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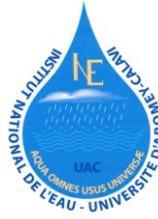
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IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES IN LAKE GUIERS, SENEGAL
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Dedication

$\mathcal{T}$o my two parents.
$\mathcal{T}$o my lovely family.
$\mathcal{T}$o my friend Abdoul Aziz Diop
$\mathcal{T}$o Niclas Hallman, rest in peace dear friend

Acknowledgments

Abstract & Synthesis

Abstract : Lake Guiers is a shallow reservoir located in the north-western part of Senegal. Its water is used both for irrigating crops and as a drinking water resource for urban centres, including Dakar, the capital of Senegal, as well as for the local population and animal herds. During the last three decades, increasing population, changing patterns of water demand has pressurized Lake Guiers's freshwater resources. To address the challenges that climate change and population growth poses in Lake Guiers water resources, it is necessary to consider its potential impacts on different dimensions of water resources. Therefore, this research aim to assess recent and future patterns on climate and future water situation (water availability and demand) in Lake until 2030. To achieve the objectives of this research, Lake Guiers climatic simulations based on the representative concentration pathways (RCPs) 4.5 and 8.5 has been analyzed and future water availability and demand has been modeled under scenarios of climate change and population growth by applying the Water Evaluation And Planning System model (WEAP). The results show that the basin of Lake Guiers experiences an increase of temperature of about $1,2°C$ and an elevated warning, leading to significant increase of atmospheric water demand is projected. In addition an increasing trend in precipitation (+6.1mm/year) has been observed from 1988-2011 and precipitation projections reveal changes an increase trend ranging between 5 and 48% in Lake Guiers area in the near-future (2050s). However,at the end of the century (2100s) an decrease of precipitation for RCP 4.5 and RCP 8.5.scenarios is projected. The changes in evapotranspiration mostly follow those from the mean precipitation and temperature with more evapotranspiration during the near future and decrease in the late century. In terms of water availability and demand, water stored in the reservoir (Lake Guiers) will be sufficient when all projects are implemented however, the pressure on Lake's water resources will increase, leading to greater competition between agriculture and municipal demand sites. Decreasing inflows scenario via taouey canal due to climate change will aggravate this situation.

Keywords : climate change, population growth, water resources, Lake Guiers, Senegal.

Synthesis

1. Résumé

Le lac de Guiers est le principal réservoir d'eau douce du Sénégal. Situé au nord-ouest du pays, ses ressources en eau sont utilisées pour l'agriculture irriguée, la pêche, mais aussi comme source principale d'approvisionnement en eau potable. Aujourd'hui, face au risque climatique, facteur de vulnérabilité des systèmes humains et naturels, il est nécessaire de produire des outils d'analyse pertinents pour une meilleure gestion et planification des ressources en eau du réservoir. Ainsi, cette étude vise d'abord à évaluer l'altération hydrologique du lac de Guiers suite aux modifications hydro-agricoles qui y sont intervenues, ensuite à analyser les tendances climatiques récentes observées, et même futures, dans le bassin, puis à quantifier la disponibilité et la demande en eau selon des scenarios de changements climatiques jusqu'en 2030. L'approche range of variability (RVA) a été utilisée pour caractériser le degré d'altération des indicateurs hydrologiques. Pour étudier les scenarios futurs d'évolution du climat dans le bassin du lac de Guiers, deux projections climatiques représentatives de l'évolution de concentration (RCP 4.5 et 8.5), ont été analysés. S'agissant de l'évaluation de la demande et de la disponibilité future en eau, le modèle d'évaluation de l'eau et du système de planification (WEAP) a été utilisé. Les résultats montrent que des changements climatiques importants sont déjà en cours dans le bassin. Une augmentation significative de $1,2°C$ s'est produite durant les deux dernières décennies. Les projections montrent aussi une tendance à la hausse des températures. En ce qui concerne les précipitations, une hausse de +6.1 mm par an a été observée durant la période 1988-2011 et les projections jusqu'au milieu du siècle (2050s) confirment cette tendance variant entre 5% et 48%. Cependant, vers la fin du siècle (2100s), une baisse drastique des précipitations aussi bien pour les scenarios RCP 4.5 que pour RCP 8.5 a été observée. En termes de disponibilité, le volume d'eau contenu dans le lac est aujourd'hui en mesure de supporter tous les projets en cours (irrigation, renforcement du système d'adduction en eau potable et la remise en eau du Ndiael). Mais, cette pression sur le lac conduira davantage à une farouche compétition entre les différents usagers et exacerbera les conflits entre eux. Les scenarios de baisse des entrées en eau dans le lac via le canal Taouey, dûs aux changements climatiques, vont aggraver cette situation. Les scenarios d'arrêt des entrées permettent d'estimer l'épuisement total de la ressource dans le réservoir au bout de 19 mois selon le scénario RCP8.5 et au bout de 20 mois d'après le scénario RCP4.5.

Keywords : changement climatique, accroissement démographique, ressources en eau, Lake Guiers, Sénégal

2. Introduction

Conformément à la politique de maîtrise et de gestion des ressources en eau, le Sénégal avait initié durant les années 1990 la mise en valeur du lac de Guiers. Le principal objectif est d'accroître les surfaces emblavées dans le delta du fleuve Sénégal pour l'agriculture irriguée et l'approvisionnement en eau potable des agglomérations urbaines en pleine croissance démographique comme la ville de Dakar. Aujourd'hui, face au risque climatique, la question de l'avenir du lac de Guiers est vitale. Répondre à cette problématique revient à analyser les impacts potentiels des changements climatiques et de l'accroissement démographique sur les différentes dimensions des ressources en eau de Lac de Guiers. Cette analyse devrait permettre de produire des outils nécessaires qui permettront d'améliorer les mesures de gestion mises en place dans le but d'atteindre les objectifs d'adaptation aux changements climatiques dans le bassin du lac de Guiers. Ainsi, cette étude vise trois objectifs:

- Évaluer l'altération hydrologique et hydro-chimique du lac de Guiers au cours des trois dernières décennies;

- Analyser les tendances climatiques récentes et futures dans le bassin du lac de Guiers;

- Évaluer la disponibilité et la demande en eau du lac de Guiers selon des scenarios de changements climatiques et d'accroissement démographique jusqu'en 2030.

3. Zone d'étude

Le lac de Guiers est situé dans le nord du Sénégal entre 14°09' latitude Nord et 16°08' longitude Ouest et en aval du bassin hydrologique du Ferlo qui s'étend sur 45.119 km² (Figure 2.2). Il est alimenté en permanence par le fleuve Sénégal via le canal Taouey à partir de Richard Toll. Initialement le Taouey était un ruisseau sinueux long de 26 Km, rectifié par un canal de 17 km. Toutefois, la longueur du lac est estimée à 50 km et la largeur maximale à 7,75 km. Sa profondeur maximale est de 4 m. La superficie du lac est estimée à 273,8 km². Il est ceinturé au nord, au sud et à l'ouest par des digues et/ou de ponts-barrages qui régulent les flux d'écoulement.

Au nord le pont barrage de Richard Toll, régule les flux fluviaux entrant dans le lac via le canal Taouey. Au nord-ouest, le chenal YettyYone, long de 28 km, connecte le lac à la cuvette du Ndiael, recensée par ailleurs comme zone humide d'importance internationale par la convention de Ramsar. Au sud du lac, la digue de Keur Momar Sarr régule les flux d'écoulement vers le bas Ferlo.

Les côtes de gestion de la hauteur d'eau du Lac de Guiers sont contrôlées et régulées entre 1,90 m et 2,5 m depuis la mise en service du barrage de Diama, situé à 50 km de l'embouchure du fleuve et de l'océan atlantique et à 100 km en aval de la jonction entre le fleuve Sénégal et la Taouey à Richard Toll.

La capacité de stockage du réservoir est estimée à 600 millions de m^3 à une hauteur de 2.5 m.

4. Matériel et méthodes

Pour atteindre notre objectif de recherche nous avons décliné l'objectif global en trois (03) objectifs spécifiques. Pour chaque objectif spécifique les données et la méthode utilisée sont décrites ici.

4.1. Évaluation de l'altération hydrologique et hydro-chimique du lac de Guiers

Nous avons recueilli des données journalières de hauteur d'eau mesurées entre 1976 et 2011. À partir de ces données, nous avons calculé le débit journalier en utilisant la formule de Manning Strickler : Q = K*Rh * i (1). Q est la vitesse débitante en m/s. K est le coefficient de rugosité. Dans le cadre du lac de Guiers, une revue de la littérature rigoureuse nous permis d'estimer le coefficient de rugosité (K) à 35. Rh est le rayon hydraulique de l'écoulement. L'analyse des résultats de l'étude bathymétrique du lac par l'OLAG nous a permis de l'estimer à 7 m. I est la pente de l'écoulement en m/m. La pente de l'écoulement au lac de Guiers (i) m / m est estimée à 0,001 par les différentes études bathymétriques effectuées sur le lac.

Les débits ainsi obtenus ont été divisés en 2 périodes. Une période pré-impact (1976-1987) représentant l'écoulement dans des conditions plus ou moins naturelles (avant la construction de barrages) et une période post-impact (1988-2011) correspondant aux conditions changeantes (après la construction de barrages).

Une analyse statistique a été faite au moyen du logiciel Streamflow Analysis and Assessment Software (SAAS) 4.0 (METCALFE AND SCHMIDT, 2014) pour déterminer les tendances des indicateurs d'altération hydrologique. Pour caractériser le niveau d'altération des différents indicateurs hydro-écologiques, nous avons utilisé l'approche Range of Variability (RVA) (RICHTER et al., 1997). Cette méthode quantifie la modification des indicateurs d'altération hydrologique en comparant les fréquences dans trois intervalles fixes. Elle mesure la déviation du régime d'écoulement post-impact et celui d'avant l'impact. Le degré d'altération (D) est défini donc comme suit: D = | (Post-Pré) / (Pre) |* 100% (2) "Post" est le débit médian de la période postérieure à l'impact; "Pre" est le débit

médian de la période antérieure à l'impact.

Richtet al. (1998) ont en outre suggéré que la valeur de D comprise entre 0 et 33% représente peu ou pas de modification (faible modification); un taux de 33-67% représente une altération modérée, 67-100% révélant une forte altération.

La RVA est une étape importante dans l'évaluation de l'altération hydrologique et a été largement utilisée par les chercheurs [(CHEN, 2012); (IRWIN and FREEMAN, 2002) ;(SHIAU and WU, 2004);(ZUO and LIANG, 2015);(ZOLEZZI et al., 2009)].

Concernant l'analyse des indicateurs de l'altération chimique des eaux du lac de Guiers, des données sur les concentrations de sels et de nutriments dans le lac entre 2008-2010 ont été analysées. Pour caractériser l'état trophique du lac de Guiers, nous avons calculé et classé l'indice de l'état trophique (TSI) du lac durant la période de l'étude en utilisation le Nutrient Criteria Technical Guidance Manual(GIBSON et al., 2000) de l'Agence Américaine de Protection de l' Environnement (EPA). Ce manuel suggère qu'un TSI $\prec$ 40 représente un état oligotrophique. Un TSI compris entre 40-50 représente un état mésotrophique alors qu'un TSI, compris entre 50-60, représente un état eutrophique. Enfin, un TSI $\succ$ 60 représente un état hypertrophique. Les résultats obtenus seront confrontés à ceux d'études précédentes pour caractériser l'altération de la qualité de l'eau.

4.2. Analyse des tendances climatiques récentes et futures dans le bassin du lac de Guiers

Dans cette étude, l'accent est mis d'abord sur la détection d'indices climatiques extrêmes qui témoignent de la variabilité du climat à l'échelle du bassin du lac de Guiers. Vingt-cinq (25) indices extrêmes ont été calculés avec le logiciel RClimDex (ZHANG et al.2004) sur la base des observations quotidiennes de températures maximales et minimales ainsi que des précipitations journalières en utilisant une approche recommandée par l'équipe d'experts sur la détection des changements climatiques et les indices (ETCCDI). Ces tendances ont été calculées pour 8 stations situées autour du lac de Guiers entre 1988 et 2012. Un test non paramétrique a été effectué pour rechercher la présence d'une tendance à long terme dans les données. Pour accepter cette tendance, nous avons évalué la probabilité p-valeur, qui exprime la force de la preuve pour ou contre cette hypothèse (la tendance est acceptée avec une p-valeur $\prec$ 0,05 en considérant le niveau de confiance de 95%).

En ce qui concerne les projections climatiques à l'échelle du bassin versant, nous avons analysé les scénarios d'influence anthropique, Représentatifs d'évolution de Concentra-

tion (RCP), qui sont quatre scénarios relatifs à l'évolution de la concentration en gaz à effet de serre, établis par le Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC) pour son cinquième rapport, AR5. Ces scenarios ont été simulés en utilisant les données corrigées de CORDEX pour l'Afrique (Coordinated Regional Climate Downscaling Experiment) qui comprennent des données de précipitation et d'évaporation potentielle. Toutefois, dans cette étude, ont été considérés le profil RCP 8.5 (trajectoire croissante) qui suppose une approche de type "business as usual" et le profil RCP 4.5 (trajectoire stabilisation sans dépassement) qui suppose des émissions de CO2 qui repassent sous les niveaux actuels en 2070.

4.3. Évaluation de la disponibilité et la demande en eau du lac de Guiers. Les simulations ont été appliquées pour le secteur des ménages, des collectivités et des agro-industries pour l'horizon 2030 des besoins en eau de ces secteurs qui dépendent du lac de Guiers. L'année de base retenue est 2005, et le calibrage du modèle WEAP avec les données de cette année nous a permis de reproduire exactement la situation au cours de cette année. La Figure 3.2 montre la structure des scénarios créés dans WEAP.

Le premier scénario testé est un scénario de changement climatique. Les profils RCP 4.5 et le RCP 8.5 ont été choisis. Le deuxième scénario est un scénario de croissance économique dans la zone du lac de Guiers avec le développement des agro-industriels dont on suppose que les superficies totales cultivées vont doubler en 2030. À cela s'ajoute le scénario de croissance démographique de la région de Dakar, qui est desservie à 60% par le lac de Guiers. Ce qui entraînera une hausse significative des prélèvements. Néanmoins, il convient de noter que des projets sont en cours de réalisation tels que le renforcement des capacités de l'usine d'approvisionnement en eau potable de Keur Momar Sarr pour résorber les déficits à Dakar, alimenter la ville d'autres villes en pleine croissance démographique. Le troisième scénario a été créé pour tester la réponse du réservoir en cas d'arrêt du remplissage par les eaux fluviales via le canal Taouey. En combien de temps le réservoir pourrait-il satisfaire les différents usages sans les apports du fleuve Sénégal ?

5. Résultats et discussion

5.1. Altération hydrologique et hydro-chimique du lac de Guiers

Les résultats indiquent que les modifications survenues sur le fleuve Sénégal et sur le lac de Guiers,au cours des trois dernières décennies, ont mené à des altérations profondes de l'état écologique, chimique et morpho dynamique du réservoir.

Une tendance à la hausse significative des débits entre la période avant et après- bar-

rages a été constatée. L'utilisation du test de Pettit indique la présence d'une rupture/ou tendance avec comme date de rupture 1992. Cette rupture est confirmée par le test de Mann-Kendall qui indique une tendance à la hausse de 93% avec un intervalle de confiance de 95%. Les résultats ont aussi montré que la variabilité hydrologique pré-barrages, qui rythmait les fonctions physiques et/ou biologiques du lac, a été complètement modifiée par le contrôle systématique des eaux d'écoulement qui a engendré, après la construction des barrages, un fonctionnement trop monotone du lac de Guiers(Figure 4.10).

Concernant la qualité des eaux, une altération chimique du lac a été notée. En effet, les résultats de TSIs de l'azote (50,22) et du phosphore (79,57) indiqueraient un état eutrophique et hypertrophique du lac de Guiers. En revanche, la prudence doit être le soubassement de l'interprétation de ces résultats. Tout d'abord parce que la méthode RVA ne prend pas en compte les paramètres de qualité de l'habitat : les paramètres physiques et chimiques (REBILLARD, 2006), ensuite parce que certains calculs ont été effectués sur la base de quelques approximations. En outre, en l'absence d'informations supplémentaires sur le régime sédimentaire, le régime thermique et les composantes biologiques, des indicateurs purement statistiques ne sauraient à eux seuls valider les résultats. Par conséquent il est suggéré de compléter l'analyse hydrologique avec d'autres modèles.

5.2. Les tendances climatiques récentes et futures dans le bassin

5.2.1. Temperature

Les résultats montrent que des changements climatiques importants sont visibles dans le bassin. Les tendances calculées sur les séries des températures maximales et minimales extrêmes, TXx et TNn, des journées ont mis en évidence l'augmentation graduelle des températures moyennes maximales $(0,03°C/an)$ et une tendance à la baisse des températures minimales $(-0,01°C/an)$.

5.2.2. Précipitations

Les tendances calculées sur les séries des précipitations annuelles (PRCPTOT) mettent en évidence une tendance croissante (+6.1 mm/an), particulièrement depuis les années 2000. Les tendances sont statistiquement significatives. Cependant, les projections, quant à elles, révèlent que vers le milieu du siècle (2050s) une augmentation des précipitations qui varient entre 5 et 48%. Pour le scenario RCP4.5, cette augmentation est plus marquée dans la partie septentrionale et centrale du bassin. Par ailleurs, pour le RCP8.5, on note une baisse des précipitations de l'ordre de 10% dans la région sud du

bassin. Néanmoins, vers la fin du siècle (2100s), les projections (Figure 5.5) indiquent une baisse conséquente des précipitations dans les deux (2) scenarios. Dans le scenario RCP4.5, cette baisse est moins importante (moins de 10%) que celle observée dans le scenario RCP8.5 (plus de 25%).

2.1.3. Évaporation potentielle

La quantité d'eau perdue à travers l'évaporation dans le bassin du lac de Guiers est de l'ordre de 5.7mm/jour, soit 2102 mm par an. Les résultats montrent également un déficit hydrique (climatique water balance) de 1781 mm/an entre 1988-2011. Toutefois, les projections révèlent une augmentation de l'évaporation potentielle (ETpot) d'environ 2539 mm pour le scenario RCP4.5 et de 2917 mm/an pour le scenario RCP8.5 comparées à la référence (ETpot 1988-2011) vers la fin du siècle. Cependant, vers le milieu du siècle, les projections indiquent une baisse de l'ETpot de 2021 mm/an pour le scenario RCP4.5 et de 2052mm/an pour le scenario RCP8.5.

Toutes les expériences locales indiquent une tendance générale au réchauffement ; ce qui concorde avec les expériences climatiques nationales et régionales (Afrique de l'Ouest) effectuées à une échelle plus large. Conjointement à ce réchauffement, une augmentation de la variabilité d'une année à l'autre est également manifeste dans les résultats concernant le climat local. Elle pourrait engendrer une plus grande fréquence de phénomènes de chaleur inhabituelle. Le haut niveau de concordance, parmi les modèles climatiques régionaux pour l'Afrique de l'Ouest, nous permet d'établir avec un haut niveau de confiance qu'une augmentation escomptée de la température se produira de manière vraisemblable. Quant aux précipitations, les projections, découlant des simulations, indiquent des hausses vers le milieu du siècle. En plus, des baisses importantes sont escomptées pour une grande partie du bassin à la fin du siècle. Des études ont également démontré cette tendance pour les projections des modèles climatiques régionaux. Mais, les expériences de modélisations climatiques régionales et mondiales sont très variables surtout en termes de précipitations. Elles ne présentent aucun consensus sur l'ampleur des changements potentiels attendus d'une région à une autre. Par conséquent, les meilleures recommandations sont de préparer une résilience solide à la variabilité actuelle des précipitations .

5.3. Évaluation de la disponibilité et de la demande en eau du lac de Guiers

5.3.1. Balance demande et offre

La satisfaction de la demande en eau pour la consommation (domestique) et pour l'irrigation représente la plupart des types de sites de demandes actuelles et futures. La Figure 6.7 met en évidence les effets des différents scénarios sur la demande en eau par les usagers. Les résultats montrent que la demande en eau d'irrigation par les agroindustriels établis autour du le lac est la plus élevée. La Compagnie Sucrière Sénégalaise (C.S.S.) arrive en tête avec une demande estimée à 175 millions de m^3 en 2005. Cette demande augmentera jusqu'à 25% en 2030. SENHUILE est la deuxième plus grande agroindustrielle dans la zone après la C.S.S. Elle connaîtra une augmentation de sa demande en eau de l'ordre de 20% d'ici à 2030. Il en sera de même pour les autres agro-industriels comme West FarmAfrica, Senindia...

Ces demandes en eau pour l'irrigation varient tout au long de l'année en fonction des saisons et des types de cultures. Elles sont plus élevées aux mois d'avril et de juin et moins élevées durant la saison des pluies.

Par ailleurs, la satisfaction des besoins en eau de consommation des villes, connaitra également une très grande hausse. Par exemple, la demande en eau de la région de Dakar qui était estimée à 70. 810. 000 m^3 en 2005 augmentera de l'ordre de 61% d'ici à 2030.

5.3.2. Demandes non-satisfaites

Bien que la quantité d'eau disponible dans le réservoir soit potentiellement suffisante pour satisfaire la demande, les usagers sont confrontés à des pénuries. La demande non satisfaite se trouve dans les 2 scénarios, mais les quantités varient. La Figure 6.8 montre le total de demandes non satisfaites dans le scénario RCP 8.5. Les résultats révèlent que certains sites de demande subiront une demande non satisfaite en raison de leur dépendance vis-à-vis du canal de Taouey, qui dépend du fleuve Sénégal. C'est le cas du Ndiael implémenté dans le WEAP par un détournement (projet de remise en eau de cette réserve naturelle).

5.3.3. Réservoir

Comparée aux flux actuels, la simulation des eaux entrant dans le lac via le canal Taouey montre une augmentation significative des débits (Figure 6.4) dans les 2 scenarios RCP4.5 et RCP8.5. Cependant, on constate une légère différence en ce qui concerne la hausse entre les deux (2) scénarios.

La quantité d'eau disponible dans le réservoir (655.616.099 m^3) est potentiellement suffisante pour satisfaire les besoins des usagers. Par ailleurs, il a été testé dans la situation actuelle, avec la mise en uvre de tous les projets en cours, un arrêt à partir de janvier 2015 des flux fluviaux d'entrée estimés à 4.177.275 m^3/jour. La Figure 6.7 montre la

vitesse de l'épuisement de la ressource dans le réservoir. Dans le scénario RCP4.5, le réservoir ne tiendra pas plus de vingt (20) mois et dans le scénario RCP8.5, moins dix-neuf (19) mois pour voir l'épuisement total de la ressource. Ces changements dans le volume d'eau sont dûs à un taux élevé d'évaporation et de pompage pour l'irrigation et à l'approvisionnement en eau potable des centres urbains.

6. Conclusion

La variabilité climatique dans le bassin versant du lac de Guiers a montré les impacts potentiellement graves de l'augmentation des températures et de la sécheresse sur l'écosystème et les ressources en eau.

Aussi, les multiples incertitudes liées à la disponibilité future des ressources hydrologiques influence grandement l'ensemble du processus d'allocation. Il est à craindre que les pénuries d'eau prévues et les phénomènes extrêmes plus fréquents, associés à une plus grande demande en eau(liée par exemple à l'irrigation agricole ou aux nouveaux projets d'approvisionnement en eau potable), aient des effets graves sur les services des écosystèmes, notamment en ce qui concerne les ressources en eau potable. Certains secteurs économiques, dont notamment les ménages, l'agriculture, la sylviculture et la navigation, sont d'ores et déjà vulnérables aux pénuries d'eau.

Ces phénomènes extrêmes ont permis de comprendre, à l'échelle du bassin, combien il est nécessaire de développer des stratégies d'adaptation.

Abbreviation & Acronyms

AEP	:	Approvisionnement Eau Potable.
ANDS	:	Agence Nationale de la démographie et de la Statistique.
ASUFOR	:	Association des Usagers du Forage.
BFDC	:	Base Flow Duration Curve .
BFI	:	Base Flow Index.
CORDEX	:	Coordinated Regional Climate Downscaling Experiment.
CSE	:	Centre de Suivi Ecologique.
CSS	:	Compagnie Sucrière Sénégalaise.
DGPRE	:	Direction de la Gestion et de la Planification des Ressources en Eau.
DSS	:	Decision Support System.
FAO	:	Food and Agriculture Organisation.
FDC	:	Flow Duration Curve.
GIS	:	Geographic Information System.
IHA	:	Indicator of Hydrologic Alteration.
IPCC	:	Intergovernmental Panel on Climate Change.
IWRM	:	Integrated Water Resource Management.
MDG	:	Millenium Development Goal.
NGO	:	Non Government Organization.
OLAG	:	Office du Lac de Guiers.
OMVS	:	Organisation pour la Mise en valeur du Fleuve Sénégal.
PEPAM	:	Programme d'Eau Potable et d'Assainissement du Millénaire.
POR	:	Period of Change.
RCM	:	Regional climate Model.
RCP	:	Representative Concentration Pathway.
REGEFOR	:	Réforme sur la Gestion des Forages du Sénégal.
RGPH	:	Recensement Général de la Population et de l'Habitat.
ROC	:	Rate of Change.
RVA	:	Range of Variability.
SAED	:	Société Nationale d'Aménagement et d'Exploitation des Terres du Delta du fleuve Sé
SDE	:	Sénégalaise des Eaux
SEI	:	Stockholm Environment Institute.
SONES	:	Société nationale des Eaux du Sénégal.
TSI	:	Trophic State Indice.
WASCAL	:	West African Science Center Service on Climate Change and Adapted Land Use.
WEAP	:	Water Evaluation and Planning System.

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General Introduction

This chapter analyses the major environmental and socio-economic problems that occur in the basin of Lake Guiers and defines the research aim and objectives.

Contents

In recent years the current and emerging issues for Lake Guiers's resources have been widely observed. The vast majority of problems originate from activities on the land surrounding the lake.

1.1 Context and problem statement

1.1.1 Water shortage in the basin

Water resources are critical to socio-economic development. In many regions in Africa, changes in water demand are projected to contribute to imbalances between freshwater availability and demand than climate change [2]; [36]; [37]. Because of population growth and climate and land use change, supply of drinking water to satisfy population needs, is a key issue, in most Sahelian countries. In recent years the current and emerging issues for Lake Guiers'resources have been widely observed [38]: the low water level of this water body, its invasion by aquatic vegetation, defective management facilities, clogged outlets, pollution risks and competing demands.

The basin of Lake Guiers has a Sahalian climate. It is characterized by alternation between a long dry season (from November to June) and a short wet season (from July to October). Average rainfall is between 300 and 380 mm. An analysis of recent climate history of the region has shown a relatively significant rainfall deficit and high spatio-temporal variability for the past several decades. Studies have shown also that the isohyets in Senegal move southwards. While the isohyet of 400mm/year crossed the Lake Guiers region from 1951-1980 it moved southwards in the observed period of 1971-2000. Annual precipitation is consequently <400mm/year in Lake Guiers region and the Ferlo valley

The highest amount of rain in the year is recorded in August, accounting for 30% to 40% of total annual rainfall. Such monthly irregularity on rainfall distribution worsens water shortage during dry months. Strong inter-annual and multi-decadal rainfall variability is observed in the delta and lower valley, and when they occur, rainfall deficits severely impact local water supplies. Niass et al.[39] reported that since 1970, the mean annual rainfall has decreased by more than 30% in the Sahelian area while major river systems's average discharge,has dropped by 40% to 60%.

The projections of mean annual rainfall averaged over the country from different models in the ensemble project a wide range of changes in precipitation for Senegal, but tend towards decreases, particularly in the wet season, July, August, September. Projected July, August,September changes ranges from -41 to +48% by the 2090s, with mean ensemble ranging from -3 and -18% [40].

The future projection of the mean annual temperature is projected to increase under any one emissions scenario by 1.0 - 2.5°C by the 2090s [41]. Changes in mean annual rainfall, as well as in its temporal and spatial distribution, would be expected to influence the water balance in Lake Guiers.

1.1.2 Increase of water demand

During the period 1966 to 1970, a marked shift in the climate was observed. This gave rise to a prolonged drought characterized by a reduction in the annual rainfall and in the length of the rainy season [19]. To overcome this deficit, Senegal turned, since 70s, to the exploitation of Lake Guiers. After 1987, with the construction of the Diama and Manatali dams, the river has been filling up normally throughout the year, thereby facilitating adequate supply of water to the Lake.

Lake Guiers is an important fresh water reserve for the country owing to its role in the supply of water to the senegalese capital (Dakar) and some inland towns, the life of natural ecosystems, agriculture, continental fishing and livestock breeding.

With the Ngnith station pumps (the central part of the lake), Lake Guiers provides a drinking water volume of 64 000 m^3 per day for the city of Dakar. Water is also pumped by the Keur Momar Sarr (in the southern part of the Lake) water treatment plant, and then piped to Dakar and Thies cities through a 250 kms long underground pipe. The construction of this last water treatment plant within the framework of the Long Term Water Project provide currently a volume of 130 000 m^3 per day. In the coming years it is expected to supply Touba and others cities [42].

Lake Guiers accounts for almost 60% of the daily need of the region of Dakar [15]. It's an important raw water source for Dakar, and riparian communities.
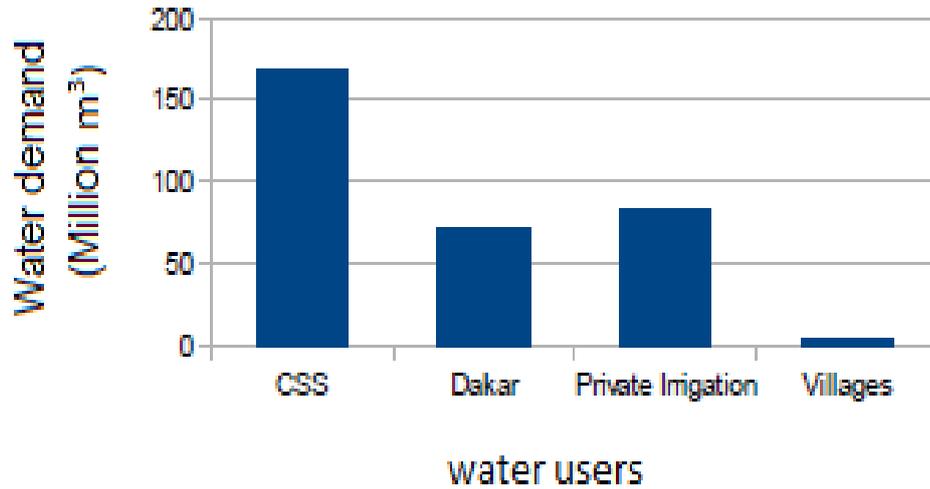
Figure 1.1: Water demand in Lake Guiers by different water users.

The city is experiencing a high population growth at a rate of 2% per year, leading to a change in the population structure due to a rising share of young people in the country. Since 2000 Dakar's population has increased from 2,132,000 million inhabitants to currently 3,137,196 [31] (Table1.1). Projections indicate that the population will have doubled to around 5 million people by 2050 [43]. This increase in population led to an increase of water demand/ person in Dakar (Figure1.2).Urban population growth is remarkable; the annual urban population growth rate for the period 2010-2015 is estimated at 3.3% [43].

Table 1.1: Projections of population and drinking water needs of Dakar.

Year	2000	2012	2020	2030
Pop.(million)	$2,132$	$2,696$	$3,220$	$3,674$
Consump.(m^3/day)	$134,918$	$175,240$	$209,300$	$238,810$

Dakar is one of the most advanced cities in sub-Saharan Africa in terms of its water

services: around 99,9% of the households had access to potable water in 2012 [44]. In the rest of the country, 66,6% of the population had access to safe drinking water. However, these figures do not reflect Dakar's very frequent water supply cuts, which increase towards the end of the dry season. The cuts often range between 8 and 12 hours in a 24 hours period. This is due to raw water shortage. According to the National Water Distributor (SDE), Dakar's water supply standard is 110 l/person/day, which is the highest among West African cities.

