed with the sampling stations, the sampling stations were regrouped into three classes, I, II and III (Figure 49 B). Axis F1 discriminated in the positive coordinate in group I, two of the sampling points in Muyuka (MW4 and MW5). The samples of group I were characterized by SS, ammonium ions, turbidity and pH. Group II which positively discriminated the F2 axis constituted of 02 sampling points

(MW1 and MW2). These sampling points were characterized by high levels of total hardness, temperature, oxidability and salinity. Group III negatively discriminated the F1 and F2 axes and was made up of station MW3, characterised by dissolved oxygen, EC, nitrate ions, alkalinity and dissolved carbon dioxide.

### III.I.2.2.5. Sampling points in the town of Ekona/Mautu

The AHC for the different sampled groundwater in function of the physicochemical parameters in Ekona/Mautu, permitted the obtention of two classes from right to left at 11.3 % of dissimilarity. Class I joined class II at 19 % of dissimilarity and class I regrouped the sampling points MS4 and MS5, characterised by low temperature, SS, EC and high values of dissolved oxygen. Class II constituted of ES6 and ES7, which were characterised by high pH, dissolved carbon dioxide alkalinity, nitrate ions and by low amounts of phosphate ions (Figure 50).

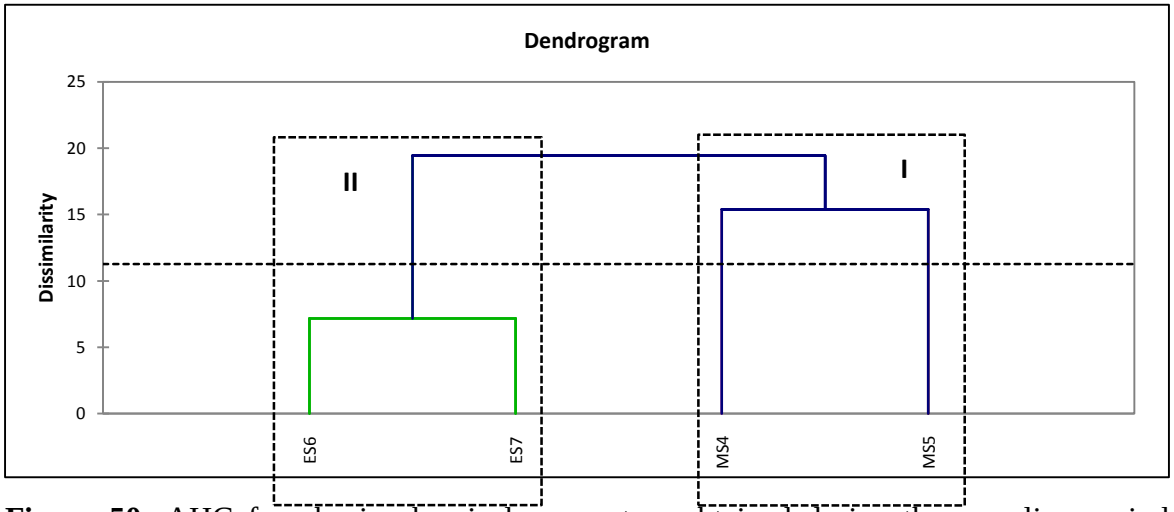



**Figure 50:** AHC for physicochemical parameters obtained during the sampling period in Ekona/Mautu.

The PCA for the physicochemical parameters studied was analysed in order to characterise them in function of the sampling points in Ekona/Mautu. The two first factorial axes explained 76.16 % of the total variance (F1 = 46.19 % and F2 = 29. 97%). The circle of correlation showed that, dissolved carbon dioxide and phosphate ions were positively and significantly correlated to the F1 axis. Turbidity, EC and slinity were negatively and significantly correlated to the F1 axis while teperature and SS were negatively and correlated to the F1 axis. Nitrate ions, pH and alkalinity were positively and significantly correlated to the F2 axis and contributed more while dissoloved oxygen, oxidability and ammonium ions

were correlated to the F2 axis and contributed less. Temperature and Suspended Solids were negatively correlated to the F2 axis (Figure 51 A).

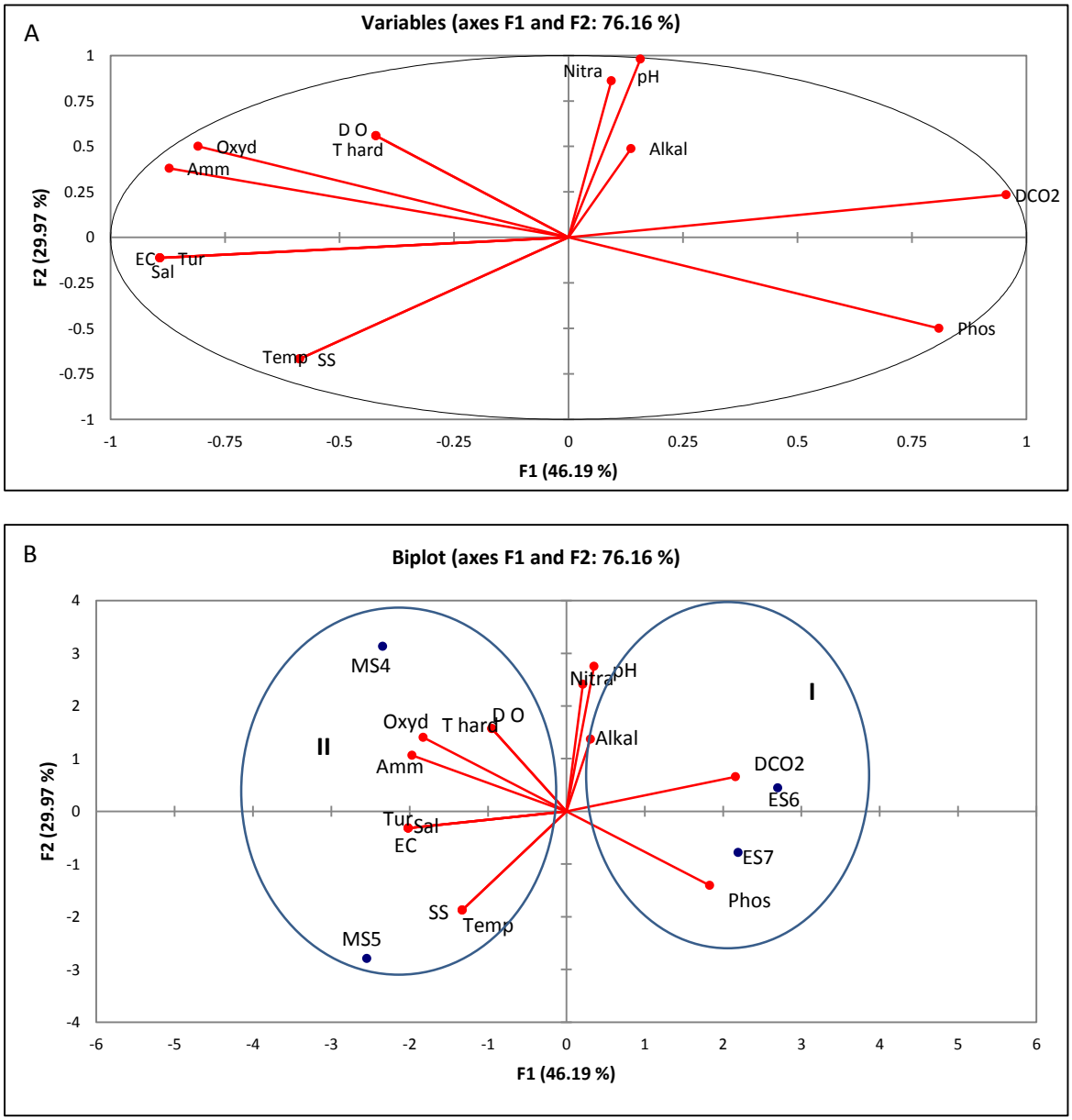



**Figure 51:** PCA of physicochemical parameters of the different sampling points during the study period in Ekona/Mautu. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

When the physicochemical parameters were transposed with the sampling stations, the sampling stations were regrouped into two groups (group I and II). Axis F1 discriminated in the positive coordinate in group I, two of the sampling points (ES6 and ES7). The samples of group I were characterized by pH, nitrate ions, alkalinity, dissolved carbon dioxide and phosphate ions. Group II discriminated the F2 axis positively and negatively discriminated the

F1 axis with two sampling points (MS4 and MS5). These sampling points were characterized by dissolved oxygen, total hardness, oxidability ammonium ions, turbidity, salinity, EC, temperature and SS (Figure 51 B).

### III.I.2.2.6. Sampling points in the town of Owe

The AHC characterisation gave two classes: class I (OS3) and class two (OS1 and OS2). The level of dissimilarity was 6 % and OS1 and OS2 met at 13 % of dissimilarity while OS3 met these two at 15 % (Figure 52).

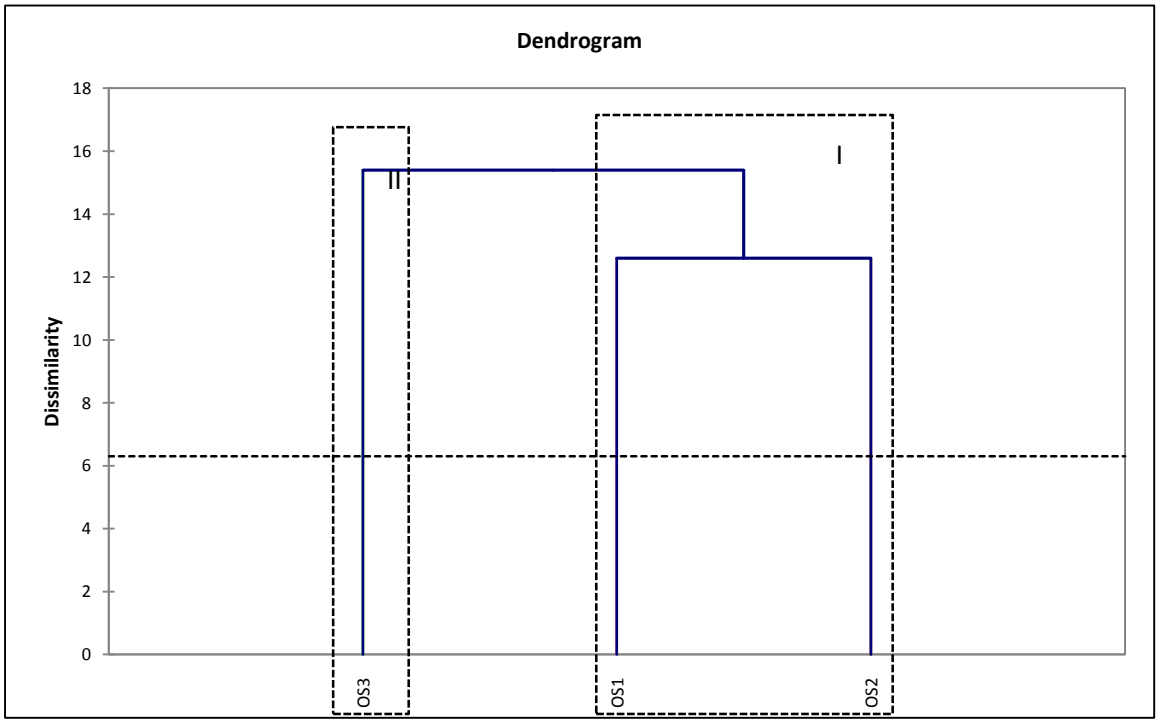



**Figure 52:** AHC for physicochemical parameters obtained during the sampling period in Owe.

The PCA for the physicochemical parameters studied was analysed and the two first factorial axes explained 100 % of the total variance (F1 = 53.57 % and F2 = 46.43 %). The circle of correlation showed that, phosphate ions, turbidity, EC and dissolved carbon dioxide, temperature, alkalinity and salinity were positively and significantly correlated to the F1 axis while dissolved oxygen was negatively and significantly correlated to the F1 axis. SS and nitrate ions were positively and significantly correlated to the F2 axis while oxidability and ammonium ions were positively correlated to the F2 axis. pH and total hardness were negatively correlated to the F2 axis (Figure 53 A).

When the physicochemical parameters were transposed with the sampling stations, the sampling stations were regrouped into wo groups: group I and group II. Axis F1 discriminated in the positive coordinate OS1 and OS3 characterised by phosphate ions, turbidity, EC,

dissolved carbon dioxide, temperature, alkalinity and salinity. Group II contained the station OS2 which was characterised by dissolved oxygen, oxidability and ammonium ions (Figure 53 B).

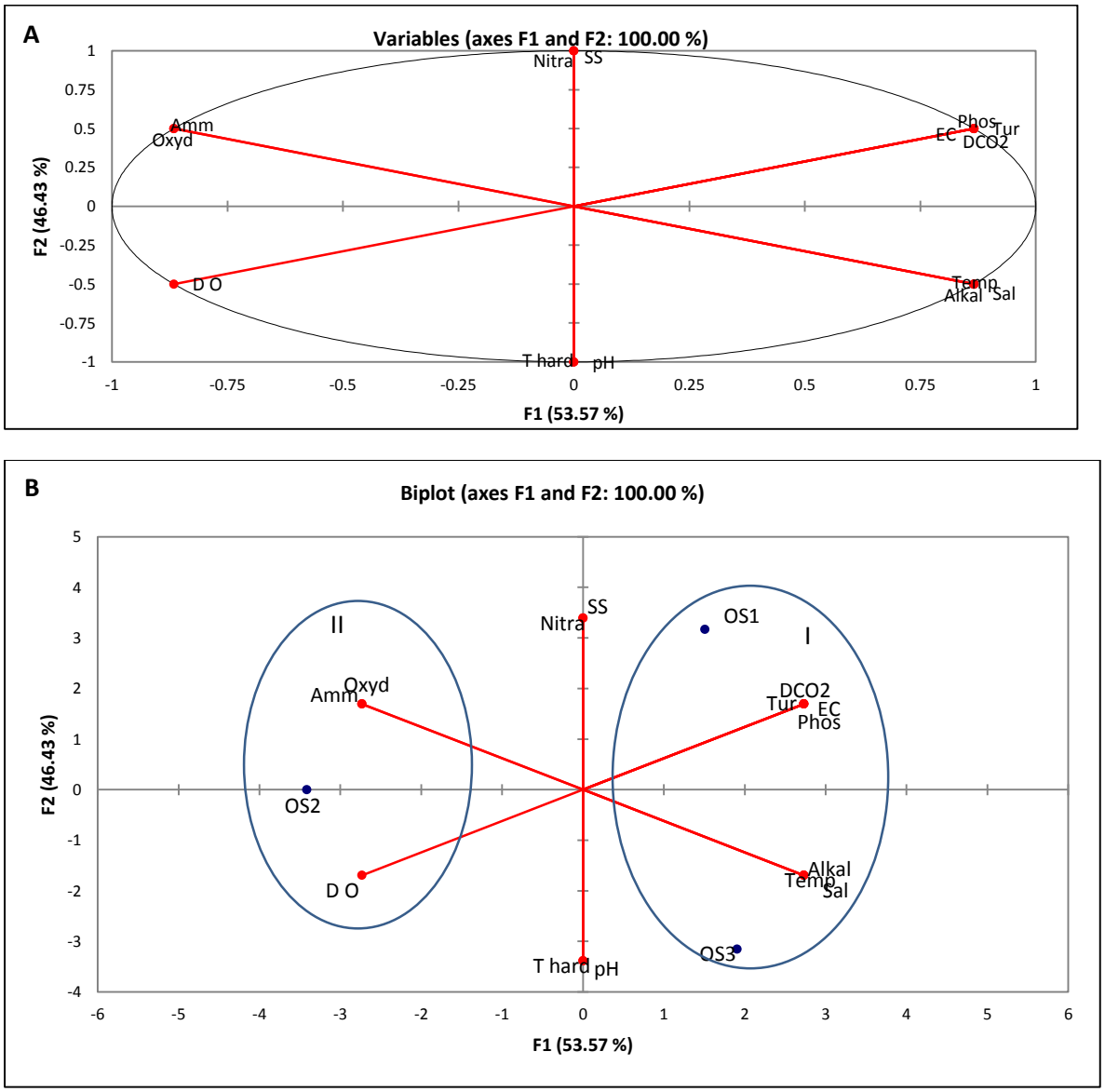



**Figure 53:** PCA of physicochemical parameters of the different sampling points during the study period in Owe. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.3. Biological Characteristics

#### III.1.3.1. Fauna of groundwater studied in Fako division

##### III.1.3.1.1. Global distribution of groundwater fauna per sampling town in Fako

The structure of the groundwater invertebrate collected during the study period varied from one town to another and from one sampling point to another. The proportions per locality

showed that, insects, ostracods, arachnids, copepods and oligochaetes were abundantly represented in all the sampling towns. Cladocerans were less distributed and were found only in the town of Tiko (169 inds). Hirudinea are the least number of organisms collected throughout the sampling period and were present in Owe (2 inds), Buea (12 inds), Tiko (15 inds) and Muyuka (2 inds). Insects were the most abundant and were distributed in all the sampling towns and were most abundant in Buea (2321 inds), Owe (1566 inds). Ostracods were the second most abundant organisms collected during the study period and a total number of 2927 of individuals were collected in Tiko, followed by 547ind and 408 inds in Buea and Limbe respectively. Arachnids were also abundant in most of the study areas such as 1771 individuals in Owe and 1346 individuals in Ekona/Mautu. Copepods and oligochaetes were abundant in some sampling areas such as 2725 copepods in Tiko and 2898 oligochaetes in Limbe. Members of the class Isopoda were distributed in all the sampling towns though the numbers were not as much as those of the other classes but they were abundant in Muyuka, Limbe and Owe compared to the other towns. The class Malacostraca was abundantly present in Ekona/Mautu, Buea and Owe.

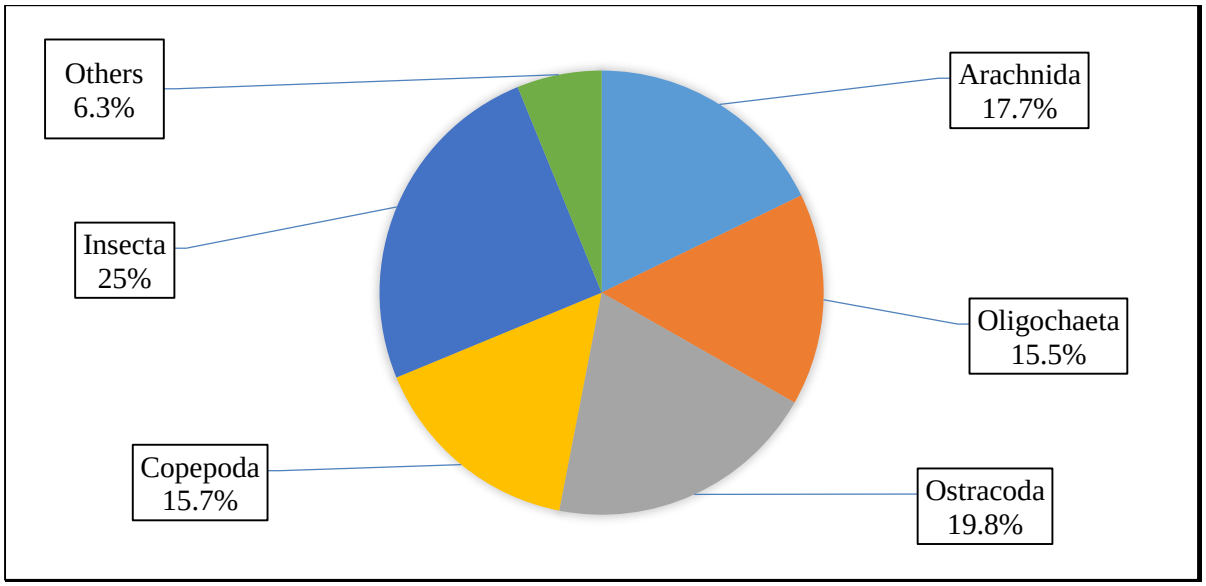



**Figure 54:** Distribution of the different classes of groundwater invertebrates collected in the sampled stations in Fako division.

In all the sampling towns and stations in Fako division, a total of 21013 organisms were collected distributed into 12 classes, 58 families, 62 genus/sub families and 81 taxa. In the dry season, 9015 organisms were collected while in the rainy season, a total of 11998 individuals were collected. Insects were the most abundant class with 5268 organisms (25%), followed by Ostracoda with 4164 organisms (19.8 %) then Arachnida with a total of 3737 (17.7 %)

organisms, Copepoda 3299 (15.7 %) and Oligochaeta with a total of 3249 organisms (15.5 %) (Figure 54). “Others” on the pie chat include classes that had less than 1% each of total abundance. They include Hirudinea, Gastropoda, Collembola, Isopoda, Cladocera, Nematoda and Malacostraca and they made up 6.3 % (1296 organisms).

### III.1.3.1.1.1. Global distribution of groundwater fauna in wells and springs in Fako

In the wells, a total of 10749 organisms were harvested, belonging to 39 taxa and 11 classes. The most abundant classes wete Ostracoda with 32.6 % of organisms, Copepoda with 31.7 % organisms and Oligochaeta with 31.3 % organisms. The well MW1 had the least number of organism (65), followed by LW4 with 75 organisms. The highest number of organisms was obtained in LW1 with a total of 2820 organisms and TW1 with 2061 organisms (Figure 55 A).

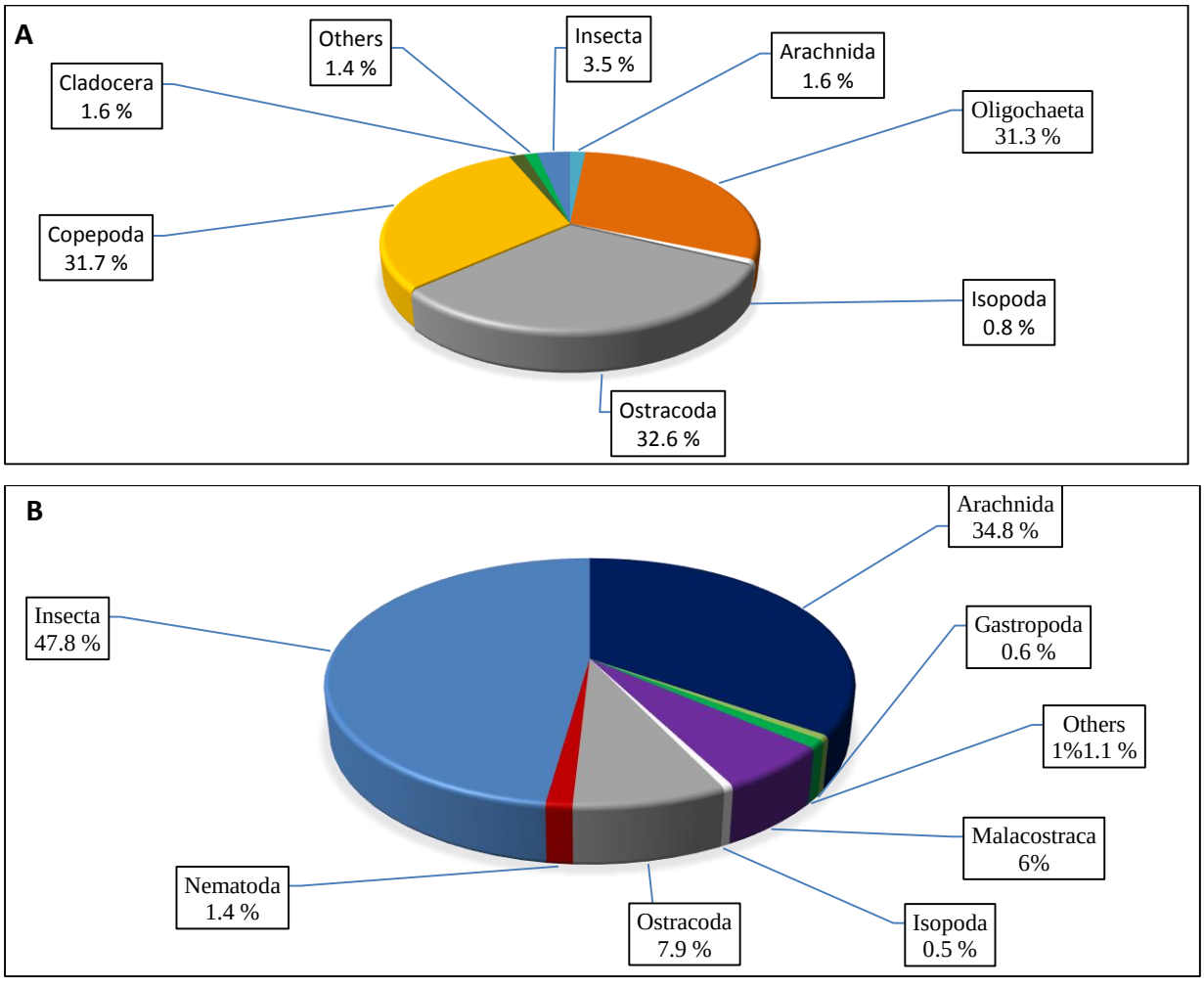



**Figure 55:** Distribution of the different classes of groundwater invertebrates collected in the wells (A) and springs (B) during the sampling period in Fako division.

In the springs, a total of 10264 organisms were collected throughout the sampling period that are distributed into 11 classes and 41 taxa. The class Insecta had the highest number of organisms (47.8 %) followed by the class Arachnida with 34.8 % of organisms. The classes with the least number of organisms are Hirudinea and Collembola with 14 organisms each and have been combined to form other organisms that represented less than 1 %. (Figure 55 B). Springs OW2 and OW1 had the highest number of organisms 1204 and 1917 organisms respectively while BS9 had 19 organisms which was the least number of organisms.

### III.1.3.1.2. Groundwater in Tiko, Limbe and Muyuka (Wells)

In Tiko, a total of 6293 organisms were collected, belonging to two phyla (Annelida and Arthropoda), nine classes, 15 orders, 33 families and 30 identified genus/sub family (Table XXI). This fauna was diversified and dominated by Ostracods which alone harboured a total abundance of 47 %, followed by Copepods with an abundance of 43 % (Figure 56 A). The taxonomic richness of the stations varied between eight individuals in TW10 and 19 individuals in TW7. The fauna collected showed that, groundwater in Tiko is largely dominated by the class Crustacean with principal representatives being the families of Cytherididae, Cyprididae and Cyclopoidae.

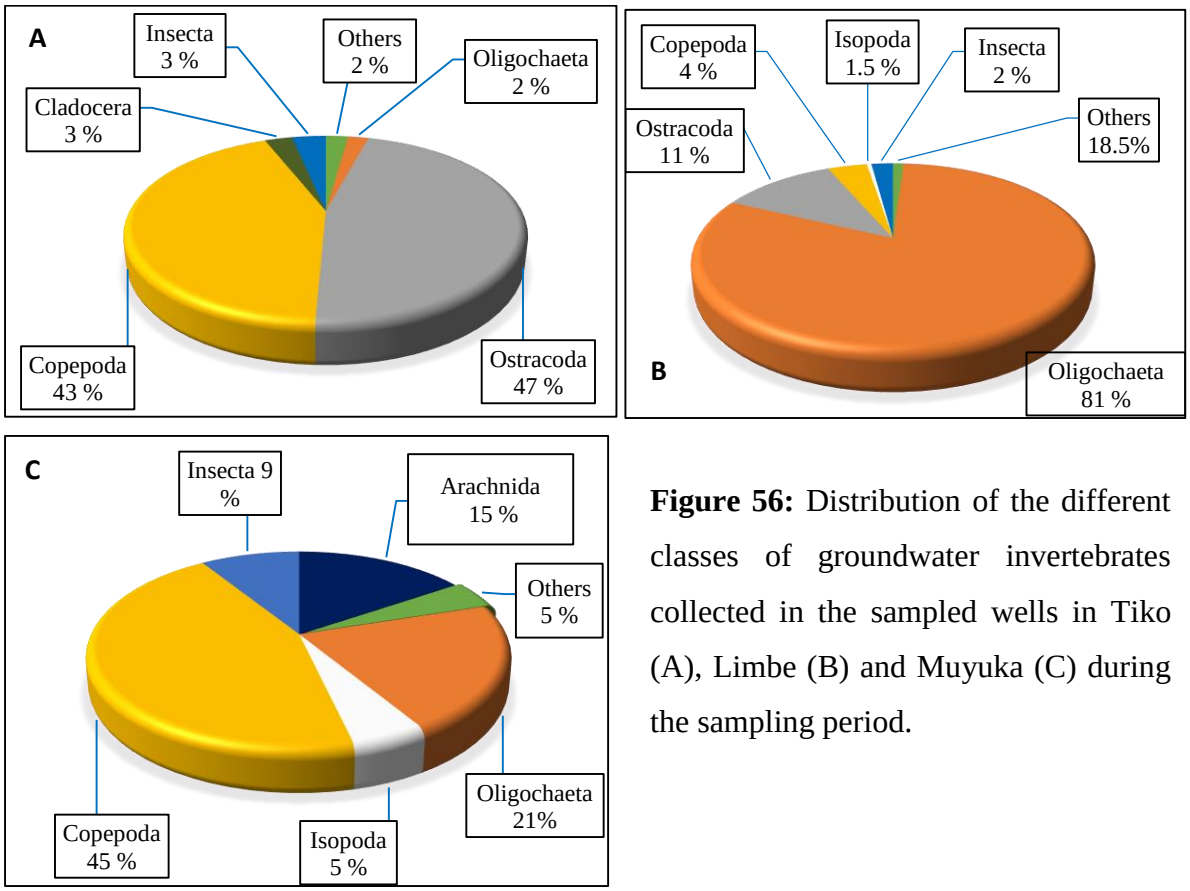



**Figure 56:** Distribution of the different classes of groundwater invertebrates collected in the sampled wells in Tiko (A), Limbe (B) and Muyuka (C) during the sampling period.

In Limbe, a total of 3574 organisms were collected, belonging to 8 classes, 12 orders, 23 families and 22 identified genera. The highest number of organisms was collected in MK3 (377 inds) while the lowest number of organisms was collected in MK1 (65 inds) (Table XXII). Oligochaetes dominated with a total of 81%, followed by ostracods with 11% (Figure 56 B).

In Muyuka, the fauna was dominated by Copepods (45 %) and Oligochaetes (21%). Insects and Isopods were the least distributed with 9 % and 5 % respectively (Figure 56 C). A total of 882 organisms were collected divided into 9 classes, 13 orders and 24 families and 19 identified genera with MW3 having the greatest number of individuals (377 inds) and MW1 having the least number (65 inds) of organisms (Table XX).

**III.1.3.1.3. Groundwater in Buea, Ekona and Owe (Springs)**

In Buea, 3644 individuals were collected belonging to 11 classes, 20 orders, 45 families and 58 identified genus /or sub family. BS9 harboured the least number of organisms (19 inds) and BS13 harboured the highest number of organisms (1123 inds) (Table XXIV). The dominant class with 64 % was class Insecta, followed by Ostracoda (15 %), then Arachnida (12 %) and other organisms combined made up just 3 % of the total abundance in Buea (Figure 57 A).

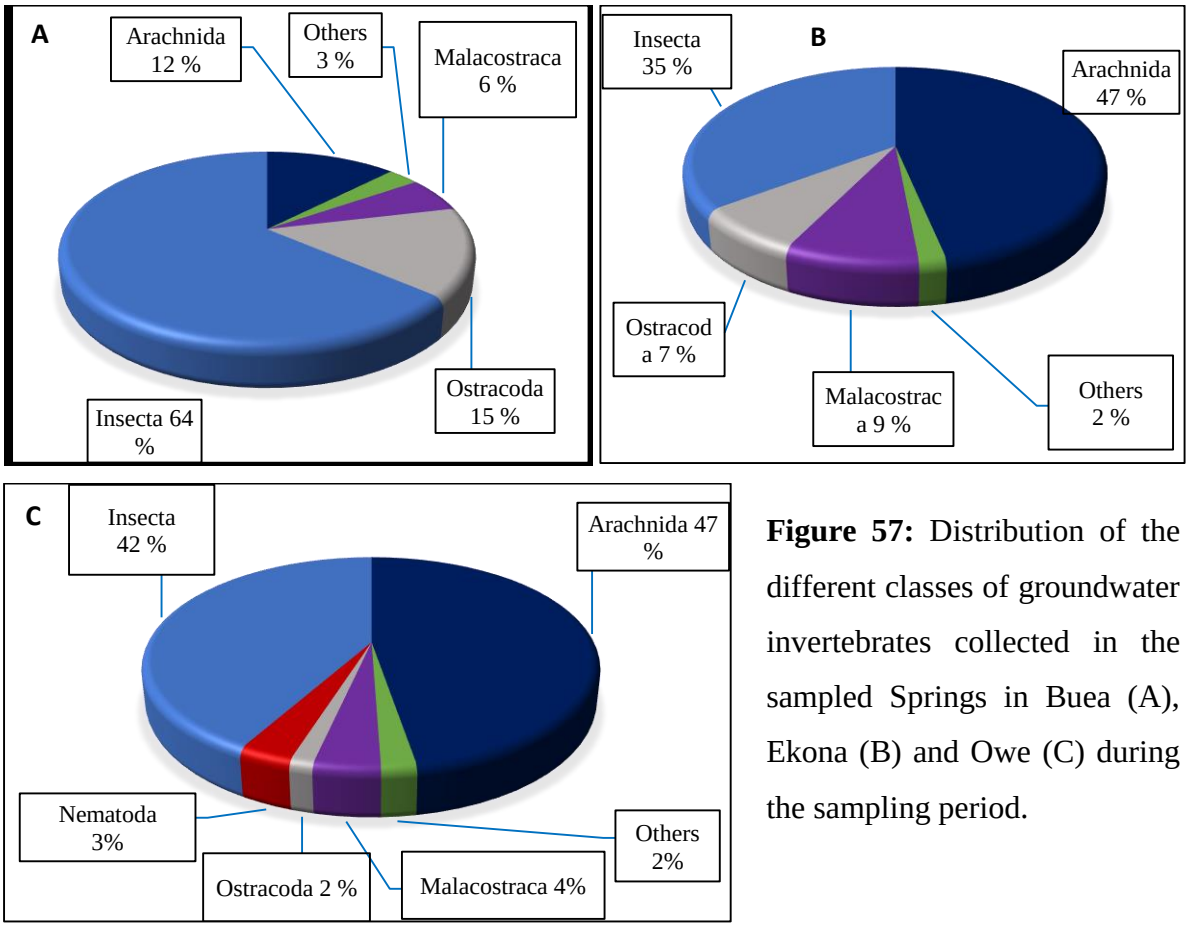



**Figure 57:** Distribution of the different classes of groundwater invertebrates collected in the sampled Springs in Buea (A), Ekona (B) and Owe (C) during the sampling period.

Ekona /Mautu had 2880 organisms, collected throughout the study period which was made up of 9 classes, 16 orders and 44 families. Arachnids (47 %) and insects (35 %) dominated while other organisms belonging to classes such as Isopoda, Nematoda, Gastropoda and Copepoda combined together had 2 % (Figure 57 B). Station ES6 had the highest number of organisms (1058 inds), followed by MS4 which had 759 individuals (Table XXV).

A total of 3740 individuals were collected in Owe throughout the study period. The Class Arachnida dominated with a total of 47 %, followed by Insecta with a 42 %. Ostracods and other organisms were the least dominant with 2 % each (Figure 57 C). The highest number of organisms was collected in OS2 with a total of 1917 individuals, followed by OS1 with 1204 individuals while OS3 had the least number of organisms (620 inds) (Table XXVI.

**Table XX: Principal taxa of groundwater invertebrates collected in Muyuka during the study period**

| **Class** | **Order** | **Family** | **Genus/sub family** | **MW1** | **MW2** | **MW3** | **MW4** | **MW5** |
|---|---|---|---|---|---|---|---|---|
| | | Ceratozetidae | | 0 | 57 | 0 | 2 | 5 |
| | | Bdellidae | *Bdellina* sp | 0 | 64 | 0 | 0 | 0 |
| | | Pisauridae | Thalassius | 3 | 1 | 0 | 1 | 1 |
| Arachnida | Araneae | Argyronetidae | *Argyroneta* sp | 2 | 0 | 0 | 1 | 0 |
| Hirudinea | Euhirudinea | Piscicolidae | Rhynchobdellida | 1 | 0 | 1 | 0 | 0 |
| | | Lumbriculicidae | *Lumbriculus* sp | 0 | 2 | 54 | 0 | 0 |
| Oligochaeta | Oligochaeta | Naididae | *Dero* sp | 0 | 0 | 37 | 54 | 40 |
| | | Isotomidae | Folsoma | 2 | 0 | 4 | 0 | 5 |
| Collembola | Entomorbryomorpha | Entomobryiidae | Orchesella | 1 | 0 | 0 | 0 | 6 |
| | | Asellidae | **Proasellus* sp | 1 | 0 | 0 | 0 | 2 |
| Isopoda | Isopoda | Stenasellidae | **Metastenasellus* sp | 0 | 3 | 34 | 4 | 1 |
| | | Cytherididae | | 6 | 0 | 0 | 0 | 0 |
| | | Cyprididae | *Psychrodromus* | 0 | 0 | 0 | 0 | 6 |
| Ostracoda | Podocopida | Darwinulidae | * *Darwinula* sp | 0 | 0 | 0 | 0 | 2 |
| Copepoda | Cyclopoida | Cyclopidae | *Cyclops* sp | 29 | 5 | 233 | 21 | 106 |
| Nematoda | Gordoida | Gordiacea | Gordius sp | 4 | 0 | 0 | 0 | 2 |
| | | Culicidae | *Culex* sp | 3 | 0 | 2 | 0 | 7 |
| | | Chironomidae | *Chironomus* sp | 0 | 4 | 9 | 0 | 2 |
| | | | Chironomini | 0 | 0 | 1 | 0 | 0 |
| | Diptera | Psychodidae | Pericoma | 0 | 0 | 0 | 1 | 0 |
| | | Dysticidae | Laccophilus | 2 | 0 | 0 | 0 | 0 |
| | Coleoptera | Hydrophylidae | *Hydrophilus* sp | 2 | 0 | 0 | 0 | 0 |
| | Odonata | Coenagrionidae | Enallagma | 0 | 0 | 0 | 1 | 0 |
| | Hymenoptera | Formicidae | | 9 | 6 | 2 | 9 | 17 |
| Insecta | Orthoptera | Blattidae | Panesthia | 0 | 0 | 0 | 0 | 2 |
| **Total number of individuals** | | | | **65** | **142** | **377** | **94** | **204** |
| **Total number of taxa** | | | | **13** | **8** | **10** | **9** | **15** |
| **Nunber of stygobite taxa** | | | | 1 | 1 | 1 | 1 | 1 |

*indicates stygobite organisms

**Table XXI: Principal taxa of groundwater invertebrates collected in the town of Tiko during the study period**

| Class | Order | Family | Genus/sub family | TW1 | TW2 | TW3 | TW4 | TW5 | TW6 | TW7 | TW8 | TW9 | TW10 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Tetragnathidae | *Tetragnatha* sp | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 1 | 0 | |
| | | Ceratozetidae | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | |
| | Acarina | Bdellidae | *Bdellina* sp | 0 | 0 | 8 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | |
| | | Pisauridae | *Thalassius* sp | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | |
| Arachnida | Araneae | Argyronetidae | *Argyroneta* sp | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | |
| Hirudinea | Euhirudinea | Piscicolidae | *Rhynchobdellida* sp | 0 | 0 | 0 | 4 | 7 | 0 | 0 | 2 | 1 | 0 | |
| | | Lumbriculicidae | *Lumbriculus* sp | 1 | 7 | 0 | 0 | 17 | 0 | 0 | 2 | 0 | 0 | |
| | Oligochaeta | Naididae | *Dero* sp | 28 | 2 | 4 | 42 | 9 | 3 | 5 | 5 | 0 | 0 | |
| Clitellata | | Physidae | *Physa* sp | 25 | 1 | 0 | 0 | 19 | 0 | 8 | 0 | 0 | 0 | |
| | | Isotomidae | *Folsoma* sp | 7 | 0 | 2 | 0 | 3 | 2 | 4 | 2 | 0 | 0 | |
| Collembola | Entomorbryomorpha | Entomobryiidae | *Orchesella* sp | 1 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | |
| Malacostraca | Isopoda | Asellidae | **Proasellus* sp | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | |
| | | Stenasellidae | **Metastenasellus* sp | 0 | 0 | 4 | 0 | 3 | 0 | 2 | 3 | 7 | 1 | |
| | | Cirolanidae | **Cirolana* sp | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | |
| | | Cytheridae | | 698 | 45 | 0 | 0 | 85 | 5 | 100 | 47 | 6 | 5 | |
| | | Cyprididae | Psychrodromus sp | 697 | 510 | 4 | 5 | 376 | 65 | 171 | 67 | 19 | 0 | |
| Ostracoda | Podocopida | Darwinulidae | * *Darwinula* sp | 12 | 0 | 0 | 0 | 0 | 2 | 0 | 8 | 0 | 0 | |
| Copepoda | Cyclopoida | Cyclopidae | *Cyclops* sp | 580 | 417 | 197 | 50 | 342 | 683 | 158 | 94 | 65 | 139 | |
| Branchiopoda | Cladocera | Moinidae | *Moina* sp | 0 | 0 | 0 | 0 | 0 | 0 | 161 | 7 | 1 | 0 | |
| | | Culicidae | *Culex* sp | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | |
| | | | *Chironomus* sp | 9 | 18 | 0 | 3 | 0 | 2 | 22 | 3 | 0 | 0 | |
| | | Chironomidae | Chironomini | 0 | 0 | 1 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | |
| | | | Dasyhelea | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 1 | 1 | |
| | | Ceratopogonidae | *Bezzia* | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | |
| | | | *Pericoma* sp | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 0 | 0 | 1 | |
| | | Psychodidae | *Lutzomyia* sp | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | | Simulidae | *Simulium* sp | 0 | 0 | 1 | 0 | 0 | 2 | 2 | 0 | 0 | 0 | |
| | Diptera | Ephydidae | *Scatella* sp | 0 | 0 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| | | Dysticidae | *Laccophilus* sp | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | |
| | | Hydrophylidae | *Hydrophilus* sp | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | |
| | Coleoptera | Elmidae | *Macrelmis* sp | 0 | 3 | 0 | 2 | 0 | 0 | 6 | 0 | 0 | 7 | |
| | | Caenidae | *Caenis* sp | 0 | 11 | 0 | 3 | 0 | 0 | 0 | 7 | 0 | 0 | |
| | Ephemeroptera | Verlidae | *Microvelia* sp | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | |
| | Odonata | Aeshnidae | *Aeshna* sp | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | |
| | Hymenoptera | Formicidae | | 0 | 3 | 5 | 2 | 12 | 1 | 13 | 10 | 0 | 0 | |
| Insecta | Orthoptera | Blattidae | Panesthia sp | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | |
| **Total number of individuals** | | | | **2061** | **1020** | **232** | **118** | **878** | **768** | **682** | **270** | **103** | **161** | |
| **Total number of taxa** | | | | **12** | **12** | **10** | **11** | **15** | **10** | **19** | **17** | **10** | **8** | |
| **Number of stygobite taxa** | | | | **1** | **0** | **1** | **0** | **2** | **1** | **2** | **2** | **1** | **1** | |

* indicates stygobite organisms

**Table XXII: List of the principal taxa of groundwater collected in the town of Limbe during the study period**

| Class | Order | Family | Genus/sub family | LW1 | LW2 | LW3 | LW4 | LW5 |
|---|---|---|---|---|---|---|---|---|
| | Acarina | Tetragnathidae | *Tetragnatha* sp | 0 | 0 | 1 | 0 | 0 |
| Arachnida | Araneae | Pisauridae | Thalassius sp | 2 | 1 | 5 | 1 | 0 |
| | | Lumbriculicidae | *Lumbriculus* sp | 0 | 0 | 2 | 1 | 0 |
| Oligochaeta | Oligochaeta | Naaididae | *Dero* sp | 2587 | 119 | 17 | 4 | 168 |
| | Bassomatophora | Planorbidae | *Planorbarius* sp | 0 | 0 | 0 | 2 | 0 |
| Gastropoda | | Physidae | *Physa* sp | 1 | 0 | 0 | 0 | 0 |
| | Entomorbryomorpha | Isotomidae | Folsoma sp | 5 | 0 | 3 | 4 | 7 |
| Collembola | | Entomobryiidae | Orchesella sp | 1 | 0 | 1 | 0 | 3 |
| | Isopoda | Stenasellidae | **Metastenasellus* sp | 10 | 0 | 0 | 0 | 0 |
| Isopoda | | Cirolanidae | * *Cirolana* sp | 6 | 0 | 0 | 0 | 0 |
| | | Cytheridídae | | 17 | 0 | 0 | 0 | 1 |
| | | Cypridídae | *Psychrodromus* | 129 | 186 | 0 | 1 | 0 |
| Ostracoda | Podocopida | Darwinulidae | **Darwinula* sp | 5 | 66 | 3 | 0 | 0 |
| Copepoda | Cyclopoida | Cyclopidae | *Cyclops* sp | 44 | 18 | 36 | 38 | 3 |
| | | Culicidae | *Culex* sp | 0 | 0 | 0 | 5 | 0 |
| | | Chironomidae | *Chironomus* sp | 2 | 2 | 6 | 3 | 6 |
| | | | Chironomini | 0 | 0 | 0 | 0 | 2 |
| | | Ceratopogonidae | Dasyhelea | 0 | 0 | 2 | 0 | 0 |
| | | | Bezzia | 2 | 0 | 0 | 0 | 0 |
| | Diptera | Psychodidae | *Pericoma* sp | 1 | 1 | 0 | 1 | 1 |
| | | Dysticidae | *Laccophilus* sp | 1 | 0 | 2 | 0 | 0 |
| | | Hydrophylidae | *Hydrophilus* sp | 1 | 0 | 3 | 1 | 0 |
| | | | *Laccobius* sp | 0 | 0 | 0 | 0 | 0 |
| | Coleoptera | Elmidae | Macrelmis sp | 0 | 0 | 0 | 4 | 0 |
| | Odonata | Coenagrionidae | *Enallagma* sp | 0 | 0 | 1 | 2 | 0 |
| Insecta | Hymenoptera | Formicidae | | 6 | 2 | 3 | 8 | 8 |
| **Total number of individuals** | | | | **2820** | **395** | **85** | **75** | **199** |
| **Total number of taxa** | | | | **17** | **8** | **14** | **14** | **9** |
| **Nunber of stygobite taxa** | | | | 3 | 1 | 1 | 0 | 0 |

*Indicates stygobite organisms

**Table XXIII:** Principal taxa of groundwater invertebrates collected in the town of Buea during the study period

| Class | Order | Family | Genus/sub family | BS8 | BS9 | BS10 | BS11 | BS12 | BS13 |
|---|---|---|---|---|---|---|---|---|---|
| Arachnida | Acarina | Limnesiidae | *Limnesia* sp | 36 | 0 | 9 | 2 | 0 | 374 |
| | Araneae | Pisauridae | *Thalassius* sp | 3 | 0 | 15 | 2 | 0 | 4 |
| | | Argyronetidae | *Argyroneta* sp | 0 | 0 | 3 | 0 | 0 | 4 |
| Hirudinea | Euhirudinea | Erpobdellidae | | 0 | 0 | 0 | 0 | 12 | 0 |
| Clitellata | Oligochaeta | Lumbriculicidae | *Lumbriculus* sp | 6 | 0 | 0 | 0 | 0 | 0 |
| | | Naididae | *Dero* sp | 8 | 0 | 0 | 0 | 8 | 0 |
| Gastropoda | Basommatophora | Planorbidae | *Planorbarius* sp | 25 | 0 | 0 | 0 | 0 | 0 |
| | Littorinimorpha | Hydrobiidae | *Lobogenes* | 4 | 0 | 0 | 0 | 0 | 0 |
| | | | *Potamopyrgus* | 7 | 0 | 0 | 0 | 0 | 0 |
| Collembola | Entomorbryomorpha | Isotomidae | *Folsoma* sp | 1 | 0 | 1 | 0 | 7 | 0 |
| Malacostraca | Decapoda | Atyidae | *Caridina* sp | 0 | 0 | 0 | 0 | 21 | 152 |
| | | Potamonautidae | *Potamonautes* sp | 0 | 0 | 0 | 6 | 7 | 28 |
| Isopoda | Isopoda | Asellidae | **Proasellus* sp | 3 | 0 | 0 | 0 | 1 | 0 |
| Ostracoda | Podocopida | Cytheridiidae | | 0 | 0 | 15 | 8 | 0 | 0 |
| | | Cyprididae | *Psychrodromus* sp | 2 | 0 | 107 | 118 | 109 | 159 |
| | | Darwinulidae | **Darwinula* sp | 29 | 0 | 0 | 0 | 0 | 0 |
| Copepoda | Cyclopoida | Cyclopidae | | 0 | 0 | 15 | 0 | 2 | 0 |
| Nematoda | Gordoida | Gordiacea | *Gordius* sp | 10 | 0 | 0 | 0 | 0 | 0 |
| Insecta | Diptera | Culicidae | *Culex* sp | 2 | 0 | 0 | 0 | 0 | 0 |
| | | Chironomidae | *Chironomus* sp | 120 | 13 | 8 | 0 | 8 | 0 |
| | | | Chironomini | 134 | 0 | 143 | 0 | 23 | 57 |
| | | | *Ablabesmyia* sp | 385 | 6 | 0 | 18 | 5 | 0 |
| | | Ceratopogonidae | Dasyhelea | 50 | 0 | 282 | 0 | 0 | 0 |
| | | | Bezzia | 16 | 0 | 2 | 13 | 8 | 0 |
| | | Psychodidae | *Pericoma* sp | 4 | 0 | 51 | 28 | 0 | 20 |
| | | | *Lutzomyia* sp | 0 | 0 | 12 | 3 | 1 | 0 |
| | | Simulidae | *Simulium* sp | 0 | 0 | 2 | 92 | 1 | 4 |
| | | | | 2 | 0 | 6 | 23 | 4 | 3 |
| | | Ephydridae | *Scatella* sp | 1 | 0 | 2 | 1 | 0 | 0 |
| | | Tipulidae | *Tipula* sp | 0 | 0 | 9 | 17 | 2 | 0 |
| | Coleoptera | Dysticidae | *Hydrovatus* sp | 0 | 0 | 0 | 0 | 1 | 3 |
| | | Hydrophylidae | *Hydrophilus* sp | 0 | 0 | 0 | 4 | 0 | 0 |
| | | | *Laccobius* sp | 0 | 0 | 0 | 0 | 0 | 2 |
| | | Psephenidae | *Eubrianax* sp | 0 | 0 | 0 | 0 | 0 | 47 |
| | | Elmidae | *Macrelmis* sp | 0 | 0 | 4 | 57 | 0 | 1 |
| | | | *Limnius* sp | 0 | 0 | 0 | 0 | 0 | 2 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | *Neoelmis* sp | 2 | 0 | 3 | 0 | 0 | 1 |
| | | | *Elmis* sp | 0 | 0 | 0 | 2 | 0 | 0 |
| | | | *Hydrovatus* sp | 0 | 0 | 0 | 0 | 1 | 3 |
| | | Caenidae | *Caenis* sp | 0 | 0 | 0 | 3 | 0 | 0 |
| | | Baetidae | *Baetis* sp | 0 | 0 | 0 | 26 | 1 | 21 |
| | | | *Paraleptophlebia* sp | 0 | 0 | 0 | 4 | 0 | 5 |
| | | Leptophlebidae | *Leptophlebia* sp | 0 | 0 | 0 | 0 | 0 | 4 |
| | | | *Ecdyonurus* sp | 0 | 0 | 0 | 51 | 0 | 21 |
| | | | *Epeorus* sp | 0 | 0 | 0 | 35 | 0 | 76 |
| | | Heptageniidae | *Electrogena* sp | 0 | 0 | 0 | 4 | 0 | 0 |
| | | Ephemerellidae | *Ephemerella* sp | 0 | 0 | 0 | 4 | 0 | 76 |
| | Ephemeroptera | Perlidae | *Perla* sp | 0 | 0 | 0 | 4 | 0 | 21 |
| | | | *moicronecta* sp | 117 | 0 | 0 | 0 | 2 | 0 |
| | | Corixidae | *Cymatia* sp | 16 | 0 | 0 | 0 | 0 | 0 |
| | | | *Rhagovelia* sp | 3 | 0 | 0 | 1 | 0 | 13 |
| | | Veliidae | *Microvelia* sp | 2 | 0 | 2 | 0 | 0 | 9 |
| | Hemiptera | Naucoridae | *Naucoris* sp | 0 | 0 | 0 | 0 | 1 | 1 |
| | | | *Smicridea* sp | 0 | 0 | 0 | 0 | 0 | 6 |
| | | Hydropsychidae | *Hydropsyche* sp | 0 | 0 | 5 | 0 | 0 | 0 |
| | | Philopotamidae | *Philopotamus* sp | 0 | 0 | 16 | 0 | 0 | 0 |
| | | | *Cernotina* sp | 0 | 0 | 17 | 0 | 0 | 0 |
| | | Polycentropodidae | *Neureclipsis* sp | 0 | 0 | 9 | 0 | 0 | 0 |
| | Tricoptera | Hydroptillidae | *Hydroptilia* sp | 2 | 0 | 3 | 0 | 0 | 0 |
| | | Coenagrionidae | *Ischnura* sp | 0 | 0 | 0 | 4 | 2 | 0 |
| | Odonata | Aeshnidae | *Aeshna* sp | 0 | 0 | 0 | 4 | 1 | 0 |
| | Hymenoptera | Formicidae | | 0 | 0 | 0 | 2 | 0 | 0 |
| | Orthoptera | Blattidae | *Panesthia* sp | 0 | 0 | 2 | 0 | 0 | 6 |
| | Lepidoptera | Crambidae | *Paraponyx* sp | 0 | 0 | 2 | 2 | 1 | 0 |
| **Total number of individuals** | | | | **990** | **19** | **745** | **538** | **229** | **1123** |
| **Total number of taxa** | | | | **27** | **2** | **27** | **28** | **24** | **29** |
| **Number of stygobite taxa** | | | | **2** | **0** | **0** | **0** | **01** | **0** |

*indicates stygobite organisms

**Table XXIV:** Principal taxa of groundwater invertebrates collected in Ekona/Mautu during the study period.

| Class | Order | Family | Genus/sub family | MS4 | MS5 | ES6 | ES7 |
|---|---|---|---|---|---|---|---|
| Arachnida | Acarina | Tetragnathidae | *Tetragnatha* sp | 0 | 56 | 0 | 0 |
| | | Limnesiidae | *Limnesia* sp | 310 | 200 | 571 | 109 |
| | | Ceratozetidae | | 33 | 0 | 0 | 0 |
| | | Hypochthoniidae | *Hypochthonius* sp | 23 | 2 | 0 | 0 |
| | Araneae | Pisauridae | Thalassius | 6 | 3 | 0 | 1 |
| | | Argyronetidae | Argyroneta sp | 2 | 1 | 0 | 0 |
| | | Thomisidae | *Thomisus* sp | 28 | 0 | 0 | 0 |
| Oligochaeta | Oligochaeta | Lumbriculicidae | *Lumbriculus* sp | 0 | 1 | 3 | 4 |
| Gastropoda | | Planorbidae | *Planorbarius* sp | 0 | 5 | 0 | 0 |
| | | | *Lobogenes* sp | 0 | 0 | 1 | 0 |
| | | Hydrobiidae | *Potamopyrgus* sp | 0 | 2 | 2 | 0 |
| Malacostraca | Decapoda | Atyidae | *Caridina* sp | 25 | 1 | 203 | 5 |
| | | Potamonautidae | *Potamonautes* sp | 3 | 0 | 15 | 0 |
| Isopoda | Isopoda | Asellidae | **Proasellus* sp | 0 | 2 | 1 | 0 |
| Ostracoda | Podocopida | Cytheridae | | 0 | 0 | 7 | 9 |
| | | Cypridae | Psychrodromus | 11 | 0 | 0 | 188 |
| Copepoda | Cyclopoida | Cyclopidae | *Cyclops* sp | 0 | 0 | 15 | 7 |
| Nematoda | Gordoida | Gordiacea | *Gordius* sp | 0 | 1 | 0 | 7 |
| Insecta | Diptera | Culicidae | *Culex* sp | 1 | 0 | 0 | 0 |
| | | Chironomidae | *Chironomus* sp | 0 | 0 | 0 | 7 |
| | | Ceratopogonidae | Chironomini | 0 | 72 | 36 | 24 |
| | | | Ablabesmyia | 68 | 37 | 8 | 82 |
| | | | Dasyhelea | 6 | 0 | 0 | 0 |
| | | | Bezzia | 0 | 133 | 0 | 0 |
| | | | Forcipomyinae | 27 | 0 | 0 | 0 |
| | | | Leptoconopinae | 0 | 0 | 0 | 0 |
| | | Psychodidae | *Pericoma* sp | 6 | 3 | 10 | 3 |
| | | | *Lutzomyia* sp | 16 | 0 | 0 | 0 |
| | | Simulidae | *Simulium* sp | 0 | 0 | 1 | 0 |
| | | Dolichopodidae | | 0 | 1 | 0 | 0 |
| | | Ephydidae | Scatella | 18 | 0 | 0 | 0 |
| | | Tipulidae | *Tipula* sp | 0 | 0 | 8 | 9 |
| | Coleoptera | Dysticidae | Copelatus | 2 | 0 | 0 | 0 |
| | | Hydrophylidae | *Hydrophilus* sp | 0 | 1 | 0 | 0 |
| | | Psephenidae | *Laccobius* sp | 0 | 0 | 4 | 0 |
| | | | *Eubrianax* sp | 0 | 0 | 4 | 0 |
| | | Elmidae | *Macrelmis* sp | 5 | 0 | 8 | 8 |
| | | | *Neoelmis* sp | 2 | 0 | 13 | 6 |
| | | | *Elmis* sp | 0 | 0 | 9 | 0 |
| | | | *Hydrovatus* sp | 0 | 0 | 0 | 0 |
| | Ephemeroptera | Caenidae | *Caenis* sp | 2 | 3 | 33 | 4 |
| | | Baetidae | *Baetis* sp | 94 | 3 | 0 | 1 |
| | | Leptophlebidae | Paraleptophlebia | 38 | 0 | 0 | 0 |
| | | | Leptophlebia | 0 | 0 | 4 | 0 |
| | | Heptageniidae | Ecdyonurus | 12 | 0 | 19 | 7 |
| | | | Epeorus | 4 | 0 | 0 | 5 |
| | | Ephemerellidae | *Ephemerella* sp | 2 | 0 | 0 | 0 |
| | Hemiptera | Corixidae | Moicronecta | 0 | 0 | 40 | 0 |
| | | Veliidae | *Rhagovelia* sp | 0 | 1 | 3 | 0 |
| | | Naucoridae | *Microvelia* sp | 0 | 3 | 6 | 0 |
| | | | *Naucoris* sp | 0 | 0 | 5 | 4 |
| | Tricoptera | Hydropsychidae | Smicridea | 0 | 0 | 13 | 0 |
| | | Hydroptillidae | *Hydropsyche* sp | 4 | 2 | 0 | 6 |
| | | | *Hydroptilia* sp | 1 | 4 | 11 | 9 |
| | Odonata | Coenagrionidae | Ischnura | 0 | 2 | 4 | 0 |
| | | | Enallagma | 7 | 0 | 0 | 4 |
| | | Aeshnidae | *Aeshna* sp | 1 | 3 | 1 | 7 |
| | Hymenoptera | Formicidae | | 2 | 0 | 0 | 0 |
| | Orthoptera | Blattidae | Panesthia | 0 | 0 | 0 | 1 |
| | Lepidoptera | Crambidae | Paraponyx | 0 | 4 | 0 | 0 |
| **Total number of individuals** | | | | **759** | **546** | **1058** | **517** |
| **Total number of taxa** | | | | **30** | **26** | **30** | **25** |
| **Number of stygobite taxa** | | | | 0 | 1 | 1 | 0 |

**Table XXV:** Principal taxa of groundwater invertebrates collected in Owe during the study period

| Class | Order | Family | Genus/sub family | OS1 | OS2 | OS3 |
|---|---|---|---|---|---|---|
| | | Tetragnathidae | *Tetragnatha* sp | 76 | 0 | 0 |
| | | Limnesiidae | *Limnesia* sp | 946 | 326 | 394 |
| | | Ceratozetidae | | 0 | 0 | 12 |
| | Acarina | Hypochthoniidae | *Hypochthonius* sp | 0 | 9 | 0 |
| | | Pisauridae | Thalassius | 0 | 0 | 3 |
| Arachnida | Araneae | Argyronetidae | *Argyroneta* sp | 0 | 2 | 3 |
| Hirudinea | Euhirudinea | Erpobdellidae | | 0 | 2 | 0 |
| Oligochaeta | Oligochaeta | Lumbriculicidae | *Lumbriculus* sp | 0 | 5 | 3 |
| | | Naaididae | *Dero* sp | 0 | 2 | 0 |
| | | Hydrobiidae | Lobogenes | 3 | 1 | 1 |
| | | | Potamopyrgus | 0 | 2 | 0 |
| | Gastropoda | | *Viviparus* sp | 2 | 5 | 0 |
| | | Isotomidae | Folsoma | 1 | 0 | 1 |
| Collembola | Entomorbryomorpha | Entomobryiidae | Orchesella | 2 | 0 | 0 |
| | | Atyidae | *Caridina* sp | 18 | 67 | 9 |
| Malacostraca | Decapoda | Potamonautidae | *Potamonautes* sp | 7 | 8 | 41 |
| | | Asellidae | **Proasellus* sp | 0 | 2 | 2 |
| Isopoda | Isopoda | Stenasellidae | **Metastenasellus* sp | 0 | 27 | 15 |
| | | Cytherididae | | 0 | 39 | 0 |
| Ostracoda | | Cypridididae | Psychrodromus | 9 | 5 | 0 |
| Copepoda | Podocopida | Cyclopidae | | 0 | 2 | 0 |
| Nematoda | Gordoida | Gordiacea | *Gordius* sp | 6 | 109 | 7 |
| | | Culicidae | *Culex* sp | 3 | 0 | 0 |
| | | Chironomidae | *Chironomus* sp | 1 | 0 | 0 |
| | | | Chironomini | 0 | 96 | 0 |
| | | | Ablabesmyia | 16 | 0 | 24 |
| | | Ceratopogonidae | Dasyhelea | 0 | 15 | 8 |
| | | | Bezzia | 0 | 10 | 0 |
| | | | Forcipomyinae | 0 | 0 | 1 |
| | | | Leptoconopinae | 0 | 3 | 0 |
| | | Psychodidae | Pericoma | 0 | 12 | 1 |
| | | | Lutzomyia | 1 | 2 | 4 |
| | | Dolichopodidae | | 0 | 15 | 2 |
| | | Ephydidae | Scatella | 0 | 22 | 0 |
| | Diptera | Tipulidae | *Tipula* sp | 4 | 0 | 5 |
| | | Dysticidae | Copelatus | 2 | 17 | 0 |
| | | | *Hydrovatus* sp | 0 | 6 | 0 |
| | | Hydrophylidae | *Hydrophilus* sp | 0 | 4 | 0 |
| | | Psephenidae | *Eubrianax* sp | 0 | 0 | 12 |
| | | Elmidae | Macrelmis | 12 | 51 | 16 |
| | | | Limnius | 2 | 10 | 0 |
| | | | Neoelmis | 0 | 1 | 3 |
| | | | Elmis | 6 | 371 | 2 |
| | Coleoptera | | Hydrovatus | 0 | 6 | 0 |
| | | Caenidae | *Caenis* sp | 0 | 14 | 2 |
| | | Baetidae | *Baetis* sp | 7 | 435 | 6 |
| Insecta | Ephemeroptera | Leptophlebidae | Paraleptophlebia | 0 | 31 | 0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | Heptageniidae | *Ecdyonurus* sp | 18 | 0 | 23 |
| | | | *Epeorus* sp | 39 | 5 | 12 |
| | | | *Electrogena* sp | 0 | 104 | 0 |
| | | Ephemerellidae | *Ephemerella* sp | 0 | 19 | 0 |
| | | Perlidae | *Perla* sp | 5 | 0 | 1 |
| | | Corixidae | *Moicronecta* sp | 0 | 33 | 0 |
| | Hemiptera | Naucoridae | *Naucoris* sp | 0 | 0 | 5 |
| | | Hydropsychidae | *Hydropsyche* sp | 5 | 0 | 0 |
| | Tricoptera | Hydroptillidae | *Hydroptilia* sp | 1 | 7 | 0 |
| | | | *Enallagma* sp | 7 | 15 | 0 |
| | Odonata | Aeshnidae | *Aeshna* sp | 4 | 0 | 0 |
| | Lepidoptera | Crambidae | Paraponyx | 0 | 0 | 2 |
| **Total number of individuals** | | | | **1203** | **1917** | **620** |
| **Total number of taxa** | | | | **27** | **42** | **30** |
| **Nunber of stygobite taxa** | | | | 0 | 2 | 2 |

### III.1.3.3. Diversity index and equitability

The diversity index of Shannon and Weaver (H) and the equitability index of Pielou (J) for all the sampling stations are represented on figure 58. The index of Shannon and Weaver varied from one season to the other and the results showed that the different sampling points were diversified. Generally, the rainy season showed more diversity than the dry season during the study period. During the dry season, the index of Shannon and Weaver varied in Muyuka from 0.48 in station TW3 to 1.81 in station TW8 (Figure 58 A1) while in the rainy season, the Shannon index varied from 0.49 in TW6 to 1.65 in TW8 (Figure 58 A2). The results showed that, the rainy season was more diversified than the dry season in the town of Tiko but the most diversified station was TW8 in the dry season. The equitability index indicated that, the sampling points in Tiko were more equally distributed in the dry season than in the rainy season. The sampling points showing low values of Equitability index in the dry season are; TW3 (J = 0.30) and TW10 (J = 0.31) while those that are highly equally distributed are TW7 (J = 0.64) and TW8 (J = 0.66) (Figure 58 A1). In the rainy season, Equitability index varied from 0.08 in TW6 to 0.96 in TW10 (Figure 58 A2).

In Buea during the dry season, the most diversified stations as shown by the Shannon index (H) were BS11 (H = 2.97) and BS13 (H = 1.98) while the least diversified stations were BS9 (H = 0) and BS8 (H = 0.86) (Figure 62 B1). In the rainy season, the most diversified stations were BS13 (H = 2.22), BS11 (H = 1.92) and BS10 (H = 1.77) while the least diversified was BS9 (H = 0.59) (Figure 58 B1). The rainy season was more diversified than the dry season in the town on Buea. The values of equitability index were higher in the rainy season than in

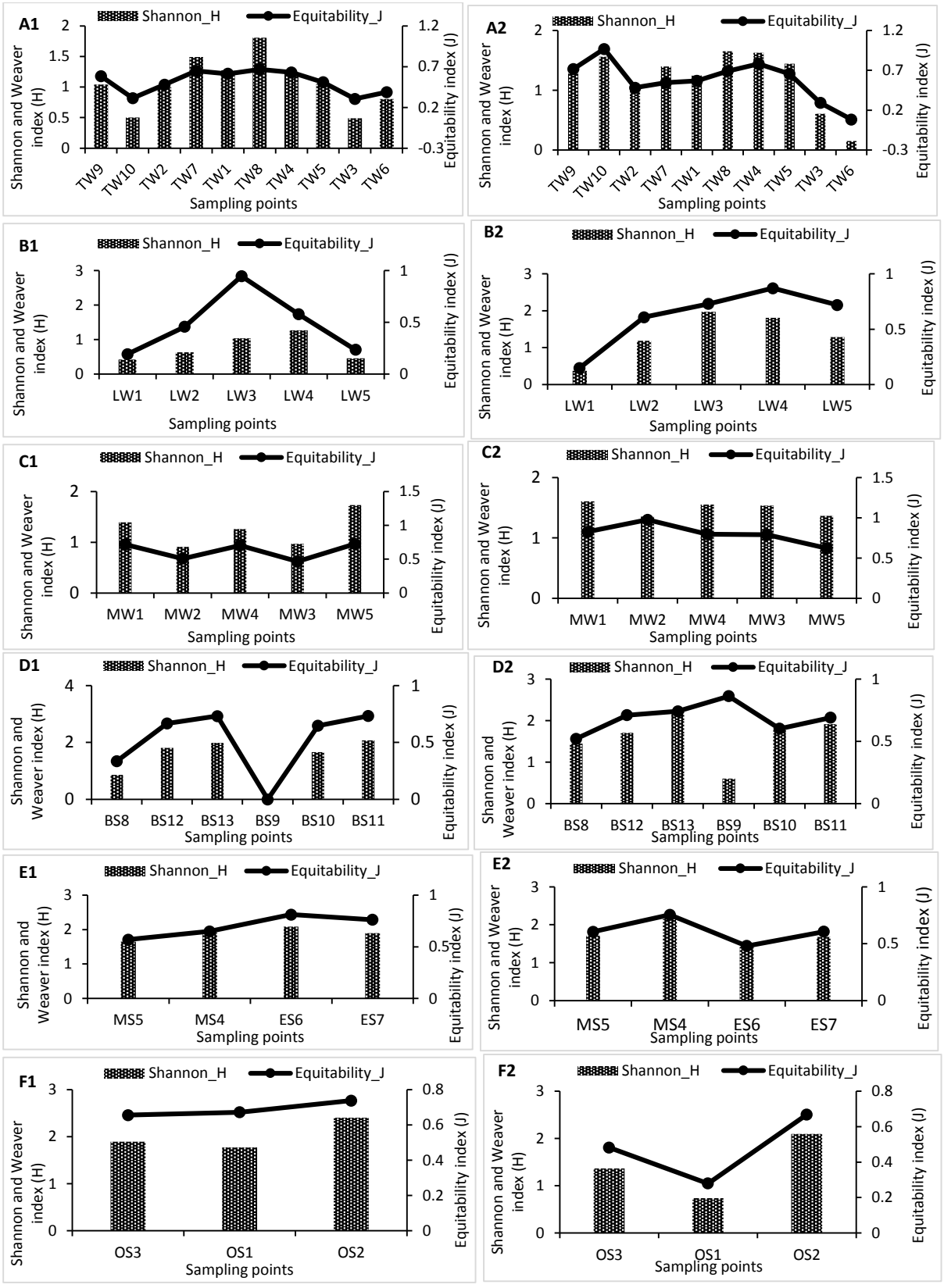



**Figure 58:** Seasonal variation of the indices of Shannon (H) and Equitability (J) in the different sampling towns in Fako division with sampling points arranged in order of increasing altitude.

A1=Dry season in Tiko, A2= Rainy season in Tiko, B1=Dry season in Limbe, B2 = Rainy season in Limbe, C1= Dry season in Muyuka, C2 = Rainy season in Muyuka, D1=Dry season in Buea, D2 = Rainy season in Buea, E1 = Dry season in Ekona/Mautu, E2 = Rainy season in Ekona/Mautu, F1= Dry season in Owe, F2 = =Rainy season in Owe.

the dry season (Figure 58 B) and the least value was obtained in BS9 (J = 0) followed by BS8 (J = 0.33) while the highest values were $J^1$=0.73 obtained in BS11 and BS13. In the rainy season, the least value was 0.52 (BS8) and the highest value was 0.86 (BS9) (Figure 58 B2). The low diversity obtained in BS9 could be due to very small amount of water and the slow water current which is incapable of carrying organisms to the pipes.

In Limbe, the most diversified station in the dry season was LW4 (H = 1.27), followed by LW3 (H = 1.04) and the least diversified station was LW1 (H = 0.42). As for equitability, the station that was more equally distributed was LW3 (J = 0.94) and the least was LW1, with a value of 0.19 (Figure 58 C1). During the rainy season, the sampling point that showed poor values of equitability index was LW1 (0.15) while the most equitable station was LW4 (0.86). The most diversified station was LW3 with a value of 1.97 while the least diversified station was LW1, with a value of 0.37 (Figure 58 C2).

Groundwater fauna was relatively highly diversified in Muyuka and more equally repartitioned in the dry season than in the rainy season. The sampling point MW5 (H=1.74) was the most diversified, followed by MW1 (H=1.39) and the least diversified station was MW2 (0.91) during the dry season. For equitability, MW3 was less equitable (0.46) and the most equitable station was MW5 with a value of 0.72 (Figure 58 D1). In the rainy season, station MW5 was the least equitable (0.62) and the most equitable station was MW2 (0.97). The most diversified station was MW1 (1.61) and the least was MW2 (1.35) (Figure 58 D2).

The diversity index of Shannon and Weaver in the town of Ekona/Mautu showed that aquatic fauna was diversified in both the rainy and dry season with all values greater than H = 1.6 except for ES6 that had a value of H = 1.41. In the dry season, the most diversified station was ES6, with a value of 2.08 while the least diversified sampling point was MS5, with a value of 1.65. The highest value of equitability was obtained in ES6 and the value was J = 0.81 (Figure 58 E1). In the rainy season, the most diversified sampling point was MS4 (2.17) while the least diversified station was ES6. The highest value of equitability was 0.75, obtained in MS4 while the least equitable station was ES6, having a value of 0.48 (Figure 58 E2).

In the town of Owe, the diversity of subterranean fauna varied from 2.403 as highest value obtained in station OS2 to 0.67, obtained in station OS1 which was the lowest value in the dry season while equitability varied from 0.65 in OS3 to 0.73 in OS2 (Figure 58 F1). In the dry season, the diversity varied from 0.73 in OS1 to 2.09 in OS2 while equitability values varied from 0.28 in OS1 to 0.66 in OS2 (Figure 58 F2). The number of organisms were relatively higher in the rainy season (11998 organisms) than in the dry season (9015 organisms) and the

diversity index of Shannon and Weaver showed that, the rainy season was more diversified than the dry season. The repartition of organisms and taxa during the rainy season is more equitable than in the dry season as seen from the results obtained for the equitability index.

### III.1.4. Multivariate analyses for biotic and abiotic factors during the sampling period

#### III.1.4.1. In Tiko

In order to characterize the effect of physicochemical parameters on biodiversity, an Agglomerative Hierarchy Clustering (AHC) was plotted which permitted the obtention of a three-class hierarchy of the sampling points from right to left in the town of Tiko. Class I was made up of the stations TW6, TW4, TW3, TW10 and TW9 which had a dissimilarity with class II at 80 %. Class II constituted of a single station (TW7) which joined to class III at 85 % of dissimilarity and was made up of TW5, TW2, TW1 and TW8 (Figure 59).

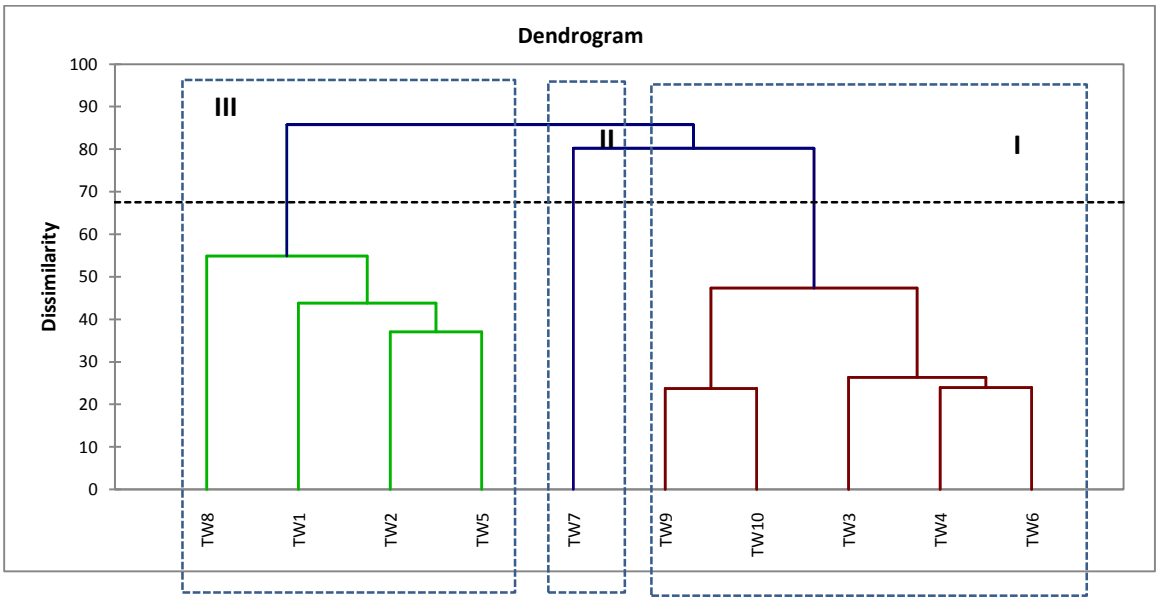



**Figure 59:** Agglomerative Hierarchical Clustering (AHC) for biodiversity and physicochemical parameter during the sampling period in Tiko.

The PCA to characterise the taxa collected during the study period in Tiko projected with the sampling points (Figure 60) gave two principal classes with a total contribution of 45.02 %. Figure 60 A shows that, the F1 axis discriminated the sampling points TW1, TW5 and TW2 positively and significantly in group I while the F1 axis discriminated negatively and significantly the sampling points TW3, TW4 and TW9 in group II. The F2 axis discriminated positively the sampling points TW6 and TW10 in group II.

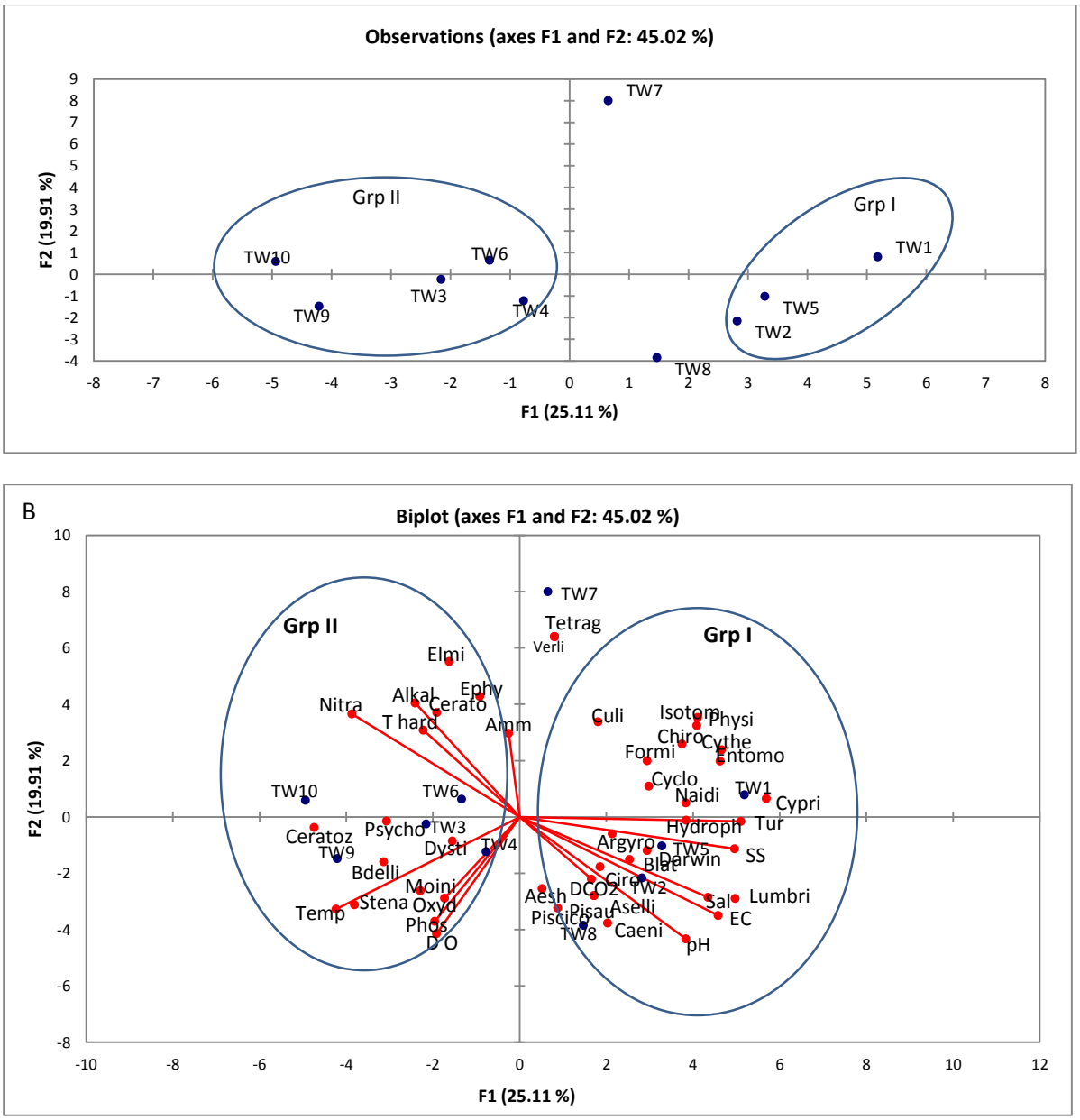



**Figure 60:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Tiko, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

Legend: Elmi=Elmidae, Baeti=Baetidae, Lepto=Leptoplebiidae, Hepta=Heptageniidae, Limne=Limnesiidae, Atyi=Atyidae, Gordia=Gordiaces, Chiro=Chironomidae, Dolicho=Dolichopodidae, Hydrop=Hydroptillidae, Perli=Perlidae, Cypri=Cyprididae, Psycho= Psychodidae, Simul= Simulidae, Naidi= Naididae, Cyclo= Cyclopidae, Entomo =Entomobryiidae, Cerat =Ceratozetidae, Bdelli=Bdellidae, Pisau =Pisauridae, Piscico=Piscicolidae, Erpob =Erpobdellidae , Hydrob=Hydrobiidae, Physi=Physidae, Isotom=Isotomidae, Potamon=Potomonautidae, Aselli=Asellidae, Darwin=Darwinulidae, Moini = Moinidae, Culi= Culicidae, Cerato=Ceratopogonidae, Ephy =Ephydidae, Tipul=Tipulidae, Psephe=Psephenidae, Epheme =Ephemerellidae, Corix =Corixidae, Velii=Verlidae, Nauco =Naucoridae, Hydrobs =Hydropsychidae, Polycen =Polycentropodidae, Coenag =Coenagrionidae, Aesh =Aeshnidae, Formi=Formicidae, Cram=Crambidae, Argyro=Argyronetidae, Thomi =Thomisidae, Stena=Stenasellidae, Ciro =Cirolanidae, Tetrag=

Tetragnathidae, Hypoch =Hypochthoniidae, Lumbri= Lumbriculidae, Planorb =Planorbidae, Cythe= Cytheridiidae, Dysti=Dysticidae ,Hydroph=Hydrophylidae, Caeni =Caenidae, Philop=Philopotamidae, Blat=Blattidae, Erpob=Erpobdellidae, ceratoz= Ceratozetidae.

Projecting the physicochemical parameters in function of the biodiversity collected gave two groups: I and II as seen on figure 60 B. From the plot, it was observed in group I that, pH, SS, dissolved carbon dioxide, EC, turbidity and salinity influenced the distribution of a total of 22 taxa. These taxa were Cypridiidae, Simulidae, Asellidae, Lumbriculidae, Argyronetidae, Hydrophylidae, Caenidae, Cyclopidae, Isotomidae, Pisauridae, Cirolanidae, Darwinulidae, Naididae, Culicidae, Formicidae, Blattidae, Chironomidae, Cytheridiidae, Eатomobryiidae, Piscicolidae, Physidae, and Aeshnidae. Group II showed that, oxidability, dissolved oxygen, phosphate ions, temperature, ammonium ions, nitrate ions, total hardness and alkalinity influenced the distribution of nine taxa which were: Moinidae, Stenasellidae, Dysticidae, Bdellidae, Ceratopogonidae, Elmidae, Ceratozetidae, Psychodidae, Ephydidae (Figure 60 B).

### III.1.4.2. In Buea

The effect of physicochemical parameters on biodiversity was characterised in the town of Buea with the help of an AHC which permitted the obtention of a three-class hierarchy of the sampling points from right to left in the town of Buea at 72 % dissimilarity. Class I englobed stations BS11 and BS110, class two englobed just BS13 and class 3 regrouped BS12, BS9 and BS8. Class I was joined to class II at 79 % and class II joined class III at 82 % (Figure 61).

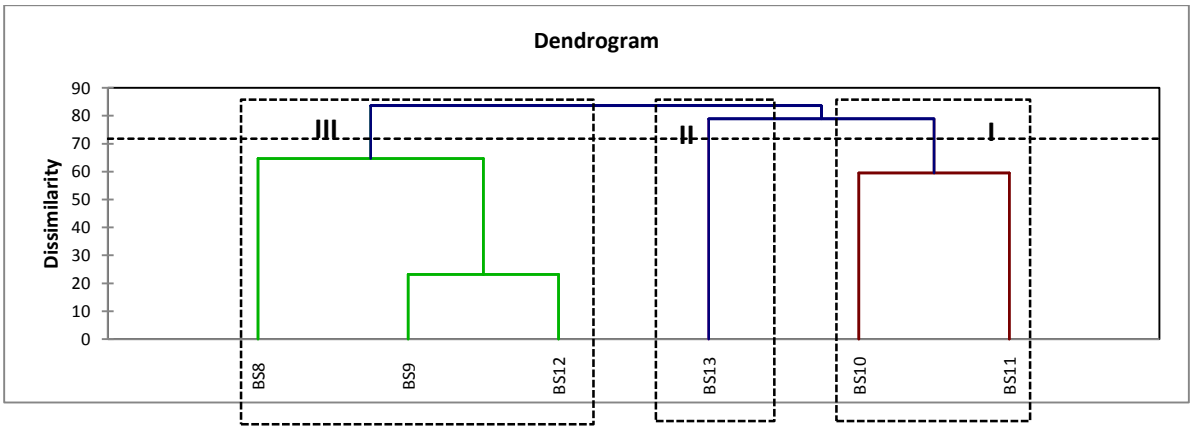



**Figure 61:** Agglomerative Hierarchical Clustering for biodiversity and physicochemical parameter during the sampling period in Buea.

The PCA to characterise the taxa collected during the study period in Buea projected with the sampling points gave two principal classes with a total contribution of 55.94 % (F1 = 31.62 %, F2 = 24.32 %). The F1 axis discriminated the sampling points BS13 and BS11

positively and significantly in group I and also discriminated positively sampling point BS10. The F2 axis discriminated positively the stations BS9 and BS12 in group II (Figure 62 A).

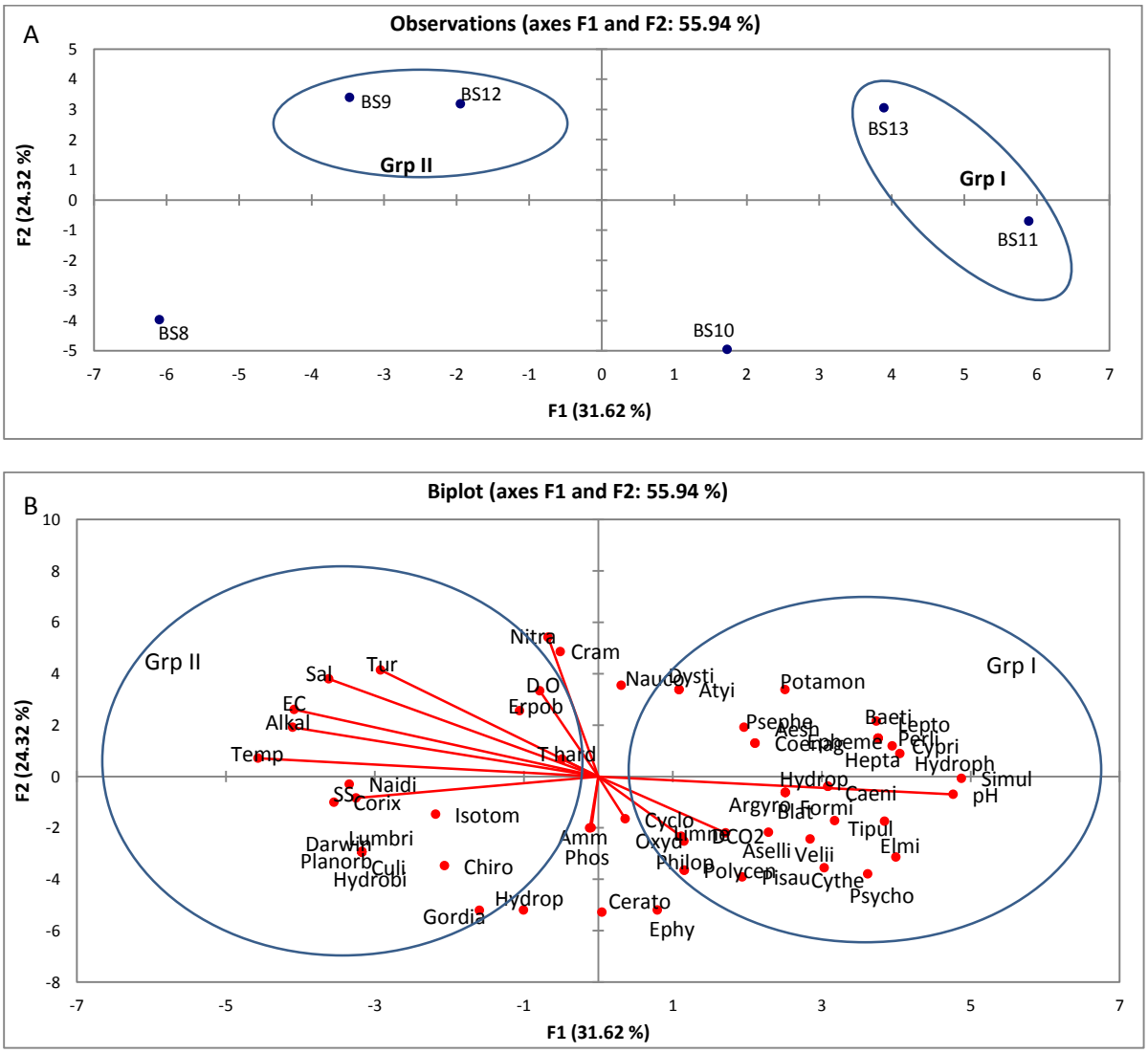



**Figure 62:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Buea, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

When the physicochemical parameters were projected in function of the taxa collected, two group were obtained which were groups I and II (Figure 62 B), whereby in group I, dissolved carbon dioxide, pH and oxidability influenced the distribution of a total of 32 taxa in stations BS10, BS13 and BS11. These taxa were Cyprididae, Simulidae, Asellidae, Argyronetidae, Hydrophylidae, Caenidae, Cyclopidae, Formicidae, Blattidae, Cytheridídae, Aeshnidae, Dysticidae, Elmidae, Baetidae, Heptageniidae, Atyidae, Potomonautidae, Psephenidae, Leptoplebiidae, Ephemerellidae, Coenagrionidae, Naucoridae, Pisauridae,

Polycentropodidae, Veliidae, Hydroptillidae, Perlidae, Tipulidae, Hydropsychidae, Philopotamidae, Psychodidae and Limnesiidae. Group II showed that, dissolved oxygen, phosphate ions, temperature, ammonium ions, nitrate ions, total hardness, EC, salinity, turbidity, SS and alkalinity influenced the distribution of 11 taxa which were: Gordiacea, Planorbidae, Erpobdellidae, Chironomidae, Hydrobiidae, Naididae, Corixidae, Isotomidae, Lumbriculicidae, Culicidae and Darwinulidae which were highly distributed in BS12 and BS9 and BS8.

### III.1.4.3. In Limbe

The characterization of the effect of physicochemical parameters on biodiversity on an AHC permitted the obtention of a three-class hierarchy of the sampling points from right to left in the town of Limbe at a 30 % dissimilarity. Class I regrouped stations LW1 and LW2 which joined to group II at 41% and this group met with group III at 49 %. Group II englobed LW5 and LW4 while group III had LW3 only (Figure 63).

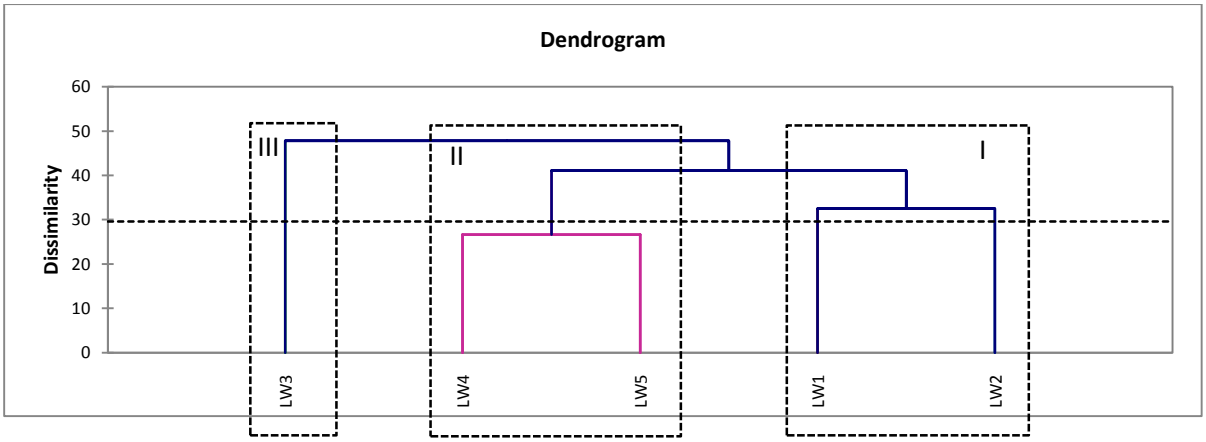



**Figure 63:** Agglomerative Hierarchical Clustering for biodiversity and physicochemical parameter during the sampling period in Limbe.