Beside the households, private irrigation depends on Lake Guiers water resources. More
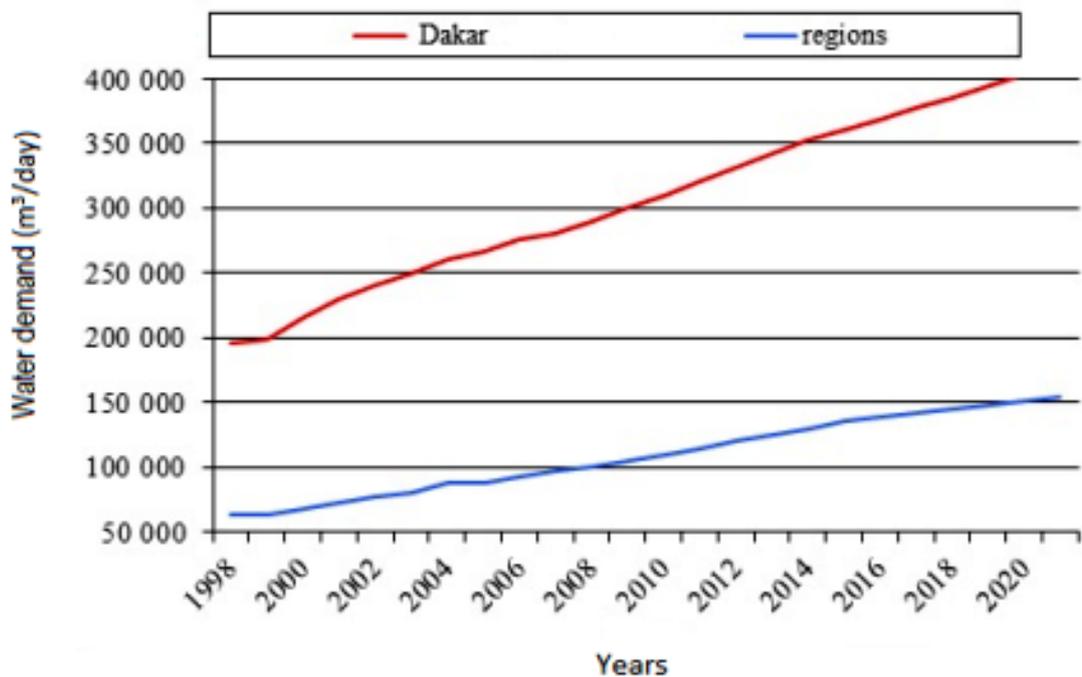
Figure 1.2: Water demand projections at Dakar and others regions.

than 10 agro-industrial units surrounding the Lake are operating (Table 2.2). The CSS is the most important ones. It has a production of more than 10,000 ha of sugar cane using water from both the Senegal River and Lake Guiers. Other companies include SENHUILE, West Farm Africa (WAF). Their increasing water demand (Figure 1.2) could have a negative impact on the Lake water level. What are the implications for Lake Guiers water resources? The question involves many variables, including the availability of the water resources, the natural vulnerability of Lake Guiers systems, the coherence and comprehensiveness of current governance regimes, the nature of existing stresses,

and climate change impacts, all weighted according to the local setting of the basin. In general though, we can expect high increased demand for Lake Guiers water resources.

The water balance in Lake Guiers (Table 1.2) reveals how water resources are already intensively used in certain and how the rate of abstraction can exceed replenishment. However, the annual balance sheet of Lake Guiers remains on the whole positive, in as much as the average supply from the Taouey is guaranteed. Evaporation remains by far the most significant cause of water loss and can hardly be controlled.

Table 1.2: Lake Guiers water balance in 2014

	Variable	Standard base period 2002 (m^3/year)	2014 (m^3/year)
Inflows	Taouey river	$1,141,603,200$	$1,971,000,000$
	Drainage CSS	$47,304,000$	$56,764,800$
	Rainfall	$72,532,800$	$72,532,800$
	Inflows	$1,261,440,000$	$2,100,297,600$
Outflow	Evaporation	$693,792,000$	$693,792,000$
	AEP Dakar	$67,525,000$	$109,500,000$
	Ferlo Supply	$220,752,000$	$220,752,000$
	Ndiaël Supply	$15,768,000$	$157,680,000$
	Irrigation CSS	$315,360,000$	$315,360,000$
	private irrigation	$81,993,600$	$151,372,800$
	Herds and environment use	$3,153,600$	$31,536,000$
	Infiltration	0	0
	AEP Touba	0	0
	Total Outflow	$1,398,344,200$	$1,679,992,800$
Gap		$-136,904,200$	$420,304,800$

1.1.3 Water quality changes

Water quality deterioration includes salinization, eutrophication, hygienic degradation, increased concentrations of suspended solids and chemical pollution.

The deterioration of water quality becomes a problem of primary importance for the delta [45]; [46]; because of drainage from irrigated areas or water stagnation, inappropriate domestic use, the mismanagement of solid waste, the discharge of industrial waste water from Senegalese Sugar Company factory into Lake Guiers [47] as well as the proliferation of aquatic plants.

The lack of an appropriate discharge outlet in low Ferlo and a high evaporation rate has resulted in a salt accumulation in Lake Guiers. Data indicate that salt concentration in the Lake can reach as much as 40,000 tons per year in Lake Guiers/low Ferlo system[19].The aquatic plant proliferation has caused excessive evapotranspiration losses, which are estimated to be 3 billion m^3 per year (OMVS/SOGED 2003). The direct and indirect impact of the recent hydraulic installations on the River Senegal on Lake Guiers are obvious. The hydrological regime of the lake was very irregular before the dams were brought into operation.

The lake is now characterized by very stable water levels. These new conditions prevent cultivation of traditional recession crops which have been replaced by irrigated crops. The water quality of the lake has been modified. Mean salinity has decreased and the significant interannual and intraannual variations noted before 1986 are now far less pronounced. The new hydrological regime of the lake and its low salt content have encouraged aquatic vegetation to grow rapidly. This vegetation used to be controlled by the periodic partial drying of the flooding zone and specific water quality conditions at certain times of the year. *Pistia stratiotes and Typha australis* are now increasing rapidly.

This proliferation of aquatic plants has no doubt accelerated the rapid spread of schistosomiasis, which now affects 80% of the population of some lakeside villages.

The management of Lake Guiers requires an integrated quantitative and qualitative approach. A water management model has been perfected. It permits an assessment of the effects of various quantitative reservoir management options on the salinity of the water [11].

The permanent presence of standing water in the valley and the suppression of the periodic salt concentration increase favours the aquatic plants and pathogenic germs development. As a consequence, the incidences of water-borne diseases already found in the area have increased. The diseases are malaria, urinary schistosomiasis, diarrhea, and intestinal parasitic diseases. The delta has become a hotbed of bilharzia and prevalence rates of 80% were observed in certain villages surrounding Lake Guiers [48].

1.1.4   Lack of appropriate management

The lack of appropriate governance is manifested by the lack of enforcement of regulations, the absence of an adequate institutional setting and the absence of democracy, which means that stakeholders cannot participate in decision-making and are not held accountable for their actions. In many cases, powerless and unwilling partners endure decisions that are often dictated by powerful economic operators.

Problems related to the lack of appropriate governance and the institutional setting are well identified and are well known, particularly the insufficiency or the absence of the organization and location of activities that are the source of many conflicts concerning the water resources use and the deterioration of living conditions.

The institutional setting is less efficient because of the rapid changes in institutions, stakeholders and the division of power. Projects and decisions are often taken without taking into account the opinion of the others. Lack of appropriate governance is also illustrated by the numerous problems related to information; the absence of any circulation of information, the deficiency at times in the quality of information, the insufficiency of the sensitization to environmental degradation and the lack of environmental education.

1.2   Literature review

Africa's water and land resources are under severe pressure. This is caused by global change which is due not only to climate change but also to land use change driven mainly by population growth [1]. In most African countries, the supply of drinking water to satisfy population needs is a key issue. For the coming decades, increasing population, changing patterns of water demand, and concentration of population and economic activities in urban areas will further pressurize Africa's freshwater resources [2]. Climate change threatens to put more pressure on water resources due to a possible increase in the already high variability in rainfall and river flows and changes to the geographical distribution of water resources [3]

In Senegal River basin (West Africa), two major factors have exerted pressure on the basin's water resources in recent years [4] : climate variability and change; and the construction of dams. These pressures on water resources, added to those linked to runaway demography and various productive activities, have had repercussions on the basin's nat-

ural environment.

Since the early 1970s, climate in the Sahelian and Sudanian areas (where the majority of the Senegal River Basin is located) is marked by chronic rainfall and water deficits, which have put this area into a major ecological crisis. This crisis has been intensified by unprecedented demographic growth, and also by the expansion of cultivated land and livestock farming. Nevertheless, the river basin environment continues to have critical ecological importance [5] .

In the lower River basin, Lake Guiers fed by the Senegal River, plays leading economic and ecological roles. It is a shallow reservoir located in the north-western part of Senegal and is the sole water reservoir in the lower Senegal River basin which can be used extensively as a stable freshwater. Its water is used both for irrigating crops and as a drinking water resource for urban centres, including Dakar, the capital of Senegal, as well as for the local population and animal herds.

Several studies have been carried out on Lake Guiers. Hydro-biology, water quality and environmental hazards in general have been among the research focuses for the last twenty years. Bouvy et al.[6] describes the phytoplankton/environment relationships and provides valuable information on algal strategies in a shallow tropical lake like Lake Guiers. Seasonal variations of zooplankton communities and their interactions with phytoplankton and environmental parameters have been investigated by Ka et al.[7]. They find out the existence of seasonality in zooplankton communities and confirm the importance of using biological indicators such as phyto- and zooplankton to monitor Lake Guiers water quality [8]. Varis et al.[9] focused on the eutrophication level in Lake Guiers. They point out the fact that the lake's water quality and ecosystem change and the use of increasing pressure must lead to a change in the management of the Lake waters. Berger et al.[10] continued the investigation in water quality and point out seasonal dynamics that will constitute an increasing challenge. The impact of dams, on hydrology and the multipurpose use and the challenge for water quality in Lake Guiers have been investigated by Cogels et al.[11]; [12]. They describe the water quality effects of the management of the lake and the use of its waters, with special emphasis on salinity and eutrophication. Recently, Diop et al.[13]; Merem et al.[14] have assessed the water quality using remote sensing tools. They compared the FUB-predicted image and study results with those from earlier studies and revealed good correlation.

As we can notice, a large number of studies carried out have been focusing on water quality, biology, invasive aquatic plants, while limited researches have been done on the impacts of climate change and population growth in Lake Guiers. These assessments have much relevance for the formulation of climate adaptation policies.

Statistics on water use and supply are sparse and incomplete. Studies carried out in the Lake Guiers such as [Diop et al.[15]- Sane.S [17]] provided only qualitative information. With regard to its vital importance, the Senegalese authorities pay a great attention to the control, monitoring and protection of the water resources of the Lake, with a particular emphasis on the need for an integrated and sustainable management of Lake Guiers' water resources. They consider that as a high national priority [15]. This leads them to the creation in 2010 of the Lake Guiers water authority (OLAG). The high spatial and temporal variability of water resource availability and its uneven spatial distribution and the further stress on this resource due to population growth, mean that Lake Guiers water supply is at risk. For future water resources management, it is important to assess the possible impacts of these changes on water resources for a longer time horizon of 20-50 years [18].

Despite all these emerging issues, there is limited knowledge of the Lake's resources and how it might respond to global changes. Statistics on water use and supply are sparse and incomplete. There has been little assessment of the impacts of climate change and population growth in Lake Guiers which has much relevance for the formulation of climate adaptation policies. Many studies carried out in the Lake [[15]-[17]] provided only qualitative information. The lack of observations and studies limits our understanding of the dynamic relationship between the resources of the Lake and climate change and demographic change. In the future, increasing water abstraction will cause problems for downstream riparian communities and ecosystems [49], not only at the local, but also the national scale. The high spatial and temporal variability of water resource availability and its uneven spatial distribution and the further stress on this resource due to population growth, means that Lake Guiers water supply is at risk [38].

1.3 Thesis objectives

1.3.1 Main objective

To address the challenges that climate change and population growth poses in the water sector, it is necessary to consider its potential impacts on different dimensions of water resources and their management. This research aim to assess recent and future patterns on climate and water situation (water availability and demand) in Lake Guiers under scenarios of climate change and population growth. These information will be used to stimulate further research, informed planning, and adaptive management that can help residents of the watershed to adapt and/or mitigate to future changes. The study focuses, in particular, on the Lake response under future changes on climate and population growth.

1.3.2 Specifics objectives

The specific objectives of this study are:

- To assess Lake Guiers hydrologic alteration within its ecosystem attributable to human influence

- To analyze the trends and the projections of climate change in the basin of Lake Guiers

- To assess future water availability and demand under climate change and population growth

1.4 Research questions

In order to understand the responses of Lake Guiers resources under climate and socio-economic changes, a number of questions need to be asked, such as:

- What is the current state (quality and quantity) of Lake Guiers?

- To what extent are the water resources of Lake Guiers altered?

- What are the behavior of extreme climate event indicators in the Basin of Lake Guiers?

- What types of physical changes might be expected over the basin of Lake Guiers in near and far future

- Will Lake Guiers reservoir be sufficient to supply all demand sites in the near future?

- What effect will climate change and population growth have on lake Guiers water resources?

1.5   Hypothesis

The general hypothesis for this research is: With climate change and population growth that occur in the Basin, Lake Guiers reservoir will not be able to satisfy all demand sites in the near and far future.

This testable hypothesis establish correlation between variables: climate change,population growth and the reservoir capacities to sastisfy demands in long term.

1.6   Novelty

This study investigates flow regime associated with ecological conditions to serve as indicators of hydrologic alteration in Lake Guiers.

Another novelty of this study is to provide information on physical change that might be expected over the basin of Lake Guiers in near (2050s) and far (2099) future.

Furthermore, for the first time, this study provide reliable and practical information about Lake Guiers response under climate change and socio economic development projects planned that water resources manager and land-use planners should prepare for and respond to. Three main scenarios have been developed for this purpose. The first scenario assumed the climate change in two of the Representative Concentration Pathway (RCP) scenarios The second scenario in Water Evaluation and Planning System (WEAP) is a growth scenario including Lake Guiers region as well as the capital Dakar. The third scenario was created to test in which time the water in the reservoir will be exploited without a refill. It is based on the climate change scenarios and the growth scenario.

1.7   Scope of the thesis

For the purposes of this study, only indicators of hydrologic alteration and impacts of climate change on water availability and demand in Lake Guiers were investigated.

Other factors such as water quality modeling and dynamical relationship between Lake Guiers and aquifers are important as well, but they are beyond the scope of this study.

1.8   Expected results and benefits

This research intends to provide reliable and practical information about water availability and demand under climate change and population growth in the context of Lake Guiers that water resources manager and land-use planners should prepare for and respond to.

The main outputs from this research will be the response of Lake Guiers water resources under differents scenarios of climate change and socio economic development projects planned..

Another outputs from this research will be a characterization of Lake Guiers current state (quantity and quality) arising from in-stream development and its impacts on ecosystem.

This research provide also the types of physical changes that might be expected over the basin of Lake Guiers in near and far future.

1.9   Structure of the dissertation

This thesis dissertation provide the background necessary to understand the challenges facing Lake Guiers Basin and its potential values and uses as a key resource for promoting sustainable human livelihoods and development in whole Senegal, as well as for maintaining important life supporting ecosystems.

The dissertation is divided into 7 chapters.

Chapter 1: General Introduction analyses the major environmental and socio-economic problems that occurs in the basin of Lake Guiers and define the research aim and objectives.

Chapter 2: Study Area, the basin of Lake Guiers covers the key biophysical

aspects and human use aspects that make the basin of Lake Guiers management such a challenge.

Chapter 3: Data, materials and methods presents tools, approaches, and data used to achieve the research objectives.

Chapter 4: First finding. Lake Guiers hydrologic alteration within ecosystem highlights Lake Guiers hydrologic alteration arising from in-stream development.

Chapter 5: Second finding. Trends and projections of climate change over Lake Guiers basin paints a coherent picture of the types of physical changes that might be expected over the basin of Lake Guiers in near and far future.

Chapter 6: Third finding: Water availability and demand in Lake Guiers looks at how Lake Guiers are used and what problems, current and emerging, it will face under scenario of climate change and population growth.

Chapter 7: General Conclusion resume the differents findings, formulate some recommandations and open differents perspectives for this research.

Study Area : The Basin of Lake Guiers

In this chapter, the Senegal River system as a whole will be described and a more detailed description of the study area, Lake Guiers, will be given.

Contents

2.1 Introduction

Lake Guiers is important for human development and for the preservation of sound ecosystems and biodiversity in the Delta River Senegal. It provides livelihoods, social and economic benefits that are essential for the quality of life in Lake Guiers basin communities. This chapter highlights those features of Lake Guiers and its basin that have the greatest implications for human use and management.

2.2 Senegal River basin: system description

The 1,800 km long Senegal River is formed by the merging of two major water streams; the Bafing and the Bakoye of which the confluence is situated in Mali at a distance of 1,083 km form the Atlantic Ocean. After having crossed the eastern part of Mali, it forms, for the rest of its trajectory, the border between Senegal and Mauritania. The Bafing is 760 km long and has its source in the Fouta-Djalon mountain ridge in Guinea at an altitude of 800 m. It flows in northern direction crossing the plateau of the Soudan region before reaching Bafoulabé. The Bakoye River has its source in the Mandingue plateau in Guinea at an altitude of 706 m. Its length is 560 km and it confluences with the Bafing River after passing a great number of small drops. On the left bank of the Senegal River, the most important affluent is the Falémé River. It is 650 km long and has its source in the northern part of the Fouta-Djalon mountain ridge at an altitude of 800 m . The confluence with the Senegal River is located at a distance of 30 km upstream of Bakel. The basin of the Senegal River is divided into three major parts :

- **Haut-Basin**, which is defined as the region from the Fouta-Djalon mountain ridge to Bakel. This area provides nearly all the water as it is humid with annual precipitations between 700 and 2000 mm. These precipitations fall between April and October in the mountainous area in the south of the basin and cause the annual flood wave between July and October. At Bakel, the river has taken in all its major tributaries.

- **Valley**, defined as the region between Bakel and Dagana, is an alluvial plain surrounded by semi deserted areas. It consists of a floodplain area with a width of 10-20 km, but can reach 25-35 km at some locations. This agricultural land is fertilised every year by the flood wave. The river shows many meanders in this region and forms a system of a main canal with floodplains and vast flow areas. The main

canal has a width of 200-400 m in this region and its bed is cut by various rocky or sandy steps.

- **Delta**, defined as the region downstream of Dagana. It is the terminal part of the river and has multiple arms, but only one river mouth. The water slope in the Delta is close to zero during low water and a slope of about $1.1E^{-5}$ during high water. This region is almost completely flat and the river is about 10 m deep. Lake Guiers, Lake R'Kiz, the Djoudj National Park and many irrigation canals and are located in this part of the river. The river water fills these two lakes in the wet season.

The Senegal River basin (Figure 2.1) covers a surface area of about 300,000 km^2 and around 3.5 million people live in the basin. The high plateau in northern Guinea represent 31,000 km^2 (11% of the basin), 155,000 km^2 are situated in western Mali (53% of the basin), 75,500 km^2 are in southern Mauritania (26% of the basin) and 27,500 km^2 are in northern Senegal (10% of the basin) [4].

In the 1970s, a shift in the climate was observed. This gave rise to a prolonged drought characterized by a reduction in the annual rainfall and in the length of the rainy season. The consequence was a reduction in river discharges as well as an invasion of seawater in all the estuaries. The mean annual discharge of Senegal River decreased from 25.9 billion m^3 for the period 1903-1967 to 13.8 billion m^3 for the period 1968-1999, indicating a trend in the reduction of stream flows since about 1967[19]. Despite this the last half a century, the river has been seen as a means of enhancing the national economies of these states. An attempt at food self-sufficiency, boosted by the problem of feeding the growing urban population and the possibility of future droughts, has been the major driving force for the development plans [20].

In the 1980s, two dams were constructed in the river under the auspices of the OMVS : the Manantali dam and the Diama dam.

Figure 2.1: Senegal River drainage basin
*S*ource,(Kmusser, 2010)

2.3 The basin of Lake Guiers

Lake Guiers is one of the major distributaries of the River Senegal. It is located on the right bank of the river, in the delta region, between latitudes 16° 23'N and 15°55'N, and longitudes 16°12'W and 16°04'W, on the downstream of the Ferlo hydrological Basin. In this study, Basin of Lake Guiers and Ferlo Basin refer both to the same thing (Figure 2.2). It's a huge basin of 45,119 km². According to Tarnavsky et al.[21] it covers approximately 43,280 km² and for Barron et al.[22], it is estimate to 22,330 km². It spreads between the region of Saint Louis and Louga.
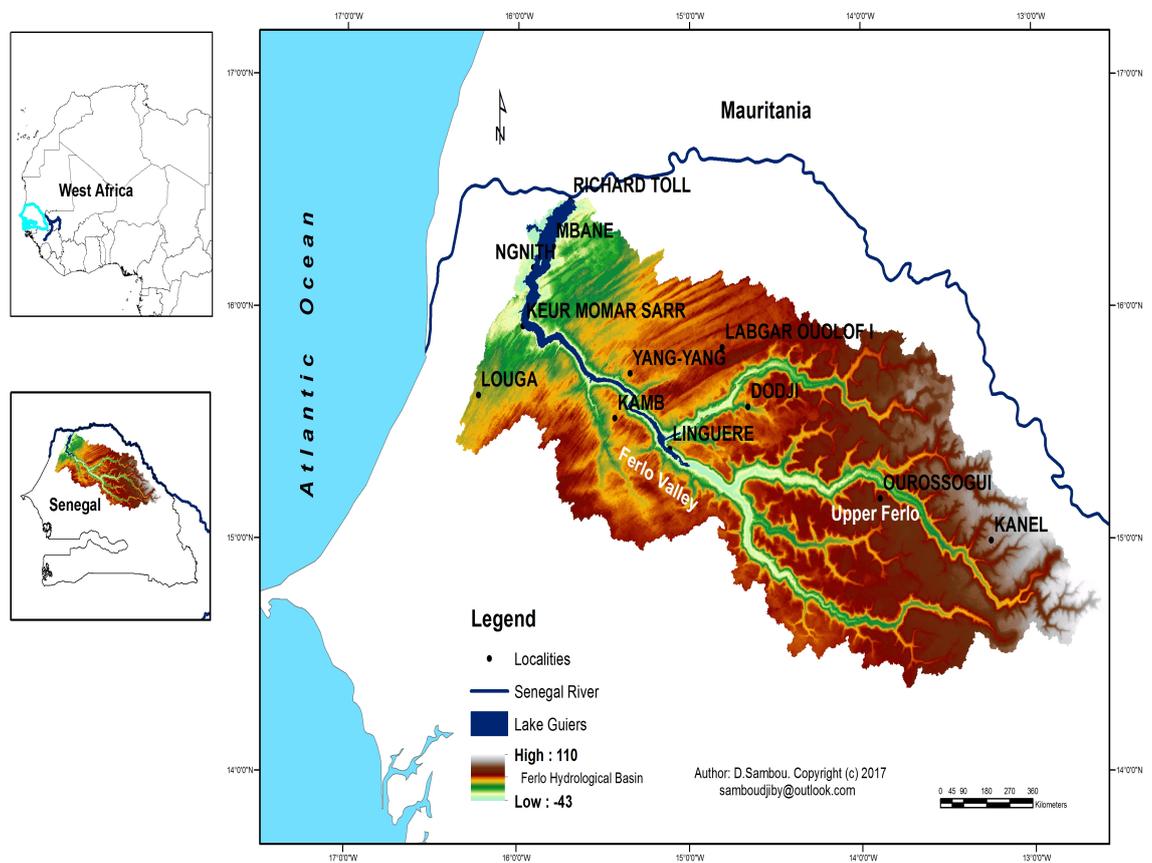
Figure 2.2: Lake Guiers within its hydrological catchment.

2.3.1   Geomorphology

The geologic structure and the stratigraphy of the Senegal River delta and valley are dominated by Quaternary events. The complexity of the local geomorphology can be explained by the combined effects of climate variability, wind erosion and deposition, riverine processes, changing Atlantic Ocean levels, and wave action. The area is a vast floodplain slightly interrupted by the Ogolian red sand dunes in the south west and the east. The delta region is characterized by a complex hydrologic network. Lake Guiers, a lake replenished by the Senegal River floods, constitutes a natural boundary between the delta area and the middle valley.

In addition, there exists a series of depressions, which are rich in clays deposited by the river during flood events (Ndiael, Khant, and Djoudj), tidal creeks, lagoonal areas, and temporary lakes (Djoudj, Gorum, Lampsar, and Djeuss). During the dry season, these depressions are covered by a salt-crust, locally known as sebkha, formed by the evaporative processes(photo 1). Barbiero et al.[23] reported that the sequence of transgression-regression cycles may have had a significant influence on soil formation. Sandy soils originated from the red deposits associated with Pleistocene sand dunes during the Nouakchottian transgression whereas the clay soils are better linked to the Taffolian regression.

2.3.2   Soil types

There are several type of aquatic or hydromorphic soils in the delta depressions. These soils are classified according to their degree/period of saturation. Hydromorphic soils are present under mangrove areas and undergo continuous saturation. These soils have black or black gray color and are the salty peat soils frequent in the intertropical regions [24] (Photo 2). Hydromorphic soils are saturated with water in all layers and they are influenced by capillary action from the water table which lies close to the surface. These soils do not have a saline crust at the surface. Periodic endosaturated soils are inundated for part of the year and exhibit mud-cracks during the dry season. Water loss through evaporation triggers formation of saline crust on the soil top (Photo 3). Hydromorphic soils have temporary saturation and other soils exhibit episaturation (saturated in one or more layers within 200 cm of the surface); these soils have cracks on the soil surface. Hallomorphic soils (Photo 4) are well represented in the delta area. *Solonchaks* soils are formed when evaporation greatly exceeds precipitation for at least part of the year, and when salt is present from moderate to high amounts in the parent material (FAO, 1998). There are *Solonchaks* with the presence of saline efflorescence and *Crypto-Solonchaks*,

which are free of saline efflorescence [24]. These soils have high salt accumulation levels and cannot be used for normal cropping unless the salt is leached out. *Solonetz* or soils in which the sodium content is present in excess over calcium are expanding in the delta. *Clay* content in the topsoil is decomposed in high pH conditions. This process results in a low salt concentration combined with high exchangeable sodium, leading to the columnar or prismatic structures [25].
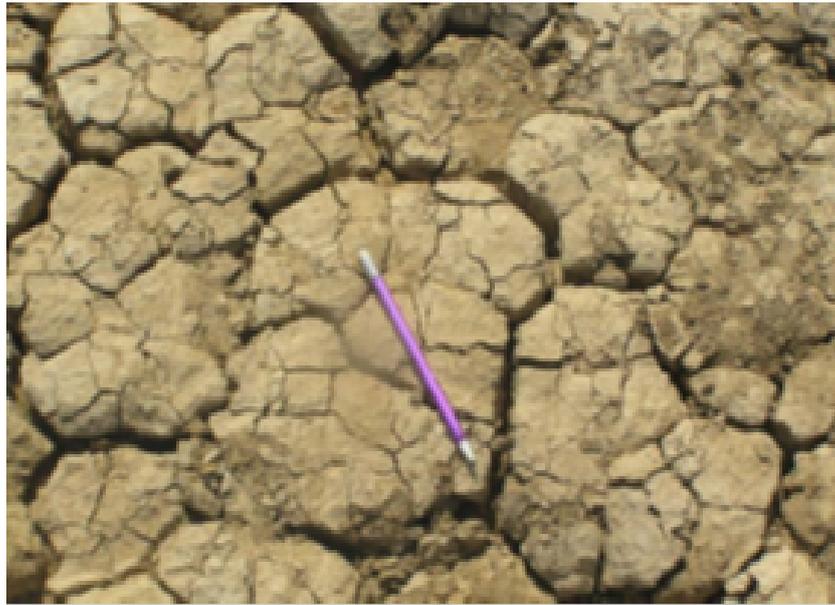
Photo 1: Soil mud-cracks in Ndiael depression [89].

Photo 2: Hydromorphic soil rich in organic matter with salt crusts [89].

Photo 3: Hallomorphic soil with cracks during the dry season [89].

Photo 4: Hallomorphic soil with salt crusts

2.3.3 Vegetation

Hygrophytic species, such as *Acacia nilotica*, colonize depression areas of clay and sandy hydromorphic soils. Low lands, where the water table is close to the surface all the year, are generally occupied by herbaceous association: including *Vetiveria nigritana, Vossia cuspidata, Cyperus sp., Sporobolus robustus, Scirpus maririmus, and Borreria verticillata* . During the dry season when the water table goes down, several other vegetation groups colonize this area. When there is a consistent salinity, halophytes plants are well represented: *Tamarix senegalensis* (Photo 5), *Prosopis juliflora, and Accacia* Senegal which are relatively tolerant to salt [26]. The submerged marsh and fringe of large water bodies are invaded by *Typha australis* (Photo 6) and *Pistia stratiotes*, a floating plant. These invasive species limit water circulation.

Photo 5: *Tamarix senegalese (halophyte)*

Photo 6: *Thypha australis* bordering the Lake

2.3.4   Hydrology

2.3.4.1 Surface water

The natural hydrologic network system in the Senegal River Basin delta region is influenced by the presence of Atlantic Ocean in the west coast and Senegal River flows coming from the east. The river is connected with several tributaries On the Senegalese side, you have Taouey, Gorom, Ndiael, Khant and Ngnith. Dozens of ephemeral streams flow into the Lake, carrying less than 7% of the water that enters into the lake [12]. The Lake is 53.5 km long from north (Pakh) to south (Keur Momar Sarr), and up to 7.7 km wide, with a surface area of 274 km² (measured and calculated with Google earth Pro and GIS) and able to contain 600 million m³. Its maximum depth is 4 m and average depth is 2 m [12]. It drains via Merinaghene dyke to the south in Ferlo valley. Lake Guiers system is composed of the following hydrological units (Figure 2.3) :

- **Taouey canal:** Lake Guiers is connected to the Senegal River by the Taouey canal at Richard Toll. Originally Taouey was a winding stream of 26 km, rectified by a canal long to 17 km. It supplies 88% of the total water in Lake Guiers from Senegal River [12] .

- **Nietti yone:** Situated on west of the Lake Guiers, it is a 28 km hydraulic axis which supplies the Ndiael depression.

- **Ndiael depression**: With a surface area of $46, 550$ ha, it is a depression designated as wetland Area by the RANSAR Convention in 1977. The great expanse that is the core of the Ndiael covers 10,000 ha. The site is listed on the Montreux Record (endangered sites) since 1990.

- **Lower Ferlo:** Located in the southern part of the Lake, it is complemented by the Ferlo Valley. A dyke built in Keur Momar Sarr regulates the outflow from the Lake into the Lower Ferlo Region.

Lake Guiers water level is regulated to 2.5 m since the Diama Dam, 50 km from the river mouth to the Atlantic Ocean and 100 km downstream from the Senegal River and Lake Junction, was built. On 2.5 m water level, the volume is estimated to 600 Million m³ and a surface of 340 km (Figure 2.5) [12].
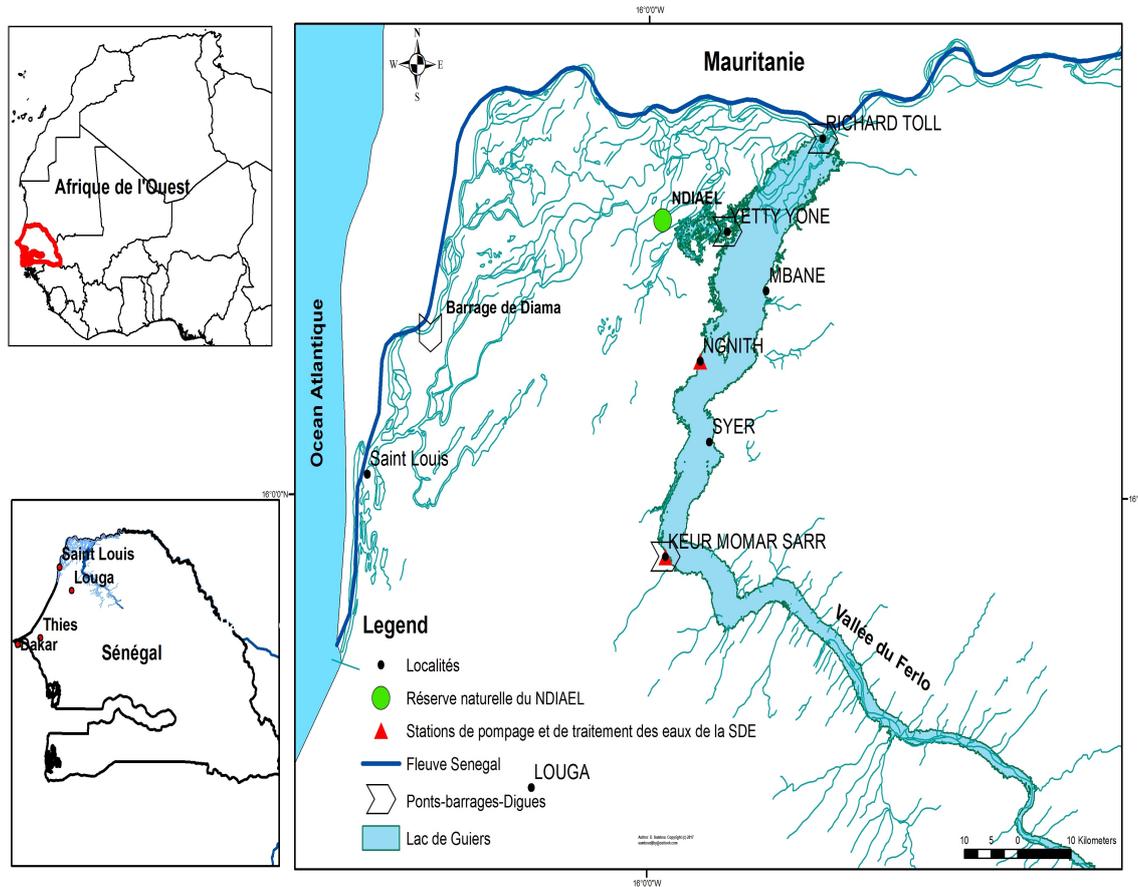
Figure 2.3: Hydrological network of Lake Guiers

The principal ground water aquifer in the Senegal River delta area is in the Eocene Maestrichian strata of the Continental Terminal formation. The Maestrichian aquifer is found at -50 m at the junction Lac de Guiers- Taouey canal and at a depth of -500 m in Western Rosso [24]. Depth to this Eocene aquifer is localized function of the shape and depth of Lac de Guiers anticline. The alluvial aquifer is the principal near surface aquifer. This aquifer extends throughout the flood plain and is present to various depths which are generally less than 2 m [4]. This aquifer is subdivided into several independent ground water domains. The main continental terminal aquifer is located in nouachotian layer sediments [24] and is thicker from North-Est to South-Est. The water level in the
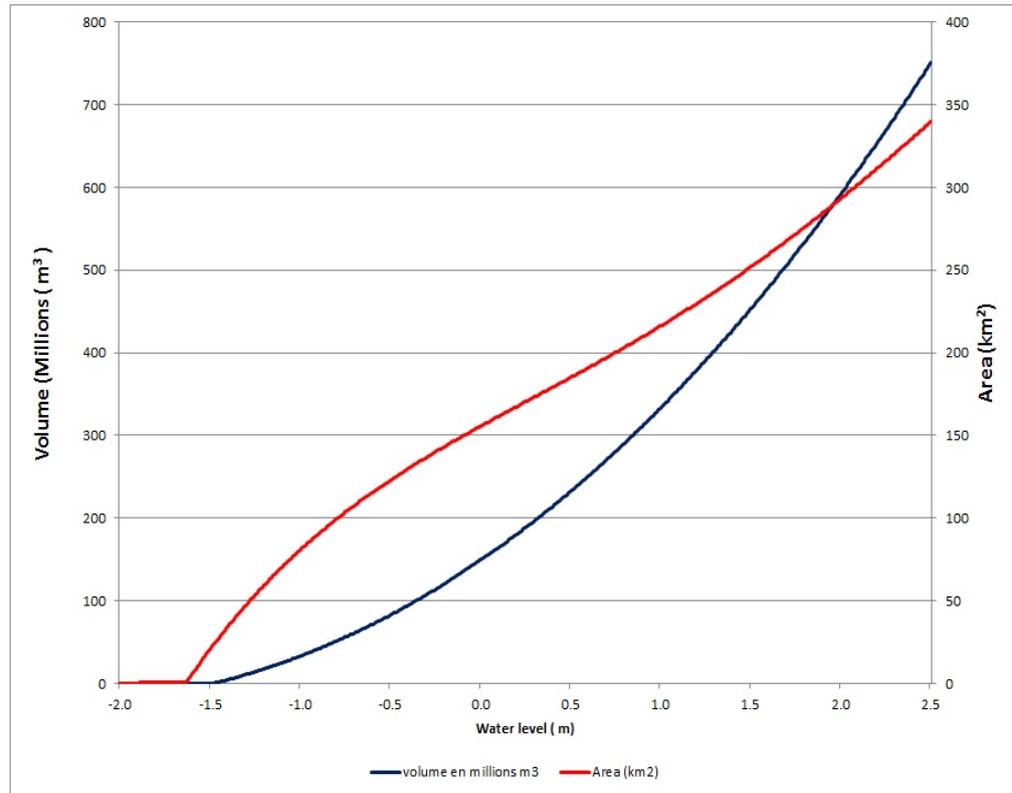
Figure 2.4: Volume-surface curve

alluvial aquifer varies with the seasons along with the general hydrological regime in the valley. Since the dam was built, groundwater recharge and the water table have been significantly modified. Reducing the volume of the floods and building dykes significantly reduced the area of natural recharge. On the other hand, flow regulation during low water periods and irrigation increases groundwater recharge during the dry season in some areas. Alluvial ground water is salty. This salinity is explained by the geological history of a region affected by several marine transgressions during the quaternary. The sea water was trapped in sediments. Sall et al.[24] reported that the ground water salinity can be higher than the sea water salinity in certain zones of the delta. The suitability of spatial distribution of ground water (Figure 2.5) is directly related to the nature of the layers of aquifer system exploited, geomorphological distribution (alluvial plain-dune formations), distribution (upstream and downstream), proximity a hydraulic axes and

the groundwater depth [27]
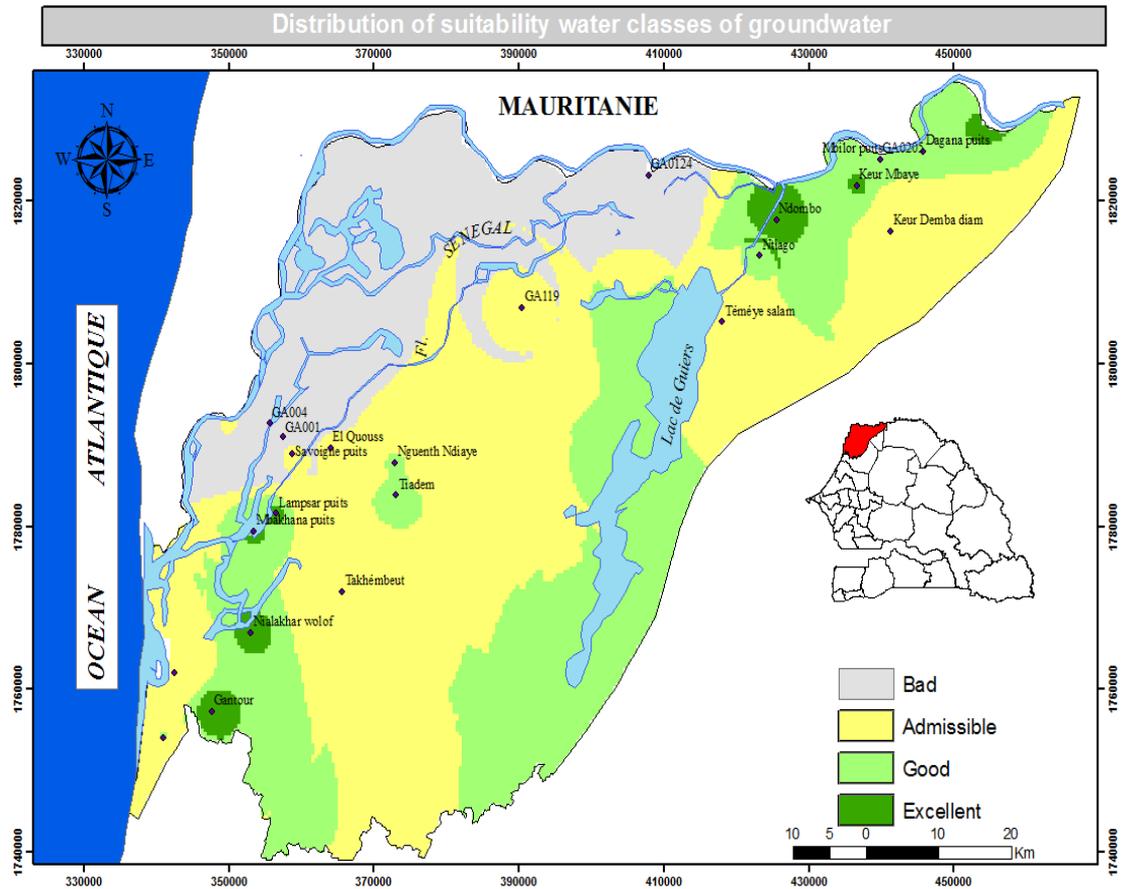
Figure 2.5: Distribution of suitability water classes of ground water in the Delta River Senegal [27].

2.3.5 Climate and climate variability

2.3.5.1 Rainfall

The climate of Basin of Lake Guiers is similar to much of the Sahel and characterized by two main seasons: a dry season that lasts nine months from October to June, and a rainy season of three months (Figure 2.6). The total annual rainfall is both low and highly variable, with an average of 225 mm per year from 1982 to 2012. The mean annual temperature oscillates around 27.6°C and fluctuates between a maximum average of 30.6°C in the month of June and a minimum of 23°C in the month of January.
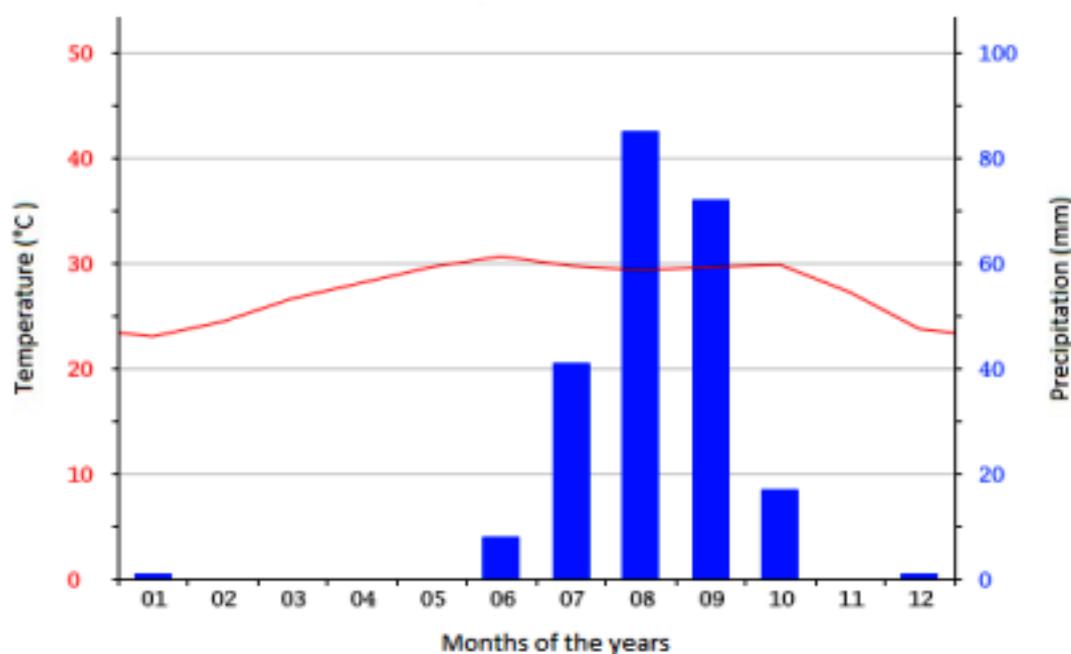
Figure 2.6: Climate graph (Pmm and Temperature) 1982-2012, Lake Guiers Area.
Data source (http://de.climate-data.org; average 1982-2012)

From June to September approximately 85 to 90% of the precipitation occurs with a monthly maximum in August (Figure 2.6). The number of days with rain averages between about 20 and 30 days per year. high inter-annual rainfall variability is evident in the plot of rainfall data for Richard Toll from 1953 to 2013 (Figure 2.7). Decadal rainfall variability is noticed, with 1970-1974 and 1982-1984 registering some of the lowest

precipitation amounts. The entire data record can be divided into a humid phase before 1970 and a dry phase thereafter.
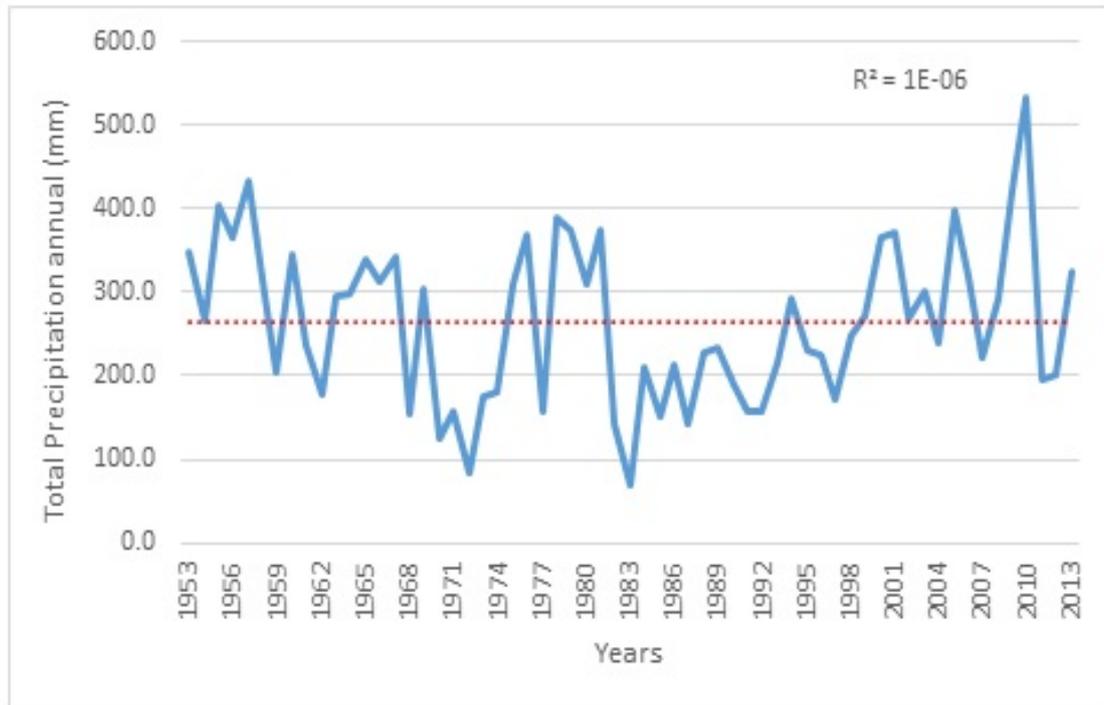
Figure 2.7: Time series of Richard Toll rainfall.
Data source globalweather.tamu.edu

Beyond that, the region has been affected by droughts since the 1970s. Their seasonal and episodic variation is due to the dependency on the monsoon. Arthurton et al. [28] have shown that the isohyets in Senegal move southwards. While the isohyets of 400 mm crossed the Lake Guiers region from 1931 to 1960. It moved around 50 km southwards in the observed period of 1961-90.

Figure 2.8 shows a maps of annual rainfall from 1998 to 2014, a high temporal and spatial variability of Precipitation in the hydrological catchment. During this period, rainfall was particularly dry throughout the Lake region.
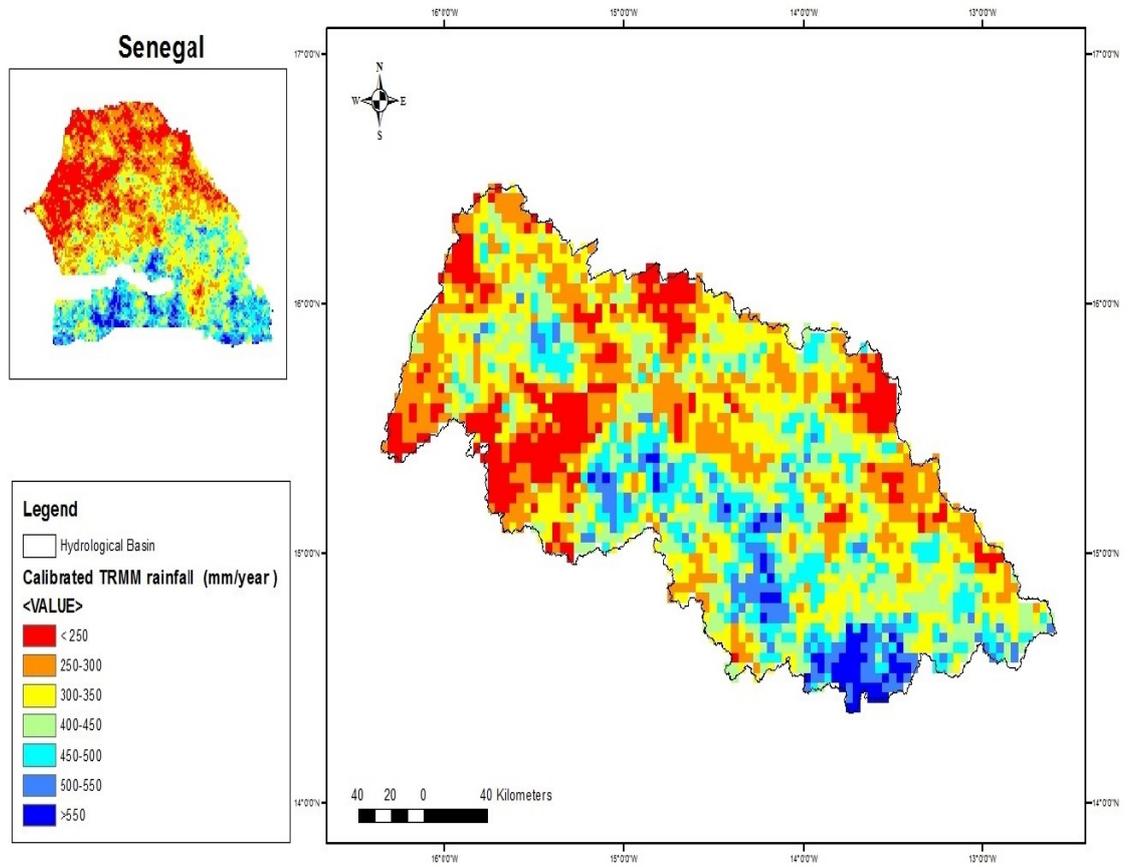
Figure 2.8: Total annual rainfall (mm) TRMM 3B31 (1998-2014) in the hydrological catchment.

2.3.5.2 Temperature

The area mostly experiences north-easterly Saharan trade winds commonly known as Harmattan. The influence of maritime (westerly) winds is moderate. The mean annual temperature oscillates around 27.6°C and fluctuates between a maximum average of 35.3°C in the month of June and a minimum of 20.2°C in the month of January (Figure 2.9).
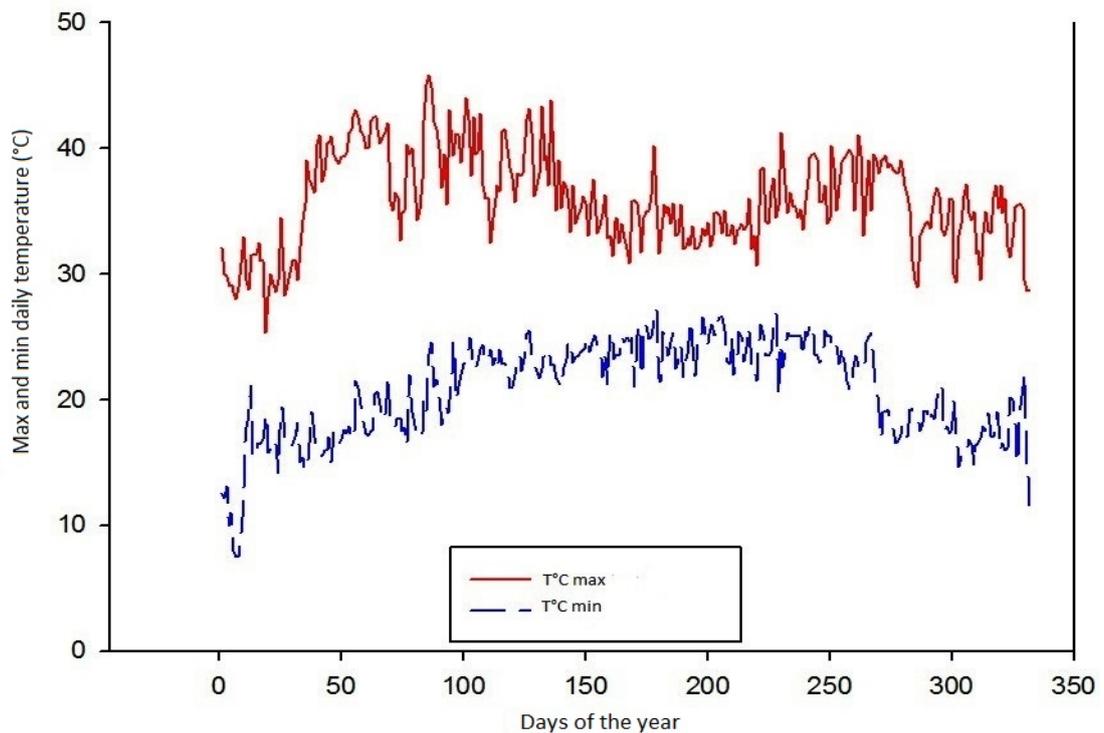
Figure 2.9: Daily temperature in Richard Toll (2005)

The climatic regime in the basin can be divided into three seasons: a rainy season from June to September, a cold dry season from October to February, and a hot dry season from March to June. In the river this creates two hydrological periods [4]: (1) a filling period between August and October with inflow from the Senegal River into the Lake ,and (2) a stable period of 9 months with little interaction between the river and the Lake.

2.3.6 Land use and land cover

Unsupervised classification of the November 2015 image produced five land cover classes. The inland water bodies were classified into the brackish water class found in Lake Guiers. The Wetland and irrigation class is present along the Lake and its tributaries and in the Richard Toll area (Figure 2.10).

A greater part of the floodplain, known as the Walo, has been cleared gradually by local peoples over the centuries for traditional subsistence agriculture, and in recent decades, for vast hydro-agricultural projects. These were designed to make Senegal self-sufficient in food production and to boost cash crop production for export (rice and sugarcane). Flood recession agriculture is practised on the heavy alluvial soils on the banks of the river and its numerous canals. Vast expanses of the alluvial plain remain relatively barren.

The southern part of the hydrological Basin, the sandy Ferlo region, also known as the Diery, constitutes the heart of Senegal's sylvo-pastoral zone. It has the typical characteristics of the central Sahelian climatic zone: a short and irregular rainy season, open grasslands with scattered shrubs and trees, a relatively limited number of woody species, and a predominance of the genus acacia. Generally too dry for crop production, the region is primarily used for grazing. In the course of the 20th century, drought has had a moderate but not a severe impact on the woody cover [29]. The deep soils, with their large water storage capacity, have helped temper the effects of drought on the woody vegetation. Nevertheless, the woody cover has declined over the past half century. Today, annual grasses flourish during a short 2-3 month rainy season, while the woody vegetation cover has become quite open and floristically poor [29]

2.3.7 Socio-economic characteristics

2.3.7.1 Human settlements

The periphery of Lake Guiers has a total of 61 villages whose activities are directly related to Lake Guiers. These villages are all within a 5 km radius around the lake. On the west bank, the density of human settlements is higher (39 villages) on the East bank (22 villages). At the administrative level, 5 of these villages belong to the rural municipality of Ronkh, 28 to the rural municipality of Ngnith, 13 to the rural municipality of Keur Momar Sarr, 11 to the rural municipality of Mbane and 4 to the rural municipality of
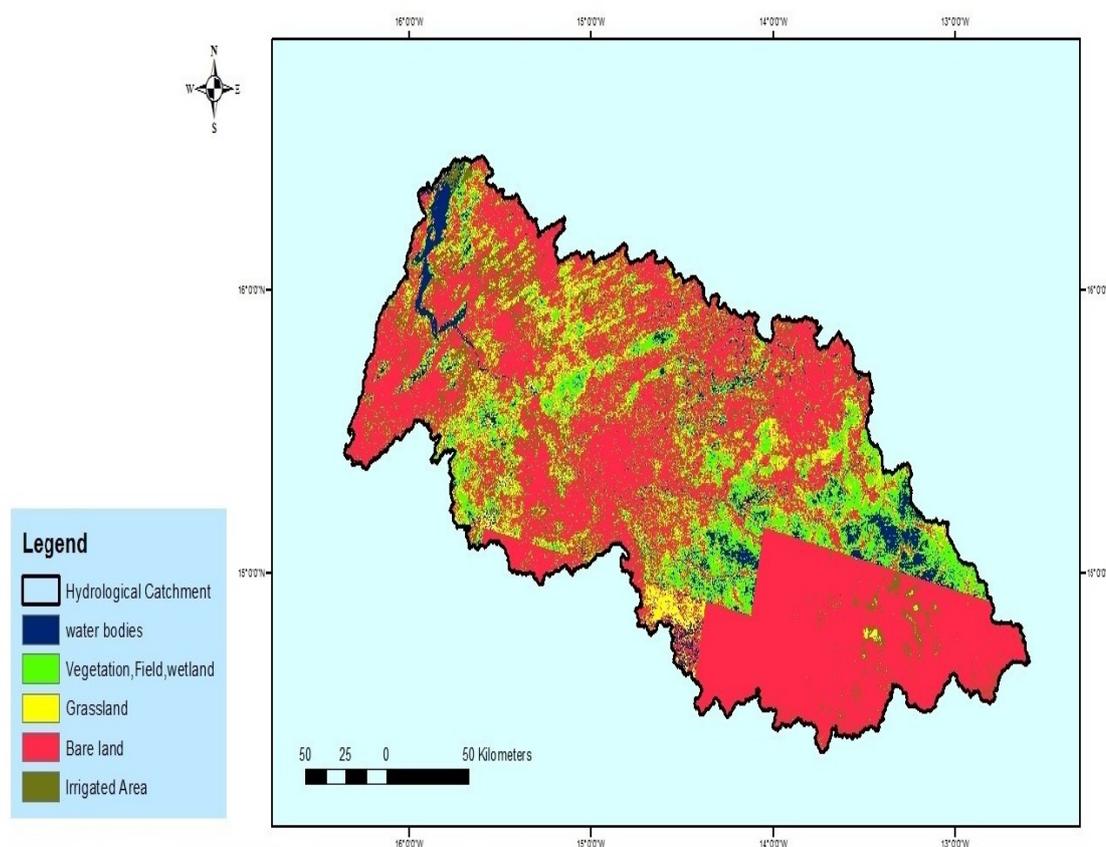
Figure 2.10: Unsupervised land use/cover classification in Lake Guiers area. *(Data source Landsat image acquired on November 2015*

Syer (Table 2.1).

2.3.7.2 Population

The Senegal River basin has a total population of around 3,500,000 inhabitants, 85 percent of whom live near the river. From the RGPH data in 2013, the total population of Senegal is 13,508,715 inhabitants. The 61 villages in the lake's surroundings and Richard Toll city amounts to 138,743 inhabitants (Table 2.1). A variety of ethnic and cultural backgrounds also characterizes the basin's population, among others, Peuls, Toucouleurs, Soninkes, Malinkes, Bambaras, wolofs and Moors.The major ones being Wolof, Peul, their close Tukulor relatives, and Moor (ethnic Mauritanians).

Table 2.1: Population of Lake Guiers area [31]

Municipality	Villages	Total Population RGPH 2013(inhabitant)
Ronkh **(Total villages : 5)**	Pakh Tola Keur Idy Diallo Bountou Back Colonat (Balky)	$1,883$
Ngnith **(Total villages : 28)**	Tordionabé Yetty Yone Ouroulbé Bégaye Odabé Kamboubouk Roumbatine Témèye Maure Keur Alhardou Ndourounabé Diagane Keur Yoro Guédel Nder Teuss Naéré Tchékène (Ndieureul) Pakhatane (Darou Salam) Diokhor Ile Dialang Ngnith Keur Samba Dia Odabé Diagane Dialbanabé Ndieumeul 2 Diokhor I Ndiayène Malle Pénène K. EL H. O. Pène Yamane Thiarène Mbayène	$21,035$

Municipality	Villages	Total Population RGPH 2013(inhabitant)
Keur Momar Sarr (Total villages : 13)	Ndimb (Mbodjène) Brar Diokoul Mérina Guéwel Félo Keur Momar Sarr Diaminar Keur Kane Mbanar Keur Yoro Tacko Diaminar Loyenne Gawga Gankette Balla Loboudou Keur C.A. Ndiaye Guéwo	$27,515$
Mbane (Total villages : 11)	Léwa Témèye Salane Témèye Peulh Témèye Nianguène Singué Diéry I et II Mbane Saneinte Tack Pomma Wolof et Maure Balandé Koyel Ndiakhaye Mar I et II Louguéré Baïlo	$28,640$
Syer (Total villages : 4)	Fass I et II Malla Tack Guidick Syer III	$1,790$
Richard Toll		$57,878$
Total		$138,743$

2.3.7.3   Principal economic activities

Agriculture, fishery are the main economic activities ongoing in the delta and lower valley region. Agriculture is the most important activity in Lake Guiers area. In rural areas over 90% of the population are involved in traditional agriculture which is dependant on climate variability. Since the construction of Diama Dam, irrigated agriculture in the delta area has been improved considerably. Fishery has also played an important ruoe in the region because of proximity to the relatively cool and productive coastal Atlantic Ocean waters and due to presence or the river, lakes, and several ponds.