The PCA to characterise the effect of physicochemical parameter on the taxa collected during the study period in Limbe projected with the sampling points gave two principal groups with a total contribution of 65.87 % (F1 =35.49 % and F2=30.38 %). Group I was made up of LW3 and LW4 while group II was made up of LW1, LW2 an d LW5. The F1 axis discriminated the sampling points LW3 positively and significantly while it negatively and significantly discriminated the sampling point LW5. The F2 axis discriminated positively and significantly the sampling point LW1 and negatively and significantly discriminated LW4 (Figure 64 A).

Projecting the physicochemical parameters in function of the different taxa collected in a PCA gave three groups: I and II and III. The 10 taxa present in group I were influenced by the following physicochemical parameters: turbidity, total hardness, SS and ammonium ions,

which affected their distribution. These taxa were Cyclopidae, Dysticidae, Ceratopogonidae, Hydrophylidae, Pisauridae Entomobryiidae, Lumbriculidae, Tetragnathidae, Coenagrionidae and Chironomidae. Dissolved carbon dioxide, EC, salinity, dissolved oxygen, pH, oxidability and alkalinity in group II influenced the distribution of eight taxa: Cyprididae, Isotomidae, Darwinulidae, Physidae, Naididae, Cytherididae, Stenasellidae and Cirolanidae. Group III constituted of four taxa (Culicidae, Elmidae, Formicidae and Planorbidae), which were influenced by nitrate ions, phosphate ions and temperature in stations LW4 and LW5 (Figure 64 B).

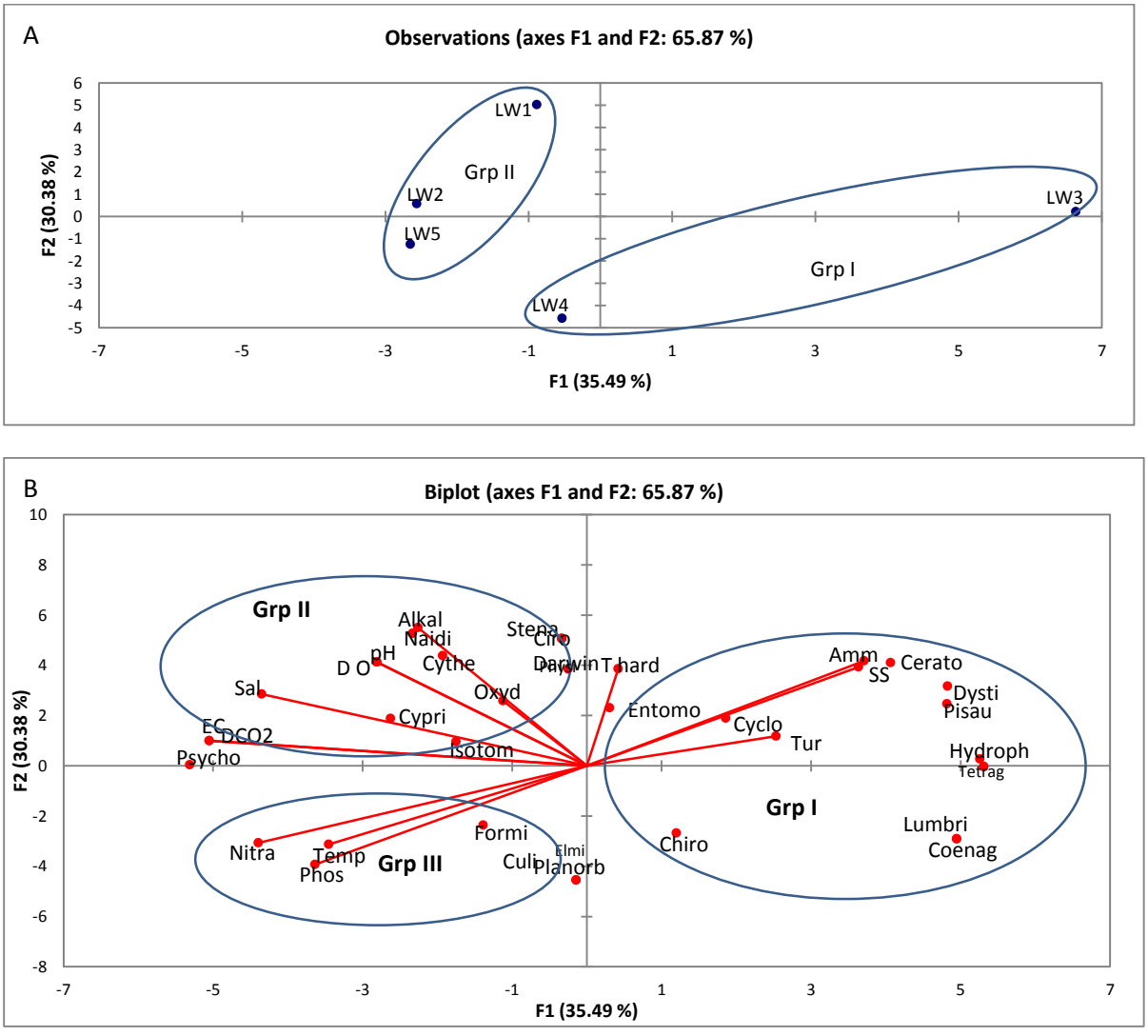



**Figure 64:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Limbe, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.4.4. In Muyuka

The characterization of the effect of physicochemical parameters on biodiversity on an AHC that was plotted permitted the obtention of a two-class hierarchy of the sampling points from right to left in the town of Tiko at 48 % of dissimilarity. Class I was made up of the stations MW2, MW1 and MW4 which had a dissimilarity with class II at 45 % and class II constituted of stations MW3 and MW5 (Figure 65).

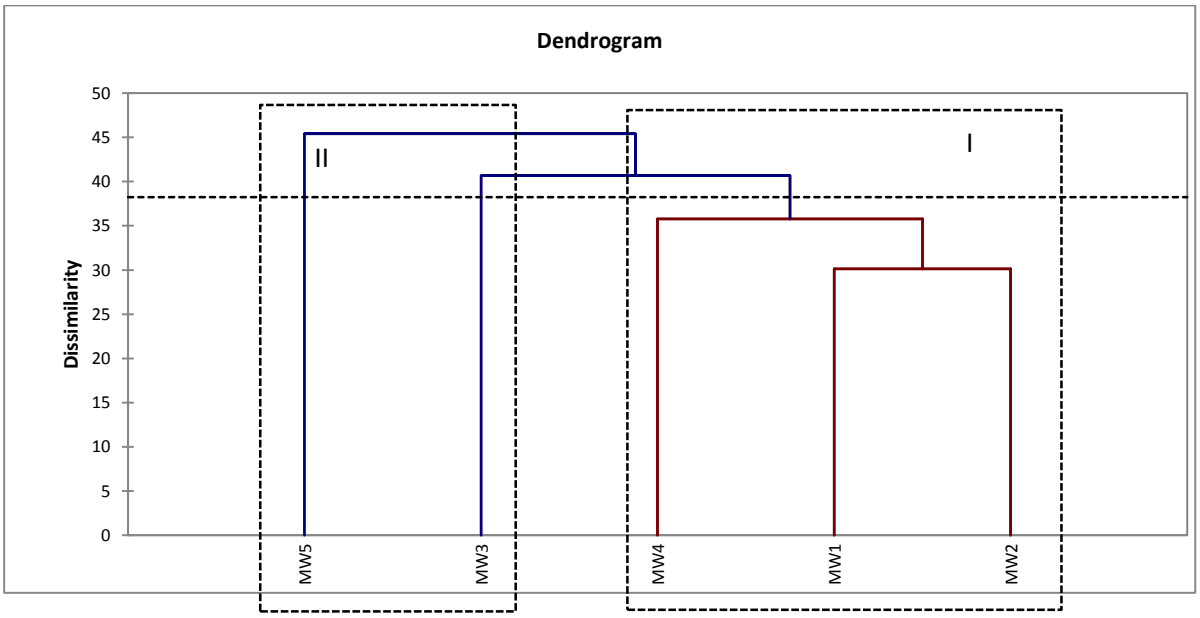



**Figure 65:** Agglomerative Hierarchical Clustering (AHC) for biodiversity and physicochemical parameter during the sampling period in Muyuka.

The PCA to characterise the effect of physicochemical parameter on the biodiversity taxa collected during the study period in Muyuka projected with the sampling points gave two principal groups I and II. Group I constituted of stations MW4 and MW5 whereby, the F1 axis discriminated positively these sampling stations. Group II was made up of MW1, MW2 and MW3 where the F1 axis discriminated negatively MW3 and F2 axis discriminated positively MW1 and MW2 in this group (Figure 66 A).

Projecting the physicochemical parameters in function of the taxa collected in a PCA gave two groups: I and II with a contribution of 58.91 % of the total variance (F1 =32.71 % and F2=26.20 %). The taxa present in group I were influenced by the following physicochemical parameters: pH, turbidity, ammonium ions and SS which affected the distribution of 14 taxa. These taxa were Naididae, Stenasellidae, Isotomidae, Ceratozetidae, Coenagrionidae, Psychodidae, Cyprididae, Darwinulidae, Entomobryiidae, Blattidae, Asellidae, Formicidae, Culicidae and Pisauridae (Figure 66 B). In group two, five taxa were present, which were influenced by temperature, oxidability, alkalinity, nitrate ions, salinity,

dissolved oxygen and total hardness. These organisms were Bdellidae, Piscicolidae, Gordiacea, Chironomidae and Lumbriculidae.

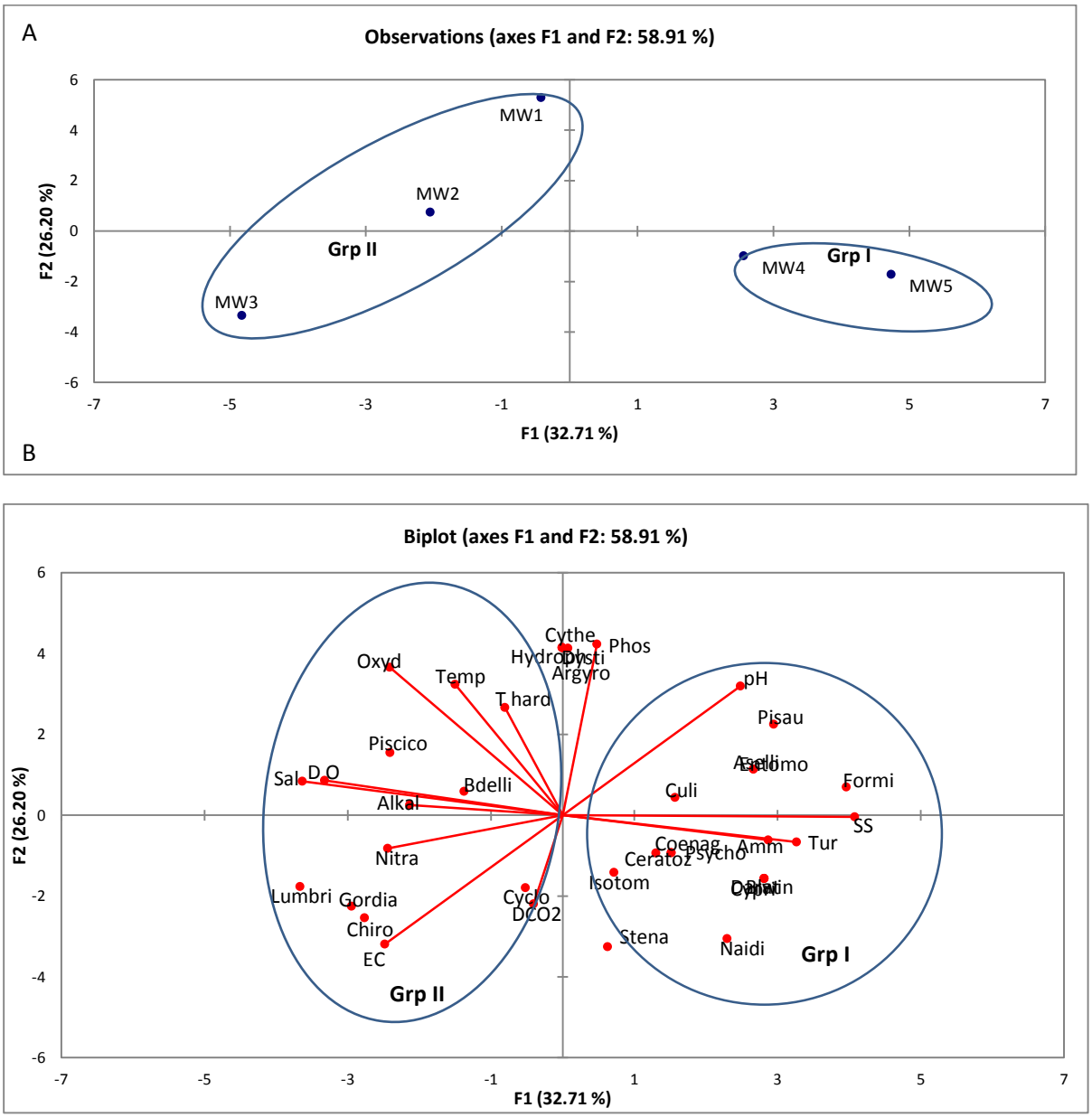



**Figure 66:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Muyuka, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.4.5. In Ekona/Mautu

In order to characterize the effect of physicochemical parameters on biodiversity, an AHC was plotted which permitted the obtention of a two-class hierarchy of the sampling points from right to left in the town of Ekona/Mautu at 51 % of dissimilarity. Class I was regrouped

the stations MS5 and MS4 which had a dissimilarity with class II at 78 %. Class II constituted of ES7 and ES6 (Figure 67).

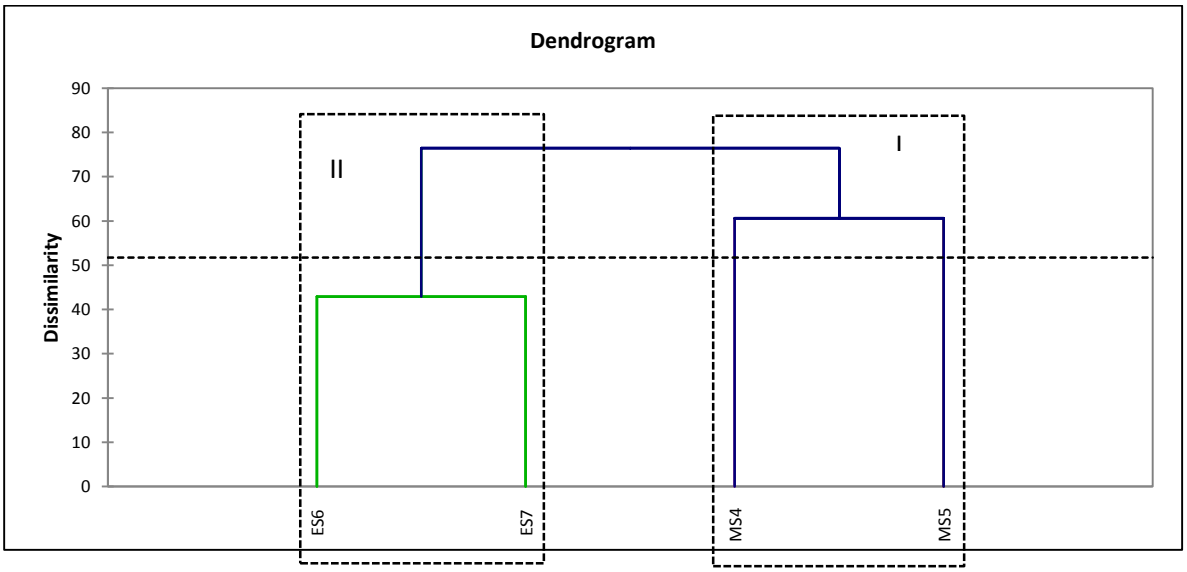



**Figure 67:** Agglomerative Hierarchical Clustering (AHC) for biodiversity and physicochemical parameter during the sampling period in Ekona/Mautu.

The PCA to characterise the different taxa collected during the study period in Ekona/Mautu projected with the sampling points gave two principal groups with a total contribution of 77.55 % (F1 = 44.19 and F2 = 33.36 %). The F1 axis discriminated the sampling points that were regrouped were MS4 and MS5 (Figure 68 A).

Projecting the physicochemical parameters in function of the organisms collected, two groups were obtained: I and II as seen on figure 72 B. From the plot, it was observed in group I that dissolved carbon dioxide and phosphate ions influenced the distribution of a total of 19 taxa. These organisms were Hydrobiidae, Hydrophylidae, Vellidae, Naucoridae, Lumbriculidae, Cytherididae, Cyclopidae, Simulidae, Atyidae, Heptageniidae, Hydroptillidae, Hydropsychidae, Elmidae, Psephenidae, Corixidae, Blattidae, Aeshnidae, Caenidae and Tipulidae. Group II showed that, oxidability, dissolved oxygen, pH, salinity, temperature, ammonium ions, nitrate ions, total hardness turbidity and alkalinity influenced the distribution of 21 taxa which were: Dolichopodidae, Tetragnathidae, Planorbidae, Asellidae, Baetidae, Pisauridae, Argyronetidae, Ceratozetidae, Cyprididae, Hypochthoniidae, Ephemerellidae, Formicidae, Dysticidae, Thomisidae, Ephydidae, Leptoplebiidae, Psychodidae, Culicidae, Coenagrionidae, Crambidae and Ceratopogonidae (Figure 68 B).

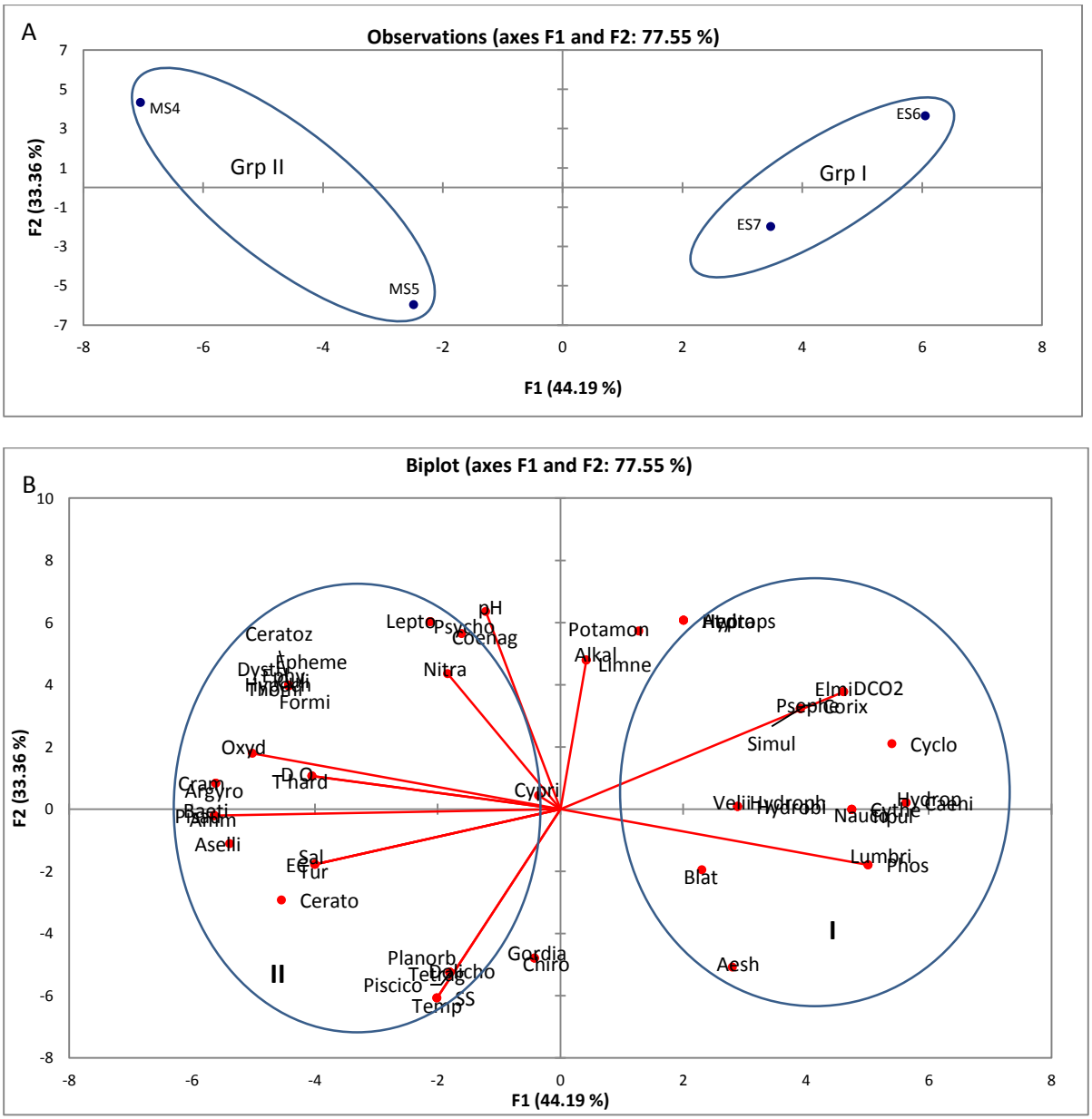



**Figure 68:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Ekona/Mautu, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.4.6. In Owe

The effect of physicochemical parameters on biodiversity was characterised in the town of Owe with the help of an AHC which permitted the obtention of a single class of the sampling points from right to left at 22 % of dissimilarity. The class constituted of the sampling points OS1 and OS3, which met with OS2 at 70 % which was alone (Figure 69).

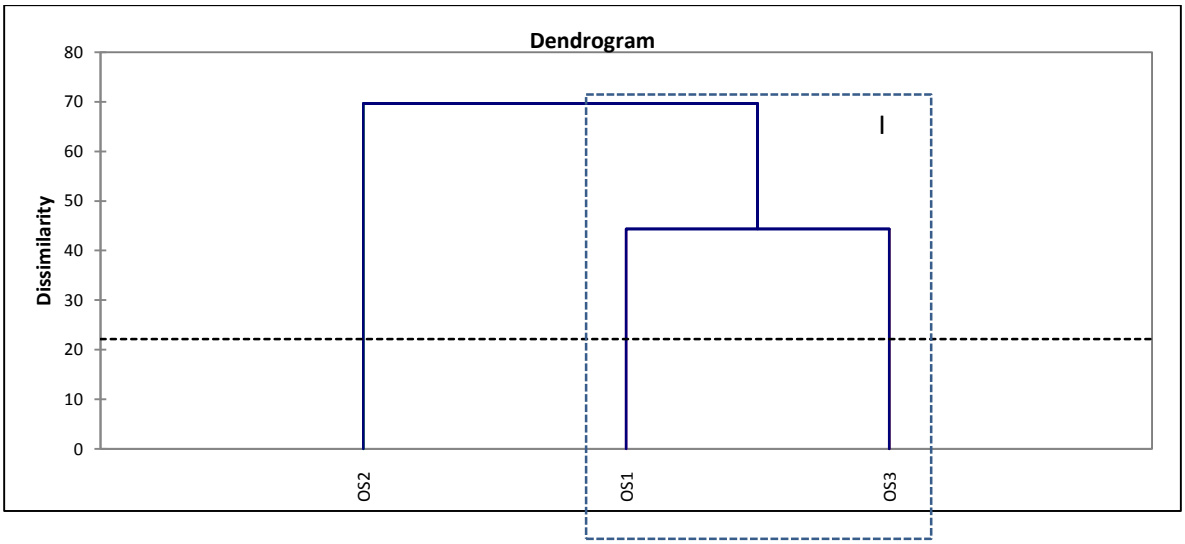



**Figure 69:** Agglomerative Hierarchical Clustering (AHC) for biodiversity and physicochemical parameter during the sampling period in Owe.

The PCA to characterise the taxa collected during the study period in Owe projected with the sampling points (Figure 70 A) gave a contribution of 98.28 % of the total variance (F1 = 57.89 % and F2 = 40.39 %). The F1 axis discriminated the sampling point OS2 positively and significantly while it discriminated negatively the sampling point OS3. The F2 axis discriminated positively the sampling point OS1. The only group was made up of OS1 and OS3 (Figure 70 A).

Projecting the physicochemical parameters in function of the taxa collected gave three groups: I, II and III. It was observed from the plot in group I that oxidability, dissolved oxygen and ammonium ions influenced the distribution of a total of 23 taxa. These taxa were Caenidae, Dolichopodidae, Chironomidae, Psychodidae, Ceratozetidae, Lumbriculidae, Naididae, Erpobdellidae, Ephydidae, Hypochthoniidae, Cyclopidae, Hydrophylidae, Ephemerellidae, Corixidae, Cytherididae, Leptoplebiidae, Hydroptillidae, Baetidae, Hydrobiidae, Atyidae, Elmidae, Heptageniidae and Dysticidae. Group II showed that, phosphate ions, dissolved carbon dioxide, EC and turbidity influenced the distribution of six taxa which were: Aeshnidae, Entomobryiidae, Hydropsychidae, Tetragnathidae, Limnesidae and Perlidae. It was observed in group III that, alkalinity, temperature, salinity, pH and total hardness influenced the distribution of 10 taxa which were: Stenasellidae, Potomonautidae, Gordiacea, Argyronetidae, Ceratopogonidae, Naucoridae, Psephenidae, Asellidae, Pisauridae and Tipulidae (Figure 70 B).

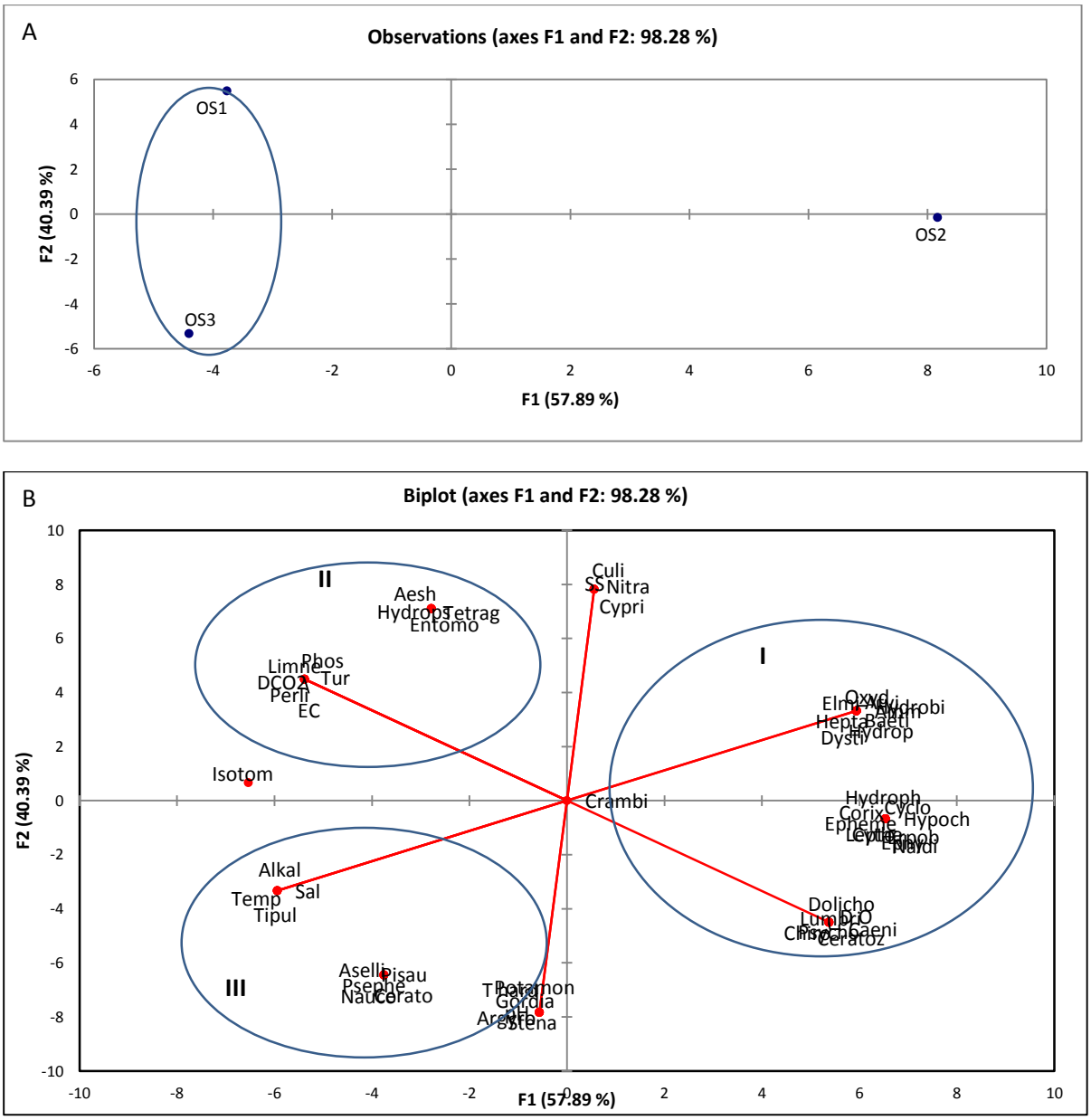



**Figure 70:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Owe, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.5. Effects of altitude on the distribution of organisms during the sampling period in Fako division

#### III.1.5.1. Repartition of sampling stations in function of altitude

The repartition of the sampling stations in function of altitude gave four groups as represented on figure 71. The figure shows four groups or classes, divided as follows; the first group regrouped sampling points whose altitude varied from 1 m to 200 m (LW1, LW2, LW3,

LW4, LW5, TW9, TW10, TW2, TW7, TW1, MW1, MW2, TW8, MW4, TW4, TW5, MW3, TW3, MW5, TW6, OS3, OS1 and OS2, MS4 and MS5), the second group was made up of sampling points with altitude ranging from 201 m to 500 m (ES7 and ES6), the third class regrouped sampling stations with altitude ranging from 501 m to 1000 m (BS8, BS9, BS12 and BS13) and the forth group constituted of stations whose altitude was greater than 1000 m (BS10 and BS11). It was observed that, the lowest altitudes were obtained in the town of Limbe, characterized by the presence of the Atlantic Ocean. The highest altitudes were obtained in the town of Buea, characterized by the presence of the highest mountain in West Africa; the mount Cameroon (Figure 71).

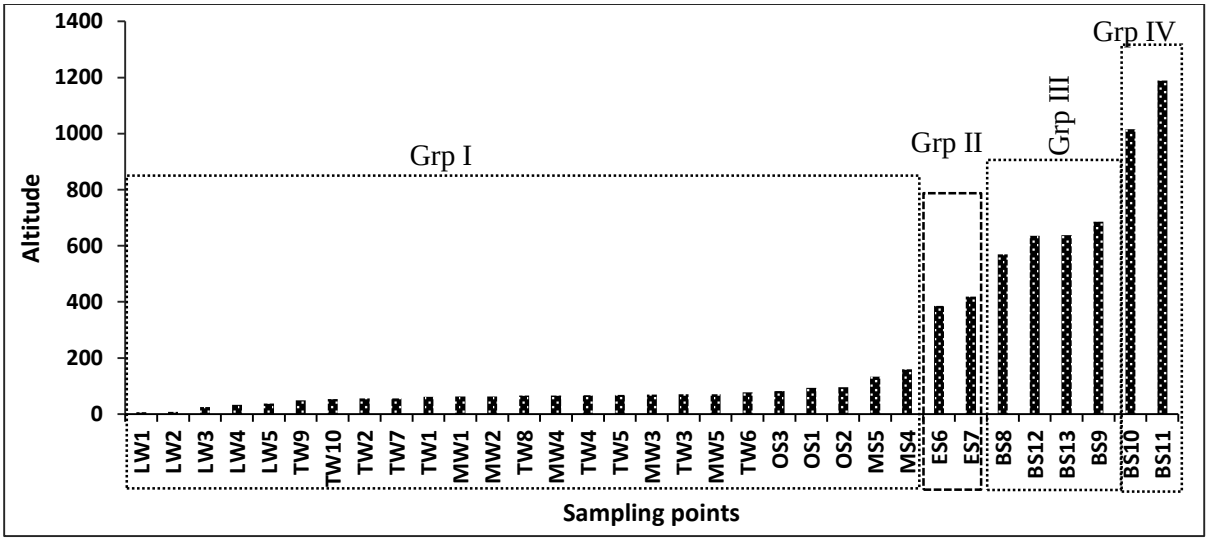



**Figure 71:** Representation of the altitudes of the different stations during the sampling period

The repartition of the wells in function of altitude gave four groups as represented on figure 72. The figure shows a clear demacation for the first two sampling points in Limbe which gives the first group, constituting of sampling points with altitude less than 10 m (LW1 and LW2). The second group regrouped three sampling points whose altitude varied from 25 m to 40 m (LW3, LW4, LW5). The third group was made up of four wells with altitude ranging from 41 to 60 m (TW9, TW10, TW2, TW7) and the fouth group englobed 11 wells with altitude ranging from 61 to 78 m (TW1, MW1, MW2, TW8, MW4, TW4, TW5, MW3, TW3, MW5, TW6 (Figure 72 A).

In the springs, four groups were obtained in function of altitude. The first group was made up of sampling points with altitude ranging from 82 to 140 and it constituted of five springs (OS3, OS1, OS2, MS4 and MS5). The second group was made up of sampling points with altitude ranging from 350 m to 420 m (ES7 and ES6), the third class regrouped sampling stations with altitude ranging from 550 m to 700 m and it was made up of four (BS8, BS12

BS13 and BS9) and the fourth group constituted of stations whose altitude was greater than 1000 m (BS10 and BS11) (Figure 72 B).

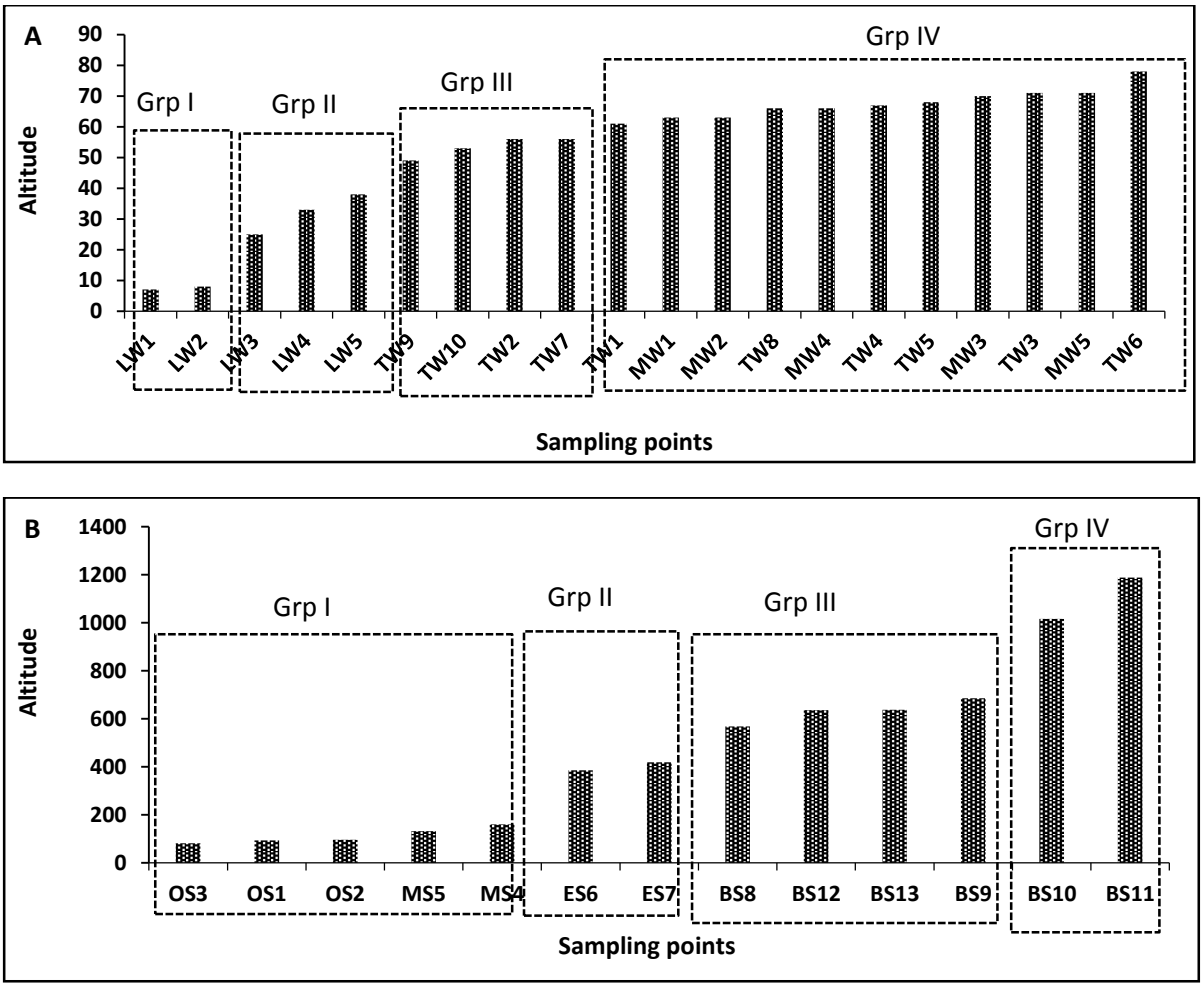



**Figure 72:** Representation of the altitudes in the wells (A) and oin the springs (B) during sampling period.

### III.1.5.2. Total number of individuals collected in function of altitude

Figure 73 shows the number of organisms as distributed in function of altitude. It was observed from the graph that; the highest number of organisms was collected from the group of sampling points with the lowest altitude (2820 inds in group I) more precisely in LW1 and the lowest number of organisms was also collected from this same group (65 inds) in MW1. Group IV had the least total number of organisms (1283), compared to the other groups and group I had the highest total number of organisms collected during the sampling period (15794 inds). It was also observed that, some sampling points with low altitudes had small number of organisms collected from them. This was the case of LW3 (85 inds), LW4 (75 inds), LW5 (199 inds), MW1 (65 inds), MW2 (142 inds), MW4 (94 inds), TW4 (120 inds), TW10 (161 inds) (Figure 73).

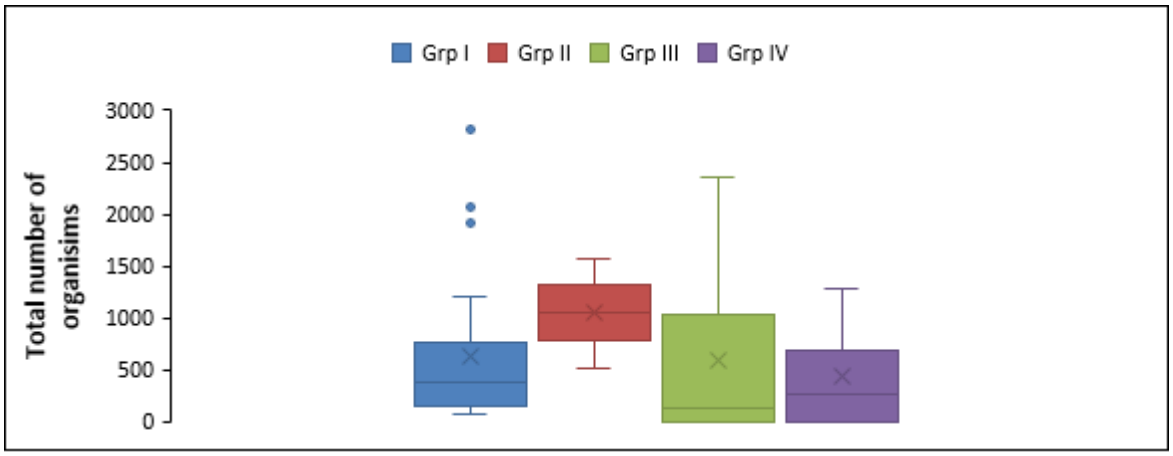
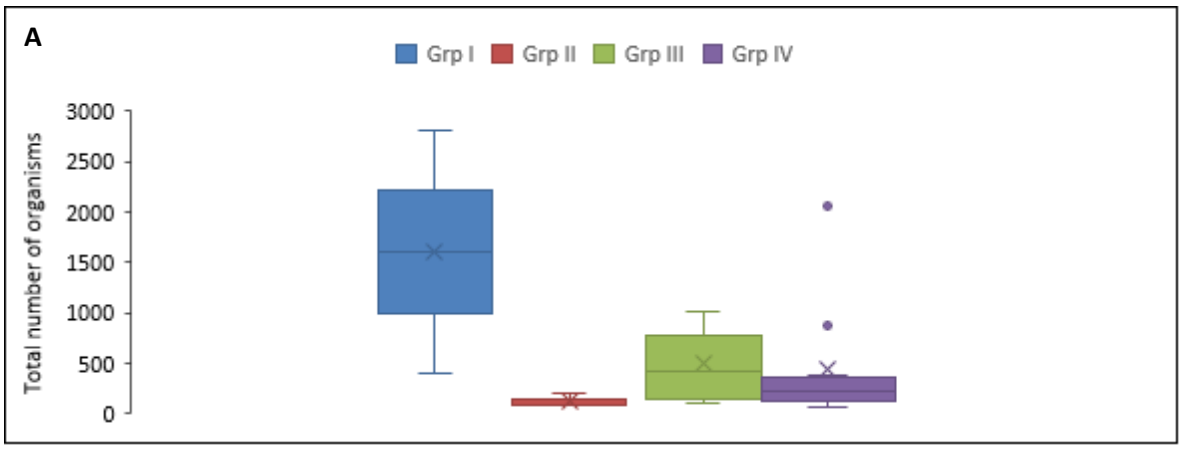



**Figure 73:** Distribution of number of organisms in relation to the different groups of altitude in the sampling stations during the study period.

The number of organisms collected in the wells in function of altitude showed that, the highest number of organisms was collected from the group I. (2820 inds in LW1) and the lowest number of organisms was collected from group IV (65 inds) in MW1. Group II had the least total number of organisms (359), compared to the other groups and group IV had the highest total number of organisms collected during the sampling period in the wells (5209 inds). (Figure 74 A).

In the springs, the number of organisms collected in function of altitude showed that, the highest number of organisms was collected from the group I. (1917 inds in OS1) and the lowest number of organisms was collected from group III (19 inds) in BS9. Group II had the least total number of organisms (359), compared to the other groups and group IV had the lowest total number of organisms collected during the sampling period in the wells (1283 inds) and group I had the highest total number of organisms (5046 inds) (Figure 74 B).



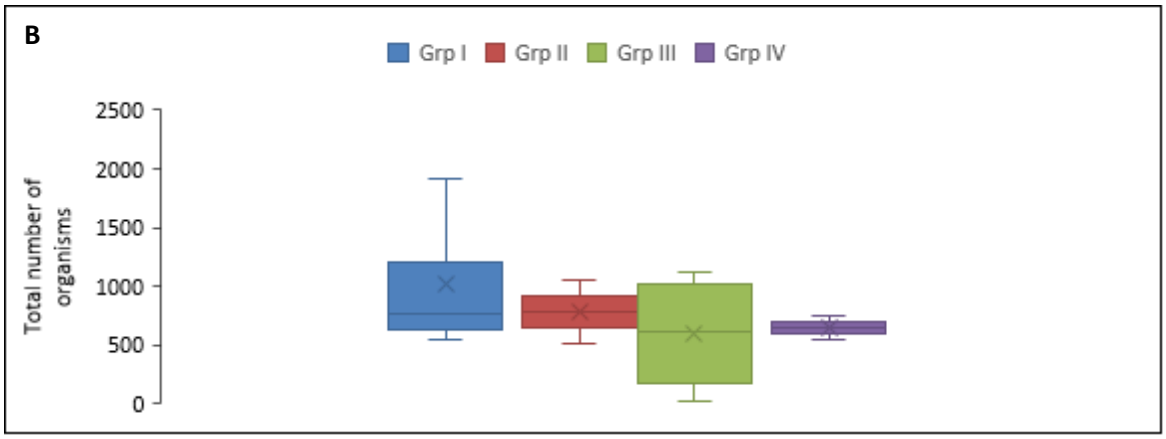



**Figure 74:** Distribution of number of organisms in the Wells (A) and in the springs (B) in relation to the different groups of altitude in the sampling stations during the study period.

### III.1.5.3. Taxonomic richness obtained in the sampling points per altitude during the study period

Comparing taxonomic richness in relation to altitude, it was observed that the highest and lowest number of taxa were obtained in group I, that is, 42 taxa recorded in OS2 and 02 taxa, recorded in BS9 respectively. Generally, the sampling points with higher altitude had a relatively higher number of taxa compared to sampling points with low altitudes (Figure 75). Apart from the two taxa obtained in BS9 found in group III of the repartition due to its canalized nature, the number of taxa in groups II, III and IV ranged from 24 to 30 taxa while the number of taxa in group I had many sampling points with less than 20 taxa.

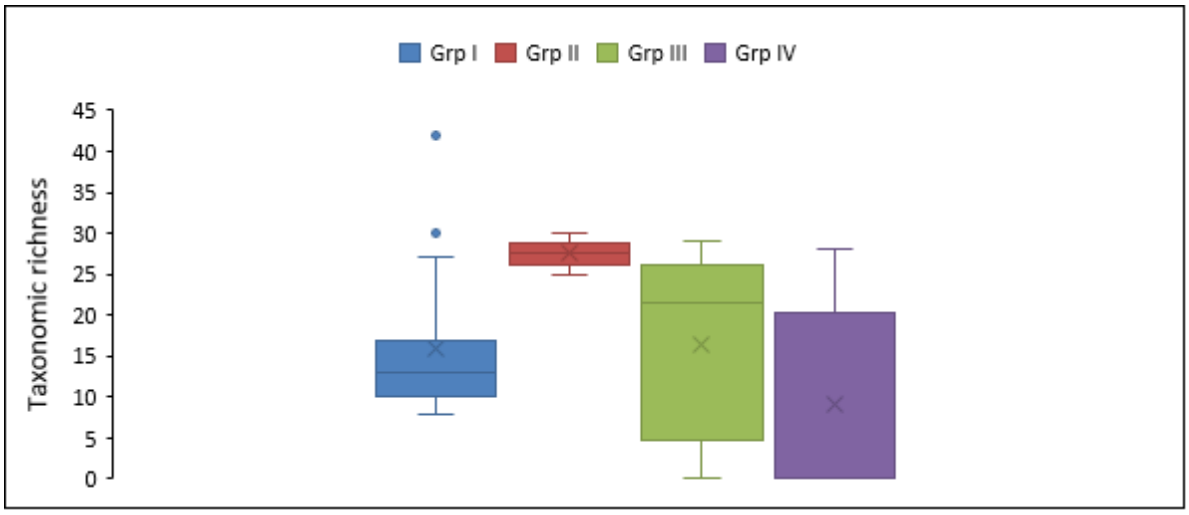



**Figure 75:** Distribution of number of taxa in relation to altitude in the sampling stations during the study period.

In the wells, the taxonomic richness in relation to altitude showed that the highest number of taxa (19) was collected in group III while the least number (08) was collected in group I, III and IV (Figure 76 A). In the springs, the taxonomic richness varied from 19 to 42. It was observed that, the springs had greater taxonomic richnesss than the wells and this could be due to their open nature and also due to their higher altitudes when compared with the wells. Generally, the sampling points with higher altitude had a relatively higher number of taxa compared to points with low altitudes (Figure 76 B).