Agriculture

Water availability always impacts the success of agricultural activities. Before human modifications to the hydrologic system, farming was limited to areas near the Senegal River and generally only after the overflow period. Before the construction of Diama dam, saline waters penetrated far inland, regularly passing Richard Toll about 140 km upstream. Several dykes and small dams were constructed in the past in order to control the annual flood and the sea water invasion, in an attempt to improve local agriculture. Several dykes were constructed in the delta zone to block sea water intrustion and in Lake Guiers area (Figure 2.11). The Taouey Canal was dug in 1974.The first dam was constructed at Richard Toll in 1947 in order to grow an irrigated rice crop and another small dam at Keur Momar Sarr was built in 1956 to isolate the Bounoum (Ferlo) tributary from south (After construction of Diama Dam in 1986, sea water is no longer invades areas located upstream of the dam. Irrigated agriculture expanded rapidly immediately after completion of the dam. About 18,000 ha of land is now cultivated in Basin of Lake Guiers.

 Rice is the principal crop targeted by SAED, a governmental development corporation, with a goal to reach food sufficiency in Senegal. By 1997, 100,000 ha had been equipped for irrigated agriculture, and only 44,000 ha were farmed because of loss of soil fertility and increased salinity [4]. The irrigated areas are located in the Walo soils specifically in the Hollalde and Fonde soils. Horticulture and orchards are also developed on the urban periphery and around Lac de Guiers. But, the production is still low. Despite these management efforts, farming is still traditional in most parts of rural areas because of the population's low income, the high rate of illiteracy, and the lack of new technologies. Few farmers can afford to use external inputs, like fertilizer to correct the overuse of their soils and increase their production [30]. Most of the farmers use manure to enrich the soil and this addition contributes to nitrate contamination in ground and surface waters.
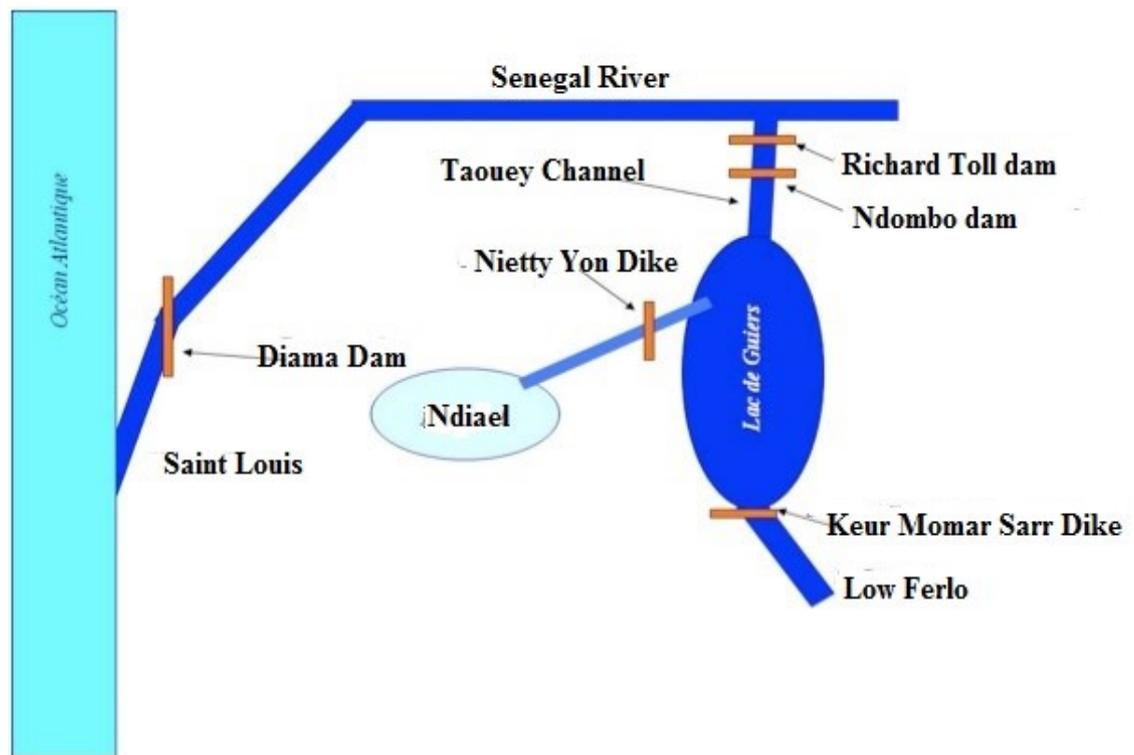
Figure 2.11: Water structures in Lake Guiers.

In many zones agriculture is largely dominated by small-scale production without mechanization and irrigation. However, there are some agro-industrial units operating in the region. CSS, the sugar cane company, is the largest and is located in Richard Toll district, Senegal. The company has a production potential of more than 10,000 ha of sugar cane using water from both the Senegal River and Lake Guiers (OMVS). Other companies include SENHUILE, a company specialized on biofuel on the basis of sunflower oil, and several smaller private agro-industrial units (Table 2.2). In the Diery zone, farmers cultivate cereals (millet, sorghum, rice, maize) and a peanut crop during the dry season. Today, irrigation is the engine for development in the basin; not only with improved technology, but also with the wider variety of produce types grown (rice, onions, tomatoes, potatoes, sweet potatoes).

Fisheries

Major factors influencing the fishery sector are the quantity of fish and biodiversity. After agriculture, fishing is an important activity for populations living near Lake Guiers. Artisanal fishing is much more developed than industrial and semi-industrial fishing and provides the urban areas with fish. However, this economic sector is threatened by a

considerable decrease in tonnage caught throughout the region. Depletion in the number of fish and an increase in price have impacted the delta and valley region for at least a decade, due to an unsustainable use of the fisheries resource. A decline in catches has been faced by local fishermen. According to OMVS, some observers link this decline to the management projects (dams, dykes) and to their impacts on the local environment: a significant decrease in salinity; proliferation of floating water weeds (due to eutrophication of the aquatic ecosystem), and water pollution.

Table 2.2: Agro-industrial units operating around Lake Guiers

Municipality	Agro-industrial unit Name	Water supply	Allotted Area (hectare)
Ngnith	West Africa Farm (WAF) SENHUILE	Lake Guiers	280 20,000
Keur Momar Sarr	Agence Nationale d'Insertion et de Développement Agricole (ANIDA) SEPAM	Lake Guiers (Low Ferlo)	110 1,000
Mbane	VITAL TEMEY AGRO EAPS FERLOGOMME TOLL JOM SENEGINDIA	Lake Guiers	No data No data 10,500 150 700 5,600
Syer	AGRINA AGRICOLA GOE SENEGAL	Lake Guiers	5,000 No data No data
Richard Toll	Compagnie Sucrière Sénégalaise (CSS)	Senegal River- Taouey Chanel - Lake Guiers	15,000

2.3.8 Environmental degradation

2.3.8.1 Environmental changes

The Senegal River delta and valley are affected by long term climate variability and change. Indicators of these climate shifts include a rainfall deficit, warmer temperatures, sea level rise, floods, and drought. These shifts have led to environmental degradation (e.g. land cover change, soil degradation, and loss in biodiversity), water deficits, and a profound effect on human life and activities. These negative aspects of climate variation affect the economy of the region and the country, which has been experiencing severe economic hardships since the 1970s. Major changes in this area link climate variability with changes in land management and resource exploitation. According to Dolman et al.[32], global change and climate change can only be understood when the major causes of land-use change are understood.

Grassland and wooded grassland are the main vegetation types in this geographical area. Changes in soil characteristics can be linked to spatial and temporal change in vegetation; with the expansion of soil salinization favoring halophytes*(Tamarix Senegalese).* In addition to natural vegetation changes, the rice crop and other cereal and vegetable species cultivated in that area are affected by this blight, leading to a decrease in soil fertility and a progressive drop in crop yields.

Construction of the salt-wedge Diama dam (1986) changed the hydrological system of the Senegal River Basin and influenced the evolution of soil characteristics. Invasive species, such as *Typha australis, Pistia stratiotes, Salvinia molesta* are now well established due to alkalization. The rapid proliferation of these invasive riparian species has had a dramatic effect on river discharge, with a decrease in water flow and sediments flux. Eutrophication of river water in the upstream delta area is worsen by the increased of nutrient supplied to the water bodies. In most cases, runoff from agricultural activities is the source of the increased nutrient flux [33]. Fertilizer consumption is increasing in the area since the implementation of management projects and increased nitrogen levels is one of the growing public health problems in the region. Areas situated downstream of the dam have seen an increased concentration of salt and a subsequent loss of biodiversity. The reason is that the alteration of natural river flows has led to an increase of salt water intrusion into groundwater supplies.

2.3.8.2 Soil salinization

Salinization is the process by which water-soluble salts accumulate in the soil. It is a natural resource concern because excess salts hinder the growth of crops by limiting their ability to take up water. Salinization may occur naturally or because of conditions resulting from management practices. In semiarid areas, salinization often occurs on depressions and edges of drainageways and in flat, low-lying areas surrounding sloughs and shallow bodies of water. In coastal Senegal, the sodic and aquic or hydromorphic soils are located inside the interdunal depressions. Soil evolution is related to the ground water fluctuation, irrigation water use, and inundation. Following drainage, the soil pedogenic processes in the depression results in organic matter mineralization, oxidation, and gleyification. Soils in semiarid areas can receive additional water from below the surface, which evaporates, and the salts are left behind on the soil surface. During the dry season the evaporation rate/process is high and this leads to crystallization and accumulation of salt in the topsoil forming white or gray deposit. Salinity is becoming more and more of a limiting factor for irrigated agriculture and natural vegetation growth in delta area of the Senegal River Basin.

Regional hydrogeology and land management are strongly related to the spatio-temporal distribution of the type of soil salinization. Irrigated soils without drainage have higher salinity and alkalinity than those which are irrigated and drained. Soil sodication varies according to the type of land management. Several studies have shown that soil quality in the valley is affected by a gradual decrease in natural salinization and a gradual increase in man-made salinization.

2.3.8.3 Desertification

Desertification is a spectacular manifestation of environmental change due to the combination of human and natural system. Desertification produces land and soil degradation in arid, semi-arid and dry sub-humid areas due to as the juxtaposition of dry climatic conditions and human demands on natural resources. It was found that desertification reduced both moisture flux convergence and rainfall in the Sahel region and produced atmospheric circulation changes and rainfall anomaly patterns [34].

Feedbacks between land degradation and precipitation link desertification and climate change. Desertification aggravates climate change through the release of CO_2 from cleared and dead vegetation and through the reduction of the carbon sequestration potential of desertified areas. Conversely, climate change exacerbates desertification through the al-

teration of spatial and temporal patterns of temperature, precipitation, solar insolation, and winds [35]. A major effect of the desertification in West Africa is a significant reduction in crop yield. Gonzalez (2001)[35] reported that : "Desertification worsens the life of millions of people in the West African developing countries. It culminated in the Sahel drought of 1968 to 1973. It was a real tragedy that resulted in famine and the death of up to a quarter of a million people."Along the Senegal River basin, two decades of drought decimated arid agriculture, livestock, and drinking water supplies in areas inhabited by a semi-nomadic population".

2.4 Conclusion

Increasingly, human activities are impacting the ecological integrity of Lake Guiers and climate change might aggravate more this situation. However in spite of its importance and growing threats to itself, Lake Guiers has not received sufficient attention in the national discourse on water policy. The key question is how to best reconcile the diverse objectives inherent in basin management.

Data, materials and methods

In this chapter we discribe data and approches we used in this study to achieve the research objectives.

Contents

3.1 Introduction

For the purposes of this study, data, tools and approches used to achieve research objective will be presented here. It composes of three sections: The first section (3.2) discribes hydrological data and methods used to assess lake Guiers hydrological alteration The second section (3.3)presents climatic data and approach used to investigate past and future climate condition in the Basin of Lake Guiers The third section (3.4)presents and discribes climatic, hydrological and socio-economic data and hydrological modeling by applying WEAP to the study area.

3.2 Objectif 1 : Stream flow Assessment

3.2.1 Data

Daily flow data were used to analyze the variation of the flow regime at Ngnith station (water treatment plant). A total of 35 years of hydrological data (water level) from 1976-2011, were gathered. Data were provided by Lake Guiers Authority (OLAG)). Discharge has been calculated from daily water level using Manning- Strickler equation $\mathbf{Q = K*RH * i}$ (1)

$\quad$ **Q**: Discharge in m/s
K: Roughness coefficient
RH:Hydraulic flow radius
i: Flow slope in m/m

Literature review allowed us to determine the following variables in the flow calculation: hydraulic flow radius (RH) = 7 m; the flow slope in Ngnith station (i) m / m = 0.001; and the roughness coefficient (K) = 35.

The stream flow from 1976 to 2011 was divided into pre-impact period (1976-1986) and post-impact period (1987-2011), representing the stream flow under natural conditions and changeable conditions, respectively. According to the pre-impact and post-impact periods, the stream flow was investigated to address hydrologic regime alteration through Stream flow Analysis and Assessment Software (SAAS) 4.0 developed by [55].(Table 3.1)shows an overview of the input data and the time periods used for analysis).SAAS is a developed tool based on focusing on hydrology-based environmental flow methods.

It calculates hydrological indicators through time with respect to a reference condition, and relates hydrological alteration to changes in ecological condition.

3.2.2 Range of Variability Approach (RVA)

In order to determine the flow regime target, the Range of Variability Approach (RVA) was used to evaluate the hydrological alterations. The Range of Variability Approach (RVA) [51] was formulated to quantify the modification of the Indicator of Hydrologic Alteration (IHA) by comparing the frequencies within three fixed intervals. The RVA is a milestone in the hydrologic alteration assessment and has been widely used ([56],[57],[58],[52]). Zolezzi et al.[59]combined the RVA with a wavelet transform analysis in order to separate the scales of variability and investigate their alterations independently. Richter et al.[60] used the degree of hydrologic alteration as a measure to quantify a deviation of the post impact flow regime from the pre-impact one. The degree of alteration D is defined as:

D=| (Post-Pre)/ (Pre)|*100%   (2)

where **"Post"** is the median flow of the post-impact period, **"Pre"**is the median flow of the pre-impact period. Richter et al.[60] further suggested that the value of **D** ranging between 0 and 33% represents little or no alteration (i.e. low alteration); 33-67% represents moderate alteration, and 67-100% represents high alteration.

3.2.3 Trophic State Indices (TSIs)

In order to characterize water quality alteration, we use monthly water quality data from 2008 to 2010 provided by Direction de la Gestion et de la Planification des Ressources en Eau du Sénégal (DGPRE), a national management body of Senegalese water resources. These data were observed in 7 sites in Lake Guiers from nord to south (Richerd Toll, Mbane, Téméye, Syer, Gnith, Keur Momar Sarr, and Lower Ferlo). However, in this study the focus in water quality analysis is primarily on salinity and eutrophication.

To characterise the trophic state in Lake Guiers,the Trophic State Indices (TSIs) of Secchi Disque (SD), Nitrogen (N) and Phosphorus (P) were calculated by using Environmental Protection Agency (EPA)'s nutrient criteria technical guidance manual [61].

The results were interpreted according to EPA's criteria. It suggested that the value of TSI <40 represents oligotrophic state. The value of TSI ranging between 50 and 60 represents a eutrophic state and the value of TSI>60 represents a hypertrophic state.

Table 3.1: Input Data and time periods used for the seasonal analysis

	Lake Guiers, Pre-Dams	Lake Guiers Post Dams
Flow Time Interval	Daily	Daily
Drainage Area	273 Km^2	273 km^2
Annual Analysis Period	Jan.1 to Dec.31	Jan.1 to Dec.31
Total Period of record (For Seasonal Analysis)	12 years	26 years
Number of Data Values Loaded	4380	9490
Season 1	180 days	180 days
Season 2	185 days	185 days

3.3 Objectif 2 : Past and future climate trends in the basin of Lake Guiers

Three climatic factors temperature, precipitation and potential evaporation will be discussed in detail. Other factors, such as wind and humidity, are potentially important as well, but they are beyond the scope of this study.

3.3.1 Climate trends

In order to determine how climatic patterns within basin of Lake Guiers have changed in the recent past,the local weather records from the Sugar Cane Company (CSS) climatic stations network within the Lake, were analyzed. Most weather datasets contain flaws due to gaps in coverage, changes in instrumentation, and inconsistencies in the number and timing of daily observations. Simply using their raw data for analysis therefore may produces spurious results. The database currently includes records from more than 8 stations. For our analysis, the records were averaged together to produce mean values for the basin as a whole. A short period (less than 30 years -"climatic normal") of daily

record (1988-2012) of maximum and minimum air temperature, total daily rainfall has been analyzed. This period is chosen for indices calculation because the selected stations are those with less than 2% of missing data.

Twenty five core indices of climate extremes across basin of Lake Guiers, were calculated.Table 5.1, presents the results and definition of indices used in this study with RClimDex (1.0) program [75] using p-values up to 0.05 to indicate statistical significance.

RClimDex is designed to provide a user friendly interface to compute indices of climate extremes. It computes all 27 core indices recommended by the CCI/CLIVAR Expert Team for Climate Change Detection Monitoring and Indices (ETCCDMI) as well as some other temperature and precipitation indices with user defined thresholds [75].

These indices characterize aspects of the tails of the distribution (The "extremes") since these tend to be more relevant to society and natural system [76]. In regards to indices calculation, some assumptions were made:(Upper threshold of daily maximum temperature, 35°C; upper threshold of daily minimum temperature, 20°C; daily precipitation threshold, 25 mm). In order to show the recurrent features of precipitation in basin of Lake Guiers, we also calculate the Standardized Precipitation Index (SPI) [77]

With regards evaporation in basin of Lake Guiers, Etpot was calculated from meteorological data by means of the FAO Penman-Monteith equation method [25] and Hamon equation method [78]

3.3.2 Climate simulation

Lake Guiers climatic projections have been simulated based on the representative concentration pathways (RCPs) scenario for the middle and late twenty-first century . RCPs are greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000. In this study the RCP 4.5 and the RCP 8.5 were selected.

The RCP 8.5 scenario assumes in addition a high population and relatively slow income growth, as well as modest rates of technology change and energy intensity improvements. These developments will lead in long term high energy demand and greenhouse

emissions in absence of climate change policies [79]. The RCP 4.5 scenario however, is a stabilization scenario. On the basis of climate policies that are introduced the greenhouse gas emissions will be medium-low [80].

These scenarios are similated by using ERA-Interim finished AFRICA-Coordinated Regional Climate Downscaling Experiment (CORDEX) data set which included data for precipitation and potential evaporation.

The CORDEX project essentially has two purposes :

- to provide a framework to evaluate and benchmark model performance

    - to design a set of experiments to produce climate projections for use in impact and adaptation studies

CORDEX project used 13 regions and define their RCM interior domain with initial focus on Africa where the model operates over an equatorial domain with a quasi-uniform resolution of approximately 50km.

3.4 Objectif 3 : Assessment of water availability and demand under scenarios of climate change in Lake Guiers

3.4.1 Adaptation and application of WEAP to the study area

First step in applying WEAP to the study area is to set up the current accounts year. The current accounts year is the baseline from which all scenarios start. Usually this is the most recent year with available data. In this study the year 2005 is chosen as the current accounts year because detailed census data.

The study relies on secondary data either derived from most recent publications or from the database established by the Lake Guiers authority (OLAG). Bearing in mind that model results are only as good as the input variables, careful attention has been paid in choosing and processing the secondary data. Even though WEAP offers water quality modeling, a topic of high importance, this study does not include water quality modeling due to a lack of reliable data. The same is true for the

integrated financial planning tool. Before setting up the model in WEAP it was necessary to identify water demands and water supplies which reflect the current demand and supply structure of Lake Guiers(Figure 3.1)

3.4.2 Current account

Water demand in WEAP can be satisfied either by groundwater or surface water. Hereby surface water extraction can be further classified into river or reservoir withdrawals. The amount and source of demanded water highly depends on the character of a demand site and specific preferences for a certain source. Therefore the following section focuses on the water supply, specific water demands and the linkages and linking rules between supply and demand in the current account's year.

3.4.3 Water supply

3.4.3.1 River, stream flow discharge

To simulate river discharge, WEAP requires river head flow and surface water inflow which can be specified by the user or modeled with the catchment option. In this study we consider Taouey canal stream flow discharge. Connected to Senegal River, feed Lake Guiers reservoir. The flow is entered on a monthly basis in m^3 /s

3.4.3.2 Reservoirs

Reservoirs are another source of surface water to satisfy water demand and can be found throughout the country and study area in varying sizes and capacities For the purpose of this study, however, only Lake Guiers, the largest reservoir either managed by OLAG or large scale consumers such as the sugar cane plantation in Richard Toll and SDE, were taken into account.

3.4.3.3 Groundwater

WEAP allows groundwater modeling using either MODFLOW or the integrated groundwater surface water model. Both methods are not applied within the current study because of the lack of information on the relationship between Lake Guiers and Alluvial aquifers.

3.4.4 Water demand sites

3.4.4.1 Domestic demand

This study considered only water supplied by SDE either directly or through a retailer. The domestic water demand has been classified into rural and urban water demand aggregated on municipality level. The ANSD report [31] provided a valuable source of information concerning the population of each village and its affiliation to an urban or rural district and the population of Dakar. Many municipalities located around Lake Guiers use other sources (e.g Richard Toll city is supplied from Senegal River and therefore it has not been taken into account. However, Dakar, 250 Kilometers away is supplied by Lake Guiers. Furthermore Touba, a city located in the south-East of the Lake, is expected to be supplied with the increase of Keur Momar Sarr water treatment plant production capacities. Dakar and Touba are implemented in the WEAP model. As it is one aim of WEAP to reveal unmet demands, it is necessary to specify actual demand and not only met demand.

3.4.4.2 Agriculture demand

Only irrigated areas are entered into WEAP as specific demand sites. The irrigated areas comprise a large scale irrigation field and peri-urban irrigated horticulture.

As mentioned in Section 1.2.7, irrigation is still the motor of development in the basin, notably in the valley and in the delta, due not only to improved technology, but also to the wider variety of produce grown (rice, onions, tomatoes, potatoes, sweet potatoes). About 100,000 hectares of land are now cultivated in the basin: 60,000 hectares during the rainy season (June-September) and 20,000 hectares during the dry season (March-June) [88].

The Senegalese Sugar Company (CSS): The Senegalese Sugar Company (CSS) is the largest agro-industrial unit operating in the basin. It has a production potential of more than 10,000 hectares of sugar cane in Richard-Toll, using water from both the Senegal River and Lake Guiers.
There are also other, smaller agro-industrial unit around the Lake. The most important are:

Senhuile: The company is specialized in biofuel on the basis of sunflower oil processing, in Ndiael, (Ngnith).SENHUILE is an agricultural joint venture of investors from Dakar and Italy. The company has been alloted an area of 20,000 ha.

West Africa Farm (WAF): The group produce onions in Yamane (Ngnith) on a surface area of 500 ha. In 2015, the group created 800 jobs from the neighboring villages and produced 2050 tons of onions for export. It aims to double this production in 2017. WAF is member of the G.S Shropshire group.

There are also industrial and private rice paddies managed by the SAED and a private rural development enterprise.

In this study agro-industrial demand are classified and implemented in WEAP into CSS and SENHUILE demand and private irrigation demand.

3.4.4.3 Ndiael

Ndiael is located in the Lake Guiers region in the north-west of the lake 16°10'N, 16°05'W. It is an "alluvial basin of impermeable, saline soil in the Senegal River floodplain". The area extends to 46,550 hectares in the estuary of the Senegal River and is characterized by a large number of wetlands [89]. With a total amount of 10,000 ha the wetlands play an important part in the Wildlife Reserve. In addition the wetlands are classified as internationally important by Ramsar in 1977 and recently placed on the Montreux Record. The Montreux Record lists Ramsar sites whose ecological features undergo, in the past, in the present or in the future modification as a result of technological developments, pollution or other human activities. It emphasizes the ecological importance for the river basin and the lake. The reserve has been subject to changes in the hydrology since the 1950s. In particular the construction of the Nieti-Yone (1951) dyke has been a main change and caused the dry out of Ndiael. In order to restore the ecological function of Lake Guiers the revitalization of the Ndiael region is included. The plan is to dredge 13 km of the Yeti Yone's active bed which acts as a scouring facility downstream of the Ndiael great pond. The connection is implemented in the WEAP model.

3.4.4.4 Lower Ferlo

The region was part of the Fossil Valley Regeneration Programme (FVRP), under the direction of the Fossil Valley Study and Development Mission (MEAVF) was designed to transfer water from the Senegal River, through Lake Guiers, to those zones demonstrating high agricultural potential. The programme aims to direct this water inland towards waterways in areas which have dried out after deterioration of the hydraulic conditions in the basin. Therefore the outflow from the Lake has to remain the same at least for some month. Subsequently a flow requirement tool is used to guarantee the outflow of seven cubic meters per second from July to November. Following that, the coverage could be pinpointed by the model.
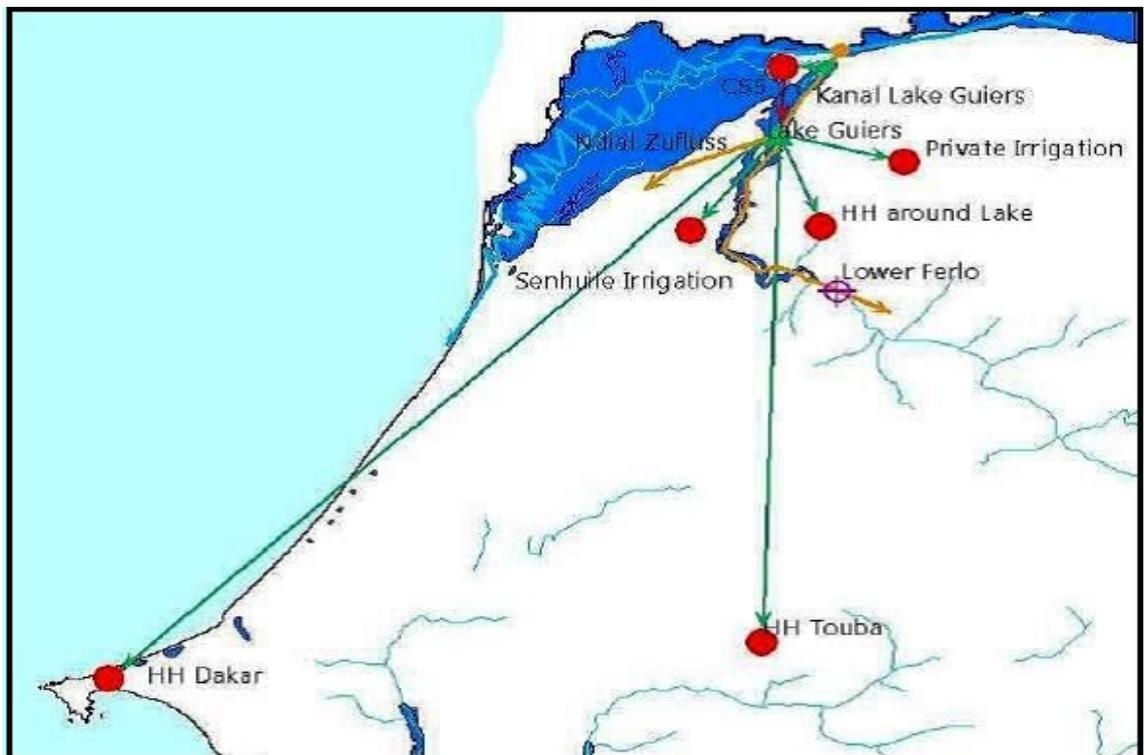
Figure 3.1: WEAP nodes and links structure in Lake Guiers reservoir.

3.4.5 Scenarios

In WEAP, the scenarios can address a broad range of what if' questions, such as: What if population growth and economic development patterns change? What

if ecosystem requirements are tightened? What if irrigation techniques and crop patterns are altered? What if various demand management strategies are implemented?

In this work the question to the model is: how does Lake Guiers behave in different climatic circumstances and population growth? Emphasis is given to the water stored in Lake Guiers.

The scenarios have been developed according to the representative concentration pathways scenarios. RCPs are greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014. It supersedes Special Report on Emissions Scenarios (SRES) projections published in 2000.

Three main scenarios have been developed on the basis of the current account year 2005 and the reference period from 2006-2030. Figure 3.2 shows the structure of the scenarios created in WEAP.

The first scenario assumed the climate change in two of the RCP scenarios. Here, the RCP 4.5 and the RCP 8.5 were selected. Both scenarios have a time span up to 2100 and measure the change in Watt per meter squared. Therefore the main difference between the scenarios is the wattage possibly reached in 2100, 4.5 Watt per meter squared in RCP 4.5 and 8.5 Watt per meter squared in RCP 8.5 [80]. The RCP 8.5 scenario assumes in addition a high population and relatively slow income growth, as well as modest rates of technology change and energy intensity improvements. These developments will lead in long term high energy demand and greenhouse emissions in absence of climate change policies [79]. The RCP 4.5 scenario however, is a stabilization scenario. On the basis of climate policies that are introduced the greenhouse gas emissions will be medium-low [80]. (Figure 3.3) shows the scope of the RCPs. In particular the development of the two chosen graphs in the period up to 2030 should be focused. The differences between them are very slight. On the fact that the scenarios have been created for the period from 2006 to 2030 the results possibly show only a slight difference.

The second scenario in WEAP is a growth scenario including the Lake Guiers region as well as the capital Dakar. The rural population in Senegal continues to grow on

Figure 3.2: Structure of the scenarios developed in WEAP

a rate of 2.1% (UN 2015). The population growth of Dakar could be implemented by a projection. Beyond that the projects were set, starting with the year of their implementation. Including that the sugar cane company almost doubles the cultivated area until 2030. Meanwhile the climate change is proceeds after RCP 8.5 or RCP 4.5.

The third scenario was created to test in which time the water in the reservoir will be exploited without a refill. It is based on the climate change scenarios and the growth scenario.

These scenarios are used in the Cordex data set which included data for precipitation and potential evaporation. The potential Evaporation was calculated using the Hamon equation. These data sets were modified into netto Evaporation to implement them into the model. Precipitation is therefore an indirect factor in the developed scenarios.
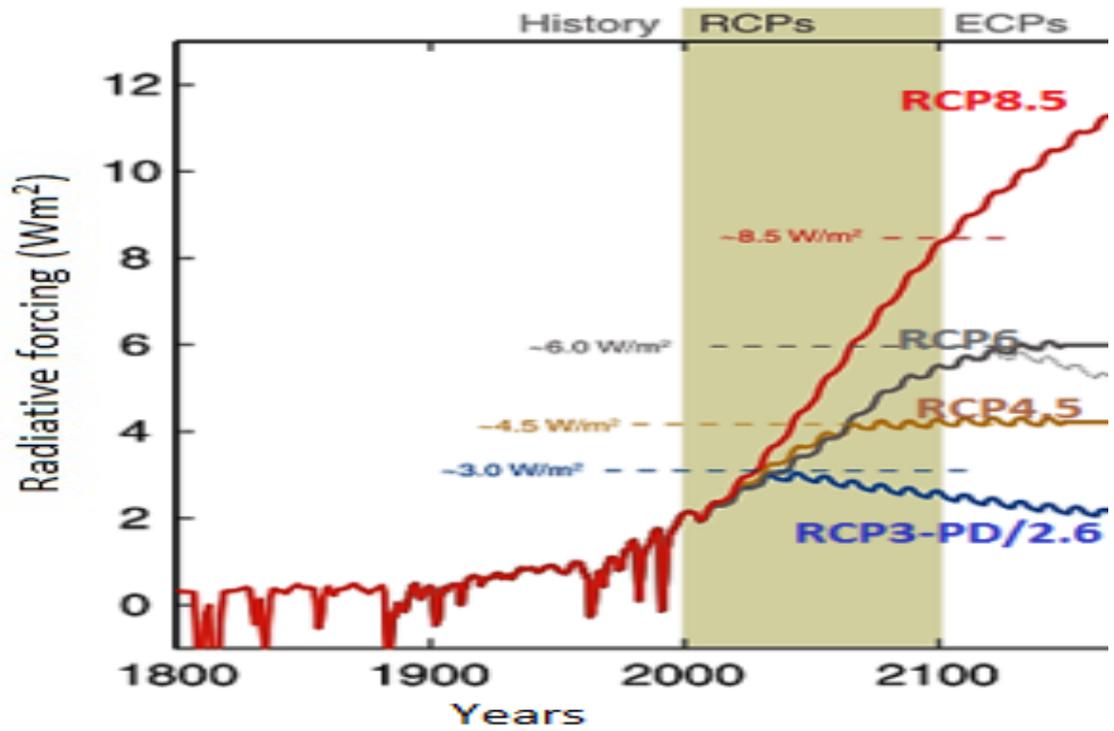
Figure 3.3: Total radiative forcing (anthropogenic plus natural) for RCPs. (Adapted from Meinshausen et al. 2011)

3.5 Conclusion

For the purpose of the study, many types of data (climatic, hydrological and socio-economic) as well as observed and similuated data, were used. Data quality control and homogeneity was tested for observed data. Futhermore, we run statistic softwares to calculate climate extreme indices and hydrological trends. To achieve the research objectives, we used hydrological methods: RVA and Hydrological modelling with WEAP.

Lake Guiers hydrologic alteration within its ecosystem

This chapter presents the first result. It focuses on variables of a flow regime strongly associated with ecological conditions and, therefore, most suited to serve as indicators of hydrologic alteration. It quantifies and assesses Lake Guiers hydrologic alteration arising from in-stream development.

Contents

4.1 Introduction

River flow regimes are considered to be the primary driving force of the river ecosystem [50]. The integrity and stability of river ecosystems is largely dependent on the natural dynamic change characteristics of the stream flow [50]. The development and management of water resources by humans has altered the natural flow of rivers around the world [51].

Taking the example of Senegal River Basin (SRB), the downstream flow regime has been widely affected when the Senegal River Development Organization (OMVS), a regional cooperative management body of the Senegal River, built along the river two dams (Diama 1986 and Manatali 1988) and structures (sluices, dykes, irrigation systems) along the river in order to meet economic and social development needs for water resources.

An assessment of these stream flow characteristics is essential for understanding and predicting the biological impact of both natural and altered flow regimes on riverine biota [52]. In Lake Guiers, this assessment is particularly important. Since 2013, the Lake Guiers Authority has undertaken a wide project that aims to "restore the ecological and economic functions of the Lake". The main actions planned are: dredging canal, rehabilitating dyke, constructing water supply network and a crossing structure. Considering all this, it is important to examine how the physical components are expected to change after the re-planned development and what the expected effect on ecological condition will be.

The ability to assess the condition of lake and river ecosystems, evaluate sensitivity to alteration, and identify potential changes to the ecosystem resulting from different development and redevelopment options is important to inform decision making.

In this perspective this study focuses on variables of a flow regime strongly associated with ecological condition and, therefore, most suited to serve as indicators of hydrologic alteration. It aims to quantify and assess Lake Guiers hydrologic alteration arising from in-stream development. This assessment will inform a decision-making process and the implementation of a post-alteration monitoring program; and build knowledge that can inform future policy and management directions by

allowing the analysis of information collected in a standard way across sites consistent with an adaptive management approach.

4.2 Lake Guiers hydrological functioning before and after dam construction

4.2.1 Before dams construction in Senegal River

Before the construction of dams, Senegal river used to be a typical rainfall runoff river [53]. The river's flow regime depends mostly, on rain that falls in the upper basin in Guinea (about 2,000 mm/year). In the valley and the delta, rainfall is generally low and reaches rarely beyond 500 mm/year. In the river, this creates a high-water period or flood stage between July and October, and a low-water period between November and May to June [11]. Furthermore, sea water intrusion up to 250 km inland occurs in Senegal River during four or five months per year due to low flow rates and a very slight slope [11].

In Lake Guiers, hydrology and water level depend on these situations described above. During high water period, the lake was filled once a year from the Senegal River and the damming up of the northern region and the closing of the southern and western outflows made it the largest water reservoir which can be used extensively as a stable freshwater source throughout the dry season, which lasts 9 -10 months a year [54].

Under the combined effect of insufficient filling (during drought years in the whole basin), increased pumping for irrigation, and evaporation (2.2 m/year), the level of the lake in certain years went below the threshold levels because its exploitation was limited. Extreme conditions were reached during water year 1983- 1984 when the lake was almost completely dried up [54].

In order to meet economic and social development needs for water resources, OMVS has undertaken the construction of Diama and Manantali dams along the Senegal River. The Diama Dam is located 30 km upstream of the city of Saint Louis. It

was built in 1986 in order to stop the dry season intrusion of seawater along the river bed and to irrigate 375 000 ha of former flood plain for production of two crops per year, especially for rice production [12].The second dam, the Manantali, was completed in 1988 and is located in Mali 1,200 km upstream from the Senegal River outlet. Its storage capacity is 12.8 km^3. It was built on the River, which supplies approximately 60% of the annual flow of the Senegal River in a reservoir.

4.2.2 After dam construction

Since 1986, the operation of the Diama Dam has prevented any seawater intrusion upstream and fresh water is available all the year at the Taouey - lake junction [54]. Since 1992, the steady and continuous operation of the Manantali Dam and the regulation of the river have changed the hydrological conditions in the lower valley and the delta region. There is now a constant supply of fresh water, sufficient to fill the lake several times a year. From 1986 to 1991, as before 1986, the lake was filled only once a year during the annual flood. However, water levels became clearly higher than before 1986 with an average levels of 0.8 m, compared with 0.4 m prior to 1986 [54]. Since 1992, the partial regulation of water flow by the Manantali Dam has further altered the hydrological regime of the Lake Guiers, which may now be filled several times a year. The annual average level has reached 1.5 m and its annual range is not greater than 0.96 m. Since 2002, the annual average level has reached 1.9 and the range of water level in the Lake is between 1.9 and 2.5 m.

4.2.3 Current water volume in Lake Guiers

There is now a constant supply of fresh water from Senegal River, into Lake Guiers.Figure 4.1below, shows the water volume in Lake Guiers. The discharge data from OLAG calculated in Ngnith station from 2008-2010 estimates the water volume to 655,616,099.3 m^3. The inflow from Taouey canal account for 4,177,274.8 m^3/day while the outflow into Lake tributaries (Low Ferlo, Nietty Yone, Ndiael etc..) account for 2,297,007.9 m^3/day.
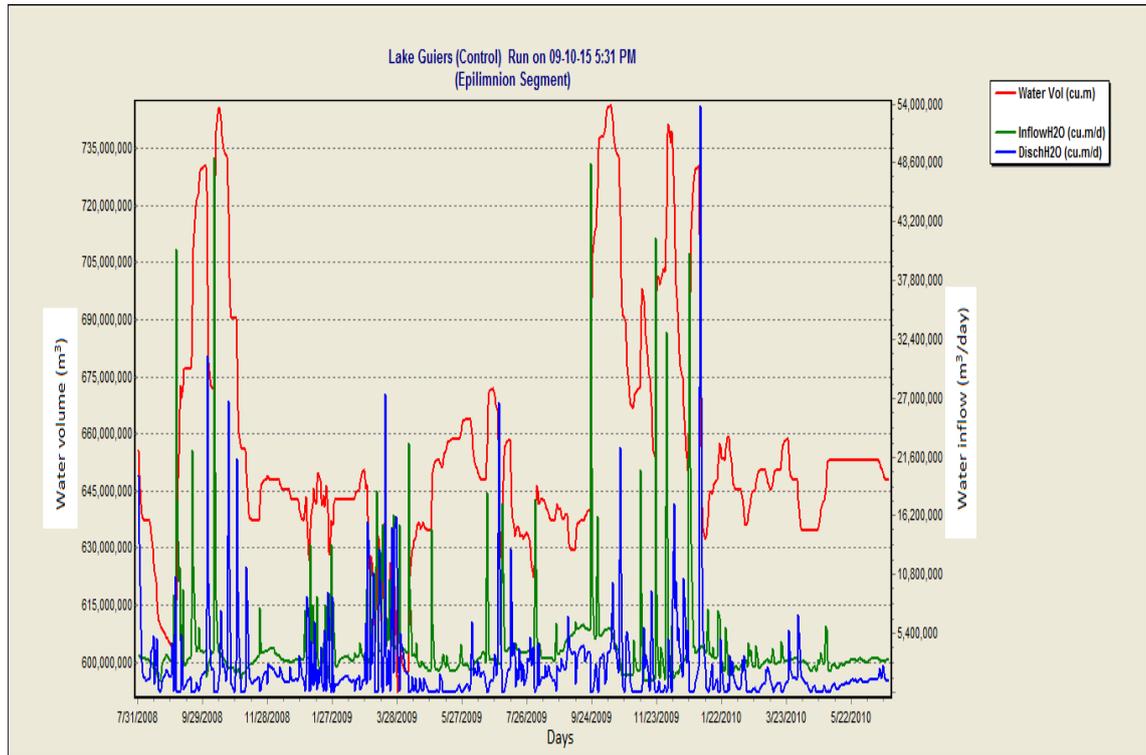
Figure 4.1: Water volume in Lake Guiers.

4.3 Indicator of flow regime alteration in Lake Guiers

4.3.1 Hydrograph

The operation of Diama and Manatali dams has significantly modified the flow regime of Lake Guiers over the past 30 years. The annual flow increased by more than 269% at Ngnith gauging station. Table 3.2 shows a record summary of stream flow statistics.

The flow pattern at Lake Guiers is reversed from the pre-dam.Figure 4.2shows the entire period of record as a continuous hydrograph (1976-2011). The red circle represents events over thresholds and the red dash represents the low flow indicator. The green line is the median and yellow line represents high flow Indicator. Significantly greater median flows occured almost during all twelve months (increases of 14.0 m^3/s), which were the typical high flow that occured in September - October during the pre-dam period. The maximum flow during pre-impact (15.6 m^3/s) is far less than in post impact (30.7 m^3/s). It can be noticed that zero flow days, decreased drastically between the pre- and post-impact periods, from 1041 to 153

Table 4.1: Stream flow statistics in Lake Guiers 1976-2011

Stream flow Statistics	Pre-Dam	After-Dam	Unit
Minimum	0	0	m^3/s
Maximum	15.6	30.7	m^3/s
Mean	4	15.1	m^3/s
Standard Deviation	4.1	6.2	m^3/s
Coefficiant of variation	1	0.4	m^3/s
Median	3	17.1	m^3/s
Upper Quartile	6.9	19.8	m^3/s
Lower Quartile	0.1	11.2	m^3/s
Relative Dispersion	2.2	0.5	m^3/s
Number of Zero Flow Days	1041	153	–

days and has been eliminated since 1991(Table 4.1). This indicated the magnitude of alteration.

4.3.2 Flow duration

A flow-duration curve (FDC) represents the relationship between the magnitude and frequency of daily, weekly, monthly (or some other time interval) of stream flow for a particular river basin, providing an estimate of the percentage of time a given stream flow was equalled or exceeded over a historical period [62]. For the calculation of FDCs, we have choosen the method described by Vogel et al.[62] which produces Median FDCsc (Appendix A1). With this method, individual FDCs is calculated for each year (e.g.26 years of data = 26 individual FDCs based on 365 days of data each for post-impact period data). The same is done for pre-Impact period data. Then a single median value is calculated for each exceedance point using the collection of values at the same exceedance taken from the multiple annual FDCs (e.g. 26 points).Figure 4.3)and Figure 4.4 compares annual and seasonal median of FDCs at Lake Guiers using two different periods of record (pre and post impact). The FDC for these two periods are significantly different. For instance,
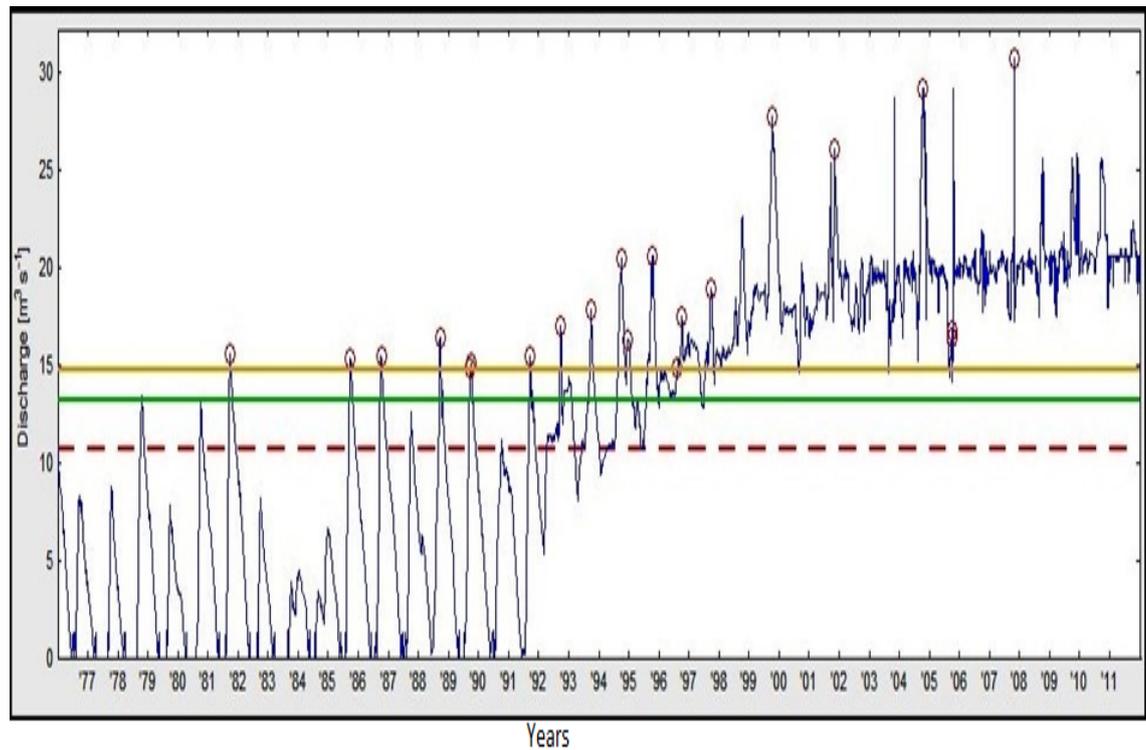
Figure 4.2: Lake Guiers, Hydrograph Indicators.

in pre impact period the Highest Q = 11.4 m^3/s and the percentage of exceedance equal to 0.01%; and the lowest Q= 0.00 m^3/s and the percentage of exceedance equal to 99.9%. For post impact the highest Q = 21 m^3/s and the percentage of exceedance equal to 0.01%; the lowest Q = 13.7 m^3/s and the percent exceedance equal to 99.9%. Comparable changes are also observed on seasonal median FDCs.
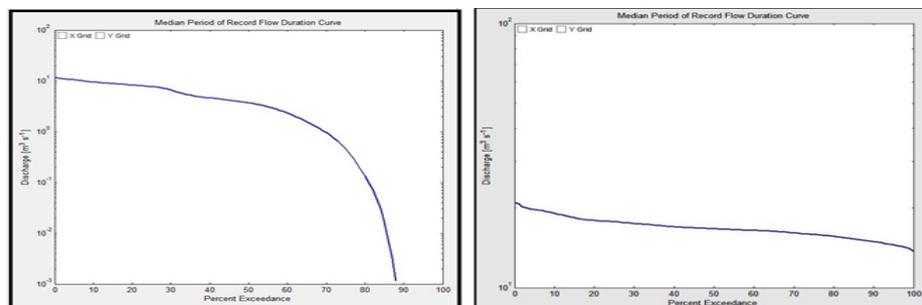
Figure 4.3: FDCs. It compares the POR FDCs pre impact, on left and post impact, on right in Lake Guiers
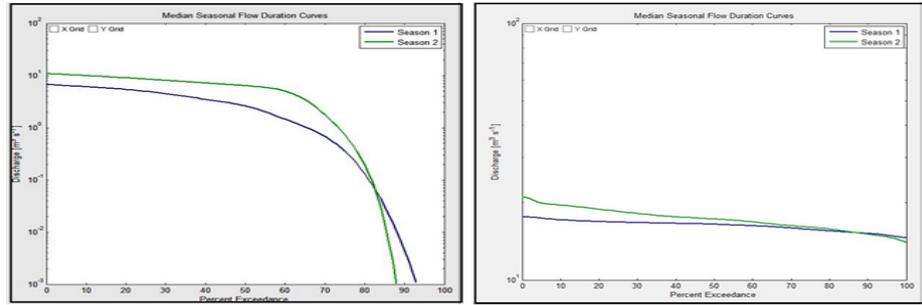
Figure 4.4: FDCs. It compares the Median FDCs pre impact, on left and post impact, on right in Lake Guiers.

4.3.3 Baseflow

Base flow is defined as the stream flow portion generated by persistent slowly varying sources (i.e. groundwater, lakes, and wetlands) between precipitation events [63]. SAAS separates base flow from stream flow using a recursive digital filtering as described by Nathan et al.[64]. The filter parameter recommended by Nathan et al.[64] of 0.9 is used in the SAAS daily stream flow and base flow separation analysis with three filter passes. Base flow separation technique (Appendix A1) was used to estimate Base flow Index (BFI).

Base flow index (BFI) is the ratio of the base flow to the total stream flow. The value ranges from 0 to 1. Therefore a BFI of 0.5 indicates that 50% of total stream flow can be attributed to base flow for the respective time period (i.e. period of record, month or season).

In Lake Guiers, before the dam's operation BFI for the entire period of record was 0.7 which is less than after dam operation (BFI= 0.9). This implies that 73.9% of total stream flow can be attributed to base flow for the respective time period. In the post impact period it's 92.6% that can be attributed to base flow (Table 4.2). However, we can conclude that for the two periods the base flow constitutes the highest part on total stream flow.

Base flow percentage of exceedance values are derived just like the stream flow du-

Table 4.2: Base flow Index

Months	Before Dams			After Dams		
	BFI	50%Excd.	FDC% Excd	BFI	50% Excd.	FDC% Excd
Jan	0.8	5.4	59	0.9	16.3	50
Feb	0.8	4.3	58	0.9	16.1	52
March	0.7	2.7	65	0.9	16.4	51
April	0.6	0.7	66	0.9	16.6	51
May	0.3	0	58	0.9	16.2	51
Jun	0.1	0	20	0.9	16.3	51
July	0	0	6	0.9	16.4	54
Aug	0.1	0	63	0.8	14.9	62
Sep	0.3	2.2	87	0.8	15.5	68
Oct	0.7	6.6	77	0.8	17.0	54
Nov	0.9	7.0	52	NaN	16.7	56
Dec.	0.8	4.2	72	0.9	15.7	61

ration curves. The only difference is that base flow values are used in the analysis instead of total stream flow. A set of base flow exceedance values essentially constitutes a base flow duration curve (BFDC)[65]. FDC equivalent values correspond to the first corresponding stream flow exceedance percentage (on the FDC) that is less than, or equal to, the selected base flow exceedance value (from the BFDC). For example in (Table 4.2), the September 83.2% base flow exceedance value equals 15.5 m³/s of the post impact period data. This value would be 'equivalent' to the 68% exceedance value on the September FDC, which is equal to 14.9 m³/s.

4.3.4 High flow and low flow

The extreme hydrologic events play an important role in regulating the structure and function of rivers, flood plains, and estuaries. Low frequency but high intensity events, such as severe floods or droughts, may have long-lasting effects on the structure and function of lotic ecosystems, as well as on man-made structures and human uses of rivers, flood plains, and estuaries [66]. Figure 4.5 and Figure 4.6 shows extreme hydrologic event (high and low flow). The extreme low flow during 1976- 1986 was more than twice the average number during 1987-2011, and increased by 480%, at Ngnith station. Low flows are necessary for many processes in riverine ecosystem functioning. If the low flow situation reaches extremely low levels, however, ecological communities are impaired. Extreme low flows may be necessary to dry out floodplain areas and enable certain species of plants to regenerate. On the other hand, water chemistry and dissolved oxygen availability can become highly stressful to many organisms during extreme low flow [67].

By using the high flow events, we explore the frequency and duration of those events on seasonal basis (Figure 4.5)and (Figure 4.6). The frequency refers to how often a flow above a given magnitude recurs over some specified time interval. The duration is the period of time associated with a specific flow condition. Duration can be defined relative to a particular flow event or a composite expressed over a specified time period [68]

While seasonal high flow frequency has increased by 109% during season 1 and 130% during season 2, high flow duration has decreased to (-53 %) during season 1 and, (- 69%) during season 2 in Lake Guiers (Table 4.3). Figure 4.5 shows the

seasonal high flow frequency on pre-impact (left) and post impact (right). For pre-impact, the total events equal to 133 and the number of year = 12. During season 1, the 25% ile = 3; Median = 5.5 and 75% ile= 7; during season 2, the 25% ile = 3; Median = 4.5 and 75%ile= 8.

For post-impact period, the total events equal to 655 and the number of year = 26. During the season 1, the 25% ile = 6; Median = 11.5 and 75% ile= 17 and during season 2, the 25% ile = 6; Median = 11.5 and 75% ile= 15. High flow pulses include any water rises that do not overtop the canal banks, which provide important and necessary disruptions in low flows.

Figure 4.6 shows the seasonal high flow duration on pre-impact (left) and post impact (right). For pre-impact, the total events equal to 133 (S1 = 63; S2 =70). During season 1, the 25% ile = 7; Median = 17 and 75% ile= 24.75 and during season 2, the 25% ile = 11; Median = 29 and 75% ile= 57. For post-impact period, the total events equal to 655(S1= 339; S2=316) and during the season 1, the 25% ile = 4; Median = 8 and 75% ile= 16 and during season 2, the 25% ile = 5; Median = 9 and 75% ile= 21.

High flow pulses are vital for reducing levels of various elements in rivers and Lakes by providing relief from higher water temperatures or low oxygen conditions caused by low flows, and delivering a nourishing subsidy [56]. High flows imply increased hazards regarding water quality because various pollutants may be poured into the river. Flooding alterations can disturb anoxia in riparian soils, which may lead to plant death [56].
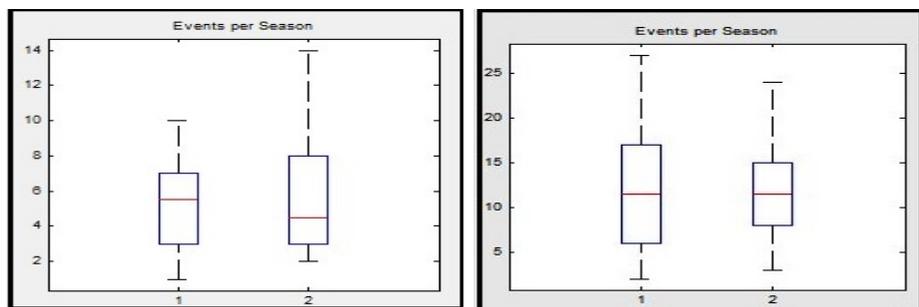
Figure 4.5: Seasonal high Flow Frequency.
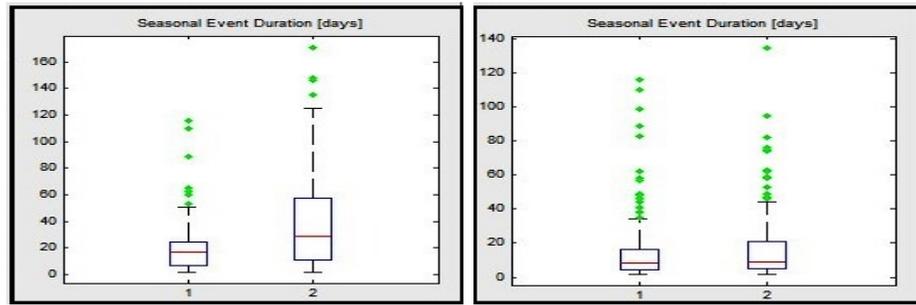
Figure 4.6: Seasonal high Flow duration.

4.3.5 Rate of change

Rate of change represents the change between stream flow data points. Figure 4.7) and Figure 4.8 shows POR and seasonal raw rate of change. It indicates the positive POR and seasonal raw rate of change (left) and negative POR and seasonal raw rate of change (right) during post-impact period. Its duration curves was created using the unfiltered rates of change (i.e. all rates including low flows)[65]. For daily input data these hourly rates are calculated by dividing the daily rates of change by 24, assuming a linear rate of change throughout each day. Raw ROC curves terminate at less than 100 percentage of exceedance because the percent exceedance is calculated using all rates (i.e. positive, negative and zero)[65].

In Lake Guiers, for pre impact the POR ROC duration curves show that 21% of the time the rates are positive and 49% of the time they are negative, implying that 2% of POR rates are zero. Compared to post impact period ROC duration curves show that 27% of the time the rates are positive and 36% of the time they are negative, implying that 1% of POR rates are zero.
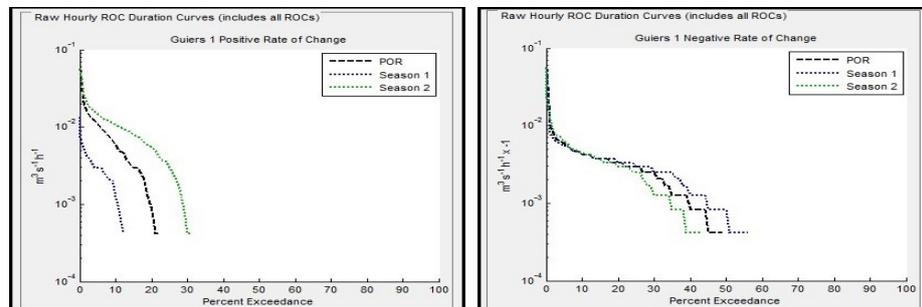
Figure 4.7: POR and seasonal raw rate of change on pre-impact period.
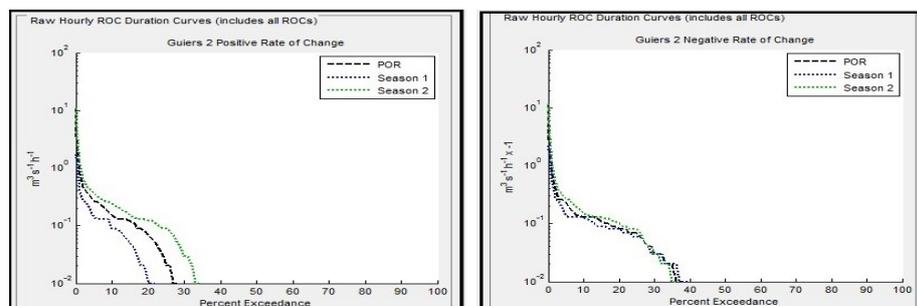
Figure 4.8: POR and seasonal raw rate of change on post impact period.

4.3.6   Assessment of trends

The Mann-Kendall non-parametric trend test is used to statistically assess whether there is an upward or downward monotonic trend in a variable. The temporal variability (summarized annually) of a variety of hydrologic metrics (annual median stream flow, annual median base flow, and annual number of high flow events) were tested. Figure 4.9 shows trends in stream flow (a), base flow (b) rate of change (c) and number of high flow events (d)during post impact period in Lake Guiers. Trend lines are shown in red if the slope of the line is significantly different from a slope of zero (i.e. temporal trend detected) with 95% confidence. The Mann-Kendall rb (tau-b) test statistic, similar to the correlation coefficient in regression analysis, and the associated p-value used to test the zero-slope hypothesis (at 95% confidence a p-value of 0.05 or less allows the zero-slope hypothesis to be rejected). During post

impact period the stream flow show an increased trend of 93% with 95% confidence. In addition, base flow and number of high flow events show respectively trends 91% and 42%. They are statistically significant. However, temporal trend were not detected in the annual median rate of change.
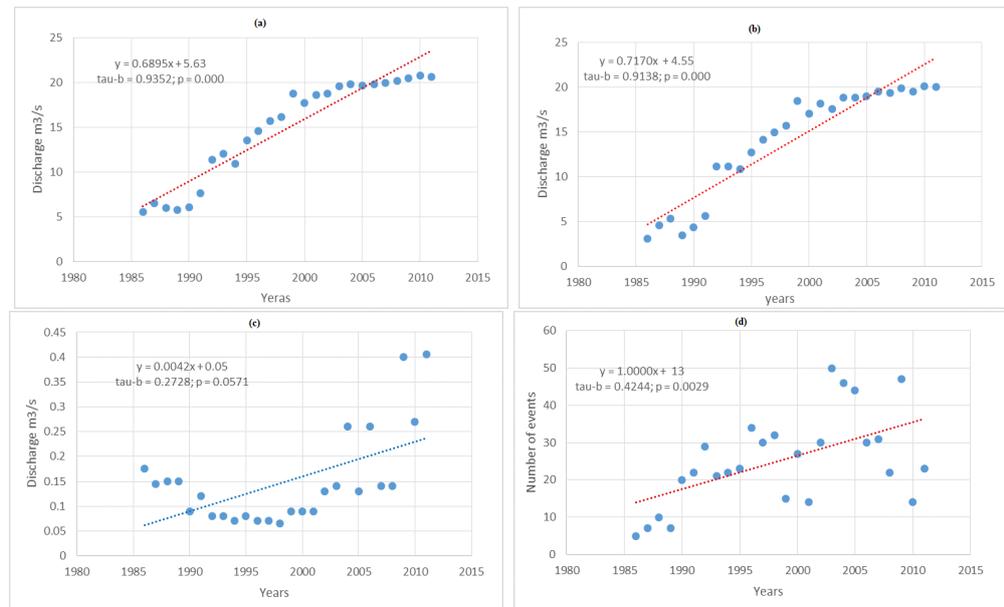
Figure 4.9: Temporal variability of hydrologic metric.

4.3.7 Degree of hydrological alteration

The median flow was used to quantify a deviation of the post impact flow regime from the pre-impact ones for Lake Guiers. The results show that the reservoir was strongly affected by the construction and operation of Diama and Mananatli dams. Table 4.3 shows RVA lower and upper targets are 25th and 75th percentiles value of pre and post impact hydrologic parameters. L, M, H represent Low, Moderate and High alterations respectively.