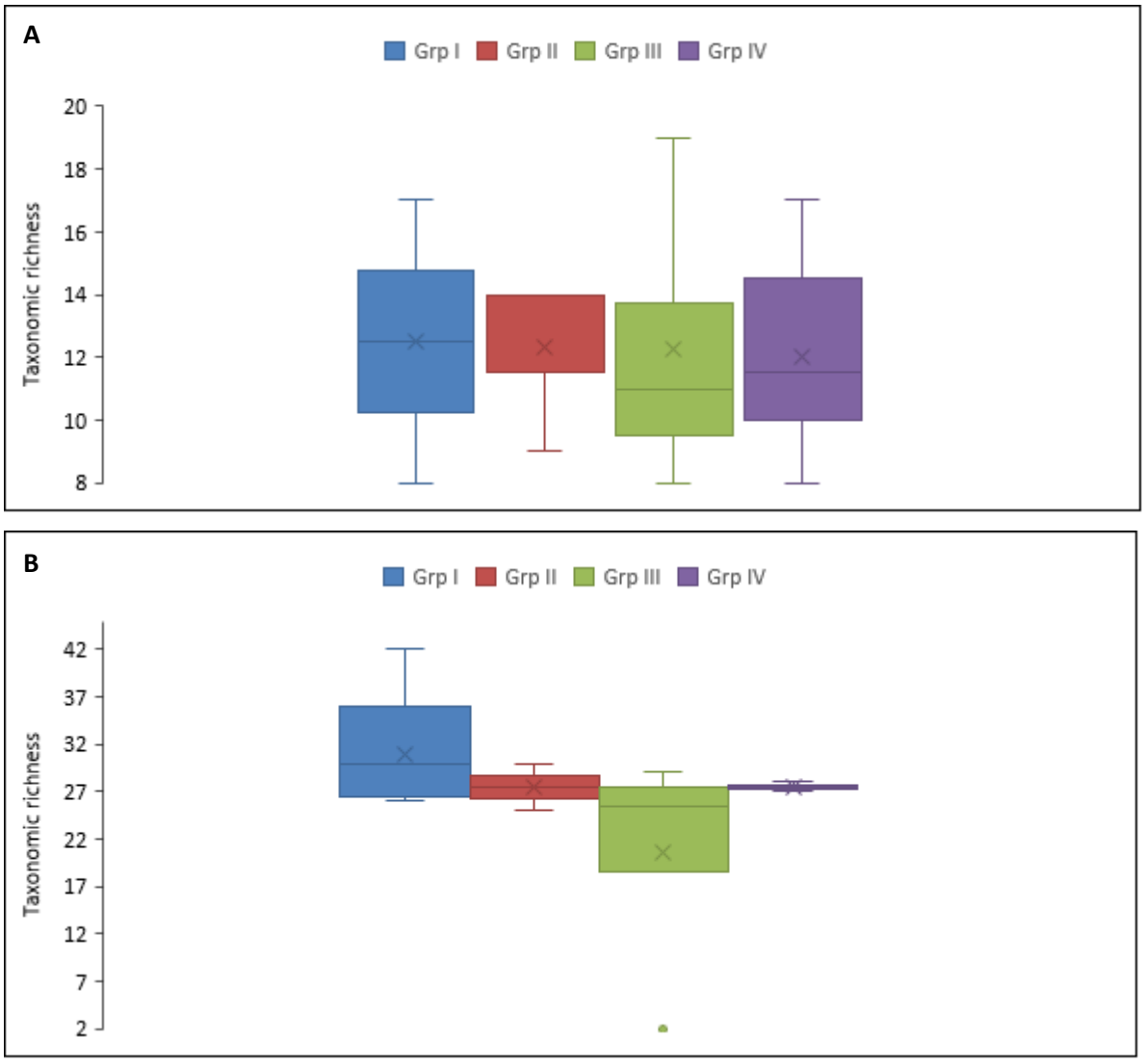



**Figure 76:** Distribution of number of taxa in relation to altitude in the wells (A) and in the springs (B) obtained in the sampling stations during the study period.

### III.1.5.4. Stygobitic richness distribution in relation to altitude

Stygobites are strictly groundwater dependent organisms that cannot survive in any other milieu. A total of four stygobitic taxa was collected during the sampling period in Fako.

The highest number of stygobitic taxa was collected in group I (04 taxa) while no stygobites was recorded in group IV. Three stygobite taxa were collected from LW1which is in group I of the repartition (Stenasellidae, Cirolanidae and Darwinulidae) and two taxa of stygobites (in addition to Asellidae) were collected in five of the sampling stations in group I (TW5, TW7, TW8, OS2 and OS3 and one sampling point in group III (BS12). Fifteen of the sampling points had one stygobite taxa collected from each of them (TW1, TW3, TW6, TW9, TW10, MW1, MW2, MW3, MW4, MW5, LW2, LW3 and MS4 in group I; ES7 in group II; BS12 in group III). No stygobite taxon was collected from eleven of the sampling points; TW2, TW4, LW4, LW5, OS1, MS5, ES6, BS8, BS9, BS11 and BS12 (Figure 77).

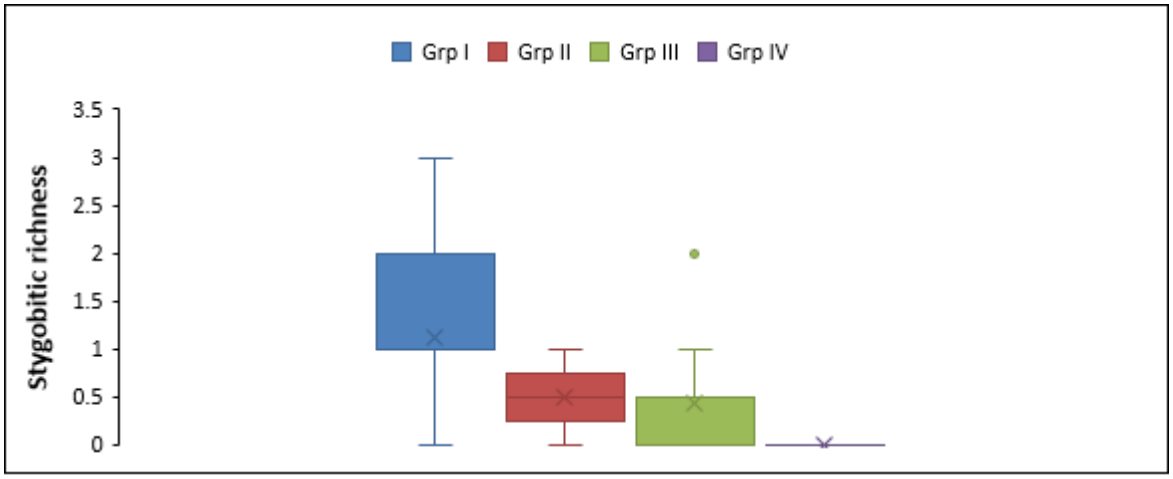



**Figure 77:** Repartition of stygobitic taxa in relation to altitude during the sampling period

A total of three stygobitic taxa was collected from the wells during the sampling period in Fako. The highest number of stygobitic taxa was collected in group I and group IV (03 taxa) while just one was recorded in group II and two stygobitic taxa were recorded in group III. Three stygobite taxa were collected from LW1 which is in group I of the repartition (Stenasellidae, Cirolanidae and Asellidae). Twelve of the sampling points had one stygobite taxa collected from each of them (TW1, TW3, TW6, TW9, TW10, MW1, MW2, MW3, MW4, MW5, LW2, LW3). No stygobitic taxa was collected from TW2, TW4, LW4, LW5 (Figure 78 A).

In the springs, two stygobitic taxa were recorded in groups I and III while one was recorded in group II and none recorded in group IV. The stygobitic taxa that were recorded in the springs were Stenasellidae and Asellidae in group I, Asellidae in group II, Darwinulidae and Asellidae in group III. The springs with the highest altitude had no stygobitic taxa (Figure 78 B).

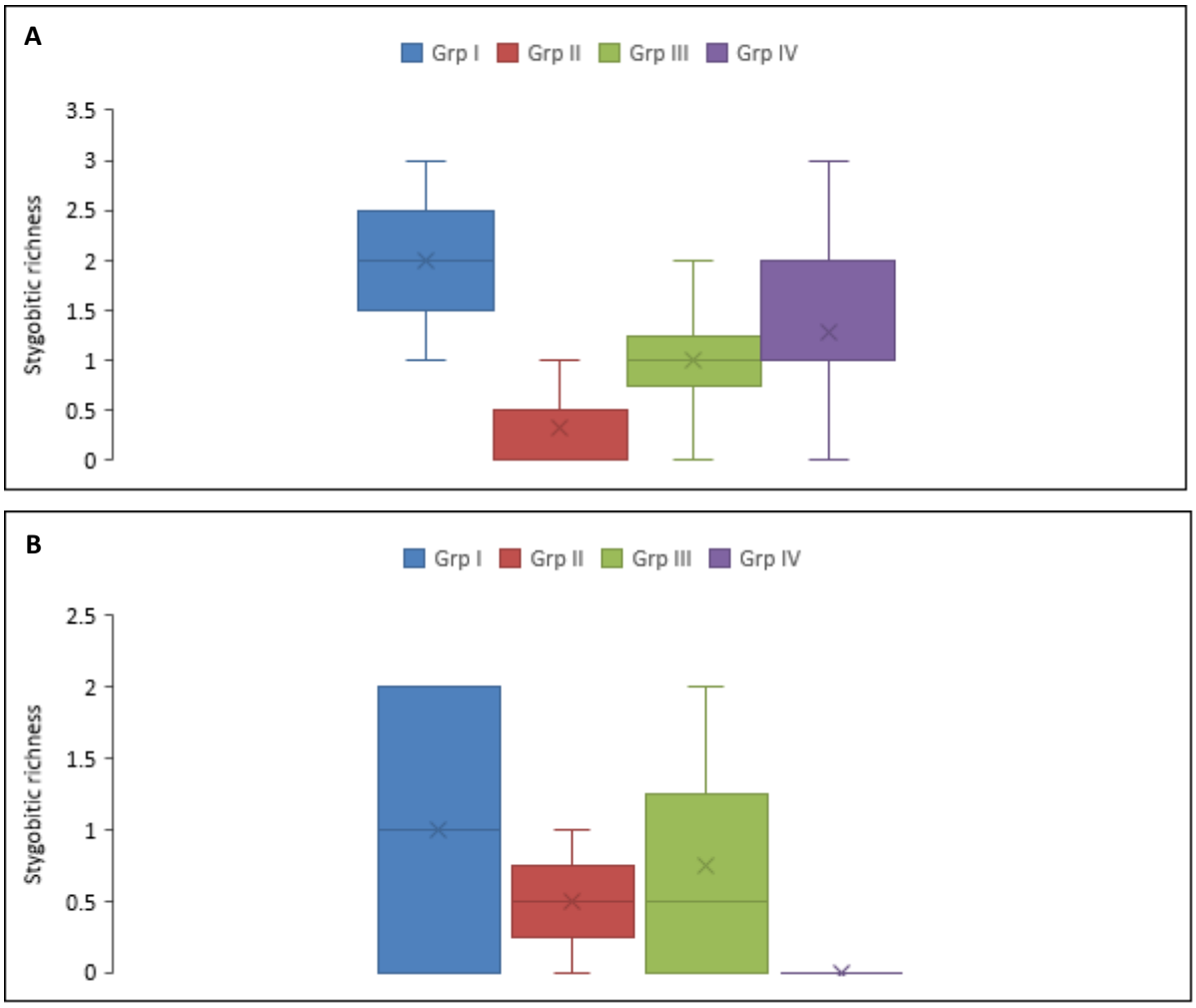



**Figure 78:** Repartition of stygobitic taxa in relation to altitude in the wells (A) and in the springs (B) during the sampling period

### III.1.5.5. Total number of Stygobite organisms collected in relation to altitude

Group I had the highest number of stygobites recorded during the sampling period (230 inds), followed by group III (33 inds). The highest number of stygobites (66 inds) was collected in LW1 (7 m altitude), followed by MW3 (34 inds) situated at an altitude of 70 m. The sampling point BS8 had 32 stygobites (569 m altitude) while OS2 had a total number of 29 stygobites and it was located at an altitude of 96 m. Stygobites were collected in most of the sampling stations that were found at low altitudes (altitudes ranging from 7m in LW1 to 96m in OS2) and at the highest altitudes in group IV (Alt > 1000), no stygobites were recorded and just one stygobite was recorded in group II (600 < Alt < 1000) (Figure 79). A total of 264 stygobite organisms was collected throughout the sampling period in Fako, with group I topping the list with 230 stygobite individuals, followed by group III (33 stygobite individuals). Group II had only one stygobitic individual and no stygobite was recorded in group IV (Table XXVII)

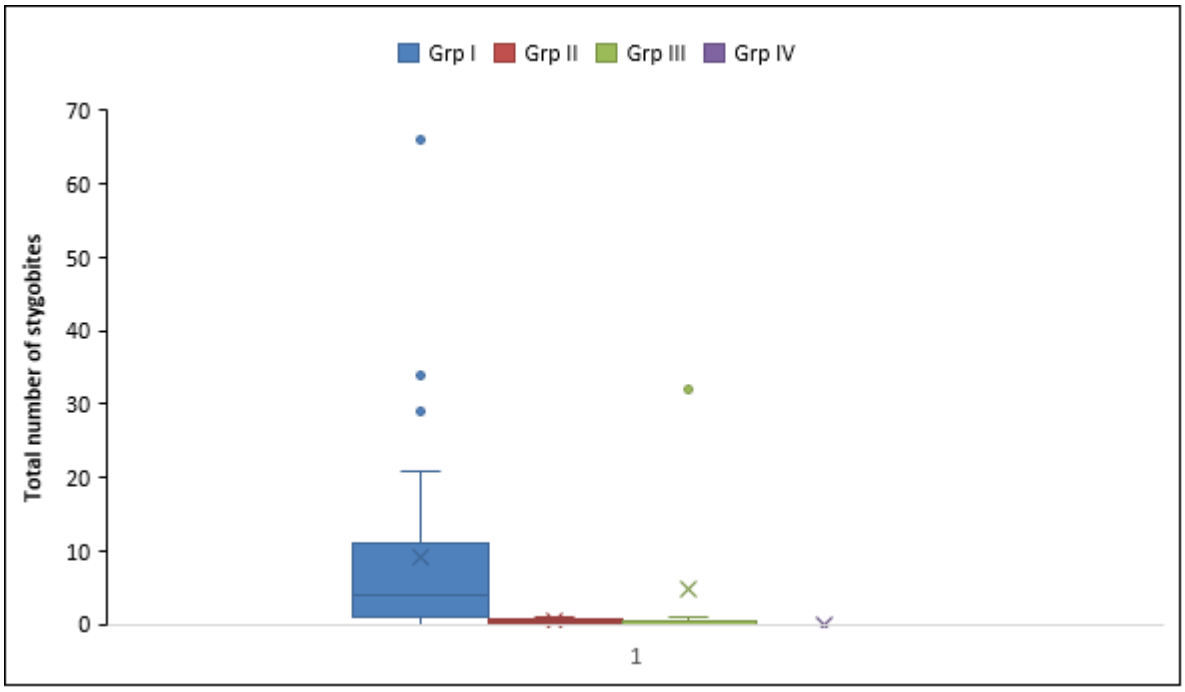



**Figure 79:** Repartition of stygobites in relation to altitude during the sampling period

The wells had the highest number of stygobites compared to the springs (Figure 80). In the wells, group I had the highest number of stygobites recorded during the sampling period (66 inds), followed by group III (34 inds). The highest number of stygobites (66 inds) was collected in LW1 (7 m altitude), followed by group IV (MW3 34 inds) situated at an altitude of 70 m. A total of 182 stygobites were recorded in the wells during the sampling period (Figure 80 A). In the springs, the sampling point BS8 had 32 stygobites (569 m altitude) belonging to group III while OS2 had a total number of 29 stygobites and it was located at an altitude of 96 m, belonging to group I. A total number of 82 stygobites was recorded in the springs throughout the study period.

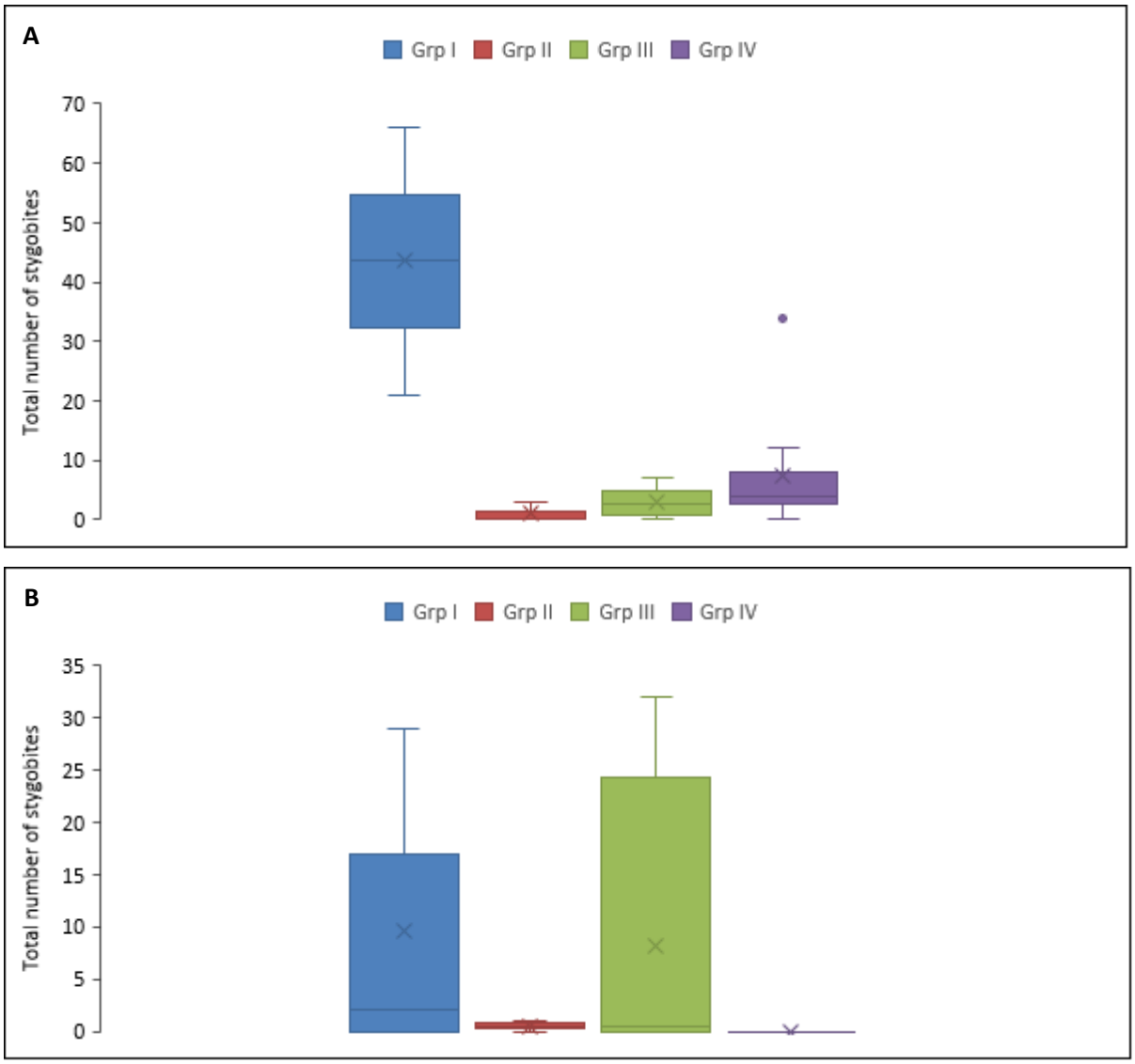



**Figure 80:** Repartition of stygobites in relation to altitude in the wells (A) and in the springs (B) during the sampling period

**Table XXVI: Number of stygobite individuals collected per altitude grouping**

| Family | Genus | Group I | Group II | Group III | Group IV | Total |
|---|---|---|---|---|---|---|
| Asellidae | *Proasellus* sp | 11 | 1 | 4 | 0 | **16** |
| Stenasellidae | *Metastenasellus* sp | 114 | 0 | 0 | 0 | **114** |
| Cirolanidae | | 7 | 0 | 0 | 0 | **7** |
| Darwinulidae | | 98 | 0 | 29 | 0 | **127** |
| **Total** | | **230** | **1** | **33** | **0** | **264** |

### III.1.5.6. Abundance of organisms per sampling town based on altitude

The abundance of organisms collected per sampling point in relation to the mean altitude of each town recorded during the sampling period is represented on figure 81. It was

observed that, the towns with high mean altitudes had the highest number of organisms such as insects (eg. Epehemeroptera, Plecoptera, Tricoptera), Malacostraca (Atyidae and Potomonautidae) and Arachnida (e.g Limnesiidae and Bdellidae). This was observed in Buea, Ekona/Mautu with mean altitude of, 789 m and 275 m respectively. On the other hand, towns like Limbe, Muyuka, Owe and Tiko with mean altitude of 22 m, 67 m, 91 m and 63 m respectively had high numbers of Oligochaetes, Ostracods and Copepods (Figure 81 B).

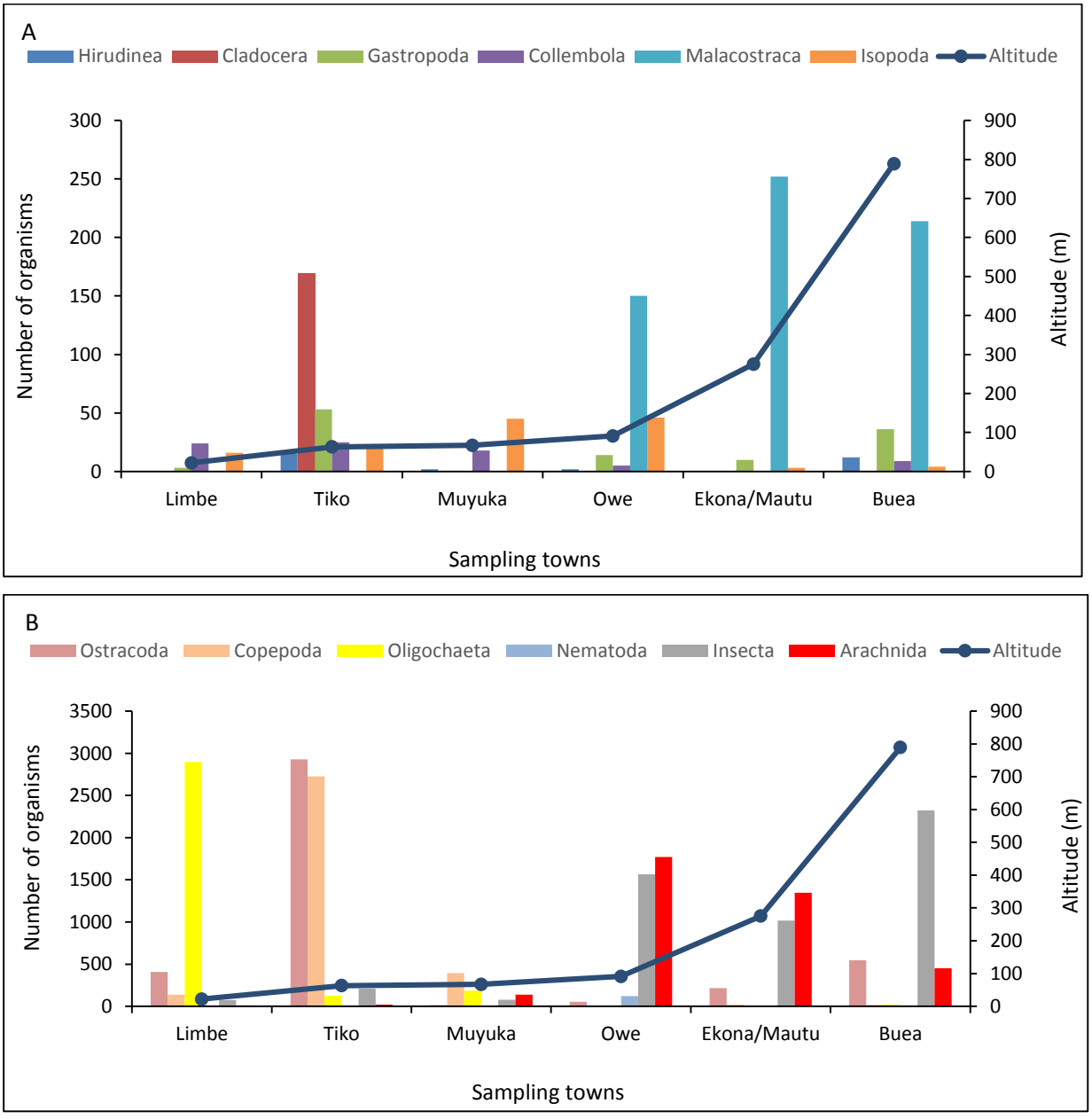



**Figure 81:** Abundance of organisms per sampling town based on altitude for Hirudinea, Cladocera, Gastropoda, Collembola, Malacostraca, Isopoda (A) and Ostracoda, Copepoda, Oligochaeta, Nematoda, Insecta, Arachnida (B).

### III.1.6. Effects of physicochemical characteristics and altitude on biodiversityin Fako Division

#### III.1.6.1. Spearman correlation between altitude and physicochemical parameters

The Spearman correlation between physicochemical parameters and altitude showed a negative correlation at a threshold value of 0.01 between altitude and nitrate ions and between altitude and temperature. This means that, when altitude increases, temperature and nitrate ions decrease significantly and when altitude decreases, these parameters increase significantly. A positive correlation between altitude and pH and between altitude and Dissolved oxygen was observed at the threshold value of 0.01, implying that an increase in altitude led to an eventual significant increase of these parameters.

At the threshold of 0.05, salinity and ammonium ions were negatively correlated to altitude meaning that salinity and ammonium ions decrease with increase in altitude. Orthophosphate was positively correlated to altitude at a threshold of 0.05 and therefore this parameter increases with increase altitude. (Table XVIII).

**Table XXVII: Spearman correlation between altitude and physicochemical parameters**

| Parameters | Correlation with altitude |
|---|---|
| Nitrate ions | -0.531** |
| Dissolve oxygen | 0.568** |
| Salinity | -.244* |
| Ammonium ions | -0.265* |
| Orthophosphates | 0.244* |
| pH | 0.359** |
| Temperature | -0.696** |

#### III.1.6.2. Spearman correlation between altitude and biodiversity

The correlation carried out between biodiversity and altitude showed a positive and significant correlation at the threshold value of 0.01 between altitude and the following taxa: Limnesiidae, Ephydidae, Elmidae, Perlidae, Potomonautidae, Baetidae, Leptoplebidae, Heptageniidae, Gordiaces, Chironomidae, Corixidae, Veliidae, Psychodidae, Simulidae, Hydropsychidae, Dolichopodidae, Hydroptillidae, Aeshnidae and Crambidae. Therefore, an increase in altitude lead to a very significant increase of these organisms, most of which were collected or sampled at high altitudes. A positive correlation that was significant at the threshold value of 0.005 was observed between altitude and the following organisms; Erpobdellidae,

Tipulidae, Psephenidae, Asellidae, Ephemerellidae, Ceratopogonidae and Naucoridae (Table XXIX). It means that, an increase in altitude led to an increase in these organisms during the sampling period. A negative and significant correlation was observed between altitude and Naididae, Entomobryiidae, Cyclopidae and Formicidae at the threshold value of 0.01. An increase in altitude led to a significant decrease in these organisms and therefore they were sampled at low altitude.

**Table XXVIII: Spearman correlation between altitude and biodiversity**

| Organisms | Correlation with altitude | Organisms | Correlation with altitude |
|---|---|---|---|
| Limnesiidae | 0.553** | Ephydidae | 0.325** |
| Erpobdellidae | 0.246* | Tipulidae | 0.273* |
| Naididae | -0.470** | Elmidae | 0.447** |
| Entomobryiidae | -0.318** | Psephenidae | 0.289* |
| Atyidae | 0.511** | Perlidae | 0.354** |
| Potomonautidae | 0.432** | Baetidae | 0.432** |
| +Asellidae | 0.255* | Leptoplebidae | 0.374** |
| Cyclopidae | -0.541** | Heptageniidae | 0.483** |
| Gordiaces | 0.349** | Ephemerellidae | 0.267* |
| Chironomidae | 0.588** | Corixidae | 0.374** |
| Ceratopogonidae | 0.303* | Veliidae | 0.412** |
| Psychodidae | 0.475** | Naucoridae | 0.290* |
| Simulidae | 0.452** | Hydropsychidae | 0.337** |
| Dolichopodidae | 0.425** | Hydroptillidae | 0.412** |
| Formicidae | -0.462** | Aeshnidae | 0.356** |
| Crambidae | 0.322** | | |

+ indicates stygobite

### III.1.6.3. Multivariate analyses

#### III.1.6.3.1. Agglomerative Hierarchical Clustering and Principal Component analysis to show the effect of altitude on physicochemical parameters

The global characterization of the sampled groundwater in function of the physicochemical parameters on an Agglomerative Hierarchy Clustering, permitted the obtention of a four-class hierarchy of the sampling points from right to left. Class I was dissimilar to class II at 42 % and they both were dissimilar to the third class at 52 % and class III was dissimilar to class IV at 65 % (Figure 82). Class I regrouped the sampling points with the following altitudes: 49 m, 78 m, 569 m, 56 m, 133 m, 61 m, 66 m, 67 m, 68 m, 56 m, 71 m, 160 m, 96 m, 53 m and 33 m. These sampling points were characterized by high temperatures, ammonium ions, phosphate ions and total hardness. Class II regrouped 66 m, 63 m, 70 m, 25

m and 71 m, characterized by high values of SS, turbidity, nitrate ions, temperatures and slightly acidic pH. All these sampling points in Class I and II belonged to group I of the altitude classification except for 569 (1 < Alt < 200 m). Class III englobed the following sampling points; 386 m, 94 m, 63 m, 638 m, 82 m, 419 m, 636 m, 1016 m, 1189 m and 686 m. These points had high levels of dissolved oxygen, EC and pH. Class IV constituted of 8 m, 7 m and 38 m. These points were characterized by low altitude and high levels of salinity, electric conductivity, temperature and a slightly acidic pH.

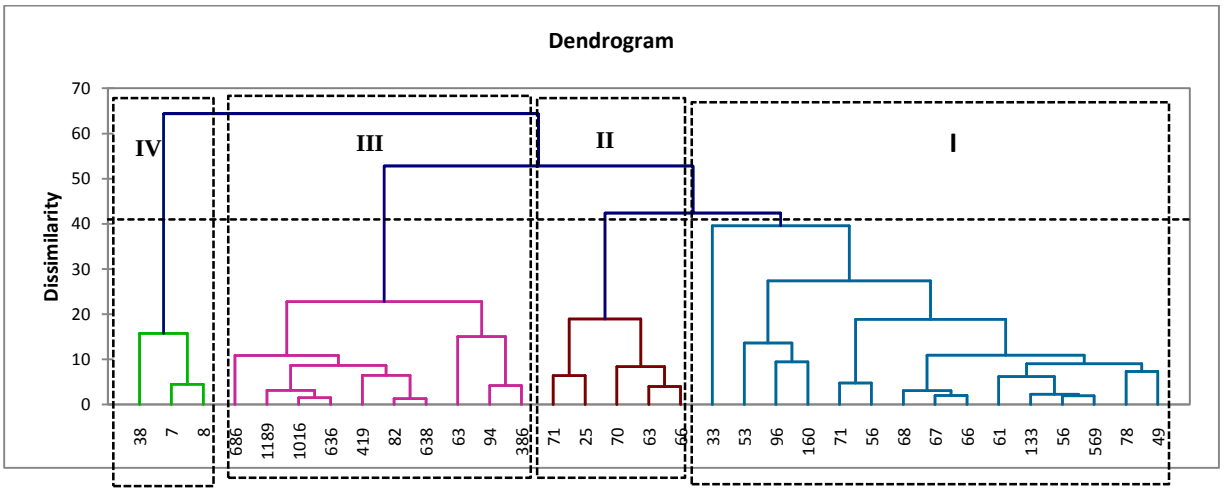



**Figure 82:** Agglomerative Hierarchical Clustering (AHC) for physicochemical parameters obtained during the sampling period in Fako.

The Principal component Analysis (PCA) for the fourteen physicochemical parameters studied was analysed to characterise them in function of the sampling points. The two first factorial axes explained 43.66 % of the total variance (F1=24.91 % and F2=18.75 %). The circle of correlation (Figure 83 A) showed that, alcalinity, oxidability, turbidity, temperature, nitrate and ammonium ions were positively and significantly correlated to the F1 axis. Salinity, electric conductivity, dissolved carbon dioxide, phosphate ions and SS were positively correlated to the F2 axis. Dissolved oxygen and pH are negatively and significantly correlated to F1 axis total hardness was negatively correlated to the F2 axis.

Transposing the physicochemical parameters with the altitudes of the sampling stations, regrouped the sampling stations into three groups: I, II and III (Figure 83 B). Axis F1 discriminated in the positive coordinate in group I, four sampling points (7 m, 8 m, 38 m and 33 m). The samples of group I were characterize by dissolved carbon dioxide, electric conductivity, salinity, turbidity, alkalinity, suspended solids, alkalinity and oxidability. Group II which positively discriminated the F1 axis but negatively discriminated the F2 axis was made up of 12 sampling points which had the altitudes (25 m, 66 m, 60 m, 78 m, 67 m, 66 m, 68 m, 63 m, 53 m, 71 m, 70 m and 56m). These sampling points were characterized by high levels of

temperature, highly influenced by nitrate ions, ammonium ions and total hardness. Group III was made up of 14 sampling points with the following altitudes: 94 m, 686 m, 419 m, 386 m, 133 m, 1189 m, 1016 m, 636, 82 m, 569 m, 56 m, 96 m, 638 m and 49 m. These sampling points discriminated F1 on the negative axis and F2 at the positive axis and were characterized by dissolved oxygen, pH and orthophosphates. With the exception of altitudes 56 and 49, group III sampling stations are considered as the control altitudes, since they are situated in areas that are less perturbed by human activity and the water are meant for consumption by the entire population.

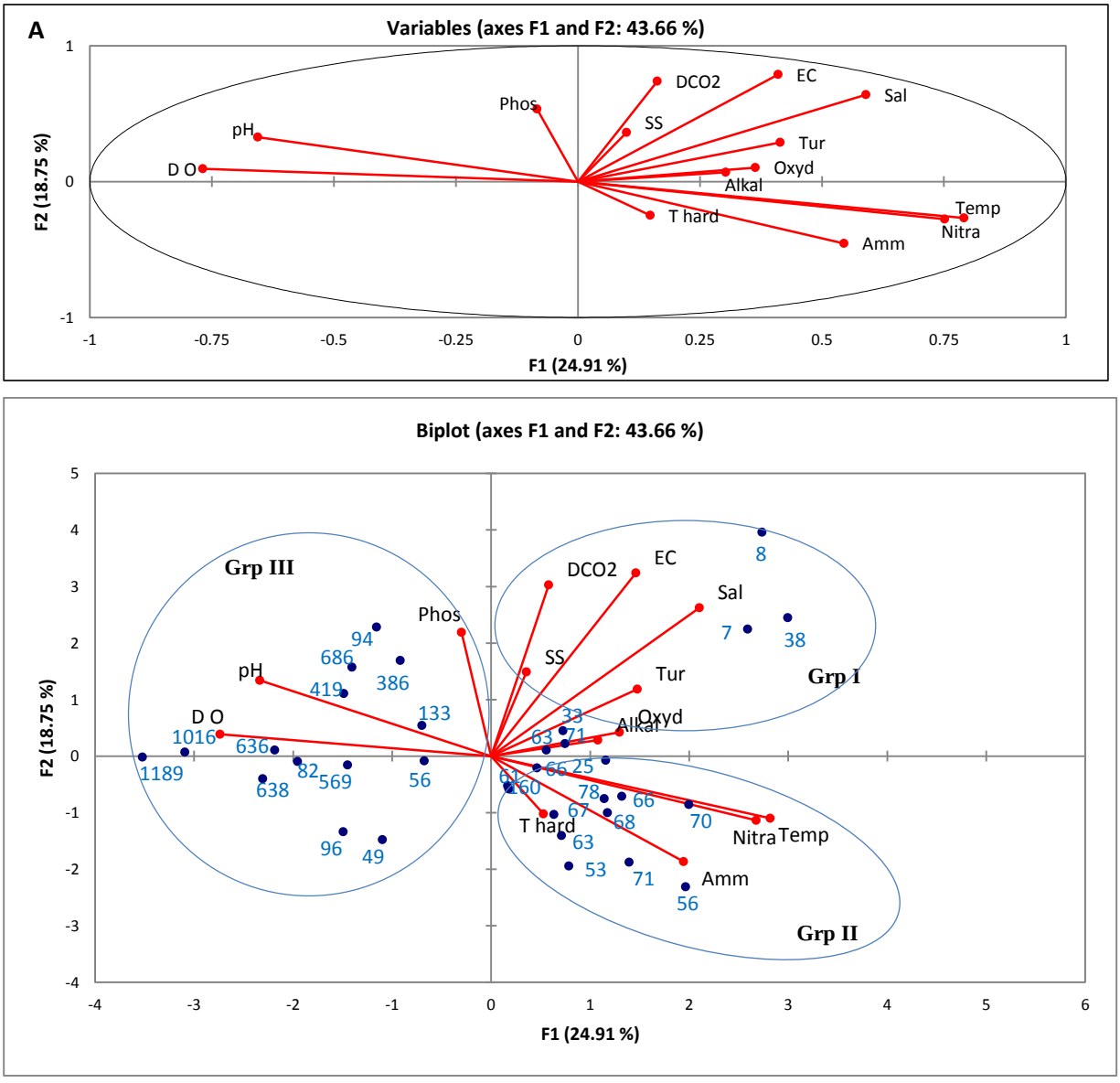



**Figure 83:** Principal Component analysis (PCA) of physicochemical parameters of the different sampling points during the study period in Fako. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan.

### III.1.6.3.2. Agglomerative Hierarchical Clustering and Principal Component analysis to show the effect of altitude on biodiversity

The Agglomerative Hierarchical Clustering (AHC) that was ran in function of biodiversity gave three groups from left to right. The groups are: group I which constitutes the stations with the altitude 160 m, 96 m and 638 m, characterized by the presence of Limnesidae, Gordiaces, Baetidae, Heptageniidae, Corixidae, Limnesidae, Atyidae, Potamonautidae, and Cyprididae. Group II regrouped the stations with the following altitudes: 639 m, 419 m, 133 m, 94 m, 386 m, 82 m, 1186 m, 569 m and 1016 m, characterized by the presence of the groundwater dependent family, Stenasellidae and Pisauridae. Group III constituted of the stations with the altitudes 70 m, 68 m, 49 m, 67 m, 53 m, 71 m, 686 m, 66 m, 78 m, 56 m, 08 m, 33 m, 56 m, 63 m, 38 m, 25 m, 71 m, 66 m, 63 m, 07 m and 61 m. This group was characterized by the following families; Ceratopogonidae, Naididae, Stenasellidae, Darwinulidae and Cyclopidae, collected in these sampling stations during the study period in Fako division (Figure 84). Table XXX shows the range of the different altitude classification.

**Table XXIX: Group of sampling points with their corresponding altitudes**

| Group | Altitude range |
|---|---|
| Group I | 1 m to 200 m |
| Group II | 201 m to 600 m |
| Group III | 601 m to 1000 m |
| Group IV | greater than 1000 m |

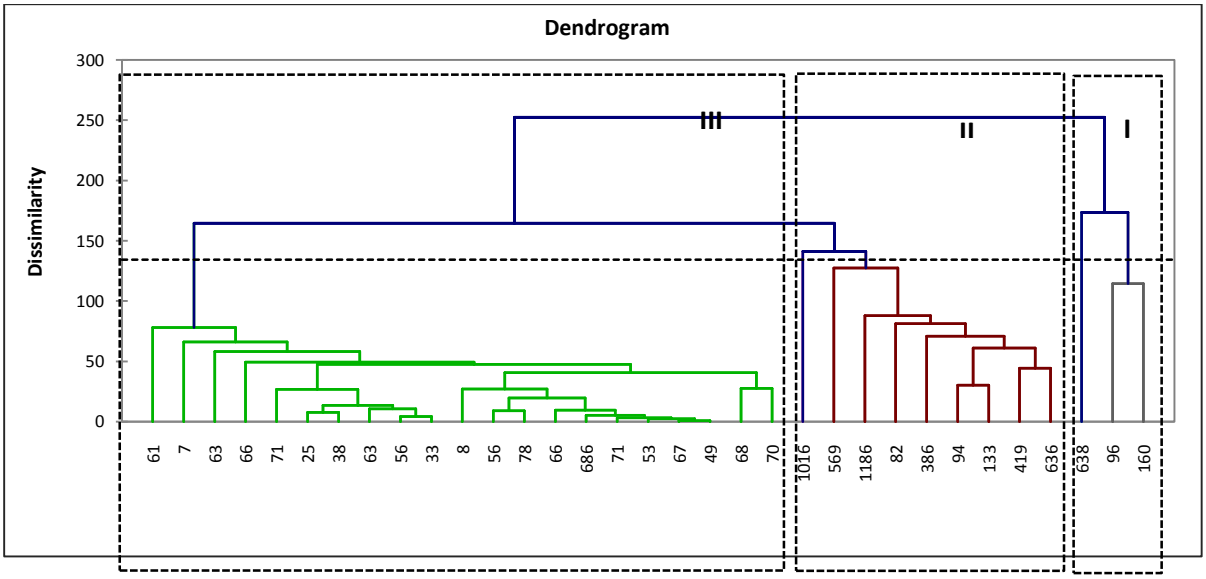



**Figure 84:** Agglomerative Hierarchical Clustering (AHC) plotted in function of biodiversity during the sampling period in Fako.

The Principal component Analysis (PCA) to characterise the 58 taxa collected during the study period in Fako division projected with the altitudes of the sampling points (Figure 85 A) gave three principal classes with a total contribution of 32.87%. Figure 84 A shows that, group I constituted of three of the sampling points with altitude 386 m, 638 m and 96 m which discriminated the F1 axis positively. Group II discriminated F1 and F2 axes in the positive

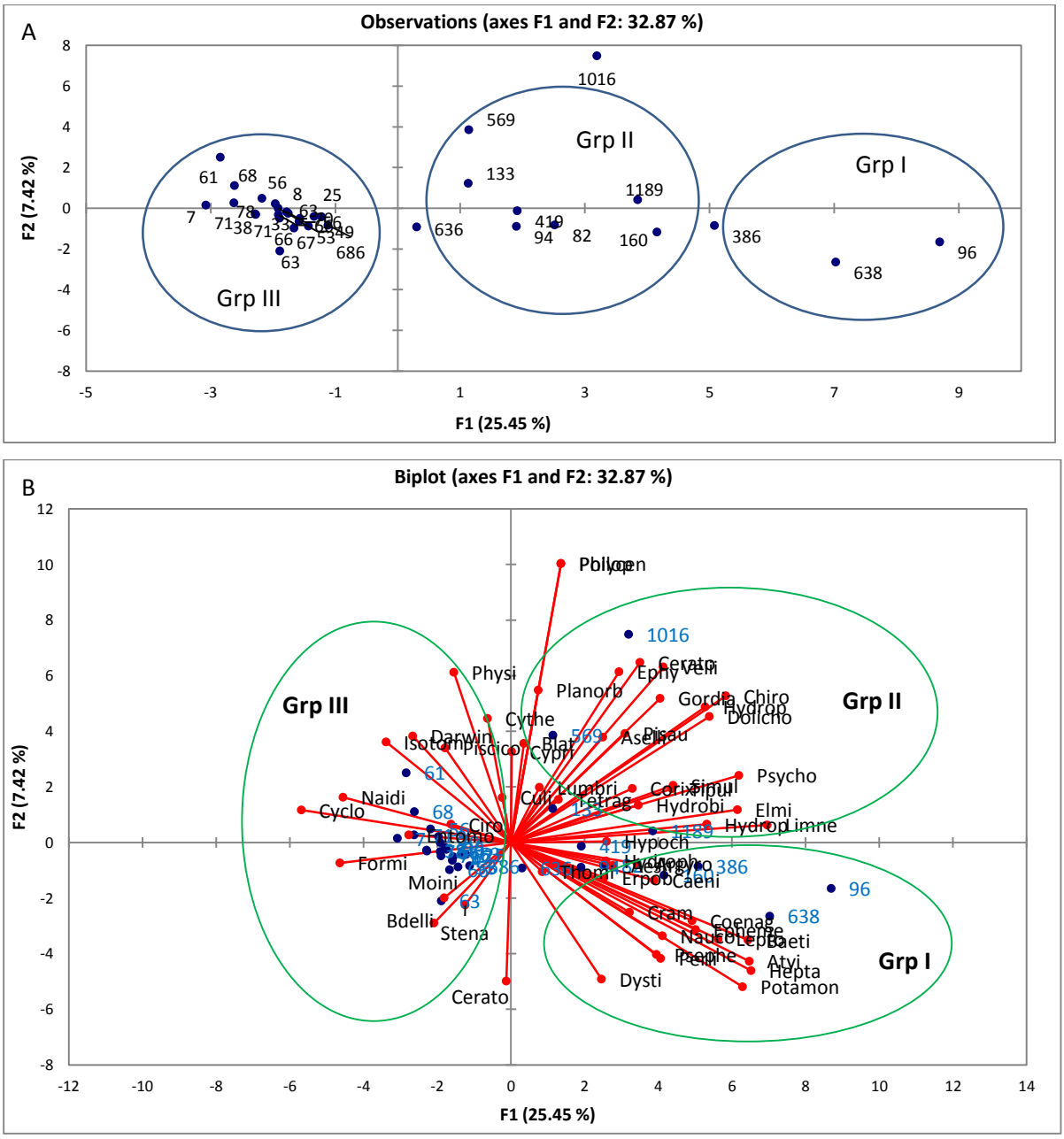



**Figure 85:** Principal Component Analysis of the different stygofauna taxa collected during the study period in Fako. (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 X F2 factorial plan.