The hydrologic regime of Lake Guiers has been altered over the past 30 years. Annual flow increased more than 100% at Ngnith gauging station. Monthly flows for May in dry season and monthly flows for October in flood season were selected to

Table 4.3: Hydrologic alteration at Ngnith station, Lake Guiers

IHA	Pre-Dam	After-Dam	RVA target Lower	RVA target upper	Devia.%	Class
Streamflow						
Mean	0.4	15.1	-	-	269	H
Max	15.6	30.7	-	-	96.3	H
Zero day flow	1043	153	-	-	-85.3)	H
POR BFI	0.7	0.9	-	-	25.5	L
Season 1- BFI	0.8	0.9	-	-	18.9	L
Season 2 -BFI	0.7	0.9	-	-	27.5	L
Monthly high flow frequency(median)	-	-	-	-	-	-
Jan	2	2	0.5	3	0	L
Feb	1	2	0	3	100	H
March	1	1.5	0	4	50	M
April	0	2	0	4	-	-
May	0.5	1	0	3	100	H
June	0	2	0	3	-	-
July	0	2	0	4	-	-
Aug	1	2	1	3	100	H
Sep	1	1.5	0	2	50	M
Oct	1.5	2	1	2	33.3	M
Nov	1	1	0	3	0	L
Dec	0.5	2	0	3	300	H
POR high flow frequency(median)	10.5	23	7.5	31	119	H
POR high flow duration(median)	20	9	4	43	-55	M
Seasonnal high flow duration(median)	-	-	-	-	-	-
Season 1	17	8	4	24.7	-52.9	M
Season 2	29	9	5	56.7	-68.9	H

analyze monthly water condition alterations, which indicated magnitude alteration in Lake Guiers reservoir. Median monthly flows for May, the driest month, at Lake Guiers increased up to 100%(Table 3.4). Median monthly flows for October, the month in which, the flood pick occurs, account for 33.3% of the total annual flows. The increasing trend of flow is obvious. During all months flow increased and the largest monthly alterations occurred during the dry season(Figure 4.10).
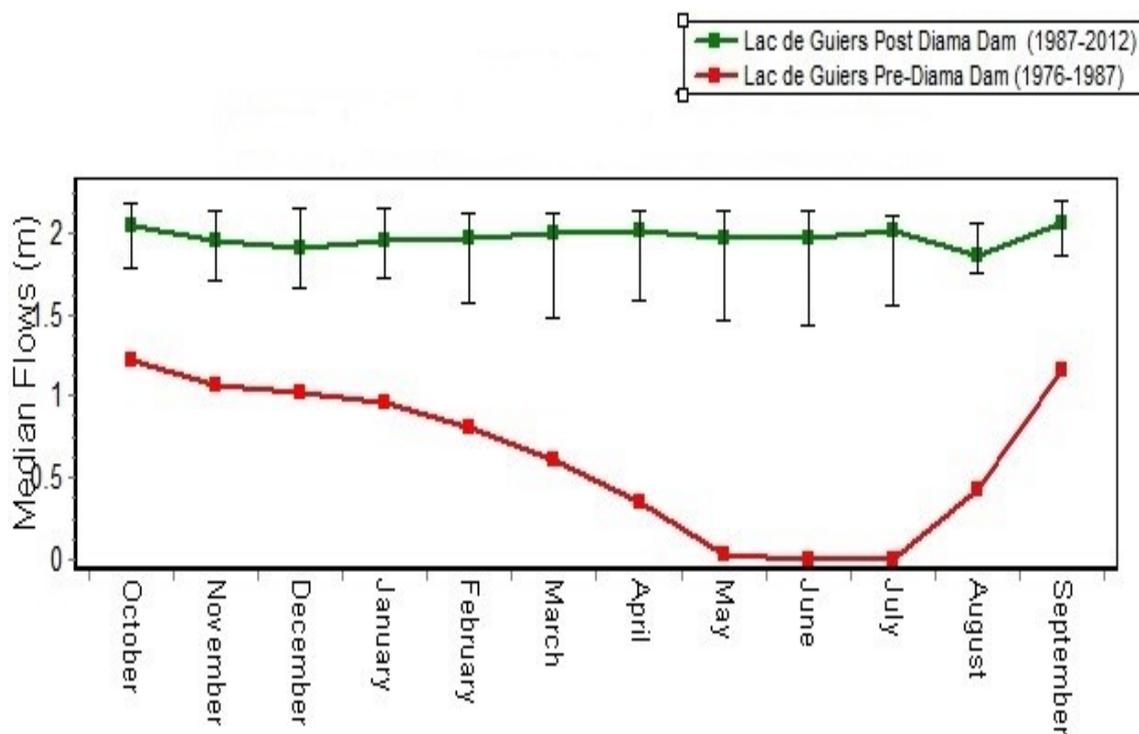
Figure 4.10: Monthly Flow alteration with RVA in Lake Guiers.

4.4 Hydrologic alteration of Lake Guiers within its ecosystem

Key ecosystem components that have important functions in determining the integrity of river ecosystems include hydrologic regime, sediment regime, water quality, thermal regime, and biologic components. However this study focuses on hydrologic regime and water quality factors that most strongly shape the ecological condition of river systems and that are often of greatest importance to the health

of valued ecosystem components. Components of flow regimes considered impor-
tant for maintaining the ecological condition of riverine ecosystems are described in
(Table 4.4), while important characteristics commonly used to define their pattern
are. (magnitude, duration, frequency, timing, and rate of change).

In Lake Guiers, flow regimes pattern considered important for maintaining the eco-
logical condition of riverine ecosystems have been investigated. Results show that
hydrology in Lake Guiers depend in natural conditions on the filling and discharge
phases following the rhythm of floods and low flows of the Senegal River. These
hydrologic events played an important role in regulating the structure and function
of the lake and flood plains. Low flows are necessary for many processes in riverine
ecosystem functioning. If the low flow situation reaches extremely low levels, how-
ever, ecological communities are impaired.

Low frequency but high intensity events, such as severe floods or droughts that used
to occur in Lake Guiers had long lasting effects on the structure and function of
lotic ecosystems.

Extreme low flows may be necessary to dry out floodplain areas and enable certain
species of plants to regenerate. On the other hand, water chemistry and dissolved
oxygen availability can become highly stressful to many organisms during extreme
low flow [69] Since 1986, in-stream developments along Senegal River and Lake
Guiers has changed the distribution of flow magnitude, duration, frequency, sea-
sonality, and rates of flow increase and recession. The steady and continuous oper-
ation of dams and its regulation have changed the hydrological conditions. These
new conditions have favored a few years after the proliferation of invasive aquatic
plants. [70] show that aquatic plants has settled on a surface area of 7,458 ha in
Lake Guiers from 1988-2010. This has led to a decrease of 2,339 ha on open water
and 4,021 ha on flood plains area.

4.5   Lake Guiers's water quality alteration indicator

Table 4.4: Environmental flow components important for maintaining the integrity of aquatic ecosystems [65].

Flow component	Description	Ecological function
Overbank flows	Infrequent, high flow events that exceed the normal channel	These flows shape and redistribute physical habitats, purge invasive species, provide lateral connectivity between the channel and the active floodplain, provide life-cycle cues for various species, and facilitate exchange of nutrients, sediments and woody debris.
High flow pulses	Short-duration, in-channel, high flow events.	These flows maintain physical habitat by flushing silt and fines and preventing the encroachment of riparian vegetation into the channel, providing lateral connectivity to oxbows and providing life-cycle cues for various species
Low flows	Normal flow conditions between high flow events sustained through the release of surface and groundwater storage	These flows maintain water tables for riparian vegetation (lateral connectivity), provide longitudinal connectivity, and provide a range of suitable habitat conditions that maintain the diversity of the natural biological community
Subsistence flows	Infrequent, naturally occurring low flow events of long duration (occurring over seasons)	These flows maintain sufficient water quality and provide sufficient habitat and connectivity to prevent direct mortality of aquatic species and ensure survival of organism populations capable of recolonising the river system once normal base flow returns

4.5.1 Water transparency

Variations in *Secchi* disque (water transparency) are quite low between 54 cm to 86 cm (coefficient of variation= 24%) with an average of 66 cm (Figure 4.11). Throughout the study period, *Secchi* values remained less than 100 cm. However, they seem to draw a slight difference from year to year and show a seasonal trend. In addition, the fluctuations in water transparency seem to follow water volume variation in the lake. The increase in lake's water volume resulted in a decrease of transparency and vice versa.
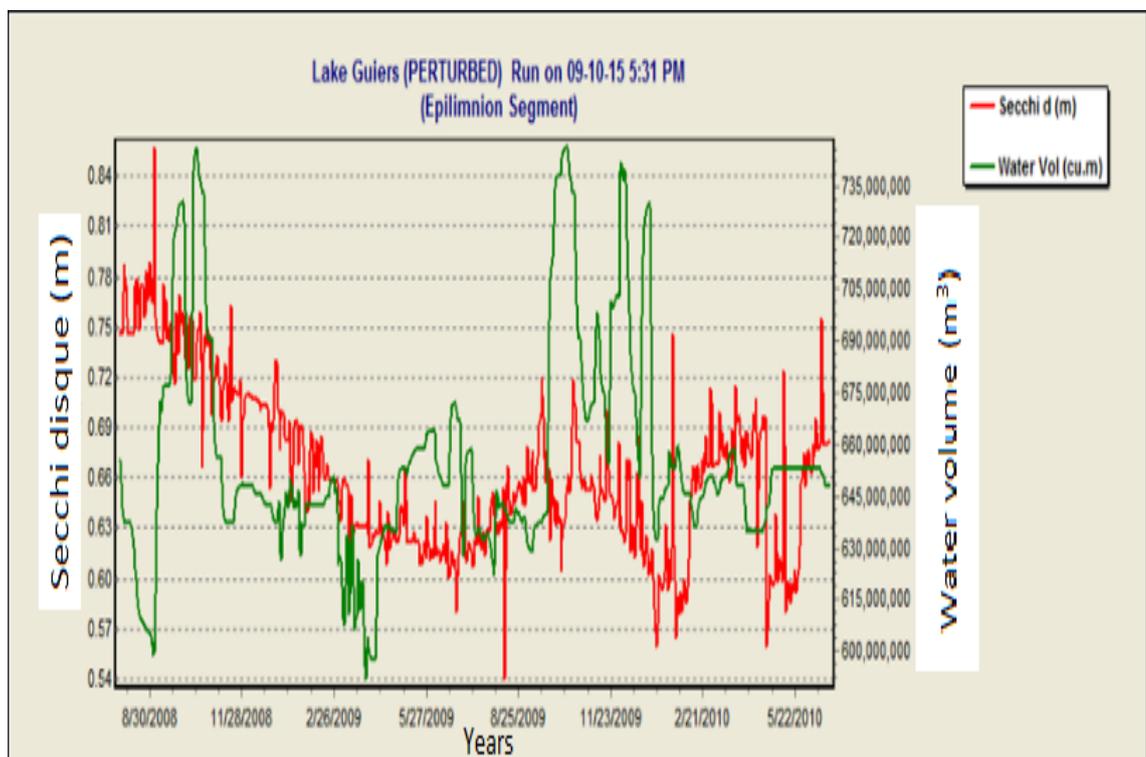
Figure 4.11: Water transparency with water volume in Lake Guiers,2008-2010

4.5.2 Salinity

The results of surveys between 2008 and 2010 indicates an average salinity in Lake Guiers of 199 *ppt* (392 μS/cm) with a maximum of 257 *ppt* (506 μS/cm) and a minimum of 124 *ppt* (244 μS/cm).

Figure 4.12 shows the evolution of the salinity during this period, superimposed with water volume in the lake. We can notice that the salinity increases when lake's water volume is low and decrease when lake's water volume is high.

In addition, there is a spatial and temporal distribution of salinity into the lake. The results show a north - south gradient of salinity. The measurements observed from Richard Toll increase significantly as we move towards Keur Momar Sarr. They are even more (10 times higher) towards lower Ferlo. They also indicate seasonal trends of salinity. Higher concentrations were noticed in August 2009.

These results are supported by studies carried out in September 2004 by *DHI water and environment and TROPIS* under the Long Term Water Project (Projet Eau Long Terme). They showed a salinity gradient of about 30 μS/cm in Taouey channel entry until about 550 μS/cm to Keur Momar Sarr dyke and a strong rise about 992 μS/cm in lower Ferlo.

Studies carried out before Diama dams showed large spatial and temporal variations in salinity in Lake Guiers (Figure 4.13). Indeed, the salts concentration from the Senegal River was relatively low with a salinity of 20-50 μS/cm [8]. However, it gradually increased in the Taouey before becoming constant in northern part of the lake. Then it increased again in lower Ferlo due to high evaporation rate and increase of dissolved salts in water.

The large variations in salinity (from 1972 until 1985) were therefore due to the intrusion of seawater. After Diama dam, the oscillations were due to the opening and closing of the valves at Richard Toll .The Lake was still subject to relatively large salinity oscillations until 1992. These continuous variations were probably due to salt discharges stored in Lake Guiers's sediments. Since 1992 with Lake Guiers water level regulation (between 1.90 m and 2.50 m), annual variations in salinity are limited to minor seasonal variations.

However, Sane et al.[8] noted that the water salinity in Lake Guiers did not show a significant difference between 2002 and 2003 with respectively average value of 180.5 and 178.4 μS/cm. A significant increase occurred in 2004 and 2005 with
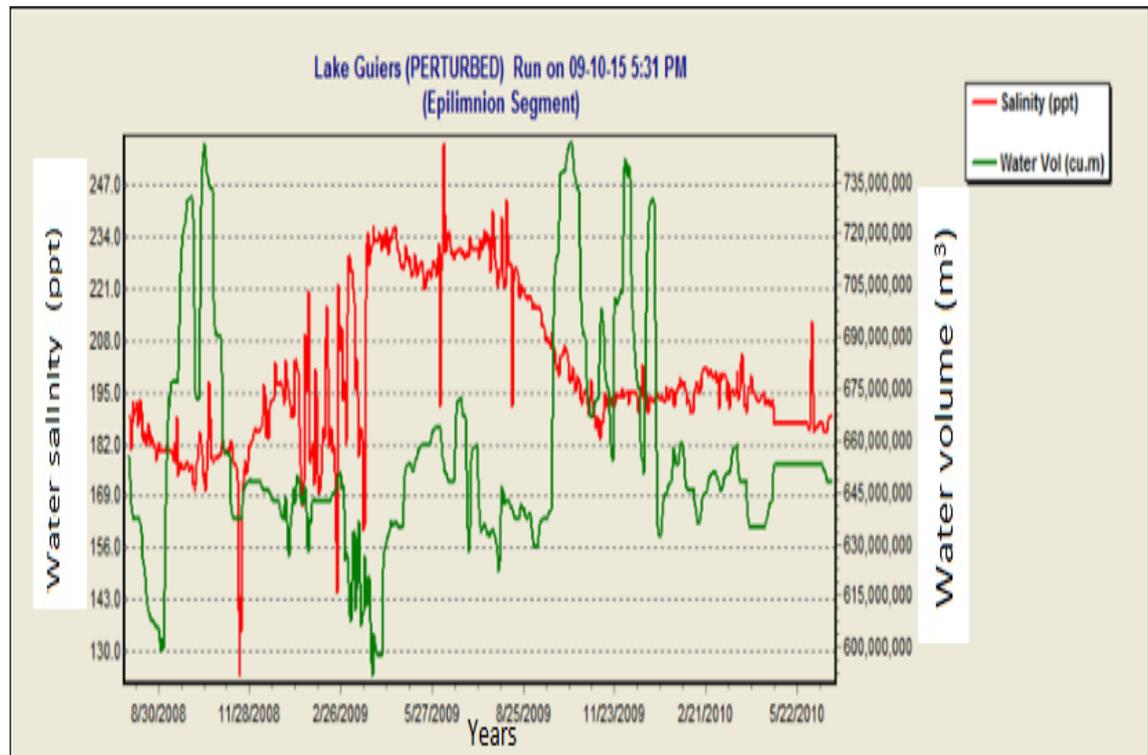
Figure 4.12: Evolution of water salinity in Lake Guiers with water volume 2008-2010

respectively an average of salinity of 220.6 and 207 μS/cm. This is probably due to water level elevation and a low water renewal.

The main source of salt concentration into the Lake is an inappropriate discharge outlet in lower Ferlo and a high evaporation rate. The irrigated crop drainage water discharged into the northern part of the lake is the second main source of salts accumulation. It accounts for 56% of the salt influx [45].

4.5.3 Nutrient loading

Results of nutrient surveys between 2008 and 2010 show stabilized concentrations not exceeding 1 mg / l . Total nitrogen (N) during the study period ranged from 0.74 to 0.90 mg / l with an average of 0.75 mg /l . Total phosphorus (P) ranged from 0.15 to 0.27 mg /l with an average of 0.19 mg / l (Figure 4.14).
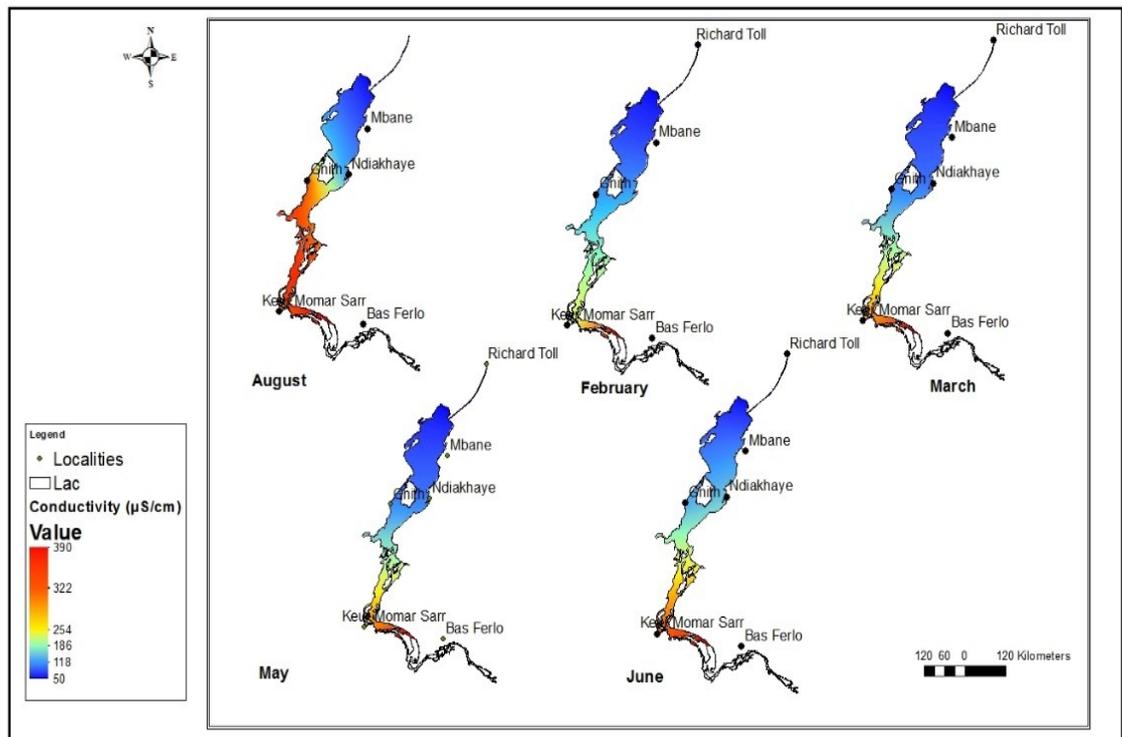
Figure 4.13: Spatial and temporal distribution of salinity in Lake Guiers 2008-2010

In addition, (Figure 4.15) shows during the study period, Total ammonia (NO_3 NO_4+ (mg/l)) varying between 0.1 mg / l and 0.09 mg / l with an average of 0.1mg / l . Nitrates (NO_3 (mg/l)) range from 0.7mg / l to 0.5 mg / l .

Concerning pH, it varies between 8.5 and 6.3. However, no correlation was found between NO_3 and pH .

These results do not reflect those obtained previously. According to Cogels et al [12], eutrophication is already a serious problem in Lake Guiers. Total N and nitrates are quite higher into the lake. They are even higher in the Taouey canal. However, they tend to decrease and stabilize in the central and southern parts of Lake Guiers. Mean concentrations of nitrogen (N) range from 1 to 2.5 mg / l in the lake and Ferlo, whereas in the Taouey they are estimated to be 6.5 mg / l [12]. The Taouey channel provides significant amount of phosphorus (24%) and nitrogen (25%) into the lake, especially during the rainy season [12]. This could probably be attributed

to agricultural activities around the lake. Faye et al.[70] indicates that irrigated agriculture is currently the most common activity in the area. The irrigated areas comprise a large scale irrigation field and peri-urban irrigated horticulture. About 20,063 ha of land are now cultivated around Lake Guiers.
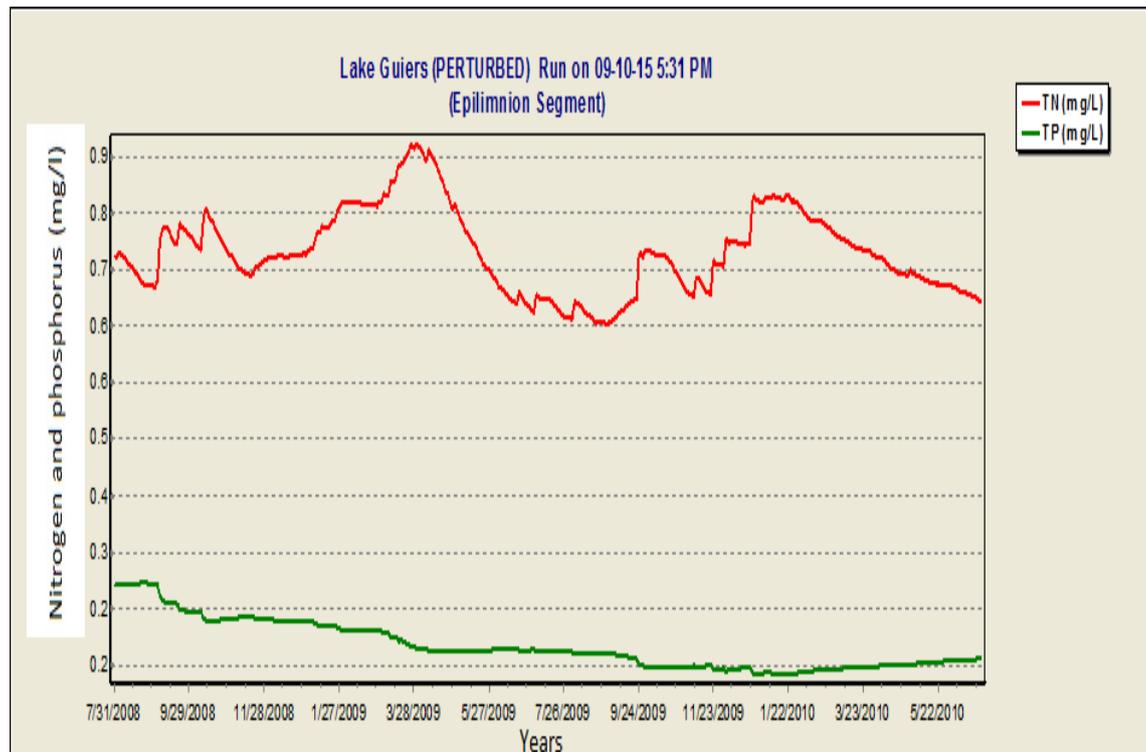
Figure 4.14: Evolution of nitrogen (N) and phosphorus (P) in Lake Guiers, 2008-2010

4.5.4 Trophic State Indices (TSIs) in Lake Guiers

Throughout the study period, the low measured water transparencies reveal a TSI of Secchi disque of 65.91, which would indicate a hypertrophic state. Total N measured shows a TSI of 50.22 indicating a eutrophic state. Finally, total P measured, indicates a TSI of 79.57 which would indicate a hypertrophic state.
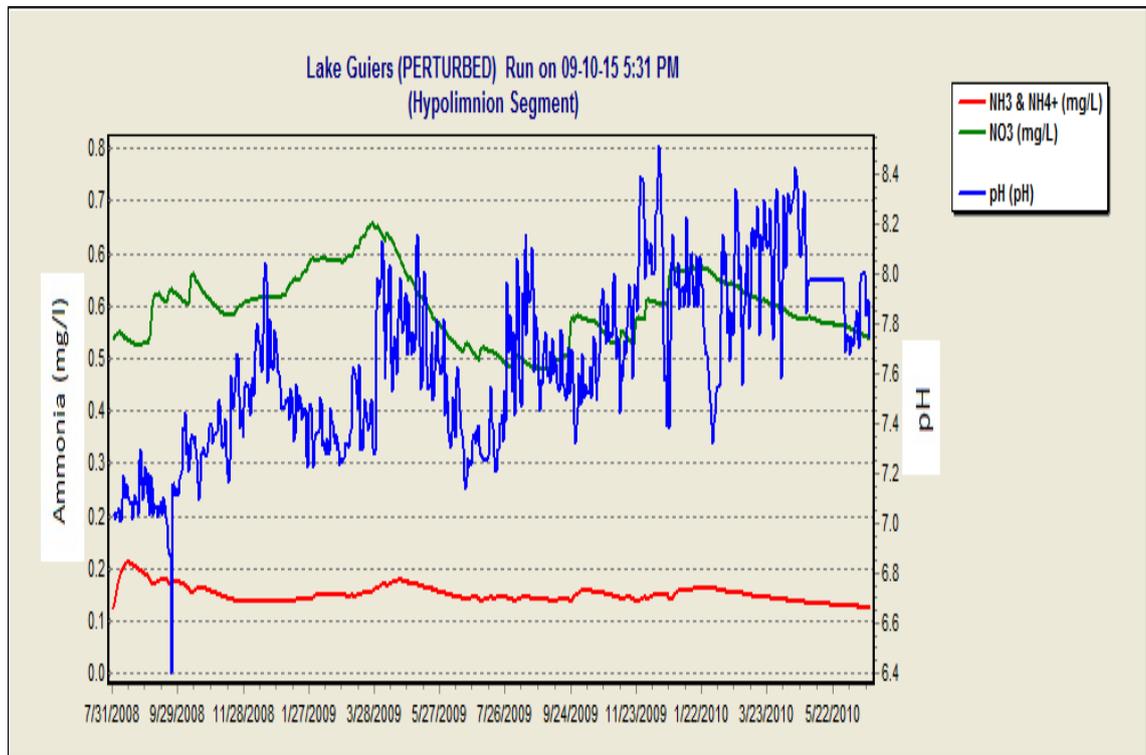
Figure 4.15: Evolution of ammonia with pH in Lake Guiers, 2008-2010.

4.6 Conclusion

Daily streamflow data of 35 years records and water quality data were investigated to determine Lake Guiers hydrologic alteration within its ecosystem. Comparison of pre and post-dams periods allow evaluation of their effects on hydrology and ecosystem. The results show that dams and sluices profoundly affect the hydrologic conditions in the Lake Guiers. They reduced high monthly variability of discharges, increased the range of daily discharges, altered the timing of high and low flows, and changed the timing of the yearly maximum and minimum flows.

Hydrologic features demonstrated obvious changes during the post-impact period. The flow magnitude was smaller and the frequency of low flow events decreased during all the year; and the maximum flows and minimum flows increased. The number of high flow events presented increasing trend. Annual median rate of change appeared as a decreasing trend. Base flow remains low both in pre and post

impact.

The trophic State Indices (TSIs) of nitrogen (N) and phosphorus (P) indicated respectively a eutrophic and hypereutrophic state.

These new features in hydrology regime resulting to in stream development lead to changes to the ecosystem. The flood plain ecosystems have been mostly affected. After 1986, Diama dam blocked seawater intrusion. The water into the Lake is now fresh year-round, creating ecological conditions favoring the proliferation of freshwater plant: *(Typhas australis, Pistia startioles, Salvinia molesta* and various alga species). Recent studies show that invasive plants currently occupy 7,458 ha in Lake Guiers. These are very invasive and eutrophication has begun at some places in the Lake. Downstream of the Diama dam, perturbations in the functioning of ecosystems takes the form of an increase in salinity and/or a drying-up during part of the year (Ndiael wetlands) due to the reduction of flooding or the destruction of water inflow channels during construction of hydrologic infrastructures (dikes, irrigated areas).

With the permanent standing freshwater, aquatic plants developed to excess and now prevent access to the water at some places. The *Typha australis* constitutes a refuge and a spawning area for fish. However, the abundance of vegetation also constitutes an obstacle for fishing. In addition, infrastructure installations represent obstacles for fish migration to spawning areas.

Lake Guiers's hydrological alteration endanger its ecological integrity. Each aquatic ecosystem requires a certain amount of water to maintain its ecological integrity. These environmental water requirements can be defined as the quantity and quality of water required to protect the structure, function, and species composition of that ecosystem. Therefore to ensure ecologically sustainable development, we propose the following recommendation: After an alteration in the flow regime, a hydrometric monitoring program should be implemented to provide a thorough assessment of the degree of alteration. This would include measurement of continuous discharge using a data recording frequency that adequately captures the pattern of flow in the altered flow regime

Continuous discharge measurements of inflows to the structure should also be estimated using back-calculations or measured directly. This will be particularly important where there are no upstream alterations, providing an indication of the natural variability in streamflow during the assessment period of interest.

We also encourage the implementation of best management practices on water resources and landscapes to reduce non-point sources of phosphorus transport in the Lake. Also we recommend that water resources manager work with municipalities to protect the lake shorelines and floodplains in order to better accommodate their natural processes as well as to improve resilience to flooding and to improve water quality. Finally water resources managers should increase public education and provide resources for local residents regarding impacts of fertilizer use on water quality and the benefits of vegetated buffers.

Trends and projections of climate change over the basin of Lake Guiers

This chapter presents the second result. It investigates past and future climate condition and compile and synthesize relevant climate information to managers and decision-makers as widely and expeditiously. It paints a coherent picture of the types of physical
changes that might be expected over the basin of Lake Guiers in near and far future.

Contents

5.1 Introduction

Most of the scientific community agrees that human-generated greenhouse gases are accumulating in the atmosphere and are causing significant changes in the global climate system during the last several decades [71].Climate models can provide useful insights into direction of future climate change. Such models allow us to predict basic air temperature and precipitation patterns on a broad, global scale [71], but they lack the spatial and temporal resolutions necessary to fully anticipate the effects of rising global temperatures associated with increasing greenhouse gas concentrations and to bridge the gap between climate change impacts on a global scale and local scale [72]. Climate simulations indicate that a warmer climate could result in a decrease in high-frequency temperature variability and in an increase in the proportion of precipitation occurring in extreme events [73]. Therefore understanding climate change demands attention to changes in climate variability and extremes. Thus, climate change detection and projection based on the analysis of extreme event indices are highly important when trying to provide information on observed and projected extremes and to prepare strategies to adapt to climate change. This detection type of study requires high-quality and long-term observed data which are not always available particularly in local scale. Finding reliable, practical information about climate trends and projections in the context of local environmental can be a challenge for natural resource managers , municipal and land-use planners in the context of Senegal. Thus, a detailed investigation of the behavior of extreme climate event indicators and the projections of futures climate condition will be tremendously useful. Even though information currently available from RCMs is inadequate (and highly variable) for most operational and design aspects of water management decisions. However, there are ways to use the relatively crude information (in terms of the specific needs of hydraulic structural design), under certain circumstances, to improve insights for longer-term watershed planning and vulnerability analysis[74].

5.2 Climate Extremes: Past and future Trends

5.2.1   Air temperature

5.2.1.1   Present and past Trends

The extreme event indices associated with maximum air temperature trends show significant augmentation but the minimum air temperature shows a slight negative trends in the basin of Lake Guiers. Thus, the DTR index, that represents the daily thermal amplitude, is rising i.e., the maximum air temperature increases at a rate higher than the minimum temperature. This index is statistically significant (0.05°C/ year).

The TMAX mean and TMIN mean indices that depict the annual average of the maximum and minimum daily air temperatures, respectively, are presented in (Table 5.1). A warming trend statistically significant in the current climate is noticed with TMAX mean (0.03°C /year) while TMIN mean shows a negative trend (-0.01°C/ year).

The TX90p (warm days), shown in (Figure 5.1), and TX10p (cold days) indices, that show the percentage of days in the year on which the maximum air temperature (TX) is, above the 90th (TX$\succ$35°C) percentile and below the 10 percentile (TX$\prec$20°C) show statistically significant trend. TX90p trend is 0.3 so every year, on average an additional 39% of days in the year are warm (1.5 more days per year) and hot (cold) days are becoming more (less) frequent, (-18%) days / year

Although the TN90p index (warm nights) and TN10p (cold nights) show trends of an increase respectively, based on observation, they are not statistically significant.

The WSDI indicator (heat waves), which represents the maximum number of consecutive days in the year when the maximum air temperature is above the 90th percentile, shows a statistically significant positive trend for basin of Lake Guiers (0.6 day/year). These heat waves tend to be more frequent and to last longer by the late 21st century, as stated [81].

Table 5.1: Definitions and magnitudes of the climate extremes indicators related to precipitation, maximum and minimum air temperature observed at basin of Lake Guiers.

Indices	Definition and unity	Slope	P-Value
TMAXmean	Annual mean of TX ($^\circ$C)	0.03	0.02
TMINmean	Annual mean of TN ($^\circ$C)	-0.01	0.4
SU25	Number of days with TX $\succ$ 25°C (days)	0.003	0.9
TR20	Annual count when TN(daily minimum)$\succ$20°C (days)	-0.6	0.3
TXx	Monthly maximum value of daily maximum temp($^\circ$C)	0.02	0.5
TXn	Monthly minimum value of daily maximum temp($^\circ$C)	0.07	0.3
TNx	Monthly maximum value of daily minimum temp($^\circ$C)	0.06	0.4
TNn	Monthly minimum value of daily minimum temp($^\circ$C)	-0.03	0.3
TX10p	Percentage of days with TX $\prec$ 10th percentile(%)	-0.1	0.03
TX90p	Percentage of days with TX $\succ$ 90th percentile(%)	0.3	0.01
TN10p	Percentage of days with TN $\prec$ 10th percentile(%)	0.2	0.1
TN90p	Percentage of days with TN $\succ$ 90th percentile(%)	0.03	0.8
WSDI	Number of days in the year with at least 6 consecutive days of TX $\succ$ 90th percentile (days)	0.6	0.005
CSDI	Annual count of days with at least 6 consecutive days when TN$\prec$10th percentile(days)	0.3	0.009
DTR	Mean of the difference between TX and TN ($^\circ$C)	0.05	0.04
RX1DAY	Annual max 1-day precipitation (mm)	1.5	0
RX5DAY	Annual max consecutive 5-day precipitation (mm)	2.8	0.001
R10MM	Annual count of days when PRCP$\succ$ =10mm (Days)	0.03	0.7
R20MM	Annual count of days when PRCP$\succ$ =20mm (Days))	0.1	0.05
R25MM	Annual count of days when RR$\succ$ or =25 mm (days)	0.1	0.005
CDD	Max number of consecutive dry days in the year (days)	-0.8	0.4
CWD	Max number of consecutive wet days in the year (days)	0.07	0.04
R95p	Annual total precipitation on the days when RR$\succ$95th (mm)	5.7	0.01
R99p	Annual total precipitation on the days when RR $\succ$ 99th (mm)	1.7	0.09
PRCPTOT	Annual total precipitation from wet days (mm)	6.1	0.008

P-values of up to 0.05 indicate statistical significance. RR is the daily rainfall rate. A wet day has RR$\succ$ 1 mm. A dry day has RR < 1mm. TX and TN are daily maximum and minimum air temperature respectively.
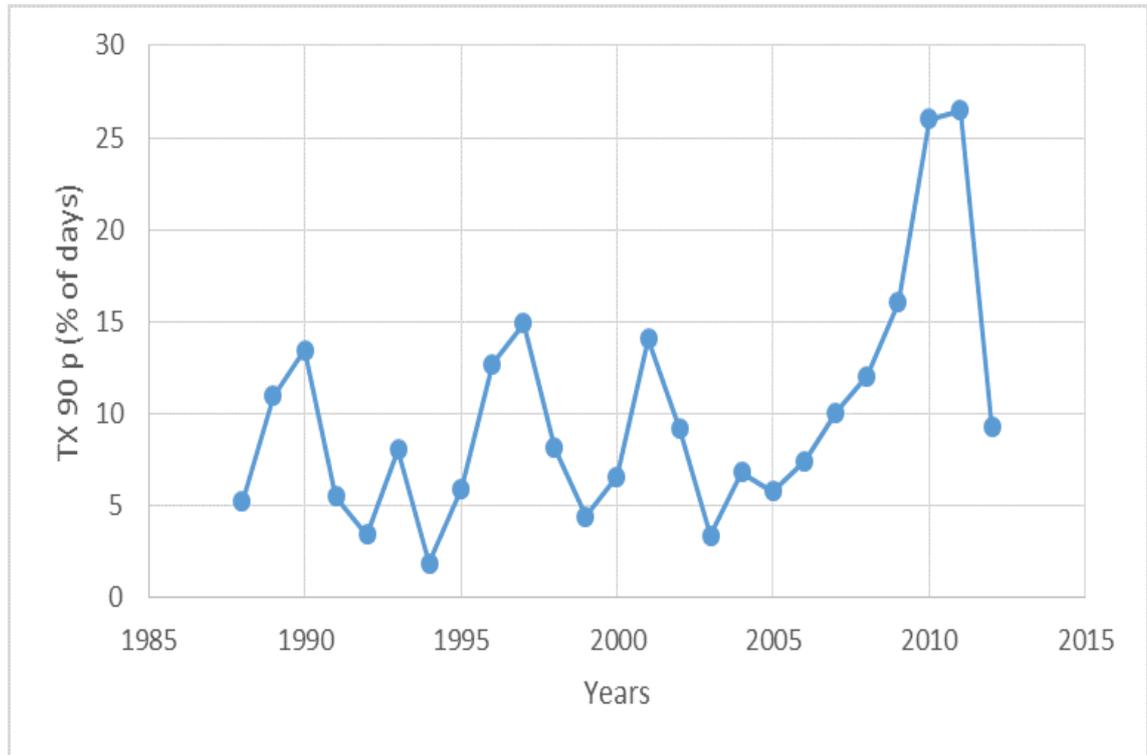
Figure 5.1: Temporal evolution of TX90p in a percentage of days per year, during 1988-2012, observed for basin of Lake Guiers.
P-Value=0.019.; Slope estimate=0.392; Slope error=0.156

5.2.1.2 Future projections

Considering projection, both RCPs scenarios 4.5 and 8.5 predicted a trend of rising annual mean temperatures throughout the rest of this century, although the magnitudes of change varied among models. Presumably, that unanimity in the basic prediction of future warming largely reflects the well-documented influence of rising greenhouse gas concentrations on global atmospheric temperatures. The Lake of Guiers basin experiences an increase of temperature of about 1.2°C and 3.1°C. respectively for RCP 4.5 and RPC 8.5. The hottest temperatures are, however, projected by the end of the twenty-first century where the GHG forcings are maximum. Although the Lake of Guiers basin temperature changes during the late twenty-first century are quite high 2.5°C and 5.3°C for RCP4.5 and RCP8.5, respectively). (Figure 5.2) show mean decadal temperature changes in Lake Guiers Basin in the near and far future.

The southeastern regions of Senegal appear to be more sensitive to global warming. These temperature changes substantially affect the future atmospheric water demand for the region. It is important however, to remember that all projections of future trends come with caveat that year to year fluctuations will also push temperatures well above or below [72]. In others words, changes from year to year will sometimes be more dramatic than long term trends.
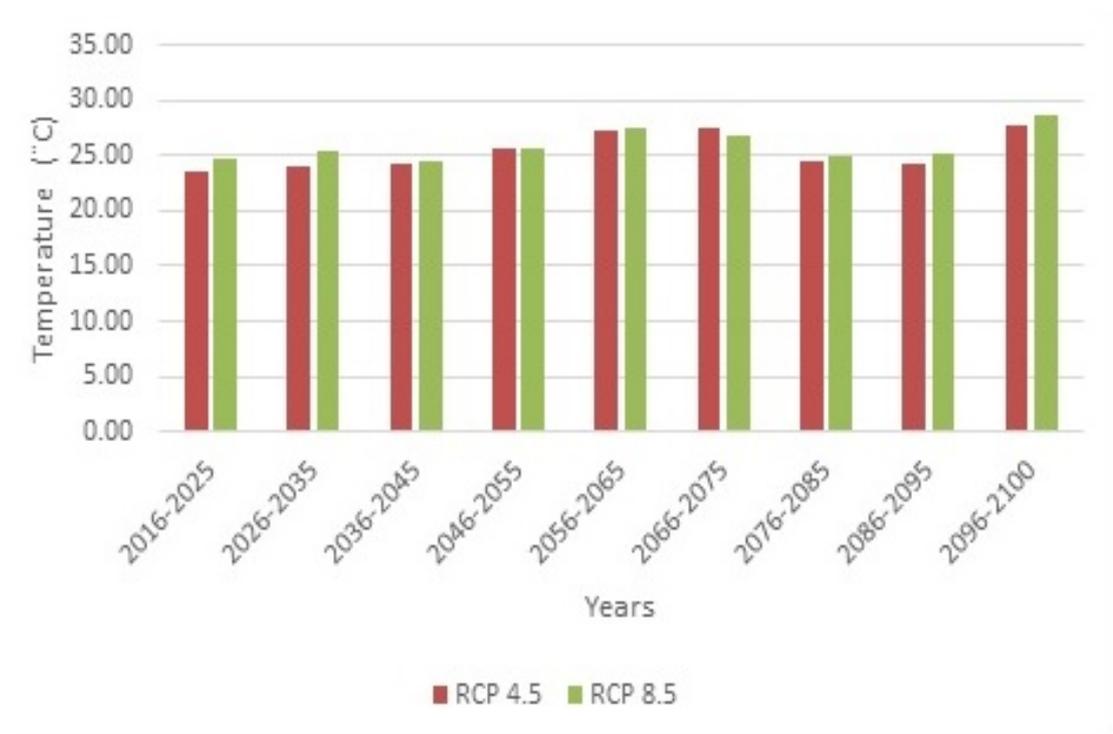
Figure 5.2: Mean decadal temperature changes in Lake Guiers Basin in the near and far future.

5.2.2 Rainfall

5.2.2.1 Present and past Trends

(Figure 5.3) features total annual rainfall from wet days (PRCPTOT) , (days when rainfall is greater than or equal to 1 mm) and the total annual rainfall of days when it is above the 95th percentile of wet days (R95p). Initially, a high inter annual

variability is noted in the observational data. There is an increasing PRCPTOT trend on a rate of +6.1 mm/year particularly since 2000s. This trend is statistically significant. These results agree with those obtained in Sahel zone by Nicholson (2005)[82] in which PRCPTOT decline between 1970 -2000 but get recovery slowly between 2000 and 2010. Also Figure 5.4 illustrates the same trends. It shows the SPI (Standardized Precipitation Index) per year since 1955 in the Lake Guiers catchment. A normal year is defined with an Index between -0.99 and 0.99, an Index $\succ$ or = 1 is classified as a wet year, while an Index of $\prec$ or = -1 is classified as a dry year. Since the 1970s, the region is affected by dry years, which reached its last maximum in 1983. The decade since 2000 is wetter than the decades before with a peak in 2010. However, the years since 2010 are normal years again. With regard to the precipitation, the climate varies with a tendency to extremes.
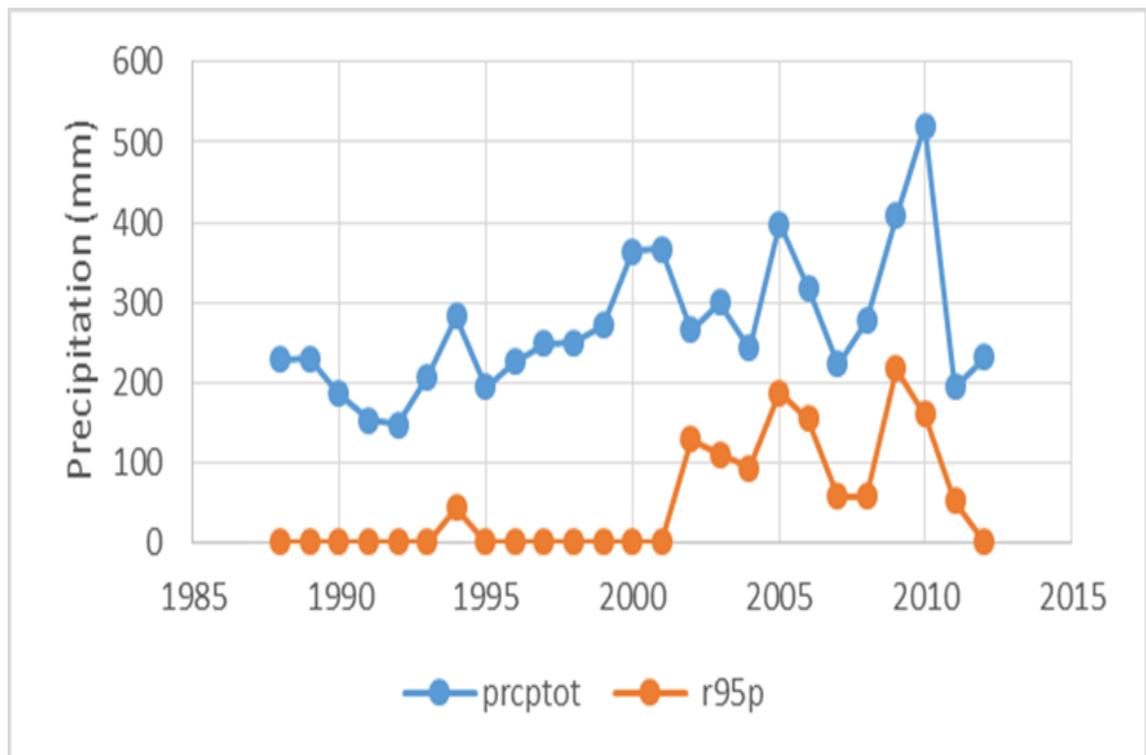
Figure 5.3: Temporal evolution of the PRCPTOT (blue line) and R95p (red line) indices, both in mm, during 1988-2012, observed for Lake Guiers.

The R95p index (Figure 5.2) shows a statistically significant increase (+5.7 mm/year). This implies that at basin of Lake Guiers either heavy rainfall events have become stronger, i.e., associated with a higher volume of rainfall each year, or they are

becoming more frequent, or both. The Annual total precipitation on the days when
RR $\succ$ 99th (R99p) index shows the same R95p behavior, i.e. positive (1.7mm/year).

The Annual max consecutive 5-day precipitation (RX5 day) and the Annual max
1-day precipitation (RX1day) indicators that show the accumulated maximum rain-
fall in 1 day and in 5 days, respectively, are rising (2.8 mm/ day) and (1.5 mm/day)
with statistical significance. In general, it is noted that the current rainfall climate
positive trends are more marked.

The Annual count of days when RR $\succ$ or $=$ 25 mm (days) (R25) mm indicator,
illustrating the number of days in the year on which the total daily rainfall was
above 25 mm, shows statistically significant positive trends (+0.1 day/year). This
confirms that moderate to heavy rain events are becoming more frequent every year.

The CDD and CWD indices that illustrate the maximum number of consecutive dry
and wet days, respectively, show negative trend (-0.8mm/day) and positive trend
(0.07 mm/day) in the basin.

Table 5.1 shows a summary of the trends observed for the climate extremes indicator
to rainfall, maximum air temperature and minimum air temperature that were
analyzed earlier. It is noted that trends are significant to air temperature and
precipitation, except TN10p and TN90p. Besides, inter-annual variability of climate
is higher for precipitation than for temperature.

5.2.2.2   Future projections

Precipitation is extremely variable in space and time, and future precipitation pat-
terns are therefore more difficult to model and predict than temperature. Figure 5.5
shows precipitation changes for the two periods and for both scenarios. Areas that
are blue are projected to increase, and areas that are yellow to red are projected
to decrease. By mid-century projections reveal, a slight increase ranging between
5 and 48% in precipitation in Lake of Guiers area. In RCP4.5, this increase occurs
in the northern and central parts of the basin. In RCP8.5, the southern region of
the basin undergo precipitation decrease of up to 10%.
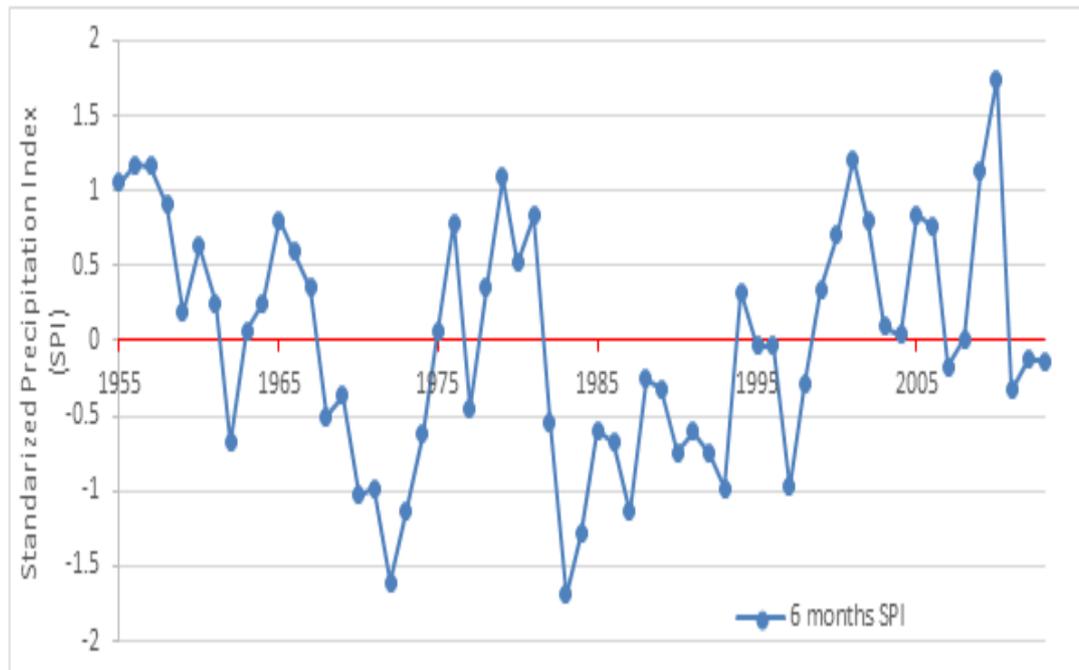
Figure 5.4: Six months SPI in the basin of Lake Guiers.

However, by the end of the century, Lake Guiers basin, experiences precipitation decreases for both scenarios. In RCP4.5, precipitation decrease are smallest (less than 10%) but in RCP4.8, they are largest (more than 25%) and this decrease occurs all over the country. This is a result of stronger long-term GHG forcing.

In Lake Guiers basin, results show that climate change causes increased precipitation in the near future and decreases in the late century indicating that during the 2050s, the natural variability is predominant (Figure 5.6) , while in the 2090s when the GHG forcing is highest, anthropogenic climate change prevails.

5.2.3   Potential evapotranspiration (ETpot)

5.2.3.1   Present and past Trends

A further important factor is, especially in the Sahel with high temperatures and less precipitation, the loss of water through evaporation. Temperatures in basin of Lake Guiers are high during the whole year and register strong winds and low air
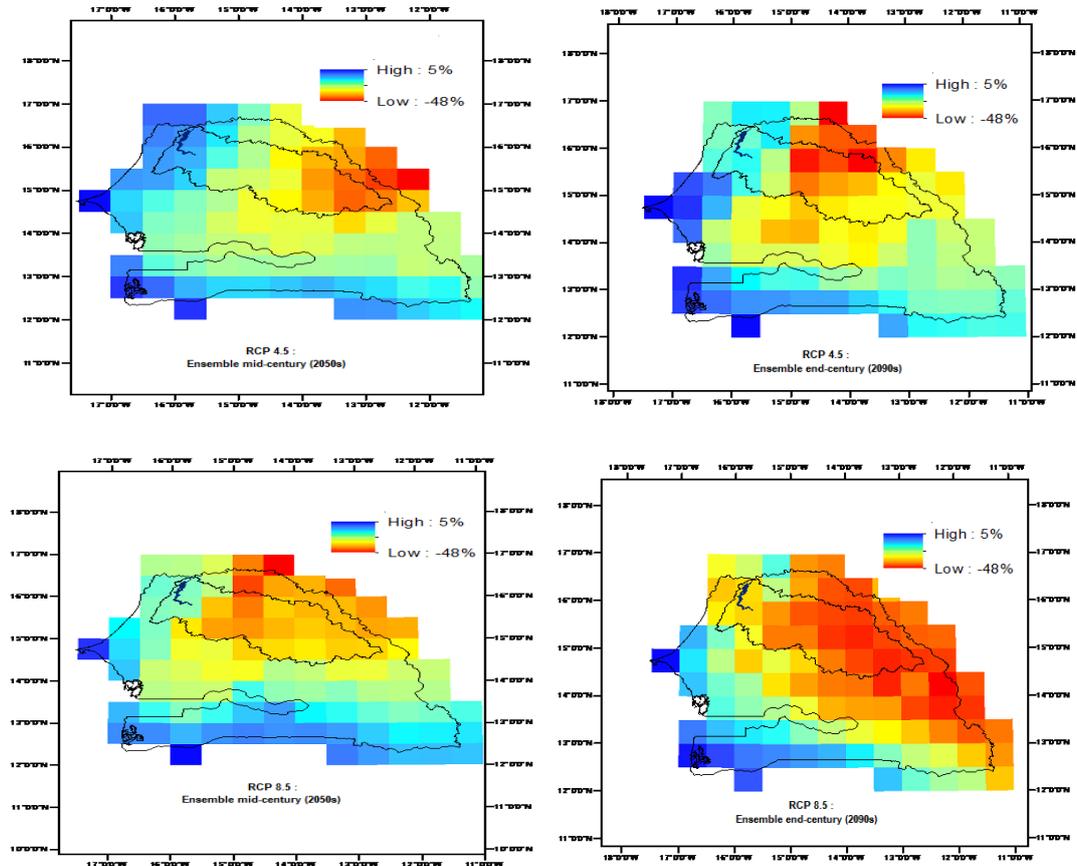
Figure 5.5: Changes in annual mean precipitation for mid century (2050s, upper panels) and for end century (2090s lower panels) and for both RCP 4.5 (left panels) and RCP 8.5 (right panels).

humidity. These atmospheric variables contribute for high evaporative rates.

(Table 5.2) show potential evapotranspiration in Lake Guiers from 1988 to 2011 calculated using FAO Penman Monteith method and Hamon method. The results of both methods show significant difference in ETpot. This Difference is likely due to the change in ETpot model from Penman Monteith (PM) to Hamon.
Correctly determining potential evapotranspiration is a problem in most hydrological models. For i.e a comparison of the Priestley-Taylor and Penman-Monteith methods for calculating ETpot with the SWAT model revealed differences of 15%. Even for the Penman-Monteith method, ETpot can differ significantly depending
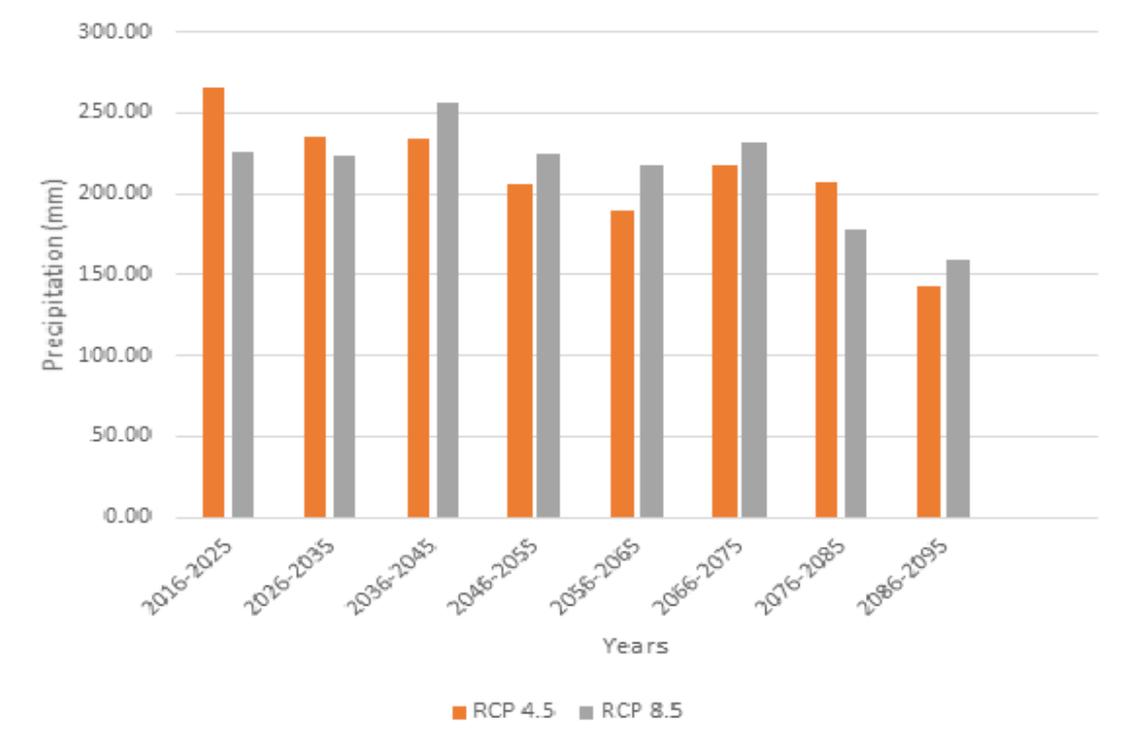
Figure 5.6: Mean decadal precipitation changes in Lake Guiers Basin in the near (2050s) and far future (2090s).

on the chosen reference crop. To avoid this, a Correction Factor was calculated. The amount of water lost to the atmosphere through evapotranspiration is estimated to be 5.7 mm/day (2102 mm/year).

5.2.4   Climatic water balance

Climatic water balance characterizes the concurrent availability of energy and water for biota and is represented here by climatic water deficit. Deficit (DEFF), a proxy for drought, represents the unmet atmospheric demand components of the climatic water balance.

(Table5.3) shows the monthly and annual climatic water balance (1988-2011) in Lake Guiers Basin. The annual estimated deficit remain high (1781 mm/year).

Table 5.2: Monthly ETpot (mm)/day(1988-2011), Lake Guiers, Senegal.

Months	ETpot Penman Monteith	ETpot Hamon	Correction Factor (CF)	ETpot Ajusted
Jan	7.4	2.6	2.75	4.6
Feb	6.8	3.6	1.8	4.9
March	9.4	5.2	1.7	7.6
April	9.0	8.8	1.0	7.9
May	8.1	11.3	0.7	7.4
June	6.4	11.2	0.5	5.8
July	5.3	10.2	0.5	4.7
Aug	4.9	8.5	0.5	4.3
Sep	6.3	8.3	0.7	5.5
Oct	7.4	6.8	1.0	6.3
Nov	6.7	4.2	1.6	5.1
Dec	6.7	2.6	2.5	4.2
Total	7.0	6.9	-	5.7

This deficit is more marked during the months of March and April (236.8mm and 239.7mm respectively).Warmer temperatures, combined with increases in wind and decreases in humidity, increase potential evapotranspiration (2102.4 mm/year) over the Basin.

5.2.4.1 Future projections

The changes in evapotranspiration (Table 5.4) essentially follow those from the mean precipitation and soil moisture with more evapotranspiration during the near future and generalized decrease in the late twenty-first century as a result of combined water availability (precipitation and soil moisture) and temperature increases.

By the end of the century ETpot is projected to increase, as compared to ETpot (1988-2011) baseline, up to 2538.80 mm/year under the RCP 4.5 scenario and 2916.82 mm/year under RCP 8.5 scenario. However by mid-century potential evaporation as compared to the (1988-2011) baseline ETpot is projected to decrease

Table 5.3: Monthly and annual climatic water balance (1988-2011), Lake Guiers Basin, Senegal.

Months	TEM	UET	ETo	PRCPTr	DIFF	DEF
Jan	25	231.5	145	1	-144	144
Feb	26.7	197.4	142.6	2	-140.6	140.6
March	28.7	292.3	236.8	0	-236.8	236.8
April	29.7	270.3	239.7	0	-239.7	239.7
May	30.9	252.6	230.3	1	-229.3	229.3
June	31.7	192.6	175.5	11	-164.5	164.5
July	31.2	164.3	148.18	53	-95.1	95.1
Aug	31.1	152.8	134.8	121	-13.8	13.8
Sep	31.6	189	166.5	103	-63.5	63.5
Oct	31.6	229.7	195.9	26	-169.9	169.9
Nov	29.1	202.8	155.1	1	-154.1	154.1
Dec	25.4	209.8	131.7	2	-129.7	129.7
Total	-	2585.4	2102.4	321	-	1781.4

TEM: is the average monthly temperature (°C/month)
UET: is the estimated, unadjusted potential evapotranspiration (mm/month)
ETo: is the estimated, adjusted potential evapotranspiration (mm/month).
PRCPT: is the average monthly total precipitation (mm/month).
DIFF: (PRCPT - ETo) is the rainfall and minus the adjusted potential evapotranspiration (mm/month).
DEF: (ETo - PRCPT) is the estimated deficit or unmet atmospheric demand for moisture (mm/month).

reaching up 2020.88 mm/year under the RCP 4.5 scenario and 2052.55mm/year under RCP 8.5 scenario, until 2030.

Table 5.4: Future climatic water balance (mm/year) based on RCP 4.5 and RCP 8.5 scenario in Lake Guiers Basin, Senegal.

Years	RCP 4.5			RCP 8.5		
	ET	PRCPT	ΔV	ET(mm/y)	PRCPT	ΔV
2030	2 020.8	414.4	1 606.4	2052.5	283.2	1769.3
2040	2305.9	203.7	2102.2	2441.2	111.7	2329.4
2050	2168.9	276.2	1892.7	2449.5	120.4	2329.1
2060	2356.9	61.8	2295.1	2366	381.7	1984.3
2070	2386.1	192.7	2193.4	2240.2	633.3	1606.9
2080	24484	280.9	2167.5	2524.8	189	2335.7
2090	2352.2	206.1	2146.1	2910.6	251.6	2658.9
2100	2538.8	125.7	2413	2916.8	102.5	2814.2

5.3 Climate change in the Basin of Lake Guiers

In terms of precipitations, we detect an increasing PRCPTOT trend particularly since 2000s. Heavy rainfall events have become stronger, i.e., associated with a higher volume of rainfall each year, or they are becoming more frequent, or both. Does this mean we are at the start of the recovery period?

It is impossible to answer this question using statistical method, especially trend detection methods. Interpretation of detected linear trends requires long time series data set especially when you are dealing with climate variability 83]. Or, the period covered by the observations is still too short to resolve the question of whether there is now a trend towards wetter conditions. Nicholson (2005)[82] found that there has been some "recovery" in western part of Sahel with respect to the very dry conditions that prevailed during the 30 years 1968-97. However, the recovery was generally weaker in August (which is generally the wettest month) than during the season as a whole.

The model simulations presented in this study allow us to estimate the range of annual-scale warming in the basin of Lake Guiers that is most reasonable to expect and prepare for. Warming is most likely to occur in the basin of the Lake guiers particulary during the dry season. During these months,(particulary March, April and May), the region is strongly influenced by air masses that move down from Saharan region (Mauritania) where warming rates generally exceed the global average. The basin of Lake Guiers might therefore be exposed to this.

A further important factor is, especially in the Sahel with high temperatures combined with increase in wind and decrease in humidity will have significant impacts on ptential evaporation rates into the Lake Such arguments, however, are only tentative. And when considering future climatic changes on a local scale it is wiser to anticipate a likely range of possibilities than focus too heavily upon a single anticipated outcome. It is important, however, to remember changes from year to year will sometimes be more dramatic than long term trends.

Climatic "extremes" are also expected to become more common as the world warms [81] , but this does not necessarily mean that every aspect of variability will increase

in Lake Guiers Basin.

Model simulations of precipitation changes for the Sahelian regions are strongly divergent and most models fail to reproduce realistic inter annual and inter decadal rainfall variability in the Sahel in 20th century simulations [84]. Our understanding of the processes causing tropical rainfall is insufficient to allow a prediction of the direction of change with any certainty. The IPCC identify this as an area requiring further research to understand the variety of model responses in this region [85]. This kind of problem is typical of many such models which owing to their relatively coarse spatial resolution (order of a few hundred kilometers), are often not suitable for simulating detailed regional weather and climate patterns [86] Thus a Regional Climate Model (RCM) driven by different AOGCMs is perhaps the most significant current requirement from a hydrological perspective in the climate community [74].

RCMs have relatively finer spatial resolution than GCM, 0.5 degree grid of spatial resolution, is still very large as compared to the area of the basin of Lake Guiers. Furthermore, some RCMs fail to simulate climate features on or near Lake Surface.