Legend: Elmi=Elmidae, Baeti=Baetidae, Lepto=Leptoplebiidae, Hepta=Heptageniidae, Limne=Limnesiidae, Atyi=Atyidae, Gordia=Gordiaces, Chiro=Chironomidae, Dolicho=Dolichopodidae, Hydrop=Hydroptillidae, Perli=Perlidae, Cypri=Cyprididae, Psycho= Psychodidae, Simul= Simulidae, Naidi= Naididae, Cyclo= Cyclopidae, Entomo

=Entomobryiidae, Cerat =Ceratozetidae, Bdelli=Bdellidae, Pisau =Pisauridae, Piscico=Piscicolidae, Erpob =Erpobdellidae , Hydrob=Hydrobiidae, Physi=Physidae, Isotom=Isotomidae, Potamon=Potomonautidae, Aselli=Asellidae, Darwin=Darwinulidae, Moini = Moinidae, Culi= Culicidae, Cerato=Ceratopogonidae, Ephy =Ephydidae, Tipul=Tipulidae, Psephe=Psephenidae, Epheme =Ephemerellidae, Corix =Corixidae, Velii=Verlidae, Nauco =Naucoridae, Hydrobs =Hydropsychidae, Polycen =Polycentropodidae, Coenag =Coenagrionidae, Aesh =Aeshnidae, Formi=Formicidae, Cram=Crambidae, Argyro=Argyronetidae, Thomi =Thomisidae, Stena=Stenasellidae, Ciro =Cirolanidae, Tetrag= Tetragnathidae, Hypoch =Hypochthoniidae, Lumbri= Lumbriculidae, Planorb =Planorbidae, Cythe= Cytherididae, Dysti=Dysticidae ,Hydroph=Hydrophylidae, Caeni =Caenidae, Philop=Philopotamidae, Blat=Blattidae, Erpob=Erpobdellidae, ceratoz= Ceratozetidae.

coordinate and F2 in the negative coordinates nine sampling points with altitudes 1016 m, 569 m, 133 m, 1189 m, 160 m, 82 m, 419 m, 94 m and 636 m. Group III positively discriminated the F2 axis and negatively and significantly discriminated the F1 axis and constituted of 21 sampling stations with altitude 61 m, 68 m, 56 m, 8 m, 25 m, 7 m, 71 m, 78 m, 38 m, 71 m, 66 m, 67 m, 33 m, 63 m, 53 m, 686 m, 63 m, 25 m, 70 m, 49 m and 56 m.

Projecting the sampling points with the organisms collected on a biplot, three groups were obtained as seen on figure 85 B. Group I was made up of the sampling points with the altitudes 419 m, 94 m, 82 m, 160 m, 386 m, 636 m, 96 m and 638 and it constituted of 18 taxa. These taxa were Baetidae, Heptageniidae, Atyidae, Potomonautidae, Psephenidae, Dysticidae, Leptoplebiidae, Ephemerellidae, Coenagrionidae, Crambidae, Argyronetidae, Thomisidae, Caenidae, Aeshnidae, Hydrophylidae, Naucoridae, Hydrophilidae and Erpobdellidae. Group II was made up of the sampling points with altitudes 1189 m, 133 m, 569 m and 1016 m and constituted of 24 taxa. These taxa were Gordiaces, Pisauridae, Polycentropodidae, Aeshnidae, Lumbriculidae, Planorbidae, Blattidae, Chironomidae, Dolichopodidae, Simulidae, Tetragnathidae, Ephydidae, Tipulidae, Corixidae, Veliidae, Lumbriculidae, Elmidae, Hydroptillidae, Hydropsychidae, Hydrobiidae, Philopotamidae, Psychodidae, Hypochthoniidae and Limnesiidae. Group III was made up of 16 taxa which constituted the following families: Cyprididae, Entomobryiidae, Naididae, Cyclopidae, Physidae, Isotomidae, Asellidae, Darwinulidae, Moinidaae, Ceratopogonidae, Cytherididae, Culicidae, Formicidae, Stenasellidae, Cirolanidae, and Piscicolidae. From the factorial map, it was observed that group three constituted the stygobite families which are Asellidae, Darwinulidae, Cirolanidae and Stenasellidae (Figure 85 B).

### III.1.6.3.3. Agglomerative Hierarchical Clustering and Principal Component analysis to show the effect of altitude and physicochemical parameters on biodiversity

The Agglomerative Hierarchical Clustering (AHC) between physicochemical parameters and the stygofauna biodiversity collected during the sampling period gave three classes from left to right. The first class regrouped the sampling points with the following altitudes: 386 m, 94 m, 636 m, 419 m, 82 m, 1189 m, 569 m, 1016 m and 638 m, characterized by high levels of dissolved oxygen, pH, $CO_2$, presence of the families Limnesiidae, Stenasellidae, Pisauridae, Chironomidae and Simulidae. Class II was made up of the altitudes 160 m and 96 m, characterized by high Dissolved oxygen, pH, total hardness, the families Limnesiidae, Atyidae, Elmidae, Baetidae and Heptageniidae. The third class was composed of the altitudes 66 m, 63 m, 25 m, 38 m, 686 m, 133 m, 71 m, 66 m, 56 m, 68 m, 78 m, 56 m, 49 m, 67 m, 71 m, 53 m, 33 m, 70 m, 63 m, 61 m, 8 m and 7 m. These sampling points had common taxa and relationship in their physicochemical parameters such as high turbidity, EC, nitrate, phosphate, temperature, salinity, presence of the families Lumbriculidae, Naididae, Stenasellidae, Cytherididae, Cypridoidae, Darwinulidae and Moinidae (Figure 86).

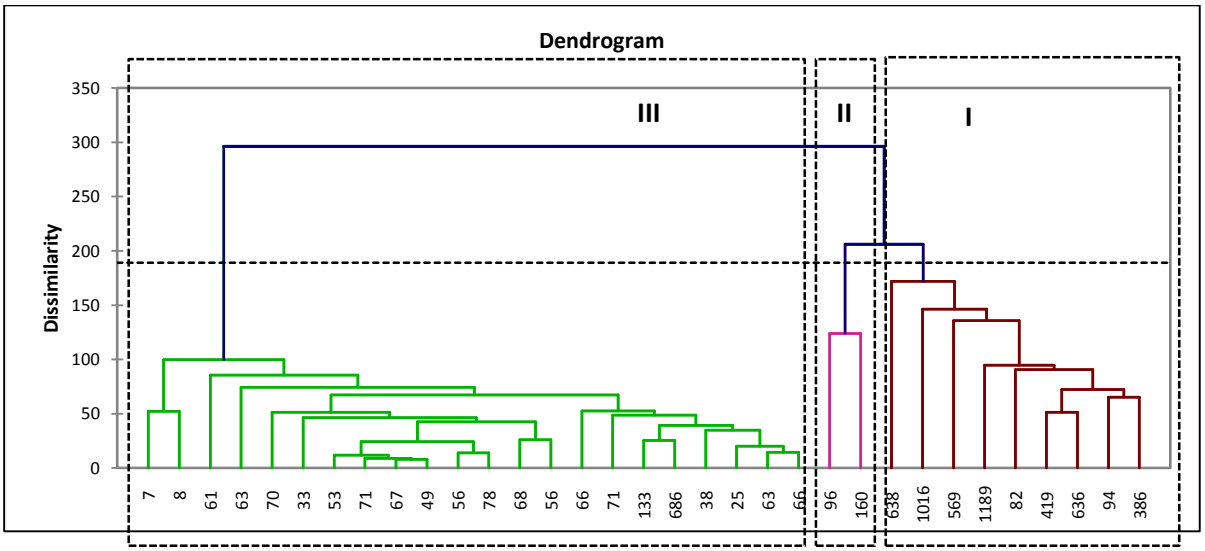



**Figure 86:** Agglomerative Hierarchical Clustering for biodiversity and physicochemical parameter during the sampling period in Fako.

The PCA to characterise the different taxa collected during the study period in Fako division projected with physicochemical parameters and altitudes of the sampling points (Figure 87 A) gave three principal classes with a total contribution of 30.68% of the total variance. Group I constituted of five of the sampling points with altitude 95 m, 638 m, 386 m, 1189 m and 1019 m. Group II was made up of seven sampling points with altitudes 160 m, 82 m, 94 m, 569 m, 419 m, 133 m and 636 m. Group III constituted of 21 sampling stations with

altitudes 61 m, 68 m, 56 m, 8 m, 25 m, 7 m, 71 m, 78 m, 38 m, 71 m, 66 m, 67 m, 33 m, 63 m, 53 m, 686 m, 63 m, 25 m, 70 m, 49 m and 56 m.

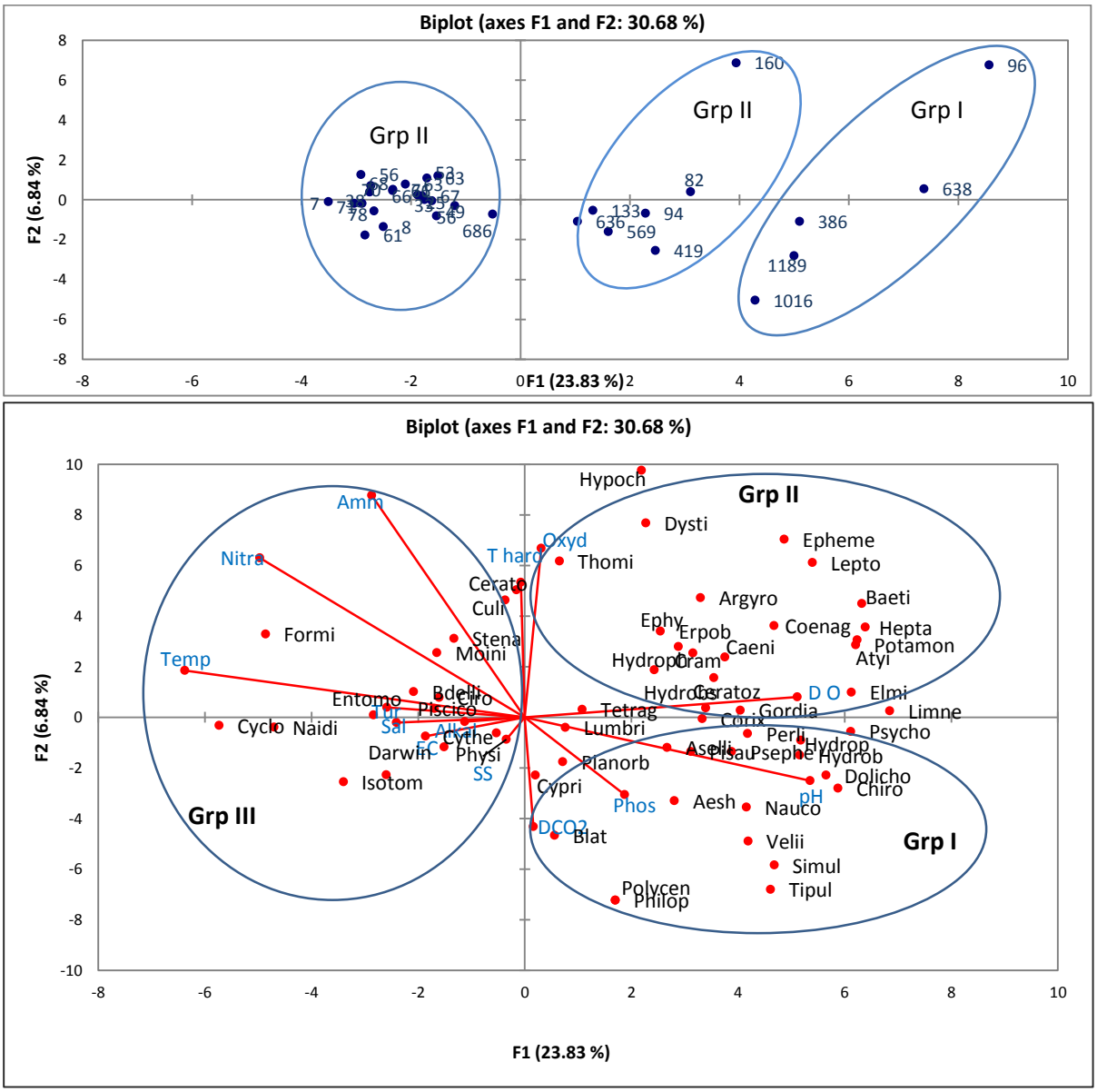



**Figure 87:** Principal Component analysis of the different stygofauna taxa collected, projected with physicochemical parameters during the study period in Fako, (A) Circle of correlation between variables and factorial axes F1 and F2, (B) Biplot showing the distribution of samples in F1 and F2 factorial plan

When the physicochemical parameters were projected in function of the biodiversity collected and the altitudes of the different sampling points, 30.68% of the total variance was explained and it was divided in two groups: I and II. From figure 86 below, oxidability and total hardness are positively and significantly correlated to the F2 axis, while dissolved carbon dioxide and Suspended solids were negatively and significantly correlated to the F2 axis. On the other hand, dissolved oxygen was significantly and positively correlated to the F1 axis while

alkalinity, SS, turbidity, salinity, electric conductivity and temperature are negatively and significantly correlated to the F1 axis. Group I showed that, pH, phosphate, and dissolved carbon dioxide influence the distribution of a total of 18 organisms. These organisms are Chironomidae, Perlidae, Cyprididae, Simulidae, Pisauridae, Asellidae, Planorbidae, Tipulidae, Psephenidae, Veliidae, Naucoridae, Polycentropodidae, Aeshnidae, Blattidae, Hydrobiidae, Dolichopodidae, Philopotamidae and Hydroptillidae. The stations distributed in this group had higher pH, dissolved carbon dioxide and phosphate ion values compared to the other stations, which favoured the distribution of the taxa mentioned above. Group II showed that, oxidability and dissolved oxygen positively affected the distribution of 19 organisms which were: Elmidae, Baetidae, Atyidae, Hydrobiidae, Potomonautidae, Ephemerellidae, Coenagrionidae, Crambidae, Thomisidae, Argyronetidae, Dysticidae, Caenidae, Hydropsychidae, Erpobdellidae, Leptoplebiidae, Gordiaces, Ceratozetidae, Ephydidae and Heptageniidae. In group III, alkalinity, nitrate ions, ammonium ions, temperature, turbidity, salinity, electric conductivity, alkalinity and suspended solids had an effect on the distribution of 15 taxa which included: Cyclopidae, Isotomidae, Darwinulidae, Moinidae, Naididae, Culicidae, Ceratopogonidae, Formicidae, Stenasellidae, Cytherididae, Entomobryiidae, Bdellidae, Piscicolidae, Physidae and Cirolanidae.

**III.1.7. Bio typology of the distribution of biodiversity in function of altitude**

When a map of the different altitudes was used to project organisms, and each group of altitudes compared, it was observed that there were some organisms that were common in all the different groups of altitude. These organisms included Lumbriculidae, Asellidae, Atyidae, Cyprididae, Chironomidae, Psychodidae, Formicidae and Limnesiidae. The sampling points were situated in two large drainage basins which are the Bimbia basin and the Mungo basin. The sampling stations in the town of Muyuka, Owe and Ekona empty their contents in the Mungo drainage while the stations in Limbe empty their water in the Bimbia creek and the sampling stations in Tiko empty themselves in the Mabeta and Missellele creeks (Figure 88). Considering the grouping of the different altitudes into four groups: I, II, III and IV, it was observed that in group I, the taxa that dominated were Baetidae, Atyidae, Gordiaces, Cyclopidae, Potomonautidae, Moinidae, Ceratopogonidae, Cytherididae, Naididae and Elmidae. In group II, the taxon that dominated was Corixidae and group III, Potomonautidae, Psephenidae and Ephemerellidae dominated. In group IV, Psychodidae was abundant compared to the other taxa.

In group I, a total number of 15794 organisms was recorded during the sampling period while a total number of 1575 of organisms were collected from group II. A total of 2361

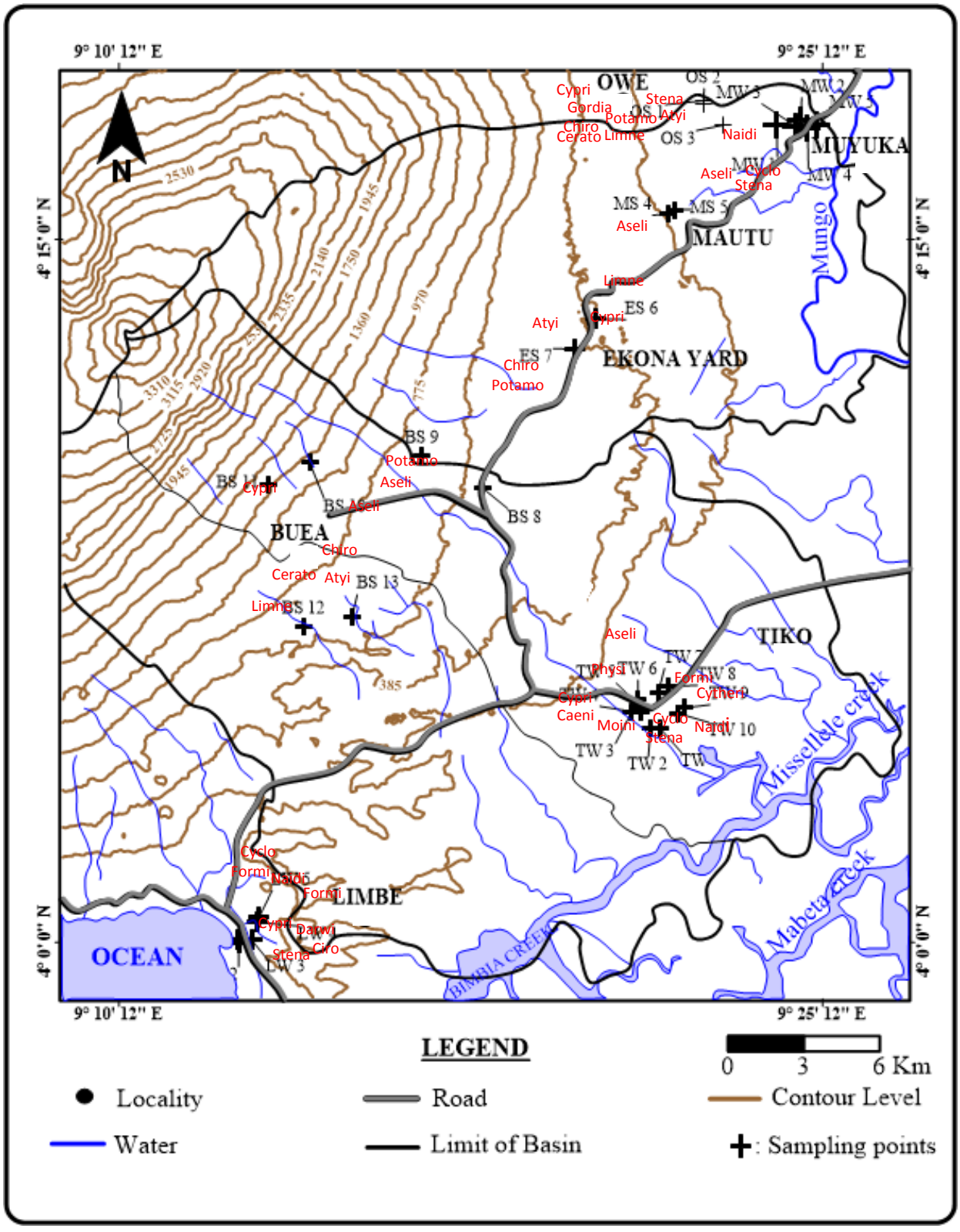



**Figure 88:** Map showing the biotypology of the different altitude of the sampling points (NIC, 1972 modified)

individuals and 1283 organisms were collected from group III and group IV respectively. Among these organisms collected were 264 stygobites that was distributed as follows: 230 stygobites in group I which was made up of 11 Asellidae, 114 Stenasellidae, 7 Cirolanidae and 98 Darwinulidae; 33 stygobites in group III, which constituted of four Asellidae and 29 Darwinulidae; 1 Asellidae in group II and no stygobite in group IV.

### III.1.8. Stygobites sampled

Much importance is placed on organisms of the family Stenasellidae principally because it has been noted to be widely spread throughout Cameroon in areas where groundwater sampling has been carried out. During the sampling period in Fako, one of the Stygobite family collected was Stenasellidae, with individuals belonging to the genus Metastenasellus. Other stygobites recorded during the sampling period belong to the family Cirolanidae, Darwinulidae and Asellidae.


**Figure 89:** Pictures of the different groups of Stygobites (A= Stenasellidae, B= Cirolanidae, C= Darwinulidae, D = Asellidae) collected in Fako division during the study period

## III.2. DISCUSSION

### III.2.1. Physicochemical characteristics of groundwater

The high temperature obtained at Limbe and Tiko throughout the study period can be explained by the reduction of the water level and by the depth of the water points, which allowed sunlight to directly penetrate and also due to the characteristics of each sampling point such as, vegetation canopy, topography of the site in relation to the external milieu (Huang *et al.*, 2019). With regards to this, Issartel (2007) proposed that, the temperature of groundwater decreases with increased altitude and increases with decreased altitude. In rural settings like most of our study area in Fako, the variation of temperature is due to the characteristics mentioned above.

Electric conductivity (EC) is considered as an approximate measure for Total Dissolved ions and they are both concordance (Allan and Castillo, 2007). Any difference in the values of electric conductivity leads to change of the TDS values. The high value obtained in BS9 (916 µS/cm) could be due to the weathering of primary minerals such as mica, feldsparth, calcite and dolomite which are considered to be the sources of Calcium and Magnesium in groundwater (Nag and Suchetana 2016). The high value of EC obtained in Limbe (725.25 ± 600.23 µS/cm) could be due to the presence of saline water from the sea that infiltrated into the wells. According to Rodier *et al.*, (2009), the acceptable level in drinking water is between 0 µS/cm and 600 µS/cm. Zébazé Togouet *et al*. (2009), Tuékam Kayo (2013) obtained same kind of results in the Centre and Littoral regions respectively. This gives a picture of very little solute dissolution generally in the groundwater, rapid ion-exchange between the soil and water. Generally, the values of EC were within the range of drinking water recommended by WHO (2011), except for Limbe.

Turbidity values higher than the 5 FTU recommended by WHO (2011) were obtained in all the areas assessed. The high values of turbidity obtained during the sampling period could be due to the poor nature of the protection of the water points and the position of the water points like being situated under a tree and their open nature which allowed the leaves of these trees to fall inside them. Boutin (1993) proposed that, good protection of groundwater points prevent the penetration of running rainwater which most of the time, is loaded with plant and animal debris. These particles could be a sign of pollution, which could bring microorganisms that live principally in biofilm state in groundwater (Zébazé Togouet *et al.*, 2011).

All the water samples showed values of Suspended Solids (SS) which were within the permissible limits of WHO (2011), which should be less than or equal to 30 mg/L. Suspended Solids in groundwater in the study area were generally low.

The pH values obtained were not within the range recommended by WHO (2013). Generally, almost all the sampling points had an acidic pH during the rainy season. These waters were slightly acidic, and this acidity is justified by Prévosto *et al*. (2004), who observed that, the pH of volcanic substratum vary between 5.7-6.4. This is true as Fako division is made up of volcanic soil due to the presence of Mt Fako which is an active volcano.

Salinity values were generally low and fall within WHO (2013) standards for drinking water. However, the high values of salinity observed in the town of Limbe could be due to its low altitude which implied nearness to the sea. There is possible lateral intrusion of sea water coming from the adjacent layers into this groundwater. This could also be explained by natural phenomenon due to excess collection of the water leading to a decrease in the water table and consequently, the salinization of these groundwater (Brentfuhner and Vanessa, 2015).

The average concentration of orthophosphates showed values higher than the standard recommended by WHO (2011) (0.40 mg/L) for drinking water in all the sampling towns. This could be related to the proximity of the sampling points to the CDC rubber and palm plantations and the presence of traditional latrines in most of the neighbourhoods which brought in high amounts of phosphate containing compounds into the water. Zebaze Togouet *et al.*, (2011) proposed that the high percentages of orthophosphates would come from agricultural fertilizers and faecal pollution which could arrive in underground milieu by infiltration. The high values could also result from the daily activities carried out in some of the water points such as bathing, washing of cloths whereby all these activities use detergents. Phosphates enter waterways from human and animals waste, phosphorus rich bedrock, laundry, cleaning, industrial effluents, and fertilizer run off (Behailu *et al.,* 2018). Levels in unpolluted waters are normally low, below 0.03 mg/L. Values greater than this indicates sewage pollution which could explain the case in the rainy season due the proximity of some points to latrines of the owners.

The average value of nitrate ions in all the sampling points were within the level that is permissible by WHO (2011) for drinking water. According to Bengouni *et al.,* (2004) the concentration of nitrates in natural environment seldom exceeds 0.45 mg/L. This would be also due to the infiltration of water containing nitrate fertilizers used by the CDC and even by the populations themselves on their farmlands. Chapman and Kimstach, (1996) affirmed that values higher than 0.45 mg/L in subsoil waters indicate worn water discharges and especially an excessive use of fertilizers for agriculture. Nitrate is the highest oxidizable form of nitrogen and occurs in trace quantities in surface water but may attain high levels in some ground water and is toxic when present in excessive amounts in drinking water (Behailu *et al.,* 2018). The

most common source of nitrate concentration is attributed to animals and human waste disposal practices and the use of agricultural fertilizer (Ediagbonya *et al.*, 2015; Welch *et al.*, 2000). The levels of nitrate concentrations are of interest for various reasons, most importantly, high nitrate levels in water meant for drinking purposes will render the water hazardous to infants as they induce the "blue baby" syndrome (methaemoglobinaemia) due to its conversion to nitrites (Istifanus *et al.,* 2013). Ammonium in water comes from agricultural fertilizers and the decomposition of living matter by micro-organisms (WHO, 2011) since naturally, groundwater does not contain nitrogen compounds. The groundwater studied in Fako did not contain amounts that could be of danger to human health and the ammonium levels were within the range permitted for drinking water, which is 10 mg/L WHO (2011).

The percentage saturation of dissolved oxygen recorded during the study period revealed that the waters were fairly oxygenated. In groundwater, the dissolved oxygen contents are relatively low compared to those of surface water, because of the absence of photosynthetic plants, the low water-atmosphere contact and the absence of water turbulence (Humphreys 2002). Stygofauna rely on connections to the land surface to provide them with food be it hydrological, with infiltrating water bringing dissolved or particulate organic matter to form the basis of subterranean food webs or it may be more direct, with tree roots that extend below the water table providing leachates, organic carbon or fine rootlets for food (Hancock *et al.*, 2005). Nevertheless, a fast circulation, involving a perpetual water renewal, ensures sometimes the good oxygenation of water, in hypogean medium (Hahn, 2006; Deharveng *et al.*, 2009). These values are lower than that obtained by Tuekam Kayo (2013) in the town of Mbalmayo. It is noted that ground water is generally more vulnerable as the roof of its nappe is close to the surface of the ground, and that the soil around the aquifer are permeable (Boutin *et al.*, 2011). The values of oxidability and ammonium ions translate richness of water in organic matter, which according to Nisbet and Verneaux (1970) would indicate a certain degree of pollution.

Alkalinity in water is caused mainly due to hydroxide, Carbonate and hydro carbonate ions. Alkalinity is an estimate of the ability of water to resist change in pH upon addition of acid (Mahananda *et al.,* 2010). Higher levels of alkalinity were recorded in Ekona/Mautu and Tiko. This may be due to low water tables and lower temperature bringing down the rate of decomposition of salts to a minimum thereby increasing the alkalinity. The acceptable limit of alkalinity is 200 mg/L and in the absence of alternate water source, alkalinity up to 600 mg/L is acceptable for drinking and therefore, the values recorded were within the permissible range of 200 mg/L (WHO 2011). Carbon dioxide concentrations in groundwater during the study period varied from 0.007 to 169.5 mg/L. Due of a high carbon limitation, the underground

ecosystems are placed in extreme position along a gradient of productivity (Chelius *et al.*, 2009). Therefore, the carbon present in the groundwater of Fako division would be primarily ascribable to the degradation of organic particles by bacteria and to expiration by underground invertebrates. Moreover, the organic carbon contributions in dissolved form constitute the basal resource of the underground trophic networks. The processes of retention, assimilation and degradation of organic matter associated with microbial compartment play a dominating role in the operation of underground ecosystems and the transfer of matter and energy towards higher trophic levels (Foulquier, 2009).

Hardness is one of the very important properties of ground water from a utility point of view for different purposes. In groundwater, hardness is mainly contributed by Bicarbonates, Carbonates, Sulphates and Chlorides of Calcium and Magnesium. Therefore, the principal hardness causing ions are calcium and magnesium (Mohammed and Nur, 2013). WHO (2011) standards given for hardness include 100 mg/L (highest desirable) and 500 mg/L (maximum permissible). This indicated that in terms of the Calcium content the water in Fako is also safe for drinking and for use for other domestic purposes (4.52 ± 3.34mg/L). Magnesium is the most abundant elements in nature and it is a significant member in water hardness, it gives an unpleasant taste to water ((Behailu *et al.,* 2018).

### III.2.2. Faunal characteristics

#### III.2.2.1. Global taxonomic richness

Groundwater can be considered as ecotones, which are characterised by high biodiversity where both groundwater and surface water are present (Gibert, 1991). It was observed during the study period that, Tiko (6293 inds) dominated with the total number of organisms, followed by Owe (3741 inds), Buea (3644 inds), Limbe (3575 inds), Ekona/Mautu (2880 inds) and Muyuka (882 inds) being the least in total number of organisms. The highest number of organisms collected from LW1 could be as a result of its nearness to the sea, whereby, there is lateral transition of marine organisms and intrusion of marine water. The number of taxa on the other hand was different whereby, the town with the highest number of taxa was Buea (46 families), closely followed by Owe and Ekona/Mautu, with 44 families each, then Tiko (33 families), Muyuka (24 families) and the least was Limbe (23 families). The poor taxonomic richness (01 family) collected in BS9 could be due to the absence of a water bed due to the canalization of this point to supply drinking water whereby, organisms are washed away by heavy water current in the rainy season and in the dry season, the speed of water cannot

wash out the organisms in the pipes. Also, given that the taps are always open with water running out from the pipes, very few organisms can survive because they are constantly being washed away by the water currents in the pipes. Stygofauna was dominated by insects (25 %) followed by arachnids (17.7 %), and the lowest families were Hirudinea (0.3 %), Collembola (0.4 %) and Gastropoda (0.5 %).

The organisms collected were made up of a majority of epigean species that are organisms that arrive groundwater accidentally (stygoxens) or organisms that spend part of their vital cycle in groundwater (stygophiles) than hypogean organisms which are groundwater dependent organisms called stygobites. This could be due to the poor nature of protection of these water points, and their direct contact with the terrestrial environment. Groundwater is supplied with water from the phreatic nappe but they are poorly protected from the external milieu and because of this, stygoxens and Stygophiles can find their way into them. In Cameroon, similar results were obtained by Zebaze Togouet *et al.,* (2009), Tuekam Kayo (2013) and Nana Nkengmeni (2015). The same phenomenon has been observed in other African countries like Morocco by Ait Boughrous (2007) and in Algeria by Merzoug *et al.*, (2010). Sinclair Knight (2001) and Murray *et al.,* (2003) had shown that, groundwater is closely interconnected with surface waters and at times groundwater provides the primary source of freshwater to rivers. These linkages and exchanges with surface water bodies, and the fact that aquifers are dynamic ecosystems and not just underground water storage, has led to the concept of groundwater dependent ecosystems (Eamus *et al.,* 2015; Tanya *et al.,* 2017).

The greatest taxonomic richness was observed in the OS1, MS5, ES7, TW8 and LW1. This could be due to the fact that, some of the water points were open (springs), having a water bed and this could have favoured the presence of benthic macroinvertebrates. In fact, springs are natural laboratories for the study of the ecological processes occurring in an aquifer (Mori and Brancelj, 2013; Galassi *et al.,* 2014; Stoch *et al.,* 2016). Natural springs host a variety of species which include taxa that dwell exclusively in the spring mouth known as crenobionts (Cantonati *et al.,* 2011, 2012; Spitale *et al.,* 2012), generalist species that colonize the spring from the surface water known as epigean taxa (Hahn, 2000; Bottazzi *et al.,* 2011), and others that colonize from the underlying aquifer called stygobionts (Galassi *et al.,* 2014; Fattorini *et al.,* 2017). Studies have revealed that, aquatic habitats are complex, and a variety of environmental variables acting at spatial scales regulate the composition and distribution patterns of aquatic macroinvertebrate assemblages in an exclusive manner (Waite and Carpenter, 2000; Bae *et al*. 2011).

### III.2.2.2. Relationship between altitude, physicochemical parameters and biodiversity

A positive correlation was observed between altitude and orthophosphate, dissolved oxygen and pH. The solubility of oxygen in water increases with decreasing temperature and has led to a general perception of high mountain water bodies as being more oxygen rich than lowland water bodies and that, the fauna inhabiting high altitude water bodies have had no need to adapt to critical oxygen conditions (Illies, 1964; Hynes, 1970; Jacobsen, 2003). Other studies have shown that, pH level is lower at higher altitudes and higher at lower altitudes which is different from the results obtained during the study period in Fako. This difference could be due to acid rain, industrial waste, mining, sewage and waste dumping in those areas (Henriques and Nessimian, 2010).

A negative correlation was obtained between altitude and nitrate, temperature, salinity and ammonium ions. This is explained by the fact that, saline water in seas is present only at very low altitudes since sea level is normally zero. Also, infiltration of sea water is only responsible at points where the sea water can get into contact with groundwater. Studies have shown that, temperature decreases as elevation increases and the decline in atmospheric temperature with increasing altitude above sea level is usually identified as the prime factor governing the distribution of plants and animals along altitudinal gradients (Jacobsen, 2003). The increase in the amount of nitrogen compounds at low altitude can be explained by the increase in anthropogenic activities such as agricultural, domestic activities and the increase in urbanization and population at these levels which increases the amount of nutrients in water bodies.

The richness and the diversity of taxa collected in the studied groundwater varied according to the local characteristics of each station and their relations with surface water (Zébazé Togouet *et al.*, 2009). Boulton *et al.*, (2008) and Maurice (2009) had already observed that local factors and pressures acting on water column would be the most significant factors to influence the richness and the diversity of taxa. Early studies between altitude and biodiversity suggested a causal relationship between the higher oxygen concentration in high altitude water bodies and the distribution of aquatic fauna along altitudinal gradients (Jacobsen, 2003) and also between the temperature and biodiversity because the water located at high altitudes had lower temperatures compared to those at low altitudes (Dole-Olivier *et al.*, 2009b; Fattorini *et al.*, 2015). There was a high relationship between altitude and biodiversity in the present study. It was observed that, Insects dominated at high altitudes while Oligochaetes, and Copepods dominated at low altitudes. Altitude was one of the best predictors of the number of taxa in this study but had a negative effect on the number of stygobiotic species collected as

more taxa were collected at high altitudes than at low altitude. This result is different from other studies which showed that, sites at lower altitudes had more aquatic fauna taxa than sites at high altitudes (Barquín and Death, 2009). Lower fauna richness at higher altitudes is a common pattern and has been attributed to glaciation, climatic changes, isolation, and the direct effects of temperature (Ward 1986, Jacobsen *et al.*, 1997).

Altitude seems to set the upper limit to the number of groundwater taxa and habitat stability appears to determine the number of taxa present at a given altitude. The relatively high number of taxa collected at high altitude was due to their open nature, whereby terrestrial and benthic macroinvertebrates could find their way into these water bodies. These open water bodies are generally poor in stygobite species due to hygiene infrastructures that isolate the outlet from the surface since they are regularly exposed to light, thus allowing primary productivity which several terrestrial and benthic macroinvertebrate organisms depend on and are therefore rich in epigean taxa. Non-stygobiotic species show distributional patterns mainly influenced by real-time ecological constraint. Stygobiotic species are highly distributed in groundwater habitats, being the only survivors of ancient lineages that become extinct in surface water bodies (Fattorini *et al.*, 2015).

Copepods are common components of groundwater fauna, and greatly increase the diversity of groundwater communities (Galassi *et al.*, 2009b, 2014). Numerous Copepod taxa (at different hierarchical levels, from species to orders) known exclusively from groundwater are both phylogenetic and distributional relicts occurring in restricted geographical areas and sometimes showing wide distributions as seen in almost all the sampling points (Michaux, 1989; Stock, 1993; Galassi, 2001). The organisms that were very much abundant in most of the sampling points were in most of the polluted stations which were characterized by strong values of nitrate ions, orthophosphate ions and dissolved carbon dioxide, were Diptera larvae such as Chironomidae and Oligochaetes such as Naididae. All these species are known to be particularly resistant to pollution and moreover, these Dipteran larvae are aquatic but their adults are all terrestrial and they come to the water just to breed. They get into groundwater milieu when the groundwater is left open or when they come in direct contact with the water bodies.

The modification of the conditions of the milieu of life such as altitude, morphometric characteristics and physico-chemical variables obtained at the different water points could be the reason for the differences in the taxonomic richness between the different study areas (Hynes, 1970; Brussock and Brown, 1991; Giller and Malmqvist, 1998; Schmera and Eros, 2004). The physico-chemical characteristics of groundwater systems can vary significantly on

temporal and spatial scales, including depth of the water table, groundwater salinity, pH and the availability of organic carbon and oxygen (Humphreys, 2006). Widespread assumptions about the suitability of groundwater systems to support ecosystems based on physico-chemical characteristics may be unfair to the diversity of groundwater habitats sampled to date (Tomlinson and Boulton, 2008). Stygofauna are not necessarily limited by common assumptions about the suitability of the physico-chemical properties of groundwater systems for supporting stygofauna (Schulz *et al.,* 2013). Stygofauna were recorded living in physico-chemically diverse groundwater systems like the case of LW1, including in systems with groundwater ranging in depth from 2.8 in LW1 and 15 metres in TW5. In fact, Glanville *et al.*, (2016) have shown that, stygofauna can be found at depth of 0.1 to 63.2 metres below ground level with electrical conductivity ranging from 11.5 to 54.800 µS/cm, groundwater temperatures ranging from 17.0 to 30.7 degrees Celsius and groundwater pH ranging 3.0 to 11. Information on the wide variance in the physico-chemical properties of known groundwater habitats is valuable in developing our understanding of the characteristics of groundwater systems that support groundwater communities.

Stygofauna taxon richness showed a general negative trend with increasing depth to groundwater, Total Dissolved Solids (TDS) and Electrical Conductivity (EC). Taxon richness was highest in neutral to slightly alkaline pH groundwater systems and in water temperatures between approximately 12.6 and 27 degrees Celsius. Humphreys (2008) considered that groundwater systems in volcanic and sedimentary rocks may tend towards acidic environments that would be less suited to support stygofauna due to constraints imposed by the reducing environment. This is consistent with Fako experience where taxon richness decreases sharply with increasing groundwater acidity and particularly alkalinity. The variations observed in the nature of the soil of Fako division (volcanic, ferralitic and sedimentary rocks) could also explain the differences of richness and diversity observed from one area to another during the study.

The taxonomic richness in the groundwater depends at the same time on the underground species (stygobites) and the surface species (stygoxene and stygophiles) (Dole-Olivier *et al.,* 2009b). In the present study area (Fako division), no significant difference was observed in the richness and diversity of organisms from one season to another but a significant difference was observed between richness and diversity for sampling points. This could be explained by the fact that the reproduction of groundwater fauna is highly sequential, with long life cycles, consequently less affected by variations in the volume of water (Hervant and Malard, 2005). A similar observation had been made in Australia by Glanville *et al.*, (2016), where they did not find any significant difference in the composition, the richness and the

diversity of the fauna of the sites sampled within the seasons but they observed a difference from one sampling point to another. Other studies have shown that, the season of sampling affects the abundance and the diversity of sampled fauna (Hancock and Boulton, 2009; Maurice and Bloomfield, 2012). Indeed, the physiology of underground organisms is less active (Issartel *et al.,* 2005; Issartel, 2007) compared to those of the species close to the surface because of the extreme conditions which prevail in groundwater medium (Morvan, 2013). In addition, abundance, richness, diversity and distribution of taxa in Fako did not follow the evolution of oxygen saturation, which was irregular from one site to another and from one station to another.

The highest percentages of oxygen saturation were observed during the dry season and had an impact on the richness and diversity especially at high altitudes. Groundwater organisms are generally adapted to utilize very little amount of oxygen and a behavioural adaptation in the event of stress is anoxia whereby they can survive in increased anoxia (Hervant and Malard, 2005; Humphreys, 2009). However, in spite of the tolerance with anoxia, oxygen saturation is claimed to be important for occurrences of groundwater fauna, particularly in lower concentrations of groundwater species, whereby the most oxygenated water contains much richer and diversified stygobites (Strayer, 1994; Hakenkamp and Palmer, 2000; Tomlinson and Boulton, 2008; Humphreys, 2009). The groundwater in Fako were moderately oxygenated and could have influenced the distribution of organisms significantly. Comparing oxygen supply and groundwater fauna in several groundwater points, it was observed that most showed a weak correlation between groundwater fauna and oxygen and therefore confirming the fact that stygofauna are adapted to anoxia.

A total of 21014 organisms were collected during the study period, belonging to 04 phyla, 12 classes and 58 families and 62 genus/or sub family. This value is high compared to 21 families obtained by Eberhard *et al.,* (2005) in the Pilberia region in Northern Australia with the domination of Cyclopoida and 08 classes obtained by Heide *et al.,* (2010) in Euskirchen Cologne in Northern Rhine Westphalia Germany. The value of the results obtained is lower, compared to the 100 taxa obtained by Tuekam Kayo (2013) in groundwater of Centre and Littoral regions in Cameroon. The class Insecta dominated during the study period in terms of number of organisms. The highest taxonomic richness was obtained in OS2, OS3, MS5 ES7, TW7, TW8 and LW1 which belonged to group I and ES7 in group (ES7), following the division based on altitude. This could be explained by the stability of the water bodies, because this water is seldomly used and thus varied little with time. Stability of water bodies is favourable to the reproduction and development of larvae forms which allow the structuring and the cohabitation of a trophic chain and a greater number of surfaces or epigean species (Gibert and

Deharveng, 2002; Zébazé Togouet, 2004). Certain organisms such as Potomonautidae, Ephemerellidae, Atyidae and Hydrophylidae were abundant in the sampling points whose quality was good since the organisms are sensitive to pollution and can only survive in well oxygenated areas and turn to disappear when the oxygen level becomes low due to organic pollution. It was also observed that, some sampling points such as LW3 (85 inds), LW4 (75 inds), MW1 (65 inds), MW4 (94 inds), with low altitudes had small number of organisms collected from them. This could be due to the fact that, many organisms cannot survive in an environment with very little oxygen and total darkness and they turn to escape with time to surface water milieu and also, only groundwater dependent organisms can survive in such milieu with harsh conditions and they are usually very few in numbers, compared to epigean species. At low altitude, the following organisms were collected; Stenasellidae, Dysticidae, Entomobryiidae and Isotomidae. One of the family is a groundwater dependent family meaning that, this family can only be found and can survive in groundwater. Pedology would also play a significant role in the richness and the diversity of the underground species of Fako, the size of soil particles and the porosity which could all have an effect on the size, the abundance and the richness of the species collected in groundwater (De Bovee *et al.,* 1995).

### III.2.2.3. Taxonomic richness of stygobites and altitude

Out of these 58 taxa (families) that were collected during the sampling period, 04 were stygobitic families, represented by Stenasellidae (114 inds), Cirolanidae (7 inds) Darwinulidae (98 inds) and Asellidae (11 inds). This is in accordance with the suggestion of Zebaze Togouet *et al*. (2011) about a positive relation between a high aquatic biodiversity and the presence of stygobite species. The number of stygobitic families collected in relation to the total number of families is relatively small. This small number could probably be linked to the physicochemical properties of the water bodies since the values of parameters that are indicators of organic pollution were high in most of the sampling points. Groundwater ecosystems are generally poorer in nutrients and oxygen than surface water ecosystems (Di Lorenzo *et al.,* 2013, 2015; Stoch *et al.,* 2016; Iepure *et al.,* 2017; Galassi *et al.,* 2017). In order to reduce energetic costs, groundwater ectotherms have evolved metabolic rates that are lower than those of their close epigean relatives (Issartel *et al.,* 2005). It was also observed that, stygobitic organisms belonging to the order Isopoda (Stenasellidae, Asellidae, Cirolanidae) were found in sampling points belonging to group I of the altitude grouping which are those sampling points with low altitudes. This could be because at low altitudes, the phenomenon of lateral transition of stygobites is possible (movement of stygobites from marine water to groundwater) and these

milieus provide a better habitat for groundwater species than those at high altitudes such as darkness, low oxygen and lack of photoperiod whereby stygobites are better adapted. It could also be due to the absence of many terrestrial and benthic macro invertebrates as compared to the high altitudes that could colonize the habitat and use up nutrients made available for stygobites, thereby causing the small number that were identified.

It is worth noting that, the families Stenasellidae, Asellidae and Cirolanidae belong to Phylum Arthropoda, Class Crustacea, and Order Isopoda. The family Stenasellidae was observed and described in Cameroon for the first time by Zebaze Togouet (2004, 2006) in Yaounde and later other genus and species were also described by Tuekam Kayo (2013) in the Littoral and Centre regions of Cameroon. In Fako division, precisely in the town of Limbe, it was observed by Chinche (2013) and this family constitute part of the biodiversity in Fako division in other towns as was observed in this study. The organisms presented the same characteristics described by Zebaze Togouet (2004) and Zebaze Togouet *et al.*, (2013) such as having different sizes, with more abdominal and cephalic appendages which are different from those found in other countries and may probably constitute a new species as he suggested in 2004. This suggestion was later on confirmed by Zebaze Togouet *et al.*, (2013). They have an entirely pink body in fresh samples and whitish body in specimens preserved in alcohol, regular in form and similar to individuals of the other species of their kind, with lateral margins on a parallel body. The tegument pigmentation is null, a diffuse pink pigment is observable in its tissues and the body is moderately flattened dorso-ventrally. A total of 114 Stenasellidae were collected in six out of the ten sampling points in Tiko (TW3, TW5, TW7, TW8, TW9 and TW10), in four out of the five in Muyuka (MW2, MW3, MW4 and MW5) and in two out of the three points sampled in Owe (OS1 and OS2).

The second stygobite family that was sampled during the study period belonged to the family Cirolanidae and a total of 07 of these organisms were collected during the study period in Limbe and Tiko (TW5 (01) and LW6 (06)). Generally, the organisms have a robust body which is five times longer than large, unpigmented in both fresh and preserved specimen, blind and flattened dorso-ventrally. They are bilaterally symmetrical with parallel borders and the female organisms are more robust and larger than the male organisms. The third stygobite family Asellidae was collected in Tiko, Muyuka, Ekona Mautu and Buea. It was also collected by Tuekam Kayo (2007) in Yaounde and the last stygobitic family was Darwinulidae. All these organisms have all the characteristics to live and survive in groundwater milieu such as, absence or reduced eyes, lack of pigments and elongated appendages. No significant difference as observed between stygobites and season but a significant difference was observed between

stygobites and sampling points (Asellidae $p = 0.002$, Stenasellidae $p= 0.006$, Cirolanidae $p= 0.002$ and Darrwinulidae $p = 0.004$) and between stygobites and sampling towns ($p < 0.05$ for Asellidae, Stenasellidae, Cirolanidae and Darwinulidae).

# CONCLUSION, RECOMMANDATIONS AND PERSPECTIVES

The impact of altitude and physicochemical parameters on the biodiversity in groundwater in Fako division, south west region of Cameroon has been studied and brought out the fact that, groundwater milieu has an important role to play which can only be gotten from the knowledge of its biodiversity which is necessary to be conserved, together with its quality. A total of thirty-three stations were studied in the following towns of Fako division; Owe, Muyuka, Ekona/Mautu, Buea, Tiko and Limbe. The water of these stations is used by the population for different purposes and more importantly, they serve as drinking water sources to these inhabitants, whereby the inhabitants use the water without prior treatment.

The physicochemical analysis of variables showed that, these groundwater found at low altitudes in Fako had high water temperatures, slightly acidic pH, due to the volcanic nature of the soils in this area, high levels of turbidity, high orthophosphate levels, good dissolved oxygen level, lowly mineralization except for the sampling stations near the sea (7 and 8 m), with high organic pollution. Based on all these results, it can conveniently be concluded that, the groundwater of these low altitude in Fako is subjected to anthropogenic pollution coming from infiltration of sewage effluent discharges, run-off from informal settlements and agricultural activities such as livestock farming and crop cultivation which requires the excessive use of fertilizers and chemical pesticides. This is due to the nearness of this low altitude water points to the settlement areas and to the plantations found in these areas.

The groundwater points that were situated at high altitudes, had very good oxygenation compared to the low altitude points and the results obtained showed that, these groundwaters had high levels of turbidity, had low temperatures, almost neutral pH, lowly mineralized, had higher levels of orthophosphates compared to the low altitudes and low organic pollution. Most of these points were located in less perturbed areas whereby, the population had to walk long distances to fetch water though some were also found close to the settlement areas. There is still need for these waters to be treated before consumption since the level of orthophosphate is high due to the presence of farmlands surrounding most of these water bodies whereby the farmers use agricultural fertilizers to improve their crop yield. Physicochemical parameters were influenced by altitude since the water quality increased with increase in altitude and became poorer with decrease in altitude.

The present study showed that, the aquatic fauna is averagely rich with a total of 58 taxa collected during the study period. The distribution and abundance of groundwater fauna families and genera were influenced by physicochemical conditions and altitude, characteristics of the groundwater stations. Changes in physical nature altered the fauna structure of both high and low altitude water points. This could directly affect the diversity and distribution of other

fauna such benthic macro invertebrates that depend upon these groundwater systems for their survival especially those found in groundwater dependent ecosystems like springs.

The study also showed the possible influence of abiotic factors and anthropogenic contaminants on the diversity of macro-fauna. The high-altitude (group II, III and IV) groundwater bodies were the most diversified in both the rainy and dry season during the study period. The population in these points was dominated by epigean taxa (Chironomidae, Cyprididae, Atyidae, Ephemeroptera) whereas hypogean taxa were very few (Asellidae, Stenasellidae, Cirolanidae, Darwinulidae). This is linked to the good ecological state of these waters (good vegetation, high oxygen concentration, low temperatures, low mineralization, little anthropogenic pollutant). The population in the low altitude stations were also dominated by epigean taxa, dominated by Crustaceans (Cyclopidae, Naididae, Cyprididae, Limnesiidae and Cytherididae). These taxa were recorded in the stations that were of poor physicochemical quality and thereby not acceptable for consumption. The groundwater dependent organisms (stygobites) were generally very few compared to non stygobites. They were dominated by Asellidae, Stenasellidae, Darwinulidae and Cirolanidae. These organisms were collected mostly in sampling points with altitude ranging from 7 m to 600 m (group I and group II). The sampling points were characterized by high electric conductivity, high salinity and low amounts of parameters that are indicators of organic pollution. The results show that, there is an important pollution of groundwater which limits the presence of stygobitic species as seen in the abundance of pollution resistant species such as copepods, ostracods and oligochaetes compared to pollution sensitive organisms like stygobites.

## RECOMMENDATIONS

Based on the results obtained during the study period, we recommend to the inhabitants of the different study towns to; ameliorate the hygienic conditions around their water points, avoiding the throwing of household waste around the water points, treat their water locally either by boiling or by using the SODIS (SOlar DISinfection) method before using it for their various household activities including consumption and to properly conserve the water at home to avoid infections, build wells that respect the standards of WHO such as far from latrines, correct elevation above ground level and they should be well covered to prevent contamination from rain water and terrestrial organisms that might accidentally fall into the wells.

To the administration of Fako division, we recommend that they should put in place campaigns for the cleaning, treatment and protection of the water points before use by the population, build sewage treatment plants for the purification of sewage from household and

industries before their disposal, rehabilitation of water points that have been constructed by certain NGOs that respected the WHO standard and provide hand pumps so as to better protect the water and reduce illnesses linked to water contamination. The ministry responsible for the provision of water to the population can increase their network by providing safe drinking water to the population either by building boreholes or wells with hand pumps, put in place urban waste management plants, protection and rehabilitation of the already existing hydro systems and educate farmers on the proper use of pesticides in order to prevent them from contaminating their drinking water points.

**PERSPECTIVES**

At the end of this research work, future studies could look into the following aspects in order to complete this study: 1) The impact of heavy metals and microplastics on the distribution and repartition of groundwater fauna. 2) Description based on morphology, anatomy and molecular structure of the groundwater dependent organisms collected so as to be able to describe and identify them right up to species level and add up to those that have been collected in other areas of Cameroon. This will help us generate our own database of stygobites in Cameroon and to know how to better conserve them. 3) Include other divisions of the South West region and link the integrated environmental groundwater and surface water quality approach including water chemistry (physicochemical quality), Stygofaunal-based bio monitoring and ecotoxicology to other urban and rural towns of the region. 4) Deduce the origin of stygobites at low altitudes and study new species.

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# APPENDIX

**Appendix I:** Spearman correlation between biodiversity and physicochemical parameters in Fako

| Parameter | Limne | Bdelli | Naidi | Isotom | Atyi | Potamon | Aselli | Cypri | Darwin | Cyclo | Gordia | Chiro | Cerato | Psycho | Simul | Dolicho | Ephy | Tipul |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS | .151 | -.080 | .108 | -.081 | .062 | -.024 | .215 | -.006 | .051 | -.048 | -.072 | .145 | -.061 | -.087 | -.066 | -.056 | -.013 | .101 |
| Turb | .028 | -.050 | .169 | -.017 | .016 | .002 | .176 | -.043 | .113 | -.015 | -.004 | .011 | -.170 | -.184 | -.187 | -.169 | -.246* | -.075 |
| Cond | -.123 | .036 | .313* | .005 | -.055 | -.195 | -.134 | -.054 | .141 | .041 | -.054 | .038 | -.282* | -.266* | -.298* | -.227 | -.255* | -.238 |
| Nitra | -.408** | .099 | .346** | .259* | -.323** | -.249* | -.177 | -.216 | -.029 | .408** | -.360** | -.472** | -.194 | -.304* | -.418** | -.452** | -.055 | -.192 |
| Amm | -.148 | .321** | .140 | -.114 | -.153 | -.260* | -.099 | .125 | .028 | .216 | -.066 | -.202 | -.251* | -.115 | -.140 | -.014 | .067 | -.153 |
| Phos | .182 | -.230 | -.046 | -.170 | .167 | .109 | .154 | -.006 | .011 | -.222 | .062 | .201 | -.066 | .225 | .263* | -.014 | -.053 | .122 |
| $O_2$ (%) | .385** | .180 | -.500** | -.293* | .475** | .309* | .262* | .006 | -.260* | -.397** | .385** | .357** | .178 | .266* | .281* | .393** | .213 | .050 |
| pH | .348** | -.056 | -.200 | -.295* | .386** | .307* | .095 | .338** | -.057 | -.304* | .310* | .365** | .153 | .341** | .321** | .383** | .197 | .085 |
| Sal | -.126 | .045 | .300* | .077 | -.078 | -.147 | -.106 | -.094 | .096 | .115 | -.053 | -.042 | -.202 | -.155 | -.289* | -.263* | -.285* | -.126 |
| Temp | -.664** | .331** | .417** | .211 | -.607** | -.555** | -.317** | -.052 | .100 | .677** | -.332** | -.626** | -.393** | -.579** | -.466** | -.402** | -.288* | -.431** |
| Alka | -.024 | -.032 | .074 | .234 | -.008 | .019 | -.072 | .156 | .192 | .084 | -.037 | -.003 | .149 | -.129 | -.004 | -.104 | .100 | .007 |
| Oxida | .123 | .182 | -.058 | -.135 | .064 | -.044 | -.115 | -.197 | -.212 | -.012 | .047 | -.106 | -.136 | -.011 | -.066 | -.013 | -.004 | -.082 |
| $CO_2$ | -.167 | .228 | .080 | -.076 | -.021 | -.240 | -.183 | -.116 | -.020 | .163 | .044 | -.037 | -.328** | -.112 | -.050 | .007 | -.127 | -.281* |
| Hard | .039 | -.005 | -.071 | .125 | -.032 | .001 | -.010 | .001 | .054 | .103 | -.082 | .101 | .188 | -.083 | -.128 | -.126 | .039 | -.111 |

| Parameter | Elmi | Psephe | Perli | Baeti | Lepto | Hepta | Epheme | Corix | Velii | Nauco | Hydrop | Polycen | Hydropti | Coenag | Aesh | Formi | Cram |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS | .045 | -.057 | -.100 | -.056 | -.065 | -.025 | -.099 | -.031 | -.015 | -.057 | .116 | .058 | .161 | .019 | -.075 | .178 | .181 |
| Turb | -.083 | .041 | -.031 | -.110 | -.205 | -.123 | -.206 | -.153 | .017 | -.013 | -.031 | -.092 | .008 | -.093 | -.055 | .187 | .212 |
| Cond | -.319** | -.081 | -.169 | -.071 | -.138 | -.160 | -.144 | -.081 | -.124 | -.020 | -.062 | -.297* | -.022 | -.054 | -.019 | .203 | .111 |
| Nitra | -.306* | -.302* | -.283* | -.293* | -.149 | -.319** | -.140 | -.275* | -.400** | -.259* | -.117 | -.210 | -.323** | -.162 | -.280* | .159 | -.074 |
| Amm | -.054 | -.234 | -.183 | -.084 | -.031 | -.181 | .015 | .011 | -.109 | -.263* | .024 | .032 | .052 | -.058 | -.221 | .414** | -.154 |
| Phos | .116 | .117 | .042 | .011 | .043 | .156 | -.103 | .058 | .228 | .223 | .199 | .065 | .085 | .121 | .307* | -.091 | .313* |
| $O_2$ (%) | .405** | .211 | .306* | .555** | .378** | .465** | .318** | .249* | .147 | .179 | .161 | .118 | .339** | .265* | .173 | -.416** | .137 |
| pH | .428** | .270* | .366** | .471** | .306* | .399** | .311* | .205 | .223 | .115 | .128 | .201 | .288* | .177 | .208 | -.305* | .086 |
| Sal | -.369** | -.046 | -.288* | -.171 | -.150 | -.221 | -.164 | -.136 | -.087 | .042 | -.001 | -.293* | -.125 | -.016 | .056 | .184 | .088 |
| Temp | -.603** | -.336** | -.400** | -.451** | -.441** | -.631** | -.286* | -.316** | -.343** | -.347** | -.420** | -.232 | -.365** | -.302* | -.260* | .581** | -.323** |
| Alka | -.045 | .144 | -.134 | -.180 | -.092 | -.093 | -.160 | .060 | -.066 | .211 | -.011 | -.048 | -.197 | -.102 | -.132 | -.101 | .100 |
| Oxida | .062 | -.028 | .012 | .167 | .184 | .098 | .272* | .099 | .060 | -.108 | .123 | -.052 | .159 | .249* | .147 | .185 | -.096 |
| $CO_2$ | -.092 | -.037 | -.050 | .165 | -.064 | -.136 | .058 | -.031 | .078 | -.133 | -.225 | -.004 | .189 | .192 | -.024 | .284* | -.242 |
| Hard | .082 | .067 | -.108 | -.092 | -.039 | .067 | -.170 | -.015 | -.060 | .038 | -.041 | -.086 | -.039 | -.201 | -.085 | -.129 | .269* |

** Correlation is significant at threshold 0.01: *correlation is significant at threshold 0.05

**Appendix 2: minimum, maximum annual mean and standard deviation of physicochemical parameters measured during the study period in the groundwater of Fako**

| Sampling points | | SS | Turbidity | Electric Conductivity | Nitrate ions | Ammonium ions | Phosphate ions | Dissolved $O_2$ | pH | Salinity | Temperature | Alkalinity | Oxidability | $CO_2$ | Total hardness |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BS9 | Mean ±Standard dev | 13.7±11.6 | 19.0±17,6 | 1059.0±1094.6 | 0.70±0.63 | 0.004±0.002 | 0.78±0.26 | 72.2±14.8 | 6.83±0.47 | 0.12±0.04 | 20..6±1.6 | 6.0±1.4 | 2.2±0.8 | 1.78±2.1 | 73.9±41.8 |
| | Maximum | 2.0 | 31.5 | 1833.00 | 1.150 | .0055 | 0.9700 | 82.75 | 7.170 | 0.155 | 21.80 | 7.000 | 2.76 | 3.290 | 103.56 |
| | Minimum | 5.5 | 6.5 | 28.00 | 0.255 | .0025 | 0.5995 | 61.75 | 6.495 | 0.095 | 19.55 | 5.000 | 1.58 | ,275 | 44.42 |
| ES6 | Mean ±Standard dev | 12.0±9.2 | 14.3±3.9 | 282.5±18.4 | 0.5±0.45 | 0.003±0.004 | 2.18±0.22 | 68.0±9.4 | 6.61±0.65 | 0.14±0.00 | 21.05±1.76 | 4.0±1.41 | 2.7±0.2 | 6.97±9.3 | 114.6±80.1 |
| | Maximum | 18.5 | 17.0 | 295.5 | 0.9 | 0.0070 | 2.3450 | 74.70 | 7.080 | 0.140 | 22.30 | 5.000 | 2.86 | 13.575 | 171.3 |
| | Minimum | 5.5 | 11.5 | 269.5 | 0.205 | 0.0005 | 2.0280 | 61.40 | 6.150 | 0.140 | 19.80 | 3.000 | 2.56 | .375 | 58.03 |
| LW1 | Mean ±Standard dev | 1.8±8.13 | 18.8±14.5 | 526.3±143.2 | 1.02±0.03 | 0.02±0.02 | 1.04±0.72 | 55.62±0.17 | 6.63±0.09 | 1.32±1.58 | 26.1±0.17 | 11.0±0.00 | 3.7±1.9 | 4.42±5.9 | 77.15±29.0 |
| | Maximum | 16.5 | 29.0 | 627.50 | 1.055 | .0280 | 1.56 | 55.75 | 6.700 | 2.445 | 26.30 | 11.000 | 5.036 | 8.570 | 97.65 |
| | Minimum | 5.0 | 8.5 | 425.00 | 1.000 | .0020 | 0.53 | 55.50 | 6.565 | 0.210 | 26.05 | 11.000 | 2.37 | .275 | 56.64 |
| LW2 | Mean ±Standard dev | 9.5±7.1 | 20.8±14.5 | 1156.0±132.93 | 1.13±0.11 | 0.011±0.001 | 1.95±1.041 | 56.3±0.18 | 7.17±0.45 | 1.52±1.41 | 27.13±0.81 | 10.5±0.71 | 3.06±2.09 | 5.1±6.62 | 27.27±4.86 |
| | Maximum | 14.5 | 31.0 | 1250.00 | 1.200 | .0120 | 2.6870 | 56.40 | 7.480 | 2.510 | 27.70 | 11.000 | 4.54250 | 9.775 | 30.70 |
| | Minimum | 4.5 | 10.5 | 1062.00 | 1.050 | .0100 | 1.2150 | 56.15 | 6.850 | .520 | 26.55 | 10.000 | 1.58000 | .400 | 23.83 |
| LW3 | Mean ±Standard dev | 20.8±6.01 | 25.75±6.72 | 99.5±0.71 | 0.9±0.63 | 0.02±0.01 | 0.25±0.03 | 54.9±2.7 | 6.13±0.09 | 0.07±0.04 | 26.4±0.6 | 6.8±4.6 | 3.35±0.55 | 0.96±0.79 | 66.5±28.3 |
| | Maximum | 25.0 | 30.5 | 100.00 | 1.300 | .0230 | .2670 | 56.75 | 6.190 | .090 | 26.80 | 10.000 | 3.75250 | 1.530 | 86.61 |
| | Minimum | 16.5 | 21.0 | 99.00 | .405 | .0090 | .2250 | 53.00 | 6.060 | .040 | 26.00 | 3.500 | 2.96250 | .400 | 46.53 |
| LW4 | Mean ±Standard dev | 3.0±3.54 | 8.3±4.6 | 242.3±26.51 | 1.5±0.5 | 0.01±0.005 | 10.9±14.5 | 54.0±1.91 | 5.83±0.23 | 0.24±0.2 | 27.0±0.21 | 4.5±2.12 | 3.6±1.95 | 1.5±1.3 | 56.6±6.62 |
| | Maximum | 5.5 | 11.5 | 261.00 | 1.850 | .0095 | 21.0840 | 55.35 | 5.985 | .355 | 27.15 | 6.00 | 4.93 | 2.36 | 61.24 |

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minimum | 0.5 | 5.0 | 223.50 | 1.155 | .0030 | .6400 | 52.65 | 5.665 | .125 | 26.85 | 3.00 | 2.17 | .575 | 51.87 |
| LW5 | Mean ±Standard dev | 10.0±9.192 | 20.3±18.74 | 1602.3±1581.4 | 2.05±1.67 | 0.01±0.01 | 1.24±1.6 | 55.23±1.52 | 6.3±0.6 | 0.3±0.014 | 27.13±0.53 | 7.5±4.95 | 3.604±2.025 | 5.95±7.502 | 75.98±76.11 |
| | Maximum | 16.5 | 33.5 | 2720.50 | 3.200 | .0130 | 2.3735 | 56.30 | 6.715 | .295 | 27.50 | 11.000 | 5.03625 | 11.260 | 129.80 |
| | Minimum | 3.5 | 7.0 | 484.00 | .900 | 0.0025 | ,1150 | 54.15 | 5.880 | .275 | 26.75 | 4.000 | 2.17250 | .650 | 22.17 |
| BS11 | Mean ±Standard dev | 10.0±1.41 | 10.5±1.414 | 79.5±0.71 | 0.20±0.3 | 0.01±0.001 | 0.64±0.07 | 68.63±12.06 | 7.3±0.65 | 0.03±,01 | 18.2±2.7 | 5.0±1.41 | 2.52±1.33 | 3.43±4.43 | 43.96±21.94 |
| | Maximum | 11.0 | 11.5 | 80.00 | .405 | .0075 | .6930 | 77.15 | 7.715 | .035 | 20.05 | 6.0 | 3.45 | 6.560 | 59.47 |
| | Minimum | 9.0 | 9.5 | 79.00 | .000 | .0060 | .5950 | 60.10 | 6.800 | .025 | 16.30 | 4.0 | 1.58 | .300 | 28.45 |
| BS10 | Mean ±Standard dev | 8.5±2.12 | 13.5±2.12 | 254.3±6.01 | 0.20±0.21 | 0.005±0.007 | 1.13±1.05 | 62.7±5.02 | 6.8±0.7 | 0.1±0.04 | 22.1±1.7 | 6.5±2.12 | 2.91±0.8 | 1.03±0.81 | 52.7±25.62 |
| | Maximum | 10.0 | 15.0 | 258.50 | .350 | .0105 | 1.8750 | 66.20 | 7.210 | 0.120 | 23.25 | 8.0 | 3.45625 | 1.605 | 70.81 |
| | Minimum | 7.0 | 12.0 | 250.00 | 0.055 | 0.00 | 0.38 | 59.10 | 6.290 | 0.070 | 20.90 | 5.0 | 2.37 | 0.450 | 34.58 |
| MW1 | Mean ±Standard dev | 9.25±3.88 | 19.25±7.42 | 136.0±9.19 | 1.85±0.92 | 0.009±0.01 | 0.77±0.60 | 61.5±3.9 | 5.6±0.07 | 0.08±0.007 | 26.17±3.14 | 4.00±1.41 | 2.96±0.28 | 1.43±1.56 | 71.92±43.95 |
| | Maximum | 12.0 | 24.5 | 142.50 | 2.500 | 0.01 | 1.20 | 64.35 | 5.650 | 0.085 | 28.40 | 5.000 | 3.16 | 2.535 | 103,0088 |
| | Minimum | 6.5 | 14.0 | 129.50 | 1.205 | 0.002 | 0.342 | 58.70 | 5.550 | 0.075 | 23.95 | 3.000 | 2.76 | 0.325 | 40.41 |
| MW2 | Mean ±Standard dev | 9.0±4.24 | 10.0±0.00 | 455.7±66.82 | 0.77±0.39 | 0.01±0.01 | 0.76±0.70 | 61.5±6.01 | 4.66±0.02 | 0.19±0.007 | 26.1±2.08 | 3.01±2.81 | 2.72±0.06 | 9.64±13.24 | 112.26±80.89 |
| | Maximum | 12.0 | 10.0 | 503.00 | 1.055 | 0.025 | 1.2600 | 65.75 | 4.675 | 0.200 | 27.65 | 5.000 | 2.76 | 19.00 | 169.467 |
| | Minimum | 6.0 | 10.0 | 408.50 | 0.500 | 0.001 | 0.2680 | 57.25 | 4.645 | 0.190 | 24.70 | 1.025 | 2.66 | 0.275 | 55.067 |
| MW3 | Mean ±Standard dev | 7.00±2.121 | 15.25±8.83 | 501.7±48.4 | 3.22±0.18 | 0.001±0.00 | 0.38±0.31 | 62.52±1.73 | 4.64±0.50 | 0.18±0.04 | 25.90±2.47 | 4.01±2.81 | 2.66±0.41 | 4.00±5.03 | 41.50±24.64 |
| MW4 | Maximum | 8.5 | 21.5 | 536.00 | 3.355 | 0.001 | 0.60 | 63.75 | 5.00 | 0.22 | 27.65 | 6.00 | 2.96 | 7.56 | 58.93 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minimum | 5.5 | 9.0 | 467.50 | 3.100 | 0.001 | 0.16 | 61.30 | 4.28 | 0.155 | 24.15 | 2.025 | 2.37 | 0.450 | 24.08 |
| | Mean ±Standard dev | 12.0±1.41 | 30.25±11.66 | 163.5±4.94 | 2.01±0.05 | 0.01±0.01 | 0.71±0.61 | 57.10 ±2.82 | 5.41±0.15 | 0.07±0.03 | 25.65±3.88 | 2.012±0.02 | 2.52±0.76 | 1.35±1.45 | 37.37±13.62 |
| | Maximum | 13.0 | 38.5 | 167.00 | 2.050 | 0.02 | 1.14 | 59.10 | 5.515 | 0.095 | 28.40 | 2.025 | 3.06 | 2.385 | 47.009 |
| | Minimum | 11.0 | 22.0 | 160.00 | 1.970 | 0.0010 | 0.2790 | 55.10 | 5.300 | 0.045 | 22.90 | 2.000 | 1.97500 | 0.325 | 27.740215 |
| | Mean ±Standard dev | 17.7±3.8 | 24.2±6.71 | 250.5±187.38 | 0.45±0.56 | 0.03±0.03 | 0.42±0.05 | 61.07±2.79 | 4.83±0.123 | 0.04±0.01 | 25.9±2.96 | 3.51±0.68 | 2.32±0.21 | 4.09±5.47 | 66.16±5.46 |
| MW5 | Maximum | 20.5 | 29.0 | 383.0 | 0.850 | 0.05 | 0.47 | 63.05 | 4.925 | 0.055 | 28.00 | 4.000 | 2.46875 | 7.965 | 70.032110 |
| | Minimum | 15.0 | 19.5 | 118.0 | 0.055 | 0.007 | 0.38 | 59.10 | 4.750 | 0.040 | 23.80 | 3.025 | 2.17250 | 0.225 | 62.299680 |
| BS13 | Mean ±Standard dev | 7.75±1.06 | 14.5±3.53 | 242.25±3.181 | 0.62±0.38 | 0.003±0.003 | 0.62±0.21 | 69.7±11.31 | 7.01±0.68 | 0.11±0.02 | 20.75±0.84 | 6.50±0.71 | 2.32±0.77 | 2.27±2.75 | 30.72±13.37 |
| | Maximum | 8.5 | 17.0 | 244.50 | 0.900 | 0.0065 | 0.7730 | 77.70 | 7.495 | 0.125 | 21.35 | 7.000 | 2.86375 | 4.220 | 40.181778 |
| | Minimum | 7.0 | 12.0 | 240.00 | 0.350 | 0.0010 | 0.4750 | 61.70 | 6.520 | 0.095 | 20.15 | 6.000 | 1.77750 | 0.325 | 21.266487 |
| MS4 | Mean ±Standard dev | 9.50±0.71 | 17.50±3.53 | 320.0±0.00 | 0.32±0.03 | 0.007±0.007 | 1.17±1.067 | 61.85±7.28 | 6.44±0.06 | 0.15±0.007 | 22.8±0.14 | 4.500±0.71 | 3.21±0.21 | 2.66±3.41 | 60.11±61.63 |
| | Maximum | 10.0 | 20.0 | 320.00 | 0.350 | 0.0130 | 1.9250 | 67.00 | 6.490 | 0.160 | 22.90 | 5.000 | 3.35750 | 5.075 | 103.690895 |
| | Minimum | 9.0 | 15.0 | 320.00 | 0.300 | 0.0020 | 0.4160 | 56.70 | 6.400 | 0.150 | 22.70 | 4.000 | 3.06125 | 0.250 | 16.530104 |
| OS1 | Mean ±Standard dev | 11.7±3.18 | 16.0±6.36 | 524.50±528.21 | 0.80±0.42 | 0.006±0.001 | 0.51±0.05 | 63.85±3.32 | 6.97±0.61 | 0.06±0.02 | 18.90±5.37 | 4.50±0.71 | 3.06±0.139 | 10.57±15.23 | 33.87±33.00 |
| | Maximum | 14.0 | 20.5 | 898,00 | 1.100 | 0.0070 | 0.5500 | 66.20 | 7.400 | 0.075 | 22.70 | 5.000 | 3.16 | 0.200 | 57.213 |
| | Minimum | 9.5 | 11.5 | 151,00 | 0.500 | 0.0050 | 0.4715 | 61.50 | 6.540 | 0.050 | 15.10 | 4.000 | 2.962 | 21.35 | 10.54 |
| OS2 | Mean ±Standard dev | 9.25±6.01 | 8.750±0.35 | 164.47±18.34 | 0.68±0.44 | 0.33±0.45 | 0.34±0.01 | 68.85±5.58 | 7.02±0.66 | 0.05±0.01 | 18.87±5.34 | 3.50±0.71 | 3.55±1.39 | 0.91±0.86 | 71.68±1.55 |
| | Maximum | 13.5 | 9.0 | 177.45 | 1.000 | 0.6505 | 0.3545 | 72.80 | 7.490 | 0.065 | 22.65 | 4.000 | 4.54 | 1.53 | 72.78 |
| | Minimum | 5.0 | 8.5 | 151.50 | 0.375 | 0.0050 | 0.3400 | 64.90 | 6.555 | 0.045 | 15.10 | 3.000 | 2.56 | 0.30 | 70.58 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| OS3 | Mean ±Standard dev | 8.25±6.01 | 14.75±0.35 | 238.75±6.01 | 0.37±0.04 | 0.00±0.00 | 94.92±133.37 | 67.22±7.74 | 7.1±0.71 | 0.12±0.007 | 19.30±5.72 | 8.50±2.1 | 2.56±0.27 | 1.89±2.57 | 108.27±65.51 |
| | Maximum | 12.5 | 15.0 | 243.00 | 0.400 | 0.0010 | 189.22. | 72.70 | 7.615 | 0.120 | 23.35 | 10.00 | 2..76 | 3.72 | 154.59 |
| | Minimum | 4.0 | 14.5 | 234.50 | 0.350 | 0.0000 | 0.6050 | 61.75 | 6.600 | 0.110 | 15.25 | 7.00 | 2.370 | 0.08 | 61.94 |
| MS5 | Mean ±Standard dev | 11.0±6.36 | 16.5±8.48 | 310.75±1.76 | 1.52±1.03 | 0.27±0.39 | 1.08±0.7983 | 72.12±10.9 | 6.81±.710 | 0.147±0.003 | 20.77±2.79 | 7.000±0.000 | 3.85±1.536 | 3.667±4.691 | 177.6±212.8 |
| | Maximum | 15.5 | 22.5 | 312.00 | 2,250 | 0.5530 | 1.6500 | 79.90 | 7.320 | 0.150 | 22.75 | 7.000 | 4.93750 | 6,985 | 328.19 |
| | Minimum | 6.5 | 10.5 | 309.50 | 0.800 | 0.0010 | 0.5210 | 64.35 | 6.315 | 0.145 | 18.80 | 7.000 | 2.76500 | 0.350 | 27.19 |
| ES7 | Mean ±Standard dev | 8.75±2.47 | 15.75±10.96 | 288.0±19.79 | 0.34±0.0742 | 0.001±0.002 | 1.864±0.544 | 61.500±1.272 | 6.77±0.403 | 0.142±0.003 | 20.5±2.05 | 9.50±7.77 | 2.81±0.209 | 82.84±116.3 | 42.27±8.43 |
| | Maximum | 10.5 | 23.5 | 302.00 | 0.400 | 0.003 | 2.2495 | 62.40 | 7.06 | 0.145 | 22.00 | 15.00 | 2.96 | 165.11 | 48.23 |
| | Minimum | 7.0 | 8.0 | 274.00 | 0.295 | 0.000 | 1.480 | 60.60 | 6.49 | 0.140 | 19.10 | 4.00 | 2.66 | 0.57 | 36.31 |
| TW6 | Mean ±Standard dev | 7.75±5.30 | 13.0±9.19 | 234.2±47.73 | 1.40±0.4242 | 0.024±0.03 | 0.486±0.206 | 52.72±4.702 | 5.93±0.417 | 0.115±0.028 | 26.7±1.27 | 9.00±4.24 | 2.76±0.000 | 2.95±3.39 | 27.49±6.756 |
| | Maximum | 11.5 | 19.5 | 268.00 | 1.700 | 0.047 | 0.632 | 56.05 | 6.225 | 0.135 | 27.60 | 12.00 | 2.765 | 5.350 | 32.27 |
| | Minimum | 4.0 | 6.5 | 200.50 | 1.100 | 0.002 | 0.340 | 49.40 | 5.635 | 0.095 | 25.80 | 6.00 | 2.765 | 0.550 | 22.72 |
| TW1 | Mean ±Standard dev | 13.00±7.77 | 17.25±9.54 | 297.7±91.57 | 1.08±0.194 | 0.005±0.007 | 0.380±0.297 | 56.00±4.808 | 6.68±0.5939 | 0.125±0.007 | 26.60±0.777 | 5.50±0.707 | 1.97±0.000 | 1.592±1.580 | 95.91±25.06 |
| | Maximum | 18.5 | 24.0 | 362.50 | 1.225 | 0.0105 | 0.5905 | 59.40 | 7.105 | 0.13 | 27.15 | 6.00 | 1.97 | 2.71 | 113.63 |
| | Minimum | 7.5 | 10.5 | 233.00 | 0.950 | 0.00 | 0.17 | 52.60 | 6.26 | 0.12 | 26.05 | 5.00 | 1.97 | 0.47 | 78.18 |
| TW10 | Mean ±Standard dev | 4.75±0 | 7.00±4.94 | 115.7±23.68 | 1.97±1.09 | 0.03±0.03 | 0.444±0.31 | 62.95±3.95 | 6.25±0.463 | 0.050±0.021 | 27.17±0.31 | 7.50±0.70 | 4.29±2.44 | 1.317±1.36 | 114.01±26.99 |
| | Maximum | 6.0 | 10.5 | 132.50 | 2.750 | 0.057 | 0.664 | 65.75 | 6.580 | 0.065 | 27.40 | 8.00 | 6.02 | 2.28 | 133.10 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minimum | 3.5 | 3.5 | 99.00 | 1.200 | 0.002 | 0.225 | 60.15 | 5.925 | 0.035 | 26.95 | 7.00 | 2.56 | 0.35 | 94.91 |
| TW2 | Mean ±Standard dev | 10.0±7.07 | 13.5±12.0 | 361.0±42.42 | 0.575±0.530 | 0.006±0.00 | 0.376±0.073 | 63.10±10.39 | 6.68±0.795 | 0.152±0.053 | 26.92±0.176 | 5.0±0.00 | 2.56±0.837 | 2.33±2.55 | 42.63±16.74 |
| | Maximum | 15.0 | 22.0 | 391.00 | 0.950 | 0.006 | 0.4285 | 70.45 | 7.245 | 0.190 | 27.05 | 5.000 | 3.16 | 4.145 | 54.47 |
| | Minimum | 5.0 | 5.0 | 331.00 | 0.200 | 0.006 | 0.3250 | 55.75 | 6.120 | 0.115 | 26.80 | 5.000 | 1.975 | 0.525 | 30.79 |
| TW3 | Mean ±Standard dev | 6.50±0.71 | 6.50±4.94 | 319.5±68.58 | 1.80±0.21 | 0.25±0.349 | 0.508±0.264 | 57.97±4.49 | 6.28±0.08 | 0.14±0.04 | 27.97±0.601 | 6.50±0.71 | 2.66±1.256 | 3.24±3.945 | 112.11±74.88 |
| | Maximum | 7.0 | 10.0 | 368.00 | 1.950 | 0.50 | 0.69 | 61,15 | 6,340 | 0.175 | 28.40 | 7.000 | 3.55 | 6.03 | 165.063690 |
| | Minimum | 6.0 | 3.0 | 271.00 | 1.650 | 0.01 | 0.32 | 54,80 | 6,225 | 0.115 | 27.55 | 6.000 | 1.77 | 0.450 | 59.157265 |
| TW4 | Mean ±Standard dev | 10.25±8.13 | 16.25±10.25 | 267.75±51.97 | 1.17±0.03 | 0.17±0.25 | 0.46±0.11 | 59.97±2.722 | 6.345±0.296 | 0.122±0.017 | 27.22±0.60 | 4.00±0.00 | 2.81±0.90 | 1.84±2.043 | 58,19±11,51 |
| | Maximum | 16.0 | 23.5 | 304.50 | 1.20 | 0.35 | 0.54 | 61.90 | 6.555 | 0.135 | 27.65 | 4.00 | 3.45 | 3.29 | 66.34 |
| | Minimum | 4.5 | 9.0 | 231.00 | 1.15 | 0.001 | 0.38 | 58.05 | 6.135 | 0.110 | 26.80 | 4.00 | 2.17 | 0.40 | 50.05 |
| TW5 | Mean ±Standard dev | 8.75±8.83 | 17.7±15.90 | 321.75±108.54 | 0.7±0.56 | 0.27±0.38 | 0.53±0.318 | 59.02±1.17 | 6.64±0.71 | 0.15±0.053 | 26.97±0.31 | 6.00±2.82 | 3.90±1.326 | 1.430±1.52 | 79.56±35.95 |
| | Maximum | 15.0 | 29.0 | 398.50 | 1.10 | 0.55 | 0.75 | 59.85 | 7.15 | 0.190 | 27.20 | 8.00 | 4.83 | 2.510 | 104.98 |
| | Minimum | 2.5 | 6.5 | 245.00 | 0.31 | 0.001 | 0.31 | 58.20 | 6.13 | 0.115 | 26.75 | 4.00 | 2.96 | 0.350 | 54.13 |
| TW7 | Mean ±Standard dev | 8.25±0.35 | 16.75±9.54 | 160.5±16.26 | 1.52±0.88 | 0.37±0.52 | 0.34±0.173 | 53.25±7.84 | 6.14±0.07 | 0.082±0.01 | 26.25±1.76 | 9.50±6.363 | 2.12±0.209 | 1.39±1.368 | 99.62±56.04 |
| | Maximum | 8.5 | 23.5 | 172.00 | 2.15 | 0.75 | 0.46 | 58.80 | 6.19 | 0.090 | 27.50 | 14.00 | 2.27 | 2.36 | 139.25 |
| | Minimum | 8.0 | 10.0 | 149.00 | 0.90 | 0.002 | 0.22 | 47.70 | 6.09 | 0.075 | 25.00 | 5.00 | 1.97 | 0.425 | 59.99 |
| TW8 | Mean ±Standard dev | 9.250±6.71 | 19.75±13.08 | 378.2±53.38 | 0.80±0.35 | 0.15±0.21 | 0.50±0.04 | 62.52±2.65 | 6.74±0.328 | 0.14±0.03 | 26.62±1.45 | 7.00±1.41 | 3.25±0.69 | 2.31±2.73 | 47.27±14.19 |
| | Maximum | 14.0 | 29.0 | 416.00 | 1.050 | 0.3020 | 0.5300 | 64,40 | 6,975 | 0.165 | 27.65 | 8.00 | 3.75 | 4.245 | 57.31 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Minimum | 4.5 | 10.5 | 340.50 | 0.550 | 0.0020 | 0.4740 | 60.65 | 6.510 | 0.115 | 25.60 | 6.00 | 2.76 | 0.375 | 37.24 |
| TW9 | Mean ±Standard dev | 4.25±,353 | 7.750±4.59 | 113.0±20.50 | 0.87±0.45 | 0.01±0.01 | 1.33±1.51 | 68.2±10.67 | 6.49±0.622 | 0.04±0.007 | 27.57±0.45 | 8.00±2.81 | 2.46±1.82 | 0.97±0.71 | 79.59±19.59 |
| | Maximum | 4.5 | 11.0 | 127.50 | 1.200 | 0.0180 | 2,4000 | 75.75 | 6.93 | 0.04 | 27.90 | 10.00 | 3.75 | 1.480 | 93.45 |
| | Minimum | 4.0 | 4.5 | 98.50 | 0.550 | 0.0025 | 0.2650 | 60.65 | 6.05 | 0.03 | 27.25 | 6.00 | 1.19 | 0.475 | 65.73 |
| BS12 | Mean ±Standard dev | 7.50±0.707 | 14.0±2.82 | 168.50±14.84 | 0.37±0.247 | 0.006±0.003 | 0.89±0.87 | 67.85±5.58 | 7.23±0.91 | 0.06±0.02 | 19.67±2.93 | 5.50±2.12 | 2.91±1.04 | 0.90±0.81 | 97.27±76.53 |
| | Maximum | 8.0 | 16.0 | 179.00 | 0.55 | 0.009 | 1.52 | 71.80 | 7.88 | 0.08 | 21.75 | 7.00 | 3.65 | 1.48 | 151.39 |
| | Minimum | 7.0 | 12.0 | 158.00 | 0.200 | 0.004 | 0.27 | 63.90 | 6.59 | 0.05 | 17.60 | 4.00 | 2.17 | 0.33 | 43.15 |
| BS8 | Mean ±Standard dev | 6.0±3.53 | 6.5±7.07 | 146.25±8.83 | 0.22±0.10 | 0.00±0.00 | 0.935±0.338 | 67.15±5.72 | 7.27±0.64 | 0.05±0.003 | 15.67±4.34 | 3.25±1.06 | 2.71±0.21 | 2.65±3.35 | 39.72±20.65 |
| | Maximum | 8.5 | 11.5 | 152.50 | 0.30 | 0.001 | 1.17 | 71.20 | 7.73 | 0.06 | 18.75 | 4.00 | 2.86 | 5.025 | 54.33 |
| Total | Mean ±Standard dev | 9.56±5.22 | 15.44±8.58 | 357.02±408.6 | 1.02±0.79 | 0.06±0.16 | 3.96±23.29 | 62.03±7.27 | 6.40±0.79 | 0.19±0.41 | 24.02±3.94 | 6.03±2.94 | 2.92±0.96 | 4.79±20.57 | 70.79±51.33 |
| | Maximum | 25.0 | 38.5 | 2720.50 | 3.35 | 0.75 | 189.22 | 82.75 | 7.88 | 2.510 | 28.40 | 15.00 | 6.02 | 165.11 | 328.19 |
| | Minimum | 0.5 | 1.5 | 79.00 | 0.00 | 0.00 | 0.11 | 47.70 | 4.28 | 0.025 | 12.60 | 1.025 | 1.18 | 21.35 | 10.54 |

**Appendix 3:** Minimum, maximum seasonal mean and standard deviation of for suspended solids, turbidity, electric conductivity, nitrate ions, ammonium ions, phosphate ions and dissolved oxygen measured during the study period in the groundwater of Fako

| Sampling point | Parameter | Suspended Solids | | Turbidity | | Electric conductivity | | Nitrate ions | | Ammonium ions | | Phosphates | | Dissolved oxygen | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Season | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS |
| TW1 | Mean | 18.50 | 7.50 | 24.00 | 10.50 | 362.50 | 233.00 | 1.23 | 0.95 | 0.01 | 0.00 | 0.59 | 0.17 | 52.60 | 59.40 |
| | StD | 16.26 | 0.35 | 19.80 | 2.12 | 166.17 | 46.67 | 1.52 | 1.06 | 0.00 | 0.00 | 0.01 | 0.01 | 14.99 | 7.35 |
| | Max | 30.00 | 8.00 | 38.00 | 12.00 | 480.00 | 266.00 | 2.30 | 1.70 | 0.01 | 0.00 | 0.60 | 0.18 | 63.20 | 64.60 |
| | Min | 7.00 | 7.00 | 10.00 | 9.00 | 245.00 | 200.00 | 0.15 | 0.20 | 0.01 | 0.00 | 0.58 | 0.16 | 42.00 | 54.20 |
| TW2 | Mean | 15.00 | 5.00 | 22.00 | 5.00 | 331.00 | 391.00 | 0.20 | 0.95 | 0.01 | 0.01 | 0.43 | 0.33 | 70.45 | 55.75 |
| | StD | 15.56 | 2.12 | 29.70 | 1.41 | 128.69 | 15.56 | 0.14 | 1.34 | 0.01 | 0.00 | 0.27 | 0.01 | 14.92 | 11.81 |
| | Max | 26.00 | 8.00 | 43.00 | 6.00 | 422.00 | 402.00 | 0.30 | 1.90 | 0.01 | 0.01 | 0.62 | 0.33 | 81.00 | 64.10 |
| | Min | 4.00 | 2.00 | 1.00 | 4.00 | 240.00 | 380.00 | 0.10 | 0.00 | 0.00 | 0.01 | 0.24 | 0.32 | 59.90 | 47.40 |
| TW3 | Mean | 6.00 | 7.00 | 10.00 | 3.00 | 368.00 | 271.00 | 1.65 | 1.15 | 0.51 | 0.01 | 0.32 | 0.70 | 61.15 | 54.80 |
| | StD | 4.24 | 2.83 | 4.24 | 1.41 | 96.17 | 29.70 | 0.92 | 0.64 | 0.70 | 0.01 | 0.04 | 0.54 | 3.04 | 13.15 |
| | Max | 9.00 | 11.00 | 13.00 | 4.00 | 436.00 | 292.00 | 2.30 | 1.60 | 1.00 | 0.02 | 0.35 | 1.08 | 63.30 | 64.10 |
| | Min | 3.00 | 3.00 | 7.00 | 2.00 | 300.00 | 250.00 | 1.00 | 0.70 | 0.01 | 0.00 | 0.29 | 0.31 | 59.00 | 45.50 |
| TW4 | Mean | 16.00 | 4.50 | 23.50 | 9.00 | 231.00 | 304.50 | 1.95 | 1.20 | 0.36 | 0.00 | 0.55 | 0.38 | 61.90 | 58.05 |
| | StD | 14.14 | 1.77 | 16.26 | 11.31 | 1.41 | 105.36 | 0.07 | 0.14 | 0.48 | 0.00 | 0.09 | 0.13 | 7.21 | 8.56 |
| | Max | 26.00 | 7.00 | 35.00 | 17.00 | 232.00 | 379.00 | 2.00 | 1.30 | 0.70 | 0.00 | 0.61 | 0.47 | 67.00 | 64.10 |
| | Min | 6.00 | 2.00 | 12.00 | 1.00 | 230.00 | 230.00 | 1.90 | 1.10 | 0.02 | 0.00 | 0.48 | 0.29 | 56.80 | 52.00 |
| TW5 | Mean | 15.00 | 2.50 | 29.00 | 6.50 | 398.50 | 245.00 | 0.31 | 1.10 | 0.55 | 0.00 | 0.76 | 0.31 | 58.20 | 59.85 |
| | StD | 12.73 | 1.06 | 31.11 | 3.54 | 26.16 | 49.50 | 0.42 | 0.28 | 0.78 | 0.00 | 0.29 | 0.11 | 0.28 | 6.29 |
| | Max | 24.00 | 4.00 | 51.00 | 9.00 | 417.00 | 280.00 | 0.60 | 1.30 | 1.10 | 0.00 | 0.96 | 0.38 | 58.40 | 64.30 |
| | Min | 6.00 | 1.00 | 7.00 | 4.00 | 380.00 | 210.00 | 0.01 | 0.90 | 0.00 | 0.00 | 0.55 | 0.23 | 58.00 | 55.40 |
| TW6 | Mean | 11.50 | 4.00 | 19.50 | 6.50 | 268.00 | 200.50 | 1.10 | 1.70 | 0.05 | 0.00 | 0.63 | 0.34 | 49.40 | 56.05 |
| | StD | 9.19 | 1.41 | 10.61 | 9.19 | 25.46 | 13.44 | 1.13 | 0.99 | 0.03 | 0.00 | 0.17 | 0.18 | 11.88 | 11.38 |
| | Max | 18.00 | 6.00 | 27.00 | 13.00 | 286.00 | 210.00 | 1.90 | 2.40 | 0.07 | 0.00 | 0.75 | 0.47 | 57.80 | 64.10 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Min** | 5.00 | 2.00 | 12.00 | 0.00 | 250.00 | 191.00 | 0.30 | 1.00 | 0.02 | 0.00 | 0.51 | 0.21 | 41.00 | 48.00 |
| **TW7** | **Mean** | 8.50 | 8.00 | 23.50 | 10.00 | 172.00 | 149.00 | 0.90 | 2.15 | 0.75 | 0.00 | 0.47 | 0.22 | 47.70 | 58.80 |
| | **StD** | 3.54 | 0.71 | 12.02 | 8.49 | 45.25 | 41.01 | 0.85 | 0.21 | 1.06 | 0.00 | 0.20 | 0.23 | 16.55 | 8.20 |
| | **Max** | 11.00 | 9.00 | 32.00 | 16.00 | 204.00 | 178.00 | 1.50 | 2.30 | 1.50 | 0.01 | 0.61 | 0.38 | 59.40 | 64.60 |
| | **Min** | 6.00 | 7.00 | 15.00 | 4.00 | 140.00 | 120.00 | 0.30 | 2.00 | 0.00 | 0.00 | 0.32 | 0.06 | 36.00 | 53.00 |
| **TW8** | **Mean** | 14.00 | 4.50 | 29.00 | 10.50 | 416.00 | 340.50 | 1.05 | 0.55 | 0.30 | 0.00 | 0.47 | 0.53 | 64.40 | 60.65 |
| | **StD** | 12.73 | 0.35 | 29.70 | 0.71 | 19.80 | 13.44 | 0.07 | 0.78 | 0.42 | 0.00 | 0.05 | 0.00 | 9.33 | 5.16 |
| | **Max** | 23.00 | 5.00 | 50.00 | 11.00 | 430.00 | 350.00 | 1.10 | 1.10 | 0.60 | 0.00 | 0.51 | 0.53 | 71.00 | 64.30 |
| | **Min** | 5.00 | 4.00 | 8.00 | 10.00 | 402.00 | 331.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.44 | 0.53 | 57.80 | 57.00 |
| **TW9** | **Mean** | 4.50 | 4.00 | 11.00 | 4.50 | 127.50 | 98.50 | 0.55 | 1.20 | 0.02 | 0.00 | 224.17 | 0.27 | 75.75 | 60.65 |
| | **StD** | 4.95 | 2.12 | 5.66 | 6.36 | 38.89 | 26.16 | 0.35 | 0.57 | 0.00 | 0.00 | 316.55 | 0.11 | 17.32 | 5.16 |
| | **Max** | 8.00 | 7.00 | 15.00 | 9.00 | 155.00 | 117.00 | 0.80 | 1.60 | 0.02 | 0.01 | 448.00 | 0.34 | 88.00 | 64.30 |
| | **Min** | 1.00 | 1.00 | 7.00 | 0.00 | 100.00 | 80.00 | 0.30 | 0.80 | 0.02 | 0.00 | 0.34 | 0.19 | 63.50 | 57.00 |
| **TW10** | **Mean** | 6.00 | 3.50 | 10.50 | 3.50 | 132.50 | 99.00 | 2.75 | 1.20 | 0.06 | 0.00 | 0.66 | 0.23 | 65.75 | 60.15 |
| | **StD** | 0.00 | 1.06 | 6.36 | 2.12 | 17.68 | 12.73 | 3.61 | 0.14 | 0.07 | 0.00 | 0.39 | 0.02 | 1.06 | 5.73 |
| | **Max** | 6.00 | 5.00 | 15.00 | 5.00 | 145.00 | 108.00 | 5.30 | 1.30 | 0.11 | 0.00 | 0.94 | 0.24 | 66.50 | 64.20 |
| | **Min** | 6.00 | 2.00 | 6.00 | 2.00 | 120.00 | 90.00 | 0.20 | 1.10 | 0.00 | 0.00 | 0.39 | 0.21 | 65.00 | 56.10 |
| **MW1** | **Mean** | 6.50 | 12.00 | 14.00 | 24.50 | 129.50 | 142.50 | 1.21 | 2.50 | 0.02 | 0.00 | 0.34 | 1.20 | 58.70 | 64.35 |
| | **StD** | 4.95 | 1.41 | 5.66 | 7.78 | 43.13 | 24.75 | 1.69 | 0.99 | 0.02 | 0.00 | 0.02 | 1.54 | 2.40 | 1.34 |
| | **Max** | 10.00 | 14.00 | 18.00 | 30.00 | 160.00 | 160.00 | 2.40 | 3.20 | 0.03 | 0.00 | 0.36 | 2.29 | 60.40 | 65.30 |
| | **Min** | 3.00 | 10.00 | 10.00 | 19.00 | 99.00 | 125.00 | 0.01 | 1.80 | 0.00 | 0.00 | 0.33 | 0.11 | 57.00 | 63.40 |
| **MW2** | **Mean** | 16.00 | 12.00 | 10.00 | 10.00 | 503.00 | 408.50 | 1.06 | 0.50 | 0.03 | 0.00 | 0.27 | 1.26 | 65.75 | 57.25 |
| | **StD** | 14.14 | 2.12 | 5.66 | 8.49 | 108.89 | 16.26 | 1.48 | 0.57 | 0.02 | 0.00 | 0.17 | 1.77 | 7.42 | 11.10 |
| | **Max** | 26.00 | 15.00 | 14.00 | 16.00 | 580.00 | 420.00 | 2.10 | 0.90 | 0.04 | 0.00 | 0.39 | 2.51 | 71.00 | 65.10 |
| | **Min** | 6.00 | 9.00 | 6.00 | 4.00 | 426.00 | 397.00 | 0.01 | 0.10 | 0.01 | 0.00 | 0.15 | 0.01 | 60.50 | 49.40 |
| **MW3** | **Mean** | 8.50 | 5.50 | 9.00 | 21.50 | 536.00 | 467.50 | 3.36 | 3.10 | 0.00 | 0.00 | 0.16 | 0.60 | 61.30 | 63.75 |
| | **StD** | 6.36 | 1.77 | 9.90 | 21.92 | 118.79 | 201.53 | 4.73 | 4.10 | 0.00 | 0.00 | 0.04 | 0.76 | 6.08 | 2.19 |
| | **Max** | 13.00 | 8.00 | 16.00 | 37.00 | 620.00 | 610.00 | 6.70 | 6.00 | 0.00 | 0.00 | 0.19 | 1.14 | 65.60 | 65.30 |
| | **Min** | 4.00 | 3.00 | 2.00 | 6.00 | 452.00 | 325.00 | 0.01 | 0.20 | 0.00 | 0.00 | 0.13 | 0.06 | 57.00 | 62.20 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MW4** | **Mean** | 11.00 | 13.00 | 22.00 | 38.50 | 160.00 | 167.00 | 1.97 | 2.05 | 0.02 | 0.00 | 0.28 | 1.15 | 55.10 | 59.10 |
| | **StD** | 7.07 | 0.00 | 15.56 | 23.33 | 14.14 | 89.10 | 1.88 | 2.76 | 0.03 | 0.00 | 0.07 | 1.42 | 2.97 | 8.49 |
| | **Max** | 16.00 | 13.00 | 33.00 | 55.00 | 170.00 | 230.00 | 3.30 | 4.00 | 0.04 | 0.00 | 0.33 | 2.15 | 57.20 | 65.10 |
| | **Min** | 6.00 | 13.00 | 11.00 | 22.00 | 150.00 | 104.00 | 0.64 | 0.10 | 0.00 | 0.00 | 0.23 | 0.14 | 53.00 | 53.10 |
| **MW5** | **Mean** | 15.00 | 20.50 | 29.00 | 19.50 | 383.00 | 118.00 | 0.06 | 0.85 | 0.05 | 0.01 | 0.39 | 0.47 | 59.10 | 63.05 |
| | **StD** | 9.90 | 1.77 | 21.21 | 16.26 | 386.08 | 11.31 | 0.06 | 1.20 | 0.07 | 0.01 | 0.09 | 0.51 | 5.80 | 2.90 |
| | **Max** | 22.00 | 23.00 | 44.00 | 31.00 | 656.00 | 126.00 | 0.10 | 1.70 | 0.10 | 0.01 | 0.45 | 0.83 | 63.20 | 65.10 |
| | **Min** | 8.00 | 18.00 | 14.00 | 8.00 | 110.00 | 110.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.33 | 0.11 | 55.00 | 61.00 |
| **LW1** | **Mean** | 16.50 | 5.00 | 29.00 | 8.50 | 627.50 | 425.00 | 1.06 | 1.00 | 0.03 | 0.00 | 0.53 | 1.56 | 55.50 | 55.75 |
| | **StD** | 10.61 | 0.00 | 16.97 | 4.95 | 45.96 | 233.35 | 1.48 | 0.14 | 0.02 | 0.00 | 0.03 | 0.59 | 17.68 | 11.67 |
| | **Max** | 24.00 | 5.00 | 41.00 | 12.00 | 660.00 | 590.00 | 2.10 | 1.10 | 0.04 | 0.00 | 0.56 | 1.98 | 68.00 | 64.00 |
| | **Min** | 9.00 | 5.00 | 17.00 | 5.00 | 595.00 | 260.00 | 0.01 | 0.90 | 0.02 | 0.00 | 0.51 | 1.14 | 43.00 | 47.50 |
| **LW2** | **Mean** | 14.50 | 4.50 | 31.00 | 10.50 | 1250.00 | 1062.00 | 1.20 | 1.05 | 0.01 | 0.01 | 2.69 | 1.22 | 56.40 | 56.15 |
| | **StD** | 10.61 | 1.06 | 24.04 | 2.12 | 70.71 | 67.88 | 0.57 | 0.21 | 0.00 | 0.01 | 1.69 | 0.16 | 17.54 | 11.53 |
| | **Max** | 22.00 | 6.00 | 48.00 | 12.00 | 1300.00 | 1110.00 | 1.60 | 1.20 | 0.01 | 0.02 | 3.88 | 1.33 | 68.80 | 64.30 |
| | **Min** | 7.00 | 3.00 | 14.00 | 9.00 | 1200.00 | 1014.00 | 0.80 | 0.90 | 0.01 | 0.00 | 1.49 | 1.10 | 44.00 | 48.00 |
| **LW3** | **Mean** | 16.50 | 25.00 | 21.00 | 30.50 | 100.00 | 99.00 | 0.41 | 1.30 | 0.02 | 0.01 | 0.27 | 0.23 | 56.75 | 53.00 |
| | **StD** | 12.02 | 4.24 | 1.41 | 2.12 | 42.43 | 26.87 | 0.13 | 0.85 | 0.01 | 0.01 | 0.10 | 0.28 | 15.20 | 15.56 |
| | **Max** | 25.00 | 31.00 | 22.00 | 32.00 | 130.00 | 118.00 | 0.50 | 1.90 | 0.03 | 0.02 | 0.34 | 0.42 | 67.50 | 64.00 |
| | **Min** | 8.00 | 19.00 | 20.00 | 29.00 | 70.00 | 80.00 | 0.31 | 0.70 | 0.02 | 0.00 | 0.19 | 0.03 | 46.00 | 42.00 |
| **LW4** | **Mean** | 0.50 | 5.50 | 5.00 | 11.50 | 223.50 | 261.00 | 0.41 | 1.30 | 0.01 | 0.00 | 21.08 | 0.64 | 52.65 | 55.35 |
| | **StD** | 0.71 | 3.89 | 5.66 | 4.95 | 9.19 | 43.84 | 0.13 | 0.85 | 0.00 | 0.00 | 29.58 | 0.65 | 16.48 | 12.52 |
| | **Max** | 1.00 | 11.00 | 9.00 | 15.00 | 230.00 | 292.00 | 0.50 | 1.90 | 0.01 | 0.01 | 42.00 | 1.10 | 64.30 | 64.20 |
| | **Min** | 0.00 | 0.00 | 1.00 | 8.00 | 217.00 | 230.00 | 0.31 | 0.70 | 0.01 | 0.00 | 0.17 | 0.18 | 41.00 | 46.50 |
| **LW5** | **Mean** | 16.50 | 3.50 | 33.50 | 7.00 | 2720.50 | 484.00 | 1.16 | 1.85 | 0.01 | 0.00 | 2.37 | 0.12 | 56.30 | 54.15 |
| | **StD** | 12.02 | 1.06 | 26.16 | 5.66 | 3223.70 | 36.77 | 1.62 | 0.21 | 0.00 | 0.00 | 2.75 | 0.09 | 14.57 | 14.35 |
| | **Max** | 25.00 | 5.00 | 52.00 | 11.00 | 5000.00 | 510.00 | 2.30 | 2.00 | 0.02 | 0.01 | 4.32 | 0.18 | 66.60 | 64.30 |
| | **Min** | 8.00 | 2.00 | 15.00 | 3.00 | 441.00 | 458.00 | 0.01 | 1.70 | 0.01 | 0.00 | 0.43 | 0.05 | 46.00 | 44.00 |
| **OS1** | **Mean** | 14.00 | 9.50 | 20.50 | 11.50 | 898.00 | 151.00 | 0.90 | 3.20 | 0.01 | 0.01 | 0.47 | 0.55 | 66.20 | 61.50 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **StD** | 19.80 | 2.47 | 28.99 | 6.36 | 1015.41 | 41.01 | 0.85 | 1.84 | 0.01 | 0.01 | 0.11 | 0.24 | 5.37 | 5.52 |
| | **Max** | 28.00 | 13.00 | 41.00 | 16.00 | 1616.00 | 180.00 | 1.50 | 4.50 | 0.01 | 0.01 | 0.55 | 0.72 | 70.00 | 65.40 |
| | **Min** | 0.00 | 6.00 | 0.00 | 7.00 | 180.00 | 122.00 | 0.30 | 1.90 | 0.00 | 0.00 | 0.39 | 0.38 | 62.40 | 57.60 |
| **OS2** | **Mean** | 5.00 | 13.50 | 9.00 | 8.50 | 898.00 | 151.00 | 0.50 | 1.10 | 0.65 | 0.01 | 0.35 | 0.34 | 72.80 | 64.90 |
| | **StD** | 4.24 | 4.60 | 4.24 | 10.61 | 1015.41 | 41.01 | 0.57 | 1.41 | 0.92 | 0.01 | 0.04 | 0.06 | 17.25 | 0.85 |
| | **Max** | 8.00 | 20.00 | 12.00 | 16.00 | 1616.00 | 180.00 | 0.90 | 2.10 | 1.30 | 0.01 | 0.38 | 0.38 | 85.00 | 65.50 |
| | **Min** | 2.00 | 7.00 | 6.00 | 1.00 | 180.00 | 122.00 | 0.10 | 0.10 | 0.00 | 0.00 | 0.33 | 0.30 | 60.60 | 64.30 |
| **OS3** | **Mean** | 4.00 | 12.50 | 14.50 | 15.00 | 177.45 | 151.50 | 0.38 | 1.00 | 0.00 | 0.00 | 0.41 | 0.61 | 72.70 | 61.75 |
| | **StD** | 1.41 | 4.60 | 4.95 | 0.00 | 10.54 | 40.31 | 0.32 | 1.27 | 0.00 | 0.00 | 0.06 | 0.40 | 10.32 | 5.30 |
| | **Max** | 5.00 | 19.00 | 18.00 | 15.00 | 184.90 | 180.00 | 0.60 | 1.90 | 0.00 | 0.00 | 0.46 | 0.89 | 80.00 | 65.50 |
| | **Min** | 3.00 | 6.00 | 11.00 | 15.00 | 170.00 | 123.00 | 0.15 | 0.10 | 0.00 | 0.00 | 0.37 | 0.32 | 65.40 | 58.00 |
| **MS4** | **Mean** | 6.50 | 15.50 | 10.50 | 22.50 | 243.00 | 234.50 | 0.35 | 0.40 | 0.55 | 0.00 | 0.52 | 1.65 | 79.90 | 64.35 |
| | **StD** | 3.54 | 5.30 | 4.95 | 16.26 | 4.24 | 21.92 | 0.35 | 0.42 | 0.77 | 0.00 | 0.13 | 1.88 | 11.46 | 0.92 |
| | **Max** | 9.00 | 23.00 | 14.00 | 34.00 | 246.00 | 250.00 | 0.60 | 0.70 | 1.10 | 0.00 | 0.61 | 2.98 | 88.00 | 65.00 |
| | **Min** | 4.00 | 8.00 | 7.00 | 11.00 | 240.00 | 219.00 | 0.10 | 0.10 | 0.01 | 0.00 | 0.43 | 0.32 | 71.80 | 63.70 |
| **MS5** | **Mean** | 16.00 | 10.00 | 15.00 | 20.00 | 312.00 | 309.50 | 0.80 | 2.25 | 0.01 | 0.00 | 0.42 | 1.93 | 67.00 | 56.70 |
| | **StD** | 9.90 | 1.41 | 0.00 | 2.83 | 2.83 | 0.71 | 0.57 | 0.78 | 0.00 | 0.00 | 0.00 | 2.28 | 0.00 | 11.03 |
| | **Max** | 23.00 | 12.00 | 15.00 | 22.00 | 314.00 | 310.00 | 1.20 | 2.80 | 0.01 | 0.00 | 0.42 | 3.54 | 67.00 | 64.50 |
| | **Min** | 9.00 | 8.00 | 15.00 | 18.00 | 310.00 | 309.00 | 0.40 | 1.70 | 0.01 | 0.00 | 0.42 | 0.31 | 67.00 | 48.90 |
| **ES6** | **Mean** | 10.50 | 7.00 | 23.50 | 8.00 | 320.00 | 320.00 | 0.30 | 0.35 | 0.00 | 0.00 | 2.25 | 1.48 | 60.60 | 62.40 |
| | **StD** | 6.36 | 0.00 | 16.26 | 4.24 | 0.00 | 0.00 | 0.00 | 0.21 | 0.00 | 0.00 | 2.67 | 1.58 | 12.16 | 3.39 |
| | **Max** | 15.00 | 7.00 | 35.00 | 11.00 | 320.00 | 320.00 | 0.30 | 0.50 | 0.00 | 0.01 | 4.14 | 2.60 | 69.20 | 64.80 |
| | **Min** | 6.00 | 7.00 | 12.00 | 5.00 | 320.00 | 320.00 | 0.30 | 0.20 | 0.00 | 0.00 | 0.36 | 0.36 | 52.00 | 60.00 |
| **ES7** | **Mean** | 5.50 | 18.50 | 11.50 | 17.00 | 274.00 | 302.00 | 0.30 | 0.40 | 0.00 | 0.01 | 2.03 | 2.35 | 74.70 | 61.40 |
| | **StD** | 4.95 | 1.06 | 3.54 | 2.83 | 5.66 | 2.83 | 0.29 | 0.14 | 0.00 | 0.01 | 2.28 | 2.76 | 4.67 | 5.09 |
| | **Max** | 9.00 | 20.00 | 14.00 | 19.00 | 278.00 | 304.00 | 0.50 | 0.50 | 0.00 | 0.01 | 3.64 | 4.30 | 78.00 | 65.00 |
| | **Min** | 2.00 | 17.00 | 9.00 | 15.00 | 270.00 | 300.00 | 0.09 | 0.30 | 0.00 | 0.00 | 0.42 | 0.39 | 71.40 | 57.80 |
| **BS8** | **Mean** | 10.00 | 7.00 | 15.00 | 12.00 | 295.50 | 269.50 | 0.21 | 0.85 | 0.01 | 0.00 | 0.39 | 1.88 | 66.20 | 59.10 |
| | **StD** | 5.66 | 4.95 | 14.14 | 7.07 | 20.51 | 0.71 | 0.28 | 0.92 | 0.01 | 0.00 | 0.01 | 2.18 | 7.35 | 8.20 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Max** | 14.00 | 14.00 | 25.00 | 17.00 | 310.00 | 270.00 | 0.40 | 1.50 | 0.02 | 0.00 | 0.40 | 3.42 | 71.40 | 64.90 |
| | **Min** | 6.00 | 0.00 | 5.00 | 7.00 | 281.00 | 269.00 | 0.01 | 0.20 | 0.00 | 0.00 | 0.38 | 0.33 | 61.00 | 53.30 |
| **BS9** | **Mean** | 5.50 | 22.00 | 6.50 | 31.50 | 250.00 | 258.50 | 0.06 | 0.35 | 0.01 | 0.00 | 0.60 | 0.97 | 82.75 | 61.75 |
| | **StD** | 4.95 | 4.24 | 7.78 | 6.36 | 0.00 | 12.02 | 0.06 | 0.49 | 0.01 | 0.00 | 0.28 | 0.58 | 27.22 | 4.60 |
| | **Max** | 9.00 | 28.00 | 12.00 | 36.00 | 250.00 | 267.00 | 0.10 | 0.70 | 0.01 | 0.01 | 0.80 | 1.38 | 102.00 | 65.00 |
| | **Min** | 2.00 | 16.00 | 1.00 | 27.00 | 250.00 | 250.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.40 | 0.56 | 63.50 | 58.50 |
| **BS10** | **Mean** | 9.00 | 11.00 | 11.50 | 9.50 | 285.00 | 1833.00 | 0.26 | 1.15 | 0.01 | 0.01 | 0.69 | 0.60 | 77.15 | 60.10 |
| | **StD** | 4.24 | 2.12 | 14.85 | 9.19 | 21.21 | 2102.94 | 0.35 | 1.63 | 0.01 | 0.01 | 0.49 | 0.42 | 15.34 | 6.08 |
| | **Max** | 12.00 | 14.00 | 22.00 | 16.00 | 300.00 | 3320.00 | 0.50 | 2.30 | 0.01 | 0.02 | 1.04 | 0.89 | 88.00 | 64.40 |
| | **Min** | 6.00 | 8.00 | 1.00 | 3.00 | 270.00 | 346.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.35 | 0.30 | 66.30 | 55.80 |
| **BS11** | **Mean** | 3.50 | 8.50 | 1.50 | 11.50 | 80.00 | 79.00 | 0.41 | 0.00 | 0.00 | 0.00 | 0.70 | 1.18 | 71.20 | 63.10 |
| | **StD** | 0.71 | 4.60 | 0.71 | 9.19 | 0.00 | 12.73 | 0.56 | 0.00 | 0.00 | 0.00 | 0.60 | 1.31 | 13.86 | 2.69 |
| | **Max** | 4.00 | 15.00 | 2.00 | 18.00 | 80.00 | 88.00 | 0.80 | 0.00 | 0.00 | 0.00 | 1.12 | 2.10 | 81.00 | 65.00 |
| | **Min** | 3.00 | 2.00 | 1.00 | 5.00 | 80.00 | 70.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.27 | 0.25 | 61.40 | 61.20 |
| **BS12** | **Mean** | 8.50 | 7.00 | 12.00 | 17.00 | 152.50 | 140.00 | 0.16 | 0.30 | 0.01 | 0.00 | 0.77 | 0.48 | 77.70 | 61.70 |
| | **StD** | 10.61 | 1.41 | 16.97 | 11.31 | 3.54 | 14.14 | 0.21 | 0.28 | 0.01 | 0.00 | 0.24 | 0.32 | 18.81 | 4.24 |
| | **Max** | 16.00 | 9.00 | 24.00 | 25.00 | 155.00 | 150.00 | 0.30 | 0.50 | 0.01 | 0.00 | 0.94 | 0.70 | 91.00 | 64.70 |
| | **Min** | 1.00 | 5.00 | 0.00 | 9.00 | 150.00 | 130.00 | 0.01 | 0.10 | 0.00 | 0.00 | 0.61 | 0.25 | 64.40 | 58.70 |
| **BS13** | **Mean** | 7.00 | 8.00 | 12.00 | 16.00 | 240.00 | 244.50 | 0.35 | 0.90 | 0.01 | 0.00 | 0.28 | 1.52 | 71.80 | 63.90 |
| | **StD** | 8.49 | 2.12 | 16.97 | 12.73 | 14.14 | 6.36 | 0.35 | 1.27 | 0.00 | 0.00 | 0.01 | 1.46 | 13.01 | 0.85 |
| | **Max** | 13.00 | 11.00 | 24.00 | 25.00 | 250.00 | 249.00 | 0.60 | 1.80 | 0.01 | 0.01 | 0.29 | 2.55 | 81.00 | 64.50 |
| | **Min** | 1.00 | 5.00 | 0.00 | 7.00 | 230.00 | 240.00 | 0.10 | 0.00 | 0.01 | 0.00 | 0.27 | 0.49 | 62.60 | 63.30 |

**Appendix 4:** Minimum, maximum seasonal mean and standard deviation for pH, salinity, temperature, alkalinity, oxidability, dissolved carbon dioxide and total hardness measured during the study period in the groundwater of Fako

| Sampling point | pH | | Salinity | | Temperature | | Alkalinity | | Oxidability | | CO2 | | Total hardness | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS | DS | RS |
| TW1 | 7.11 | 6.27 | 0.12 | 0.13 | 26.05 | 27.15 | 5.00 | 6.00 | 1.98 | 1.98 | 2.71 | 0.48 | 78.18 | 113.63 |
| | 1.10 | 0.39 | 0.16 | 0.01 | 1.48 | 1.20 | 4.24 | 2.83 | 2.23 | 0.56 | 1.15 | 0.04 | 28.66 | 104.36 |
| | 7.88 | 6.54 | 0.23 | 0.14 | 27.10 | 28.00 | 8.00 | 8.00 | 3.56 | 2.37 | 3.52 | 0.50 | 98.45 | 187.43 |
| | 6.33 | 5.99 | 0.01 | 0.12 | 25.00 | 26.30 | 2.00 | 4.00 | 0.40 | 1.58 | 1.90 | 0.45 | 57.91 | 39.84 |
| TW2 | 7.25 | 6.12 | 0.12 | 0.19 | 26.80 | 27.05 | 5.00 | 5.00 | 3.16 | 1.98 | 4.14 | 0.53 | 54.48 | 30.79 |
| | 1.49 | 0.28 | 0.01 | 0.00 | 1.13 | 0.64 | 1.41 | 1.41 | 3.35 | 0.56 | 4.09 | 0.04 | 33.28 | 2.01 |
| | 8.30 | 6.32 | 0.12 | 0.19 | 27.60 | 27.50 | 6.00 | 6.00 | 5.53 | 2.37 | 7.04 | 0.55 | 78.01 | 32.22 |
| | 6.19 | 5.92 | 0.11 | 0.19 | 26.00 | 26.60 | 4.00 | 4.00 | 0.79 | 1.58 | 1.25 | 0.50 | 30.94 | 29.37 |
| TW3 | 6.34 | 6.23 | 0.18 | 0.12 | 28.40 | 27.55 | 6.00 | 7.00 | 3.56 | 1.78 | 6.03 | 0.45 | 59.16 | 165.06 |
| | 0.78 | 0.32 | 0.05 | 0.05 | 1.98 | 0.64 | 2.83 | 4.24 | 5.03 | 0.84 | 6.41 | 0.21 | 49.46 | 176.98 |
| | 6.89 | 6.45 | 0.21 | 0.15 | 29.80 | 28.00 | 8.00 | 10.00 | 7.11 | 2.37 | 10.56 | 0.60 | 94.13 | 290.21 |
| | 5.79 | 6.00 | 0.14 | 0.08 | 27.00 | 27.10 | 4.00 | 4.00 | 0.00 | 1.19 | 1.50 | 0.30 | 24.18 | 39.92 |
| TW4 | 6.56 | 6.14 | 0.11 | 0.14 | 27.65 | 26.80 | 4.00 | 4.00 | 3.46 | 2.17 | 3.29 | 0.40 | 50.05 | 66.34 |
| | 1.42 | 0.32 | 0.00 | 0.04 | 2.33 | 0.28 | 2.83 | 3.20 | 4.61 | 0.84 | 2.81 | 0.07 | 40.97 | 53.72 |
| | 7.56 | 6.36 | 0.11 | 0.16 | 29.30 | 27.00 | 6.00 | 4.00 | 6.71 | 2.77 | 5.28 | 0.45 | 79.02 | 104.33 |
| | 5.55 | 5.91 | 0.11 | 0.11 | 26.00 | 26.60 | 2.00 | 4.00 | 0.20 | 1.58 | 1.30 | 0.35 | 21.09 | 28.36 |
| TW5 | 7.15 | 6.14 | 0.19 | 0.12 | 27.20 | 26.75 | 4.00 | 8.00 | 4.84 | 2.96 | 2.51 | 0.35 | 54.14 | 104.99 |
| | 1.32 | 0.33 | 0.01 | 0.02 | 0.28 | 0.35 | 0.00 | 5.66 | 6.01 | 1.40 | 1.43 | 0.21 | 36.60 | 121.51 |
| | 8.08 | 6.37 | 0.20 | 0.13 | 27.40 | 27.00 | 4.00 | 12.00 | 9.09 | 3.95 | 3.52 | 0.50 | 80.02 | 190.91 |
| | 6.22 | 5.90 | 0.18 | 0.10 | 27.00 | 26.50 | 4.00 | 4.00 | 0.59 | 1.98 | 1.50 | 0.20 | 28.26 | 19.07 |
| TW6 | 6.23 | 5.64 | 0.14 | 0.10 | 25.80 | 27.60 | 6.00 | 12.00 | 2.77 | 2.77 | 5.35 | 0.55 | 32.28 | 22.72 |
| | 1.22 | 0.73 | 0.02 | 0.01 | 2.55 | 0.57 | 2.83 | 8.49 | 3.35 | 1.68 | 4.88 | 0.00 | 25.33 | 16.14 |
| | 7.09 | 6.15 | 0.15 | 0.10 | 27.60 | 28.00 | 8.00 | 18.00 | 5.14 | 3.95 | 8.80 | 0.55 | 50.19 | 34.13 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 5.36 | 5.12 | 0.12 | 0.09 | 24.00 | 27.20 | 4.00 | 6.00 | 0.39 | 1.58 | 1.90 | 0.55 | 14.36 | 11.31 |
| **TW7** | 6.20 | 6.10 | 0.09 | 0.08 | 27.50 | 25.00 | 5.00 | 14.00 | 2.27 | 1.98 | 2.36 | 0.43 | 59.99 | 139.25 |
| | 0.93 | 0.97 | 0.03 | 0.01 | 0.71 | 2.83 | 1.41 | 11.31 | 2.37 | 1.12 | 1.64 | 0.04 | 51.65 | 154.62 |
| | 6.85 | 6.78 | 0.11 | 0.08 | 28.00 | 27.00 | 6.00 | 22.00 | 3.95 | 2.77 | 3.52 | 0.45 | 96.51 | 248.59 |
| | 5.54 | 5.41 | 0.07 | 0.07 | 27.00 | 23.00 | 4.00 | 6.00 | 0.59 | 1.19 | 1.20 | 0.40 | 23.47 | 29.92 |
| **TW8** | 6.98 | 6.51 | 0.12 | 0.17 | 25.60 | 27.65 | 6.00 | 8.00 | 2.77 | 3.75 | 4.25 | 0.38 | 37.24 | 57.31 |
| | 1.00 | 0.16 | 0.13 | 0.01 | 2.26 | 0.49 | 1.23 | 1.25 | 3.35 | 2.51 | 3.95 | 0.11 | 30.82 | 17.92 |
| | 7.68 | 6.62 | 0.21 | 0.17 | 27.20 | 28.00 | 6.00 | 8.00 | 5.14 | 5.53 | 7.04 | 0.45 | 59.04 | 69.98 |
| | 6.27 | 6.40 | 0.02 | 0.16 | 24.00 | 27.30 | 6.00 | 8.00 | 0.40 | 1.98 | 1.45 | 0.30 | 15.45 | 44.64 |
| **TW9** | 6.45 | 6.05 | 0.04 | 0.05 | 27.25 | 27.90 | 6.00 | 10.00 | 3.75 | 1.19 | 1.48 | 0.47 | 65.74 | 93.46 |
| | 1.51 | 0.78 | 0.02 | 0.01 | 0.35 | 0.85 | 2.83 | 5.66 | 4.19 | 1.12 | 0.40 | 0.11 | 37.89 | 35.07 |
| | 8.00 | 6.60 | 0.05 | 0.05 | 27.50 | 28.50 | 8.00 | 14.00 | 6.72 | 1.98 | 1.76 | 0.55 | 92.53 | 118.25 |
| | 5.86 | 5.50 | 0.02 | 0.04 | 27.00 | 27.30 | 4.00 | 6.00 | 0.79 | 0.40 | 1.20 | 0.40 | 38.95 | 68.66 |
| **TW10** | 6.58 | 5.93 | 0.07 | 0.04 | 0.07 | 0.85 | 7.00 | 8.00 | 6.02 | 2.57 | 2.28 | 0.35 | 94.92 | 133.10 |
| | 1.58 | 0.67 | 0.01 | 0.02 | 27.00 | 28.00 | 1.41 | 2.50 | 8.24 | 0.28 | 1.75 | 0.07 | 1.70 | 143.68 |
| | 7.70 | 6.40 | 0.07 | 0.05 | 26.90 | 26.80 | 8.00 | 8.00 | 11.85 | 2.76 | 3.52 | 0.40 | 96.12 | 234.70 |
| | 5.46 | 5.45 | 0.06 | 0.02 | 27.40 | 26.95 | 6.00 | 8.00 | 0.20 | 2.37 | 1.05 | 0.30 | 93.72 | 31.50 |
| **MW1** | 5.55 | 5.65 | 0.09 | 0.08 | 5.59 | 0.85 | 3.00 | 5.00 | 3.16 | 2.77 | 2.53 | 0.33 | 40.84 | 103.01 |
| | 0.78 | 1.29 | 0.02 | 0.01 | 27.90 | 29.00 | 4.24 | 1.41 | 3.35 | 2.23 | 1.39 | 0.11 | 24.29 | 98.15 |
| | 6.10 | 6.56 | 0.10 | 0.09 | 20.00 | 27.80 | 6.00 | 6.00 | 5.53 | 4.35 | 3.52 | 0.40 | 58.02 | 172.41 |
| | 5.00 | 4.74 | 0.07 | 0.07 | 28.40 | 23.95 | 0.00 | 4.00 | 0.79 | 1.19 | 1.55 | 0.25 | 23.66 | 33.60 |
| **MW2** | 4.65 | 4.68 | 0.20 | 0.19 | 3.82 | 0.49 | 5.00 | 1.03 | 2.67 | 2.77 | 19.01 | 0.28 | 55.07 | 169.46 |
| | 0.70 | 1.34 | 0.11 | 0.00 | 27.40 | 28.00 | 7.07 | 1.38 | 3.49 | 2.23 | 25.39 | 0.04 | 64.98 | 201.38 |
| | 5.14 | 5.62 | 0.28 | 0.19 | 22.00 | 27.30 | 10.00 | 2.00 | 5.14 | 4.35 | 36.96 | 0.30 | 101.01 | 311.86 |
| | 4.15 | 3.73 | 0.12 | 0.19 | 27.65 | 24.70 | 0.00 | 0.05 | 0.20 | 1.19 | 1.05 | 0.25 | 9.12 | 27.07 |
| **MW3** | 4.29 | 5.00 | 0.16 | 0.22 | 24.15 | 27.65 | 6.00 | 2.03 | 2.96 | 2.37 | 7.57 | 0.45 | 58.93 | 24.08 |
| | 0.47 | 1.58 | 0.21 | 0.10 | 4.45 | 0.49 | 8.49 | 2.79 | 3.63 | 0.00 | 9.21 | 0.00 | 58.34 | 3.97 |
| | 4.62 | 6.12 | 0.30 | 0.29 | 27.30 | 28.00 | 12.00 | 4.00 | 5.53 | 2.37 | 14.08 | 0.45 | 100.19 | 26.89 |
| | 3.95 | 3.88 | 0.01 | 0.15 | 21.00 | 27.30 | 0.00 | 0.05 | 0.39 | 2.37 | 1.05 | 0.45 | 17.68 | 21.27 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **MW4** | 5.30 | 5.52 | 0.05 | 0.10 | 22.90 | 28.40 | 2.00 | 2.03 | 3.06 | 1.98 | 2.39 | 0.33 | 27.74 | 47.01 |
| | 0.96 | 1.32 | 0.05 | 0.06 | 6.93 | 0.85 | 2.83 | 2.79 | 4.05 | 0.00 | 1.61 | 0.18 | 12.20 | 20.64 |
| | 5.98 | 6.45 | 0.08 | 0.14 | 27.80 | 29.00 | 4.00 | 4.00 | 5.93 | 1.98 | 3.52 | 0.45 | 36.37 | 61.61 |
| | 4.62 | 4.58 | 0.01 | 0.05 | 18.00 | 27.80 | 0.00 | 0.05 | 0.20 | 1.98 | 1.25 | 0.20 | 19.11 | 32.41 |
| **MW5** | 4.75 | 4.93 | 0.04 | 0.06 | 23.80 | 28.00 | 4.00 | 3.03 | 2.47 | 2.17 | 7.97 | 0.23 | 70.03 | 62.30 |
| | 0.30 | 0.91 | 0.03 | 0.01 | 5.66 | 0.71 | 2.83 | 4.21 | 2.65 | 0.28 | 8.65 | 0.18 | 76.70 | 62.84 |
| | 4.96 | 5.57 | 0.06 | 0.06 | 27.80 | 28.50 | 6.00 | 6.00 | 4.35 | 2.37 | 14.08 | 0.35 | 124.27 | 106.73 |
| | 4.54 | 4.28 | 0.02 | 0.05 | 19.80 | 27.50 | 2.00 | 0.05 | 0.59 | 1.98 | 1.85 | 0.10 | 15.80 | 17.87 |
| **LW1** | 6.70 | 6.57 | 2.45 | 0.21 | 26.30 | 26.05 | 11.00 | 11.00 | 5.04 | 2.37 | 8.57 | 0.27 | 56.64 | 97.66 |
| | 0.00 | 0.22 | 3.01 | 0.11 | 1.84 | 1.34 | 7.07 | 7.07 | 6.84 | 1.68 | 10.28 | 0.04 | 33.38 | 74.32 |
| | 6.70 | 6.72 | 4.57 | 0.29 | 27.60 | 27.00 | 16.00 | 16.00 | 9.88 | 3.55 | 15.84 | 0.30 | 80.25 | 150.21 |
| | 6.70 | 6.41 | 0.32 | 0.13 | 25.00 | 25.10 | 6.00 | 6.00 | 0.20 | 1.19 | 1.30 | 0.25 | 33.04 | 45.10 |
| **LW2** | 7.48 | 6.85 | 2.51 | 0.52 | 26.55 | 27.70 | 10.00 | 11.00 | 4.54 | 1.58 | 9.78 | 0.40 | 23.83 | 30.71 |
| | 0.98 | 0.30 | 2.70 | 0.03 | 2.19 | 1.84 | 5.66 | 9.90 | 4.19 | 0.00 | 11.07 | 0.14 | 13.03 | 8.41 |
| | 8.17 | 7.06 | 4.42 | 0.54 | 28.10 | 29.00 | 14.00 | 18.00 | 7.51 | 1.58 | 17.60 | 0.50 | 33.05 | 36.65 |
| | 6.79 | 6.64 | 0.60 | 0.50 | 25.00 | 26.40 | 6.00 | 4.00 | 1.58 | 1.58 | 1.95 | 0.30 | 14.62 | 24.76 |
| **LW3** | 6.19 | 6.06 | 0.04 | 0.09 | 26.80 | 26.00 | 3.50 | 10.00 | 3.75 | 2.96 | 1.53 | 0.40 | 46.53 | 86.61 |
| | 1.00 | 0.48 | 0.00 | 0.07 | 1.13 | 0.00 | 0.71 | 0.00 | 5.31 | 0.84 | 0.33 | 0.07 | 13.48 | 54.01 |
| | 6.90 | 6.40 | 0.04 | 0.14 | 27.60 | 26.00 | 4.00 | 10.00 | 7.50 | 3.56 | 1.76 | 0.45 | 56.06 | 124.80 |
| | 5.48 | 5.72 | 0.04 | 0.04 | 26.00 | 26.00 | 3.00 | 10.00 | 0.00 | 2.37 | 1.30 | 0.35 | 37.00 | 48.42 |
| **LW4** | 5.99 | 5.67 | 0.36 | 0.13 | 27.15 | 26.85 | 3.00 | 6.00 | 4.94 | 2.17 | 2.36 | 0.58 | 51.87 | 61.24 |
| | 1.29 | 0.94 | 0.35 | 0.02 | 0.21 | 1.20 | 1.41 | 0.00 | 5.31 | 0.84 | 1.64 | 0.04 | 26.53 | 27.22 |
| | 6.90 | 6.33 | 0.60 | 0.14 | 27.30 | 27.70 | 4.00 | 6.00 | 8.69 | 2.76 | 3.52 | 0.60 | 70.63 | 80.49 |
| | 5.07 | 5.00 | 0.11 | 0.11 | 27.00 | 26.00 | 2.00 | 6.00 | 1.19 | 1.58 | 1.20 | 0.55 | 33.11 | 41.99 |
| **LW5** | 6.72 | 5.88 | 0.28 | 0.30 | 26.75 | 27.50 | 11.00 | 4.00 | 5.04 | 2.17 | 11.26 | 0.65 | 22.17 | 129.80 |
| | 1.31 | 0.55 | 0.04 | 0.01 | 1.06 | 0.71 | 7.07 | 0.00 | 5.17 | 1.40 | 13.94 | 0.07 | 11.45 | 102.84 |
| | 7.64 | 6.27 | 0.30 | 0.35 | 27.50 | 28.00 | 16.00 | 4.00 | 8.69 | 3.16 | 21.12 | 0.70 | 30.26 | 202.52 |
| | 5.79 | 5.49 | 0.25 | 0.10 | 26.00 | 27.00 | 6.00 | 4.00 | 1.38 | 1.19 | 1.40 | 0.60 | 14.08 | 57.08 |
| **OS1** | 7.40 | 6.54 | 0.05 | 0.08 | 15.10 | 22.70 | 4.00 | 5.00 | 2.96 | 3.16 | 22.65 | 0.20 | 57.21 | 10.54 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0.59 | 0.08 | 0.06 | 0.02 | 10.47 | 0.42 | 1.10 | 1.41 | 3.63 | 1.12 | 30.19 | 0.07 | 54.63 | 7.36 |
| | 7.82 | 6.60 | 0.09 | 0.09 | 22.50 | 23.00 | 4.00 | 6.00 | 5.53 | 3.95 | 44.00 | 0.25 | 95.84 | 15.75 |
| | 6.98 | 6.48 | 0.01 | 0.06 | 7.70 | 22.40 | 4.00 | 4.00 | 0.40 | 2.37 | 1.30 | 0.15 | 18.58 | 5.34 |
| **OS2** | 7.49 | 6.56 | 0.05 | 0.07 | 15.10 | 22.65 | 3.00 | 4.00 | 2.57 | 4.54 | 1.53 | 0.30 | 72.79 | 70.59 |
| | 0.64 | 0.25 | 0.05 | 0.05 | 10.47 | 0.49 | 1.41 | 6.28 | 3.63 | 1.40 | 0.33 | 0.14 | 25.19 | 72.10 |
| | 7.94 | 6.73 | 0.08 | 0.10 | 22.50 | 23.00 | 4.00 | 4.00 | 5.14 | 5.53 | 1.76 | 0.40 | 90.60 | 121.57 |
| | 7.04 | 6.38 | 0.01 | 0.03 | 7.70 | 22.30 | 2.00 | 4.00 | 0.00 | 3.56 | 1.30 | 0.20 | 54.97 | 19.61 |
| **OS3** | 7.62 | 6.60 | 0.12 | 0.11 | 15.25 | 23.35 | 7.00 | 10.00 | 2.37 | 2.77 | 3.72 | 0.08 | 61.95 | 154.60 |
| | 1.22 | 0.01 | 0.00 | 0.01 | 10.68 | 0.92 | 1.41 | 11.31 | 1.68 | 1.12 | 4.70 | 0.04 | 41.30 | 199.87 |
| | 8.48 | 6.61 | 0.12 | 0.12 | 22.80 | 24.00 | 8.00 | 18.00 | 3.56 | 3.56 | 7.04 | 0.10 | 91.15 | 295.93 |
| | 6.75 | 6.59 | 0.12 | 0.10 | 7.70 | 22.70 | 6.00 | 2.00 | 1.19 | 1.98 | 0.40 | 0.05 | 32.74 | 13.26 |
| **MS4** | 7.32 | 6.32 | 0.15 | 0.15 | 18.80 | 22.75 | 7.00 | 7.00 | 4.94 | 2.77 | 6.98 | 0.35 | 27.19 | 328.19 |
| | 1.23 | 0.09 | 0.01 | 0.00 | 5.37 | 0.35 | 1.41 | 4.24 | 5.87 | 0.00 | 7.54 | 0.14 | 16.12 | 402.96 |
| | 8.19 | 6.38 | 0.15 | 0.15 | 22.60 | 23.00 | 8.00 | 10.00 | 9.09 | 2.77 | 12.32 | 0.45 | 38.59 | 613.12 |
| | 6.45 | 6.25 | 0.14 | 0.15 | 15.00 | 22.50 | 6.00 | 4.00 | 0.79 | 2.77 | 1.65 | 0.25 | 15.80 | 43.26 |
| **MS5** | 6.49 | 6.40 | 0.16 | 0.15 | 22.70 | 22.90 | 4.00 | 5.00 | 3.06 | 3.36 | 5.08 | 0.25 | 16.53 | 103.69 |
| | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.14 | 1.25 | 4.24 | 2.93 | 0.84 | 5.27 | 4.70 | 0.07 | 88.72 |
| | 6.49 | 6.40 | 0.16 | 0.16 | 22.70 | 23.00 | 4.00 | 8.00 | 5.14 | 3.95 | 8.80 | 0.25 | 16.58 | 166.42 |
| | 6.49 | 6.40 | 0.16 | 0.14 | 22.70 | 22.80 | 4.00 | 2.00 | 0.99 | 2.77 | 1.35 | 0.25 | 16.48 | 40.96 |
| **ES6** | 7.06 | 6.49 | 0.14 | 0.15 | 19.10 | 22.00 | 4.00 | 15.00 | 2.67 | 2.96 | 16.55 | 0.57 | 36.31 | 48.23 |
| | 1.19 | 0.01 | 0.01 | 0.01 | 4.38 | 0.71 | 2.83 | 9.90 | 3.49 | 0.28 | 21.85 | 0.11 | 25.56 | 23.16 |
| | 7.90 | 6.50 | 0.15 | 0.15 | 22.20 | 22.50 | 6.00 | 22.00 | 5.14 | 3.16 | 32.00 | 0.65 | 54.39 | 64.61 |
| | 6.22 | 6.48 | 0.13 | 0.14 | 16.00 | 21.50 | 2.00 | 8.00 | 0.20 | 2.77 | 1.10 | 0.50 | 18.24 | 31.85 |
| **ES7** | 7.08 | 6.15 | 0.14 | 0.14 | 19.80 | 22.30 | 5.00 | 3.00 | 2.86 | 2.57 | 13.58 | 0.38 | 58.04 | 171.34 |
| | 1.41 | 0.30 | 0.01 | 0.01 | 2.55 | 0.28 | 4.24 | 1.41 | 3.77 | 0.84 | 18.14 | 0.04 | 45.74 | 209.13 |
| | 8.08 | 6.36 | 0.15 | 0.15 | 21.60 | 22.50 | 8.00 | 4.00 | 5.53 | 3.16 | 26.40 | 0.40 | 90.38 | 319.22 |
| | 6.08 | 5.94 | 0.13 | 0.13 | 18.00 | 22.10 | 2.00 | 2.00 | 0.20 | 1.98 | 0.75 | 0.35 | 25.70 | 23.47 |
| **BS8** | 7.21 | 6.29 | 0.07 | 0.12 | 20.90 | 23.25 | 8.00 | 5.00 | 3.46 | 2.37 | 1.61 | 0.45 | 34.58 | 70.82 |
| | 1.16 | 0.11 | 0.07 | 0.01 | 2.69 | 0.35 | 1.88 | 1.41 | 2.93 | 0.00 | 0.22 | 1.09 | 23.12 | 62.38 |

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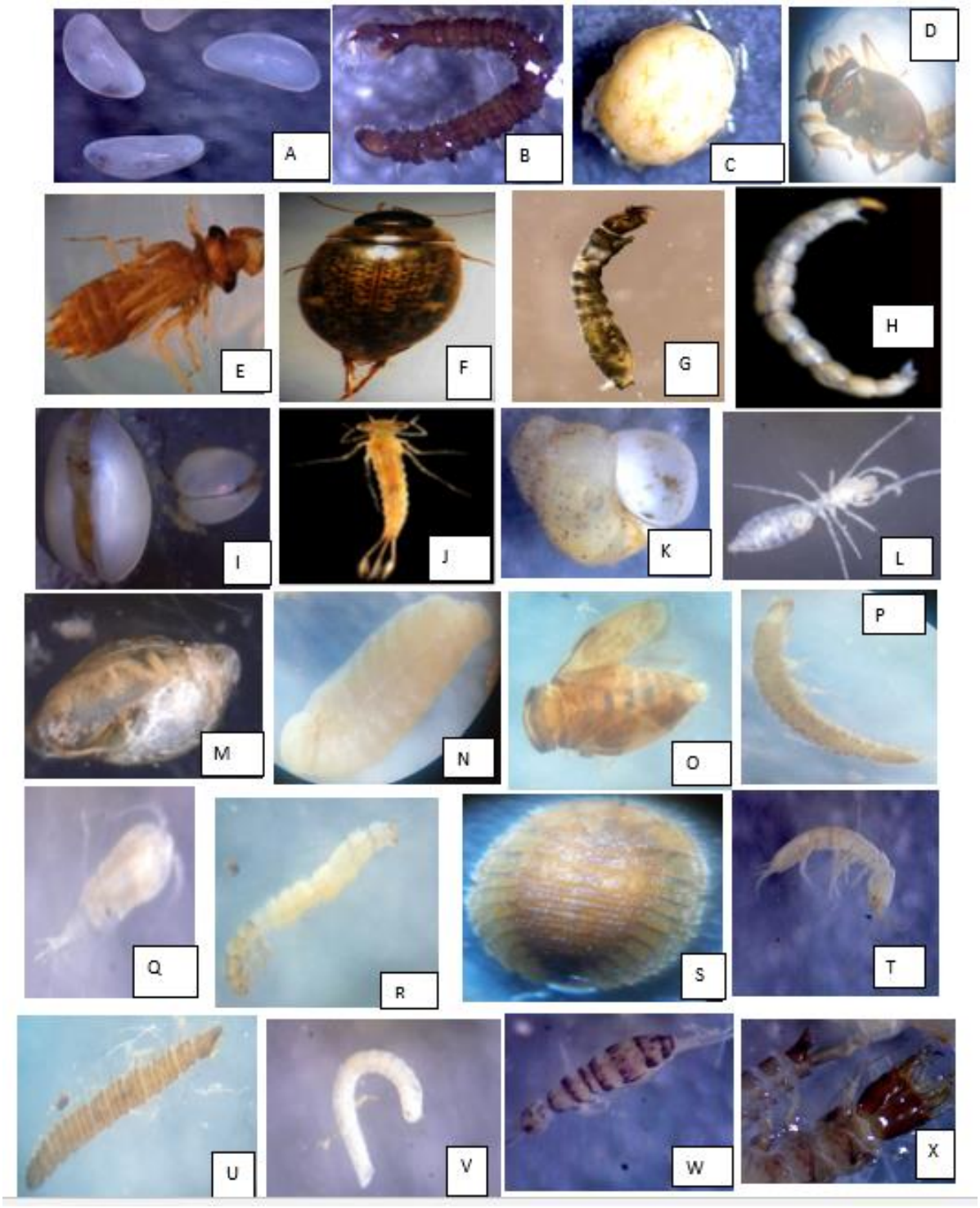
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 8.03 | 6.37 | 0.12 | 0.13 | 22.80 | 23.50 | 8.00 | 6.00 | 5.53 | 2.37 | 1.76 | 0.45 | 50.93 | 114.92 |
| | 6.39 | 6.21 | 0.02 | 0.11 | 19.00 | 23.00 | 8.00 | 4.00 | 1.38 | 2.37 | 1.45 | 0.45 | 18.24 | 26.71 |
| **BS9** | 7.17 | 6.50 | 0.10 | 0.16 | 19.55 | 21.80 | 7.00 | 5.00 | 2.77 | 1.58 | 3.29 | 0.28 | 44.42 | 103.56 |
| | 1.19 | 0.12 | 0.08 | 0.01 | 2.19 | 0.99 | 1.41 | 1.41 | 3.35 | 0.56 | 2.81 | 0.11 | 5.55 | 101.13 |
| | 8.01 | 6.58 | 0.15 | 0.16 | 21.10 | 22.50 | 8.00 | 6.00 | 5.14 | 1.98 | 5.28 | 0.35 | 48.35 | 175.08 |
| | 6.33 | 6.41 | 0.04 | 0.15 | 18.00 | 21.10 | 6.00 | 4.00 | 0.39 | 1.19 | 1.30 | 0.20 | 40.50 | 32.05 |
| **BS10** | 7.72 | 6.80 | 0.03 | 0.04 | 16.30 | 20.05 | 6.00 | 4.00 | 3.46 | 1.58 | 6.56 | 0.30 | 59.48 | 28.45 |
| | 1.25 | 0.23 | 0.02 | 0.01 | 4.67 | 0.64 | 5.66 | 2.83 | 4.61 | 0.00 | 8.15 | 0.21 | 44.81 | 5.47 |
| | 8.60 | 6.96 | 0.04 | 0.04 | 19.60 | 20.50 | 10.00 | 6.00 | 6.71 | 1.58 | 12.32 | 0.45 | 91.16 | 32.32 |
| | 6.83 | 6.64 | 0.01 | 0.03 | 13.00 | 19.60 | 2.00 | 2.00 | 0.20 | 1.58 | 0.80 | 0.15 | 27.79 | 24.58 |
| **BS11** | 7.73 | 6.82 | 0.06 | 0.06 | 12.60 | 18.75 | 2.50 | 4.00 | 2.86 | 2.57 | 5.03 | 0.28 | 25.12 | 54.33 |
| | 0.66 | 0.35 | 0.01 | 0.02 | 7.92 | 0.35 | 0.71 | 6.28 | 3.21 | 0.28 | 5.34 | 0.04 | 8.56 | 17.60 |
| | 8.20 | 7.06 | 0.07 | 0.07 | 18.20 | 19.00 | 3.00 | 4.00 | 5.14 | 2.77 | 8.80 | 0.30 | 31.17 | 66.78 |
| | 7.26 | 6.57 | 0.05 | 0.04 | 7.00 | 18.50 | 2.00 | 4.00 | 0.59 | 2.37 | 1.25 | 0.25 | 19.07 | 41.88 |
| **BS12** | 7.50 | 6.52 | 0.10 | 0.13 | 20.15 | 21.35 | 7.00 | 6.00 | 2.86 | 1.78 | 4.22 | 0.33 | 40.18 | 21.27 |
| | 0.94 | 0.35 | 0.04 | 0.01 | 1.63 | 0.21 | 4.24 | 1.00 | 3.21 | 0.84 | 3.99 | 0.04 | 7.60 | 14.47 |
| | 8.16 | 6.77 | 0.12 | 0.13 | 21.30 | 21.50 | 10.00 | 6.00 | 5.14 | 2.37 | 7.04 | 0.35 | 45.55 | 31.50 |
| | 6.83 | 6.27 | 0.07 | 0.12 | 19.00 | 21.20 | 4.00 | 6.00 | 0.59 | 1.19 | 1.40 | 0.30 | 34.81 | 11.03 |
| **BS13** | 7.88 | 6.59 | 0.05 | 0.09 | 17.60 | 21.75 | 4.00 | 7.00 | 3.65 | 2.17 | 1.48 | 0.33 | 43.15 | 151.39 |
| | 0.88 | 0.13 | 0.06 | 0.01 | 0.85 | 0.35 | 2.83 | 7.07 | 4.89 | 0.28 | 0.40 | 0.04 | 0.23 | 129.10 |
| | 8.50 | 6.68 | 0.09 | 0.09 | 18.20 | 22.00 | 6.00 | 12.00 | 7.11 | 2.37 | 1.76 | 0.35 | 43.32 | 242.68 |
| | 7.26 | 6.50 | 0.01 | 0.08 | 17.00 | 21.50 | 2.00 | 2.00 | 0.20 | 1.98 | 1.20 | 0.30 | 42.99 | 60.11 |

**Legend:** DS = Dry season, RS = Rainy season

**Appendix 5:** Pictures of some groundwater fauna collected during the study period in Fako




A=Psychrodromus, B= Lutzomyia, C= Limnesia, D= Rhagovelia, E= Aeshna, F=Hydrovatus, G=Simulium, H=Chironomus, I= Darwinula, J= Ischnura, K=Viviparus, L= Pseudoscorpion, M= Physa, N= Erpobdellidae, O= micronecta, P=Macrelmis, Q=Cyclops, R= Hydroptilia, S=Eubrianax, T=Metastenasellus, U=Pericoma, V=Lumbriculus, W=Folsoma, X=Philopotamus.

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# Impact of physicochemical parameters on biodiversity and groundwater quality in Tiko, Cameroon

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**Abstract**
In order to evaluate the impact of physicochemical variation on biodiversity in ten wells in the town of Tiko, physico-chemical parameters of the well water were analyzed using standard methods while their fauna were collected using a phreatobiological net. The physicochemical analysis showed that, the well water in Tiko had high temperature (27 ± 0.84 °C), slightly acidic pH (6.42 ± 0.45 CU), highly turbid (13.55 ± 8.7 FTU), high orthophosphate levels (0.53 ± 0.45 mg/L), good dissolved oxygen level ( 59.57 ± 6.48 %), weak mineralization ( 256.75 ± 104.52 µS/ cm) with high colour content (32.17 ± 13.35 Pt/Co), with all the values being relatively higher in the dry season than in the rainy season except for colour. A total number of 6290 organisms were collected during the study period in the sampling points, belonging to 02 phyla, 09 classes, 29 families and 26 identified genus/or sub families. This community was dominated by Ostracods (46.51%) followed by Copepods (43.3 %) while the least taxa were Hirudinea (0.24 %) and Arachnids (0.35 %). Groundwater was rich in mostly epigean taxa and very poor in groundwater dependent organisms (hypogean taxa) due to the poor management and protection levels of the wells and also due to the relationship between ground water and surface water. A total of 43 stygobites were collected, belonging to the families Asellidae (01), Stenasellidae (20) and Darwinulidae (22). The results obtained showed that the water is not good for consumption by the population without treatments. There is therefore need to sensitize these population on the development of positive habits towards their water points in order to prevent them from water borne diseases that could be caused by the poor physicochemical properties.

**Keywords:** Cameroon, groundwater, physico-chemical quality, stygobites, Tiko

## 1. Introduction
Groundwater is water that flows beneath the earth's surface, filling the porous spaces in soil, sediments and rocks. It is the source of water for aquifers, springs and wells. It is the main source of drinking water reservoir on earth, but also a major ecosystem in terms of biological diversity (Leijs *et al*., 2009) [1]. Maintaining groundwater quality and conserving its biodiversity are converging goals towards ensuring healthy wells for the population. Groundwater ecosystems contain many endemic species adapted to live in an environment with no light and limited resources (Lou & Bloomfield, 2012) [2].

Ecological and microbiological exploration of groundwater over the past two decades has identified a diverse range of organisms inhabiting groundwater systems called stygofauna (Asmyhr *et al.*, 2014) [3]. They are made up of many kinds of crustaceans and other invertebrates which are typically well adapted for the subterranean environment with features such as lack of pigments, elongated appendages and reduced or absence of eyes (Humphreys, 2006) [4]. Stygofauna are valued as a biodiversity resource, as indicators of groundwater ecosystem health, and potential providers of ecosystem goods and services (Tomlinson *et al.*, 2007) [5]. Groundwater adapted species provide an important contribution to biodiversity (Lou and Bloomfield, 2012) [2]. In Cameroon, previous work has been done in this domain in the Centre, Littoral and West regions. The results of the physico-chemical parameters of the different stations studied showed that these regions have a high level of organic and chemical pollution and the groundwater habours Stygobites of the genus *Metastenasellus* (Zebaze Togouet, 2006, 2011, Tuekam Kayo, 2013, Nana Nkengmeni, 2015) [6, 7, 8, 9].

The main objective of this work was to determine the water quality of some wells in the town of Tiko by measuring the physicochemical parameters. It is also intended to identify potential biodiversity indicators in groundwater and to reinforce public awareness of the necessity to conserve the quality and quantity of groundwater and its biodiversity by emphasising on its economic, social, and scientific value together with its detriment on the health of the population when it's quality is bad or not good for consumption.

## 2. Materials and Methods

### 2.1 Study area

Fako division experiences the subequatorial climate with two distinct seasons: more than four months of dry season from November to mid-March and seven months of rainy season that runs from mid-March to October with a mean annual rainfall of about 3.100 mm ±1.100 (Che *et al.*, 2012) [10]. Annual rainfall is thus high, with yearly precipitations varying from 1.500 to 6.000 mm whereby peak rainfall is recorded from June to August and at times in September. The mean annual temperature is approximately 26 °C and shows only limited variations of approximately 4°C throughout the year (Che *et al.*, 2012) [10].

### 2.2 Sampling points

The sampling for physicochemical and fauna analyses was carried out from January to December 2017. A total of ten sampling points was chosen for this study and sampling was done twice per season in the town of Tiko, which is situated in Fako division of the South West Region of Cameroon with coordinate points being latitude 4°04'00" N and longitude 9°21'18" E (Figure 1).

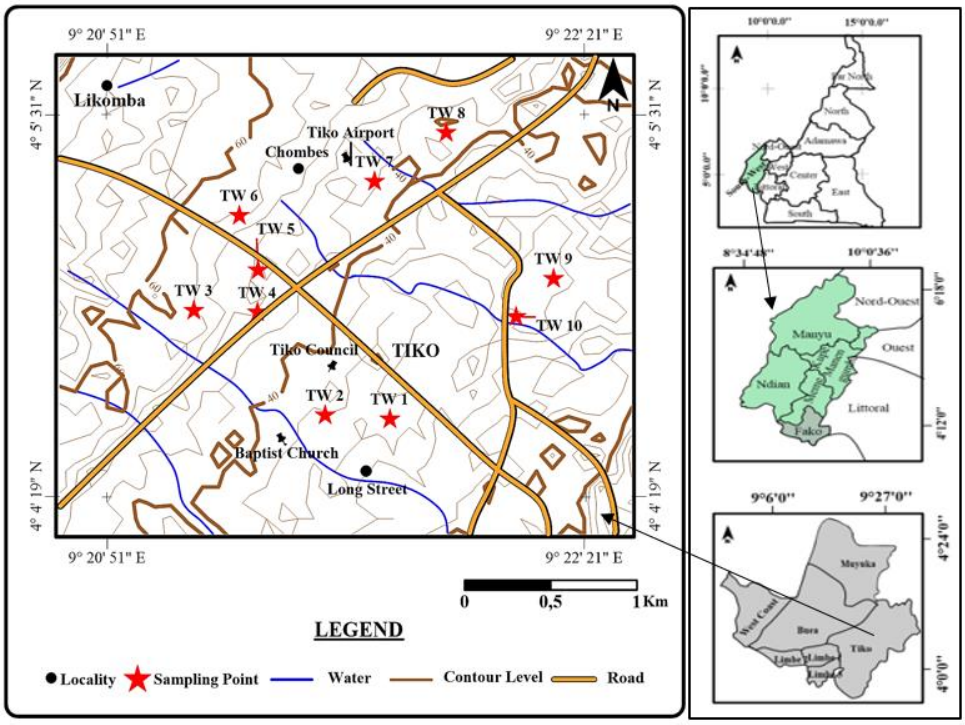


**Fig 1:** Map of Tiko showing sampling points during the study period

### 2.3 Sampling of water

Water for the physicochemical analysis was collected in 250 mL and 1000 mL polyethylene bottles and transported to the laboratory in a cooler at approximately 4° C. The physicochemical properties were measured following standard techniques described by APHA (1998) [11] and Rodier (2009) [12] using appropriate devices.

### 2.4 Sampling of fauna

The fauna were collected from the bottom of the wells using a Phreatobiological net sampler (Cvetkov, 1968) [13] with the net having a mesh size of 180-200 µm (Dumas & Fontanini, 2001) [14]. In the laboratory, the fauna were rinsed, sorted and identified and counted using a binocular magnifying loupe of the Wild M5 brand and an optical microscope IVymen R system using appropriate identification keys (Tachet *et al.*, 2010, Moisan, 2010) [15, 16].

### 2.5. Statistical analysis

The software SPSS 20.0 was and Microsoft Excel 2016 program were used to analyse the results. Boxplots were used to represent the distribution of the physicochemical variables while a pie chat was used to represent the different taxa collected during the sampling period.

## 3. Results and Discussion

### 3.1 Physicochemical parameters

The lowest mean seasonal value of temperature was obtained in the rainy season (25 °C) and the highest value was obtained in the dry season (28.4 °C) with a mean seasonal value of 27 ± 0.83 °C. (Figure 2A). The mean seasonal value of total dissolved solids (TDS) was higher in the dry season than in the rainy season and the highest value was obtained in the dry season (210.5 mg/L) while the lowest value was obtained in the dry season (49 mg/L) with a mean seasonal value of 129.52 ± 52.75 mg/L(Figure 2B). The U test of Mann Whitney did not show any significant difference from one season to another for temperature and TDS. The highest value of suspended solids (SS) was obtained in the dry season (18.5 mg/L) while the lowest mean seasonal value of 2.5 mg/L was obtained in the dry season, with a mean seasonal value of 8.27 ± 4.90 mg/L. The U test of Mann Whitney showed a

significant difference for SS value from one season to another (p=0.002) (Figure 2C). The value of colour varied from 10.50 mg/L in the dry season to 52.00 mg/L in the rainy season with a mean seasonal value of 32.17±13.35 mg/L (Figure 2D).

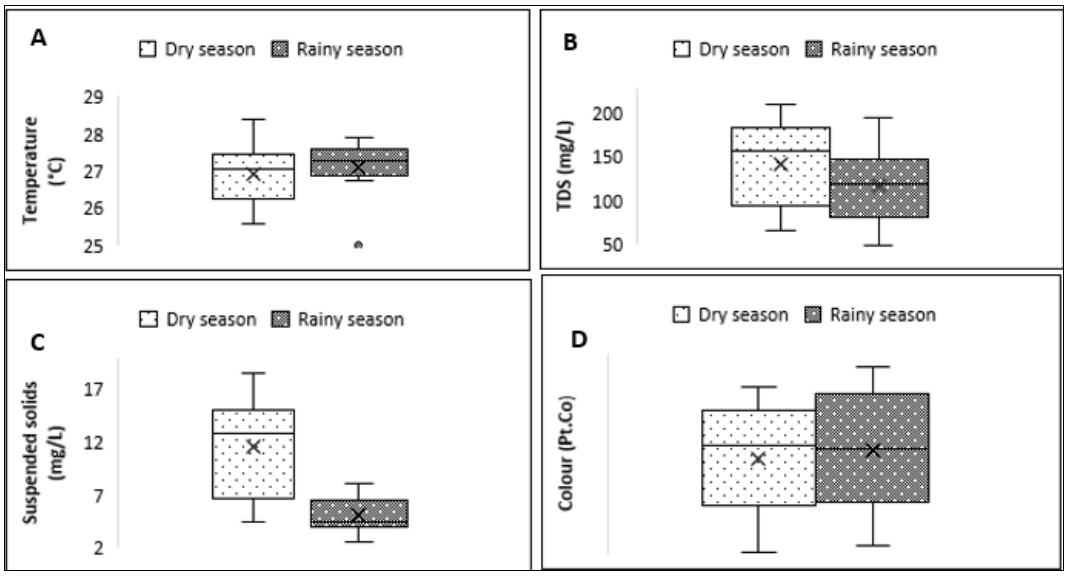


**Fig 2:** Boxplots showing the seasonal distribution of temperature (A), TDS (B), SS (C) and Colour (D) in the wells studied in Tiko

Turbidity values oscillated between 3.00 FTU in the rainy season and 29.00 FTU in the dry season and the U test on Mann Whitney showed a significant difference between the rainy and the dry season ($p < 0.05$) (Figure 3A).The mean seasonal value of salinity was distributed between 0.04 PSU in the dry season and 0.19 PSU, obtained in both the rainy season and the dry season, with a mean value of 0.11 ± 0.04 PSU (Figure 3B).The value of electric conductivity varied from 98.50 µS/cm in the rainy season to 416 µS/cm in the dry season, with a mean seasonal value of 256.95 ± 104.52 µS/cm and no significant difference was observed for this parameter (Figure 3C). The mean seasonal value of pH varied significantly during the study period, with lowest value being 5.63, obtained in the rainy season while the highest value was 7.24, obtained in the dry season. A significant difference was observed between the dry and rainy season as shown by the U test of Mann Whitney ($p<0.05$) (Figure 3D).

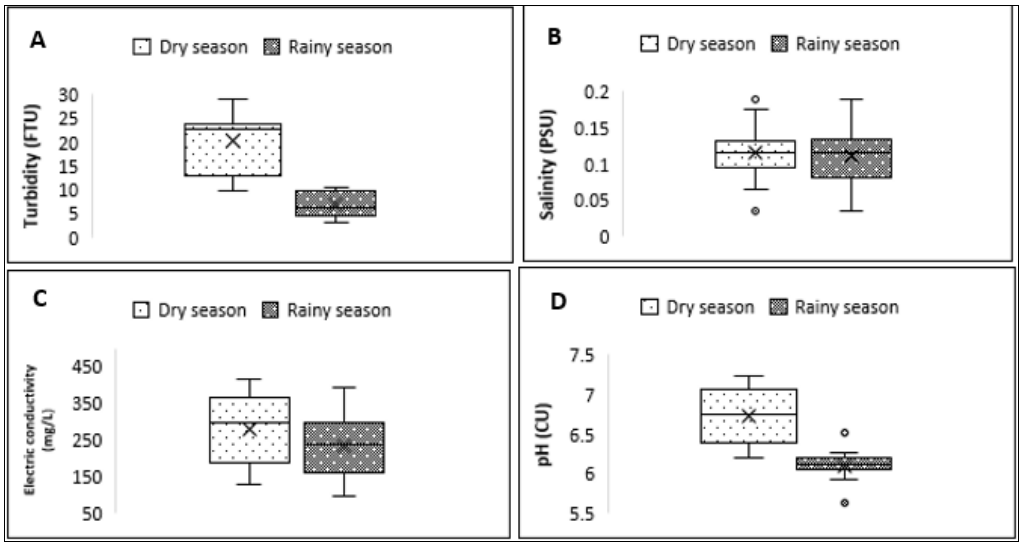


**Fig 3:** Boxplots showing the spatial and temporal distribution of turbidity (A), salinity (B), electric conductivity (C) and pH (D) in the wells studied in Tiko.

Orthophosphates values fluctuated between 0.17 mg/L in the rainy season with a mean of 0.51 ± 0.15 mg/L and 2.40 in the dry season whereby the U test of Mann Whitney showed a significant difference from one season to another ($p = 0.007$) (Figure 4A). The values of oxidability oscillated between 1.19 mg/L in the rainy season and 6.02 mg/L in the dry season and the U test of Mann Whitney showed a significant difference between the rainy and dry season ($p = 0.09$) (Figure 4B). The mean seasonal value of nitrate ions varied from 0.20 mg/L as lowest value to 2.75 mg/L as highest value, both obtained in the dry season with a mean value of 1.19 ± 0.61 mg/L and the U test of Mann Whitney did not show any significant difference between the seasons (Figure 4C). As for nitrite ions the values were higher in the rainy season than in the dry season and varied from 0 mg/L, obtained in the dry season to 0.06 mg/L, obtained in the rainy season, with a mean value of 0.02 ± 0.01. The U test of Mann Whitney did not show any significant difference from one season to another for nitrite ion (Figure 4D).

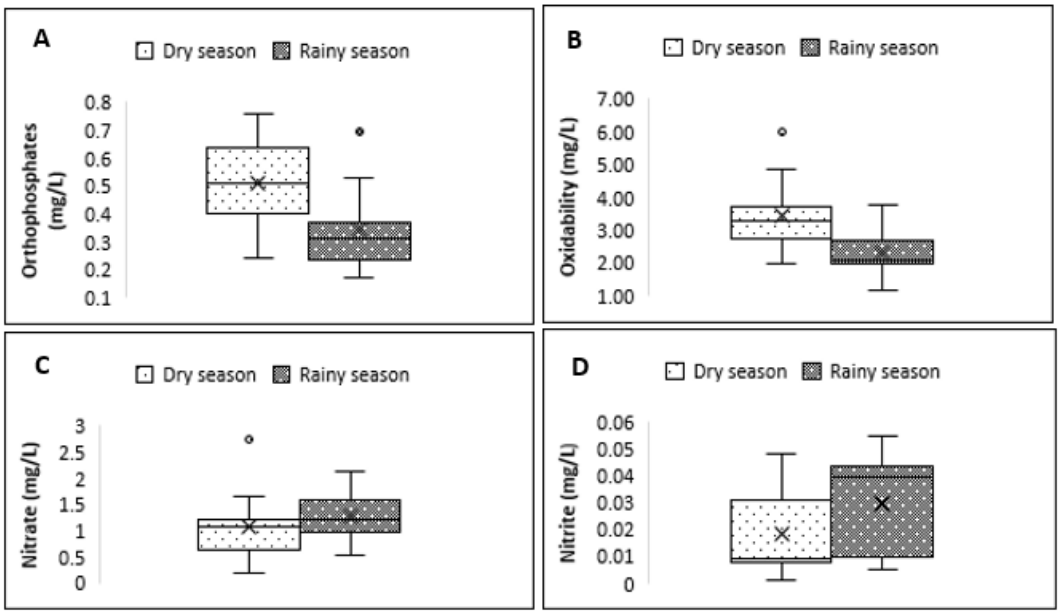


**Fig 4:** Boxplots showing the seasonal distribution of orthophosphate (A), oxidability (B), nitrate (C) and nitrite (D) in the wells studied in Tiko

Dissolved oxygen values were distributed from 47.70 % to 75.75 %, with all values obtained in the dry season with a mean value of 59.57± 6.48 % (Figure 5A). The mean seasonal value of dissolved carbon dioxide was varied from 0.35 mg/L in the rainy season to 6.03 mg/L in the dry season and the U test of Mann Whitney showed a significant difference between the rainy and dry season with a p value of 0.001 (Figure 5B).

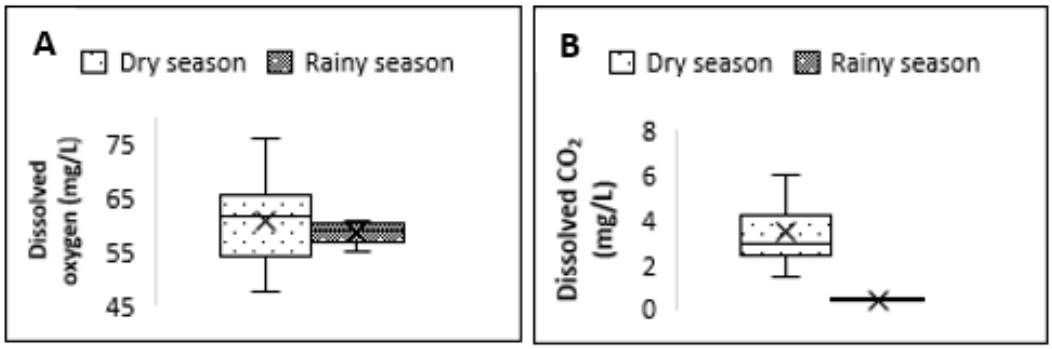


**Fig 5:** Boxplots showing the seasonal distribution of dissolved oxygen (A) and dissolved carbon dioxide (B) in the wells studied in Tiko

### 3.2 Groundwater fauna of Tiko

The organisms collected during the sampling period was a total of 6290 organisms belonging to 02 phyla (Annelida and Arthropoda), 09 classes, thirteen orders, 29 families and 26 genus/sub family. This fauna was diversified and dominated by Ostracods which alone had a total abundance of 46.51%, followed by Copepods with an abundance of 43.3 %. The taxonomic richness of the wells varied between eight individuals in TK 10 and 19 individuals in TK7. The fauna collected in the studied stations is characterized by the prevalence of epigean taxa (from external origin), at the detriment of a very small number of hypogean taxa (stygobiont groups). The fauna collected shows that, the wells in Tiko are largely dominated by the class Crustacean with principal representatives being families of Cytherididae, Cyprididae and Cyclopoidae (Figure 6).

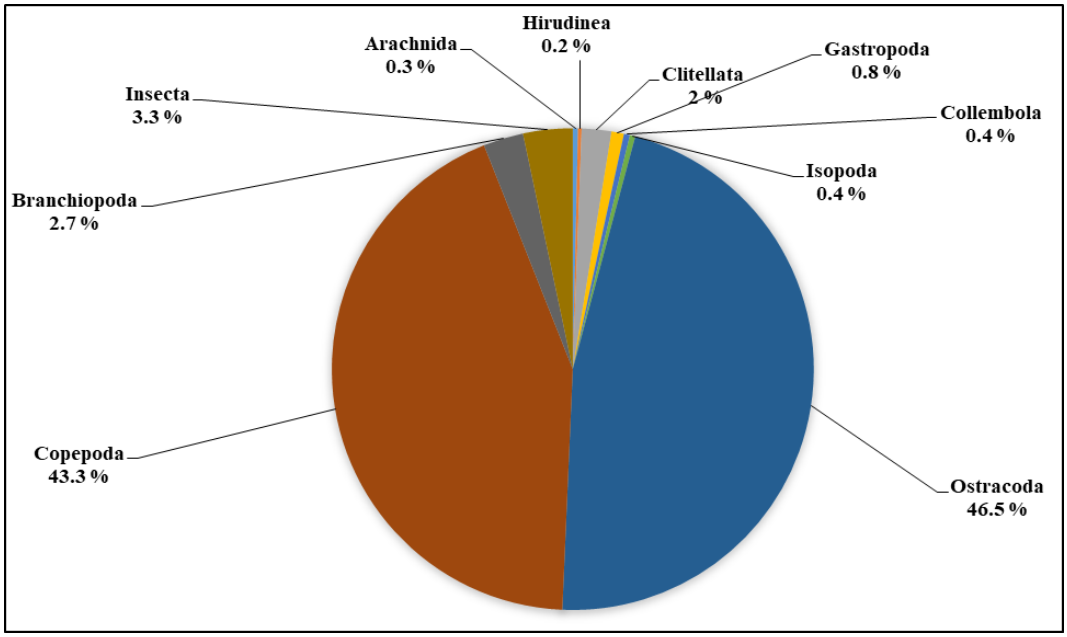


**Fig 6:** Distribution of the different classes of the 6290 invertebrates collected in groundwater during the sampling period in the wells in Tiko.

Cyclopoidae were present in all the 10 sampling points and were abundant in sampling points that showed high organic matter and that are fairly mineralized as far as the physicochemical analyses are concerned. Cyprididae (Ostracods) stygophiles or stygobites taxa, very small of size, widespread and less studied, were present in all the wells except for TW10 (Table I). Insects of the family Chironomidae were abundantly collected. Out of the 6292 organisms collected, 43 organisms were stygobites represented by three families; Stenasellidae, Darwinulidae and Asellidae and a total of 20 Stenasellidae was collected in six out of the ten wells that were sampled (TW3, TW5, TW7, TW8, TW9 and TW10). The second stygobite family was Asellidae (Proasellus), collected in TW7 with a total of just one individual. The third group was Darwinulidae whereby a total number of 22 individuals were collected in TW1, TW6 and TW8. The diversity index (H) of Shannon and Weaver showed that the fauna in Tiko was more diversified in the rainy season (1.19 ± 0.48) than in the dry season (1.06 ± 0.4) and the equitability index (J) also showed that the rainy season was more equitable (0.57 ± 0.25) than the dry season (0.51 ± 0.13).

**Table 1:** Groundwater fauna collected during the study period in the ten wells in Tiko

| Class | Order | Family | Genus/sub family | Tk1 | Tk2 | Tk3 | Tk4 | Tk5 | Tk 6 | Tk7 | Tk8 | Tk9 | Tk10 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Arachnida | Acarina | Tetragnathidae | Tetragnatha | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 0 | 1 | 0 | 6 |
| | | Ceratozetidae | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 |
| Hirudinea | Euhirudinea | Bdellidae | Bdellina | 0 | 0 | 8 | 2 | 0 | 0 | 0 | 0 | 1 | 0 | 11 |
| | | Piscicolidae | Rhynchobdellida | 0 | 0 | 0 | 2 | 4 | 0 | 0 | 2 | 1 | 0 | 9 |
| Clitellata | Oligochaeta | Lumbriculicidae | Lumbriculus | 1 | 7 | 0 | 0 | 29 | 0 | 0 | 2 | 0 | 0 | 39 |
| | | Naididae | Dero | 28 | 2 | 4 | 42 | 9 | 3 | 5 | 5 | 0 | 0 | 98 |
| | | Physidae | Physa | 24 | 1 | 0 | 0 | 19 | 0 | 8 | 0 | 0 | 0 | 52 |
| Collembola | Entomorbryomorpha | Isotomidae | Folsoma | 7 | 0 | 2 | 0 | 3 | 2 | 4 | 2 | 0 | 0 | 20 |
| | | Entomobryiidae | Orchesella | 1 | 2 | 0 | 0 | 1 | 0 | 1 | 0 | 0 | 0 | 5 |
| Isopoda | Isopoda | Asellidae* | Proasellus* | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| | | Stenasellidae* | Metastenasellus* | 0 | 0 | 4 | 0 | 3 | 0 | 2 | 3 | 7 | 1 | 20 |
| Ostracoda | Podocopida | Cytheridae | | 698 | 45 | 0 | 0 | 85 | 5 | 100 | 47 | 6 | 5 | 991 |
| | | Cyprididae | Psychrodromus | 697 | 510 | 4 | 5 | 376 | 65 | 171 | 67 | 19 | 0 | 1914 |
| | | Darwinulidae* | | 12 | 0 | 0 | 0 | 0 | 2 | 0 | 8 | 0 | 0 | 22 |
| Copepoda | | Cyclopidae | | 580 | 417 | 197 | 50 | 342 | 683 | 158 | 94 | 65 | 139 | 2725 |
| Branchiopoda | Cladocera | Moinidae | Moina | 0 | 0 | 0 | 0 | 0 | 0 | 161 | 7 | 1 | 0 | 169 |
| Insecta | Diptera | Culicidae | Culex | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 1 | 0 | 0 | 7 |
| | | Chironomidae | Chironomus | 9 | 18 | 0 | 3 | 0 | 2 | 22 | 3 | 0 | 0 | 57 |
| | | | Chironomini | 0 | 0 | 1 | 0 | 0 | 0 | 8 | 0 | 0 | 0 | 9 |
| | | Ceratopogonidae | Dasyheilea | 0 | 0 | 0 | 3 | 1 | 0 | 0 | 0 | 1 | 1 | 6 |
| | | | Bezzia | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 6 |
| | | Psychodidae | Pericoma | 0 | 0 | 0 | 2 | 0 | 3 | 0 | 0 | 0 | 1 | 6 |
| | | Ephydidae | Scatella | 0 | 0 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 4 |
| | Dysticidae | Dysticidae | Laccophilus | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 6 |
| | | Hydrophylidae | Hydrophilus | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 2 |
| | | Elmidae | Macrelmis | 0 | 2 | 0 | 1 | 0 | 0 | 6 | 0 | 0 | 7 | 16 |
| | Ephemeroptera | Caenidae | Caenis | 0 | 11 | 0 | 3 | 0 | 0 | 0 | 7 | 0 | 0 | 21 |
| | Hemiptera | Mesovelidae | Mesovelia | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 2 |
| | | Aeshnidae | Aeshna | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 10 | 0 | 0 | 13 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Hymenoptera | Formicidae | | 0 | 3 | 5 | 2 | 12 | 1 | 13 | 10 | 0 | 0 | 46 |
| | Orthoptera | Blattidae | Panesthia | 2 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 4 |
| Total number of individuals | | | | 2060 | 1019 | 231 | 115 | 885 | 767 | 680 | 269 | 103 | 161 | 6290 |
| Total number of taxa | | | | 12 | 12 | 10 | 11 | 15 | 10 | 19 | 16 | 10 | 8 | |
| Stygobitic richness | | | | 1 | 0 | 1 | 0 | 2 | 1 | 2 | 2 | 1 | 1 | |

* represents the stygobite families and genus

## 4. Discussion

### 4. 1. Physicochemical analysis

The high values of temperature obtained in the rainy season could be due to the reduction of the water level and the depth of the wells, which allowed sunlight to directly penetrate into these wells and the characteristics of each sampling point such as, vegetation canopy, topography of the site in relation to the external milieu (Huang F. *et al.,* 2019) [17].As for TDS, the values were relatively high due to infiltration of sea water into the underground milieu as a result of the nature of the soil in Limbe. Values are within the limit set by WHO (2017) [18] for water meant for consumption and the high values in the dry season was due to the decrease in water level and from the weathering of volcanic rocks and erosion of the soil around by rain water. The high values of electrical conductivity in the dry season is due to the decrease in water level brought about by constant fetching of the water by the users. According to Rodier (2009) [12], the acceptable level in drinking water is between 0 µS/cm and 600 µS/cm. Zébazé Togouet *et al.* (2009) [19], Tuékam Kayo (2013) [8] obtained same kind of results in the Centre and Littoral regions respectively. This gives a picture of very little solute dissolution generally in the groundwater, rapid ion-exchange between the soil and water.

Turbidity values were higher than the 5 FTU recommended by WHO (2017) [18] and it could be due to the poor nature of the protection of the wells which allows rain water to penetrate into wells. Good protection of wells prevents the penetration of running rainwater which most of the time, is loaded with plant and animal debris and these particles could be a sign of pollution, which can bring microorganisms that live principally in biofilm state in groundwater (Nana Nkengmeni *et al.,* 2015, Zébazé Togouet *et al.,* 2011) [9, 7]. The values of Suspended Solids were very high in the dry season compared to the rainy season due to particles as a result of decrease in water column. Generally, almost all the sampling points had an acidic pH during the rainy season and acidic to slightly basic pH in the dry season. These waters were slightly acidic, and this acidity is justified by the Prévosto *et al.,* (2004) [20] who observed that, the pH of volcanic substratum vary between 5.7-6.4. This is true as Fako division is made up of volcanic soil due to the presence of Mt Fako which is an active volcano. This kind of result had first been observed by Tuékam Kayo (2013) [8] in the town of Douala and Yaounde, which is a characteristic of the Cameroon substrata. Salinity values were generally low and fall within WHO (2017) [18] standards for drinking water. Orthophosphate values are above the standard recommended by WHO (2017) [18] (0.40 mg/L) for drinking water, which could be related to the proximity of the sampling points to the CDC rubber and palm plantations and the presence of traditional latrines in the neighbourhoods. Zebaze Togouet *et al.,* (2011) [7] observed that the high percentages of orthophosphates would come from agricultural fertilizers and fecal pollution which would arrive in underground milieu by infiltration. The average value of nitrate ions in all the sampling points was within the level permitted by WHO (2017) [16] for drinking water. According to Bengouni *et al.,* (2004) [21] the concentration of nitrate ions in natural environment seldom exceeds 0.45 mg/L. The high values could be due to the infiltration of water containing nitrate fertilizers used by the CDC and even by the population themselves in their farmlands. Chapman *et al,* (1996) [22] affirmed that values higher than 0.45 mg/L in subsoil waters indicate worn water discharges and especially an excessive use of fertilizers for agriculture. Nitrite is an intermediate in the oxidation of ammonia to nitrate, such oxidation can proceed in soil, and because sewage is a rich source of ammonia, water which show any appreciable amounts of nitrite is regarded as being of highly questionable quality (Istifanus *et al.,* 2013) [23]. Levels in unpolluted waters are normally low, below 0.03 mg/L. Values greater than this indicate sewage pollution which could explain the case in the rainy season due the proximity of the wells to latrines of the owners. The percentage of saturation of dissolved oxygen recorded during the study period reveals that this water is fairly oxygenated, with an average value of (62.03 ± 7.27 %). In groundwater, the dissolved oxygen contents are relatively weak compared to those of surface water, because of the absence of the photosynthetic plants, the weak water-atmosphere contact and the absence of water turbulence (Humphreys 2002) [24]. Ammonium ions translate richness of water in organic matter, which according to Nisbet and Verneaux (1970) [25] would indicate a certain degree of pollution and it comes from agricultural processes and the decomposition of living matter by the micro-organisms since naturally, groundwater does not contain nitrogen compounds.

The groundwater studied did not contain amounts that could be of danger to human health and the ammonium levels were within the range permitted for drinking water, which is 10 mg/L WHO (2017) [18]. Due of a strong carbon limitation, the underground ecosystems are placed in extreme position along a gradient of productivity (Chelius *et al.,* 2009) [26]. Therefore, the carbon present in the groundwater of Tiko would be primarily ascribable to the degradation of organic particles by bacteria and to expiration by underground invertebrates. Moreover, the organic carbon contributions in dissolved form constitute the basal resource of the underground trophic networks. The studied wells in Tiko are rich in parameters of organic pollution and therefore, the groundwater water quality in Tiko is polluted due to anthropogenic impacts such as infiltration of sewage effluent discharges, run-off from informal settlements and agricultural activities such as livestock farming.

### 4.2 Groundwater fauna in Tiko

These are two very important communities of organisms (epigean and hypogean) in groundwater and each of them play a well-defined role: hypogean organisms inform about the state of ground water while epigean organisms give an idea on the input from exogenic origin, on the hydrological characteristics, the level of protection and on the morphometric and hydrological characteristics of the wells (Nana Nkemegni *et al.,* 2015) [9]. Zebaze Togouet *et al.,* (2011) [7] suggest that the taxonomic richness of a well depends on the intrinsic characteristics of each station, its relations with the surface medium and also on the nature and

characteristics of the various land which form the aquifers in which this ground water flows from. The prevalence of microcrustaceans would be in relation with the moderate or even weak quantity of organic matter recorded in the wells. In this connection, Broyer and Rodin **(**2003) [27] proposed that under natural conditions, Crustaceans are most widespread in groundwater; they account for approximately 60% of underground aquatic fauna. In Tiko, Crustaceans dominated (Ostracods (46.5 %) and Copepods (43.3 %). Chironomids Diptera larvae born from the laying of eggs by adult insects. Their existence depends on the local microclimate, protection of water points and on the physico-chemical characteristics of water (Tuékam Kayo, 2013) [8]. Chironomids were abundant in TK7, TK2 and TK1, which are wells that were partially protected by the owners. The presence of stygobites in some wells is in accordance with the suggestion of Zebaze Togouet *et al*. (2011) [7] about a positive relation between a high aquatic biodiversity and the presence of stygobite species though in relatively small numbers. This small number of stygobites compared to epigean taxa can probably be linked to the nature of the water bodies since there is a certain degree of pollution. Groundwater ecosystems are generally poorer in nutrients and oxygen than surface water ecosystems (Galassi *et al.,* 2017) [28]. In order to reduce energetic costs, groundwater ectotherms have evolved metabolic rates that are lower than those of their close epigean relatives (Issartel *et al.,* 2005) [29]. The family Stenasellidae was observed in Cameroon by Zebaze Togouet (2006) [6] for the first time and later described by Zebaze Togouet *et al.,* (2009, 2011, 2013) [19, 7, 28]. The Stenasellidae family sampled in Tiko presented the same characteristics described by Zebaze Togouet *et al.,* (2009) [19] by being of different sizes and with more abdominal and cephalic appendages which are different from those found in other countries. They have an entirely pink body in fresh samples and whitish body in specimens preserved in alcohol, regular in form and similar to individuals of the other species of their kind, with lateral margins of a parallel body. The high levels of most of the parameters in the dry season could be the result of the less diversity obtained in the dry season.

### 4.3. Relationship between biodiversity and physicochemical parameters

Stygofauna were recorded living in physico-chemically diverse groundwater systems like the case of LW1, including in systems with groundwater ranging in depth from 0.61 in LW1 and 15 metres in TW5. Glanville *et al.,* 2016 [31] have shown that, stygofauna can be found at depth of 0.1 to 63.2 metres below ground level with electrical conductivity ranging from 11.5 to 54.800 µS/cm, groundwater temperatures ranging from 17.0 to 30.7 degrees Celsius and groundwater pH ranging 3.0 to 11 CU. Information on the wide variance in the physico-chemical properties of known groundwater habitats is valuable in developing understanding of the characteristics of groundwater systems that support groundwater communities. Stygofauna taxon richness shows a general negative trend with increasing depth to groundwater, Total dissolved solids and electrical conductivity in the wells. Taxon richness was highest in neutral to slightly alkaline pH groundwater systems and in water temperatures between approximately 12.6 and 27 degrees Celsius. Humphreys, 2008 [32] considered that groundwater systems in volcanic and sedimentary rocks may tend towards acidic environments that would be less suited to supporting stygofauna due to constraints imposed by the reducing environment. This is consistent with Tiko experience where taxon richness decreases sharply with increasing groundwater acidity. The richness in the well depends at the same time on the underground species (Stygobites) and the surface species (Stygoxene and Stygophiles) (Dole-Olivier *et al.,* 2009b) [33].

## 5. Conclusion

The present study showed that, the aquatic fauna of Tiko is relatively rich with a total of 29 families collected during the study period. The distribution and abundance of groundwater fauna families and genera are influenced by physicochemical conditions, and the characteristics of the wells and also the season. Most of the physicochemical parameters measured were high in the dry season than in the rainy season which brought about changes in fauna structure of the wells. This change in functional groups and habits of aquatic ecosystems could fundamentally alter the normal functioning of these ecosystems. This could directly affect the diversity and distribution of groundwater fauna especially stygobites that depend upon the water quality for their survival. Stygobites were collected in sampling points with high electric conductivity and low results of parameters that are indicators of organic pollution. The results show that, there is an important pollution of groundwater which limits the presence of stygobitic species as seen in the abundance of pollution resistant species such as copepods, ostracods and oligochaetes.

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