5.4   Conclusion

Combining past observed trends with RCM simulations of future climate enables us to paint a coherent picture of the types of physical changes that might be expected across the region over the coming century. Temperature rise will affect the water balance by enhancing potential evapotranspiration in the Basin. This effect will be more severe when combined with the decrease of precipitation. In general, the future climate of Lake Guiers Basin seems to be exposed to more severe conditions and water availability will be under much greater stress.

Water availability and demand in Lake Guiers

This chapter presents the third result. It investigates Lake Guiers response under climate change and socio economic development projects planned..

Contents

6.1 Introduction

In the last decades, in particular since the 1970s, the Lake Guiers region was subject to several changes. These changes concern socio-economic factors like population growth and increased agro-industrial farming as well as hydrological changes in the Senegal River basin. The entire Senegal River basin suffers decreasing water supply and water quality [88]). The Senegal River Development Organization (OMVS) declares on the basis of the transboundary environmental analysis sixteen priority environmental problems. At first place,it is the surface water availability, followed by groundwater availability and water quality. Considering climate change, the water supply of the Senegal River will decrease and therefore will challenge the region and the management institutions. It will concern the population in the Lake Guiers region, the agricultural industry, the population of Dakar and all projects that are planned in the future on the basis of sufficient water supply.

6.2 Actual strategies to satisfy water demand - the sector of water supply in Senegal

6.2.1 Current situation of water supply and demand in Senegal

Water supply in Senegal is characterized by a relatively high level of access compared to the average of Sub-Saharan Africa. According to a report of WHO/U-NICEF/JMP in 2015; 79% of Senegalese population had access to an improved water source (compared to an average of 61% for Sub-Saharan Africa. However, there is a significant gap between urban areas (93%) access and rural areas (67%).

6.2.1.1 Urban water supply

Since 1996, the responsibility for urban water supply is shared between the Senegalese national water company (SONES), a holding company, and (SDE), a private operating company. SDE does not own the water system but manages it through affermage contract with the Senegalese government. As shown in (Figure 6.1) ,

the urban water supply sector is governed by four different contracts between three actors.
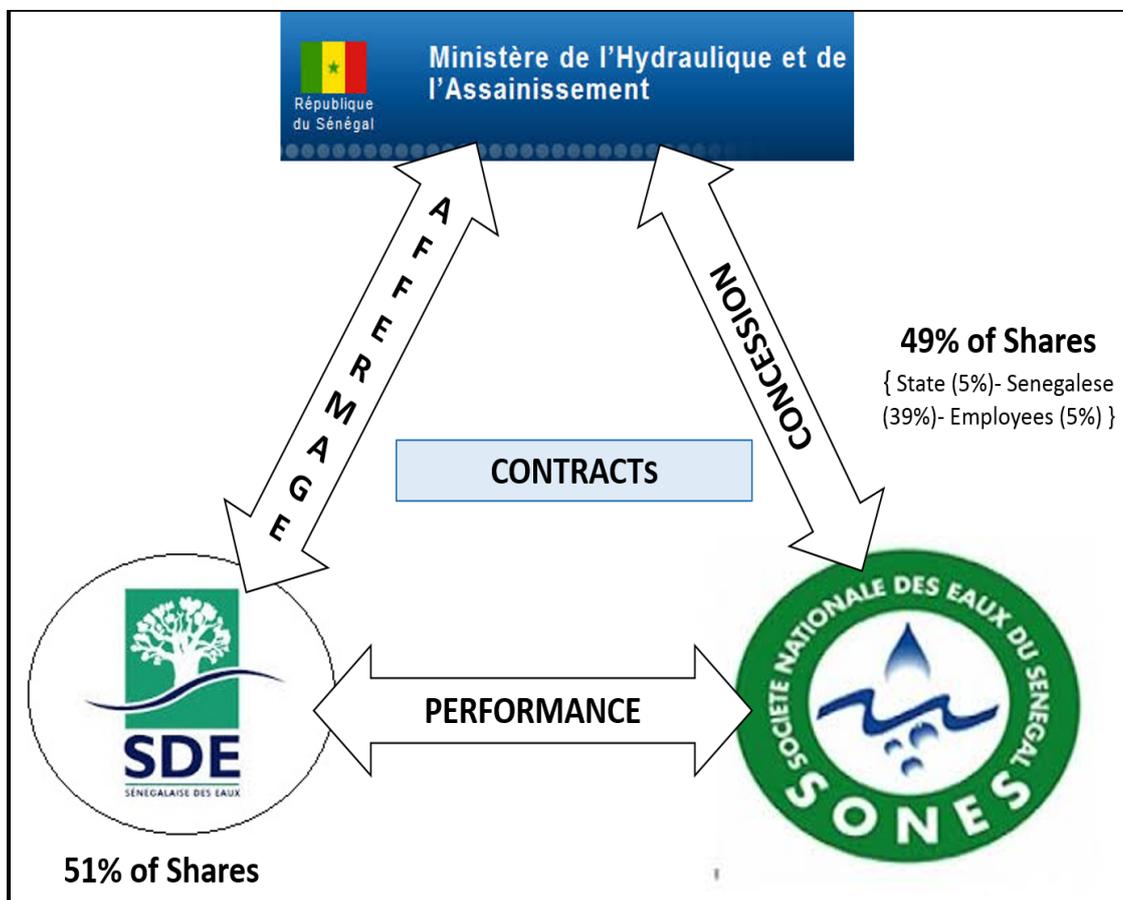
Figure 6.1: Contractual Framework for urban water supply in Senegal.

SONES has in charge assets and investments in urban centers that have been contracted out as well as in the villages located near Lake Guiers water distribution pipeline. The concession contract for SONES runs until 2026.

SDE is responsible for operating the public water service in urban centers that have been contracted out. It is linked to the state through a lease contract and to SONES through a performance contract.

The SONES and SDE come under the supervision of the Ministry of Hydraulic. Initially, the French water company SAUR owned a 51% share in SDE, the remaining

49% being divided between the Senegalese state (5%), private Senegalese individuals (39%) and the employees (5%). Since July 2015, SAUR was not listed any more as a shareholder on the website of SDE. its shares are held by the West African infrastructure holding company FINAGESTION, which in turn is majority-owned by the US-based, Africa-focused private equity fund Emerging Capital Partners.

6.2.1.2 Rural water supply

Faced with widespread difficulties in maintaining supply drinking water systems in rural areas, the Senegalese government launched in early 1997 a large-scale programme to reform the management of boreholes (REGEFOR).

This reform aimed at improving the management of motorised supply drinking water systems in rural areas and transferring it from the state to the associations of borehole users (ASUFORs), created by the reform programme. It aimed also to consolidate the water service in rural areas by separating the function of representative of the users to the function of borehole exploitation.

The reform has introduced the sale of water per volume (and not anymore per fixed price) by installing meters at every distribution point. The objective is that users buy the water at a price fixed by the general assembly of the ASUFOR which includes the costs of production, maintenance and renewal of the equipment.

Every ASUFOR has a current account supplied with the receipts of exploitation of the borehole. It also has a savings account qualified as sinking and repair fund periodically fed by transfers from the current account. The aim of the depreciation account is to guarantee the supply of amounts necessary for the renewal of pump equipment and the payment of service providers.

The reform has given satisfactory results, in particular concerning the organization and responsibilisation of the population through the ASUFORs, the sale of water per volume, the creation of savings to ensure the renewal of pump equipment and the contractualisation with the local private sector by means of management and maintenance agreements.

At the end of 2000, just before the start of the new millennium, the member states of the United Nations signed the Millennium Declaration, which leads to the definition of eight Millennium Development Goals (MDGs). The seventh MDG "ensure environmental sustainability" is reached inter alia by the following target: "Reduce by half, before 2015, the proportion of people without sustainable access to safe drinking water."

The millennium programme for drinking water and sanitation (PEPAM) of the Senegalese government aims, within the framework of the MDGs, to increase the rate of access of rural households to drinking water from 64% in 2004 to 82% in 2015 by ensuring a sustainable access to drinking water for 2, 3 million additional people in rural areas. PEPAM, launched in 2005, is a national programme framework based on the principle that only the sum of efforts of the State, the civil society, the local collectivities, the NGOs, the private sector and the partners of development will allow the achievement of the MDGs.

6.2.2 Current problems of the water supply sector

The issue of water in Senegal does not arise in terms of global quantity but in terms of availability and or quality of the resources. Indeed, these resources are badly distributed, because too far away from the big centres of consumption and the poles of development, or are not easy to mobilize to satisfy the drinking water demand of the populations, the industries and the other users. The multiple water uses (industries, agriculture, drinking water production) lead to persisting tensions in the use of the Lake. Major environmental risks press on the resource (the eutrophication of the Lake entailing the impovement of the fauna and the flora, the pollution of the lake by the discharges of food-processing industries of the zone, the importance of evaporation with an accumulation of salts, the proliferation of aquatic plants).

Since the reform process began, the volume of water produced per day at Ngnith and Keur Momar Sarr water treatment plant for use in the urban centers has risen in each year, from 64,000 m^3 /day in 1983 to 194,000 m^3/day in 2015 while the demand was 320,000 m^3/day [87].

The resulting deficit led to 16 hours of service per day on average, and intermittent supply had a detrimental effect on quality due to infiltration of soil water into the pipes during periods of negative pressure. Water losses from leakage and illegal connections were estimated to 27% of the production in Dakar. Drinking water quality in many cities was poor, with fecal streptococcus and coliforms present at the end of the distribution system, and no chlorine. Public agencies were responsible for much of the losses and wastage in the system as they did not pay their bills. The bulk of Dakar's poor did not have access to affordable water. Some boreholes in Dakar region are already polluted by market garden activities and they run the risk of being over-exploited and contaminated by salt water intrusion.

6.3 Water balance

WEAP allows manifold analyses of the results including demand, supply and resources, catchment, water quality, and financial analysis. According to the input data only demand as well as supply and resources results are analyzed in this study (Fig.6.2). The demand results comprise demand requirements and allocations with reports on water demand, supply requirement, supply delivered, unmet demand and coverage/reliability. While the water demand presents the actual demand of a site, the supply requirement adds the demand site losses showing the amount of water required to meet the water demand.

The supply delivered gives detailed information about the amount and source of water delivered to each demand site. The delivered amount can differ from the amount required based on restrictions in the model and therefore result in unmet demand. The fraction of unmet demand can be viewed in the coverage/reliability report. Supply and resources reports show results from inflows (river headflows, surface water inflows, groundwater recharge) and outflows of an area.

The results presented by WEAP are based on a monthly water mass balance calculation for each node and link of the system. Therefore the results can be viewed independently for each supply or demand site on different time scales. Furthermore, depending on the detail of the input data the results can be analyzed on different spatial scales.
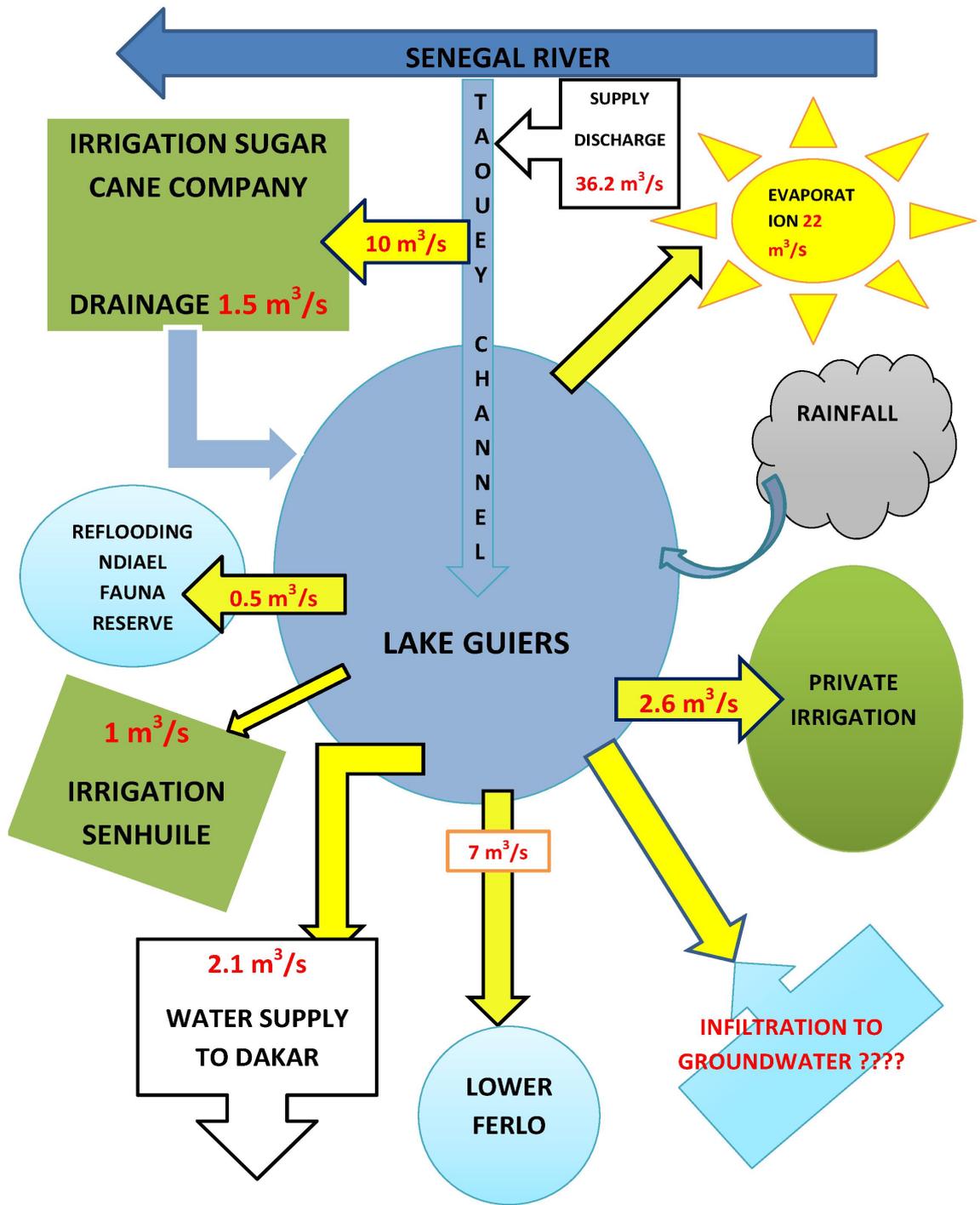
Figure 6.2: Water balance in Lake Guiers

6.3.1   Water supply

The water balance for Lake Guiers reservoir has been calculated for the period of 2006 to 2030 with 2005 as the basis year. The climate projections follow the two RCP 4.5 and the RCP 8.5 scenarios from the latest IPCC. These different assumptions result in typical precipitation patterns for each climate scenario. As shown in Figure 6.3 based on CORDEX data, a decrease in precipitation is observed for RCP 4.5 climate scenarios, while a slight decrease and increase through decadal mean precipitation is observed.

Figure 6.3: Comparison of CORDEX decadal mean precipitation forecast in mm/year for the basin of Lake Guiers; climate scenario RCP4.5 and RCP8.5

With climate change dry years with less precipitation and accompanied higher netto-evaporation rates will occur. It was examined how climate change and the growth of projects will affect the Stream flow in the Taoué Canal and finally how the inflow to Lake Guiers has to be adjusted. The modeled stream flow in Taoué Canal

into Lake Guiers show a distinct variation throughout the year representing the influence of Senegal River. Furthermore Figure 6.4 illustrates the distinct increase in inflow from 2006 - 2030 in both scenario RCP 4.5 and RCP 8.5 compare to current account year. The increasing differences between the two combined scenarios are very slight.
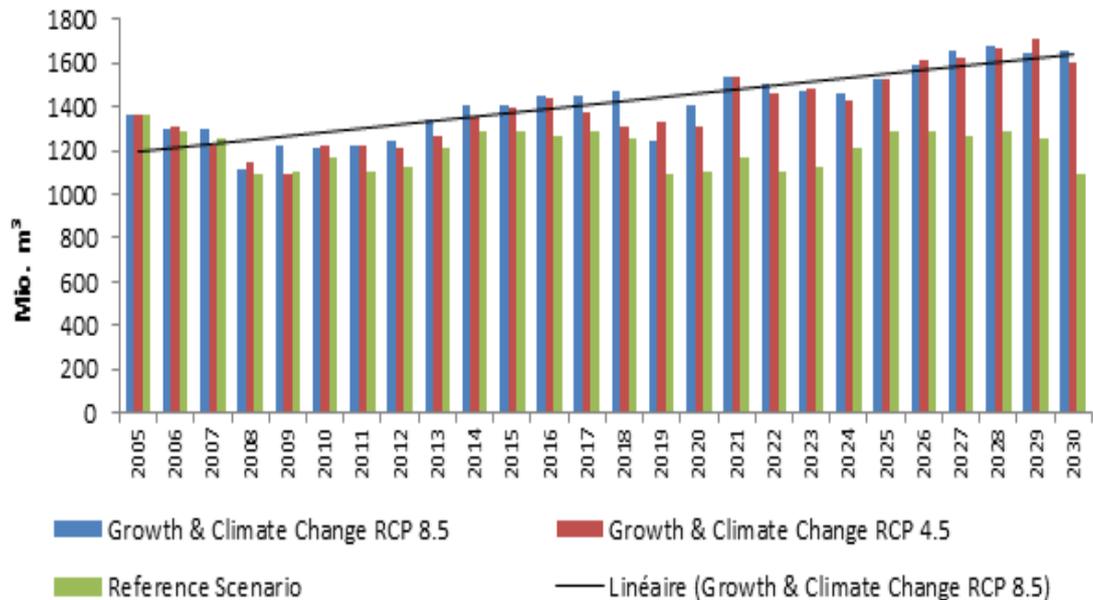
Figure 6.4: Annual stream flow in Taoué Canal under RCP8.5 or RCP4.5 scenarios.

Considering monthly stream flow in the period 2006 to 2030 the differences between the months are illustrated Figure 6.5. The deviation between the combined scenarios and the reference is the highest in August. Apart from the values for May and July the scenarios RCP 8.5 and RCP 4.5 are hardly noticeable. It can be inferred that a development followed the RCP 4.5 which assumes stabilization will cause an increased stream flow volume in the Canal. With regard to the climatic character-

istics of dry and rainy season (August to October) the inflow will increase even in
the rainy season. It might be the consequence of increasing evaporation rates.

Furthermore it was tested which influence demand sites and netto evaporation val-
ues have on the stream flow. Comparing the annual fluctuation of netto evaporation
and the stream flow volume it can be deduced that they correlate albeit the volume
is located on a higher level. The annual variation is hence caused by the evap-
oration. The monthly view in (Figure 6.5) strengthens the argument that higher
evaporation leads to an increasing inflow also in August. Since the other factor that
can influence the stream flow is the demand, the tendency of increasing volume can
be explained by the increasing water demand of the consumers.

6.3.2   Reservoir

The results show that the available amount of water in the reservoir is potentially
high enough to satisfy users demand . It was tested, in case of a limitation of
inflow (4,177,274.8 m^3/day)from the Senegal River, how long the water stored in
the reservoir (655,616,099.3 m^3) will be sufficient when all projects are implemented.

Figure 6.6 shows the reservoir storage development after stopping the inflow in
2015 for the two scenarios. The results reveal the speed of the running out in the
reservoir. The water supplied by the reservoir will not suffice for more than twenty
months in RCP 4.5 scenario and nineteen months in RCP 8.5. These changes in
water volume are due to a high rate of evaporation and pumping rates for irrigation
and supply drinking water for urban centres.

6.3.3   Water demand and supply requirement

The domestic water demand as well as the irrigation demand account for most of
the current and future demand site type. Figure 6.7 highlight the effects of the
different scenarios on water demand by users.

The water demand for irrigation between RCP 4.5 and RCP 8.5 scanario are very
small. Results show that CSS water demand is the highest. In 2005, it was estimate
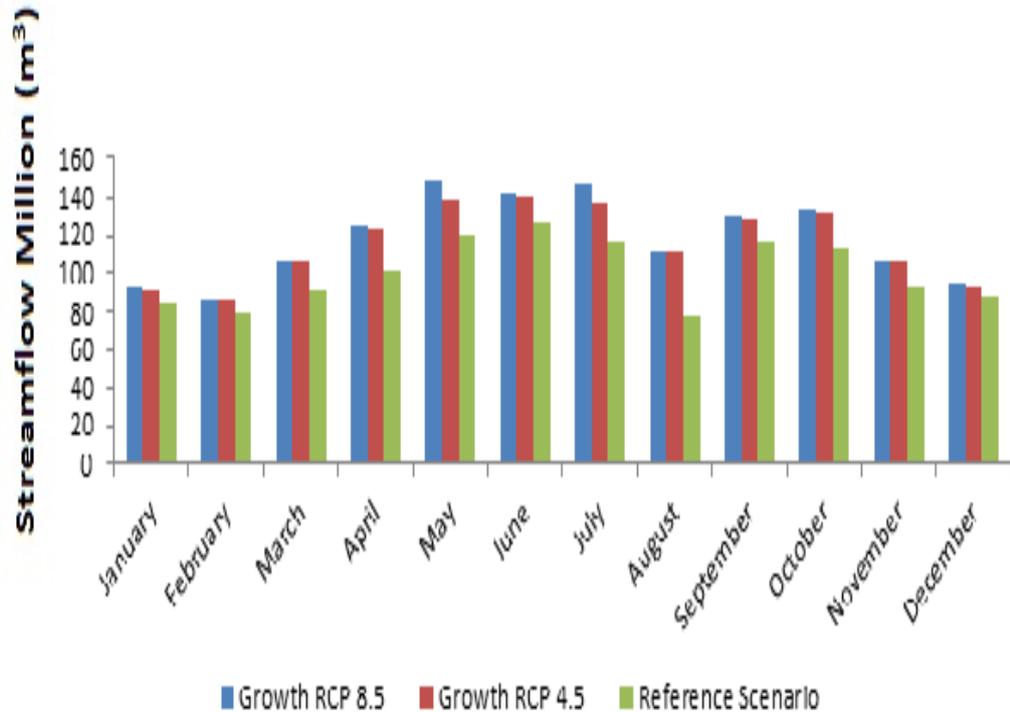
Figure 6.5: Monthly stream flow (2005-2030) in Taoué Canal under RCP 8.5 and RCP 4.5 scenarios.

to 175 millions m^3 and by 2030 the demand will increase up to 25% in total.

Futhemore Senhuile, the second big agro-industrial units and private irrigation (others agro-industrial units) will face an increasing water demand by 2030. It was estimated that their demand will increase up to 20%.

With the monthly variation in agriculture demand due to crops type, the water demand reveals a variation throughout the year. Demand is highest from April to June during the dry season and decrease with the start of rainy season.

For domestic demand the water demand in Dakar was estimate to 70,810,000 m^3 in
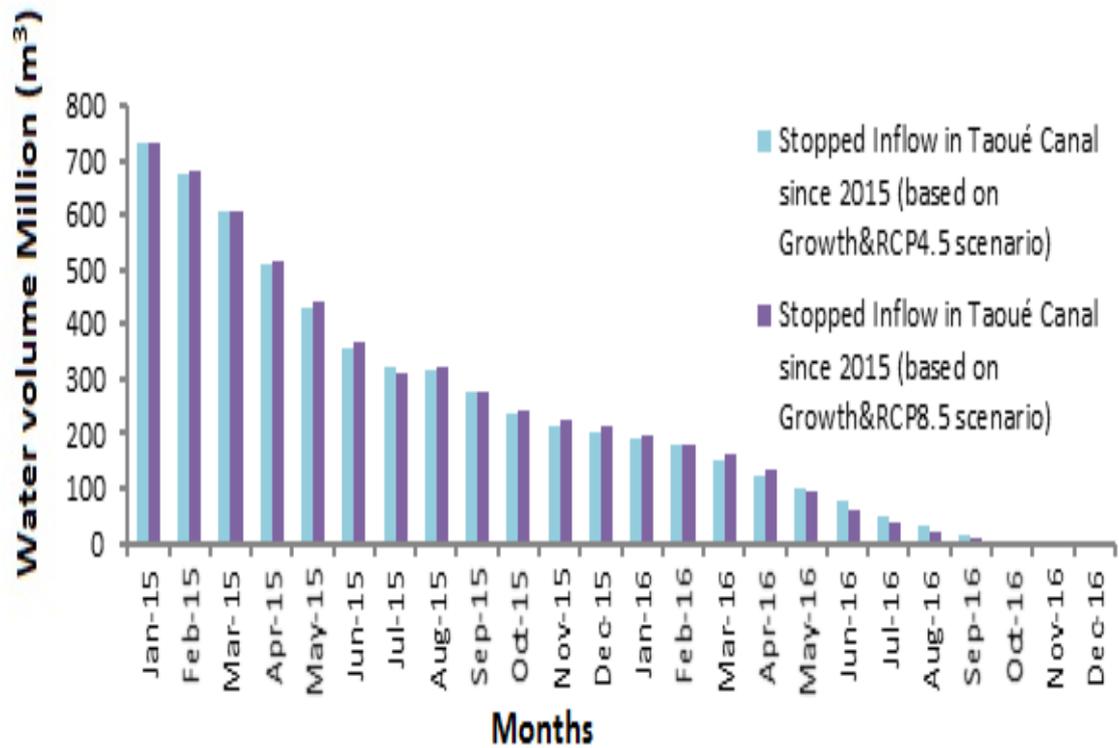
Figure 6.6: Storage Volume in Lake Guiers with stopped inflow beginning in January 2015, combined scenarios of growth and climate change RCP 4.5 and RCP 8.5.

2005(Figure 1.1). This demand will increase up to 116,800,000 m^3 /year by 2030.

6.3.4   Unmet demand

While the available amount of water in the reservoir is potentially high enough to satisfy the demand, users experience shortages.The observed annual changes in water availability as well as water demand also have an effect on the distribution of unmet demand throughout the year. Unmet demand is found in all scenarios, however, its amounts vary. Figure 6.8 shows the total unmet demands under RCP 8.5 scenario The results reveal that some demand sites will suffer unmet demand
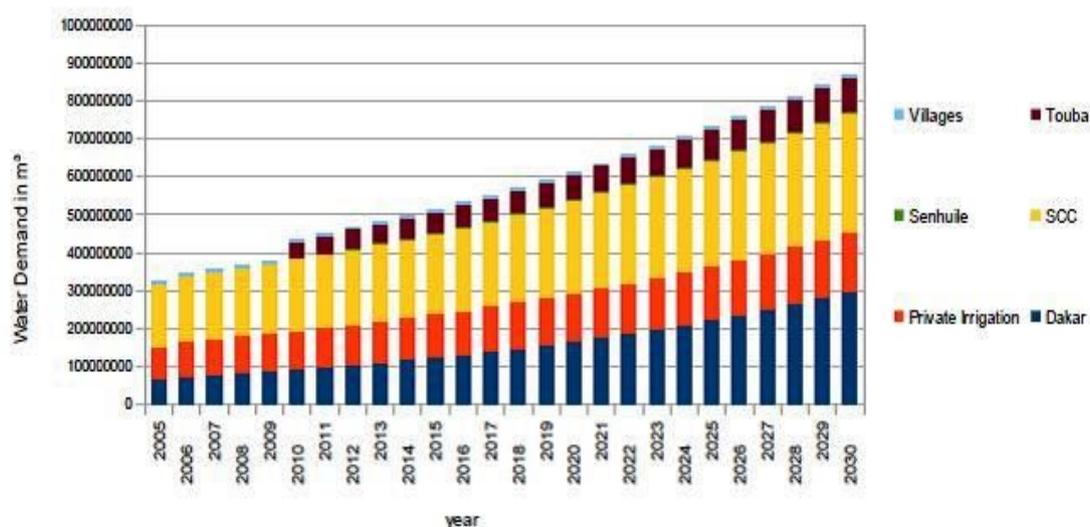
Figure 6.7: Total water demand per user type in m^3

due to their dependency of Taouey canal wich in turn depend on the inflow from Senegal River.

For the period of usual inflow, it was found that Ndiael, implemented in WEAP by a diversion will face unmet demand. The same unmet demand applies to the Sugar Cane Company which is supplied partially by Taouey channel. The results indicate unmet demand neither for the period of usual inflow nor in the testing period of the reservoir. The Lower Ferlo region has been observed by a flow requirement tool in WEAP. Figure 6.9) gives an insight into its reliability that means the percentage the water supply can be met is given out.

In order to focus on climate change and the limitation by a stopped inflow, four scenarios have been chosen. The climate change scenario in itself not either the combined scenarios do have an effect on the supply for the region. However, the stopped inflow will shorten the reliability by 40%. A test with limited discharge in the Taoué Canal revealed that the reliability would be restricted to 88.5% in climate change scenarios and 84.3% for the combination with growth rates (Figure 6.9).
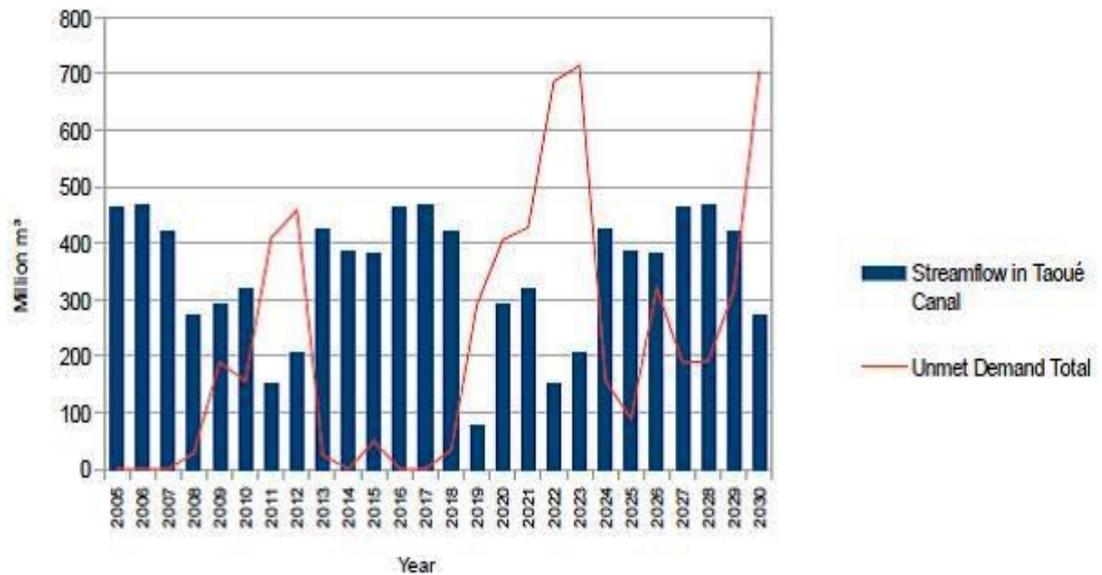
Figure 6.8: Annual stream flow in Touey canal and Total Unmet demand.

6.3.5 Summary of the water balance results

The water balance results show that a slight difference between the two scenarios. However, they have strong impacts on water availability. It has been observed an increasing trend in inflow from 2006 to 2030 in both scenario RCP4.5 and RCP8.5. This might be attributed to a better supply from Senegal River. Considering observed discharge measured at Bakel, a survey station upstream in Senegal River(Figure 6.10), the water volume during the last years varied in amount as well as in time. Up to 2010 the time span of the peak discharge during rainy season diminished. It indicates an up going variation and the need to strengthen the resilience of the region. Furthermore, the detailed view on the reservoir reveals that the pressure on reservoir water increases. However, the reservoir capacities are sufficient in meeting future increased demand (implementation of projects) only if the inflow in Taouey canal is maintained.

The results show also that the water supplied by the reservoir will not suffice for more than twenty months in RCP4.5 scenario and nineteen months in RCP8.5 if the inflow via Taouy canal is stopped. The water demand of the different demand site types is increasing throughout the study period and in all of the applied scenar-
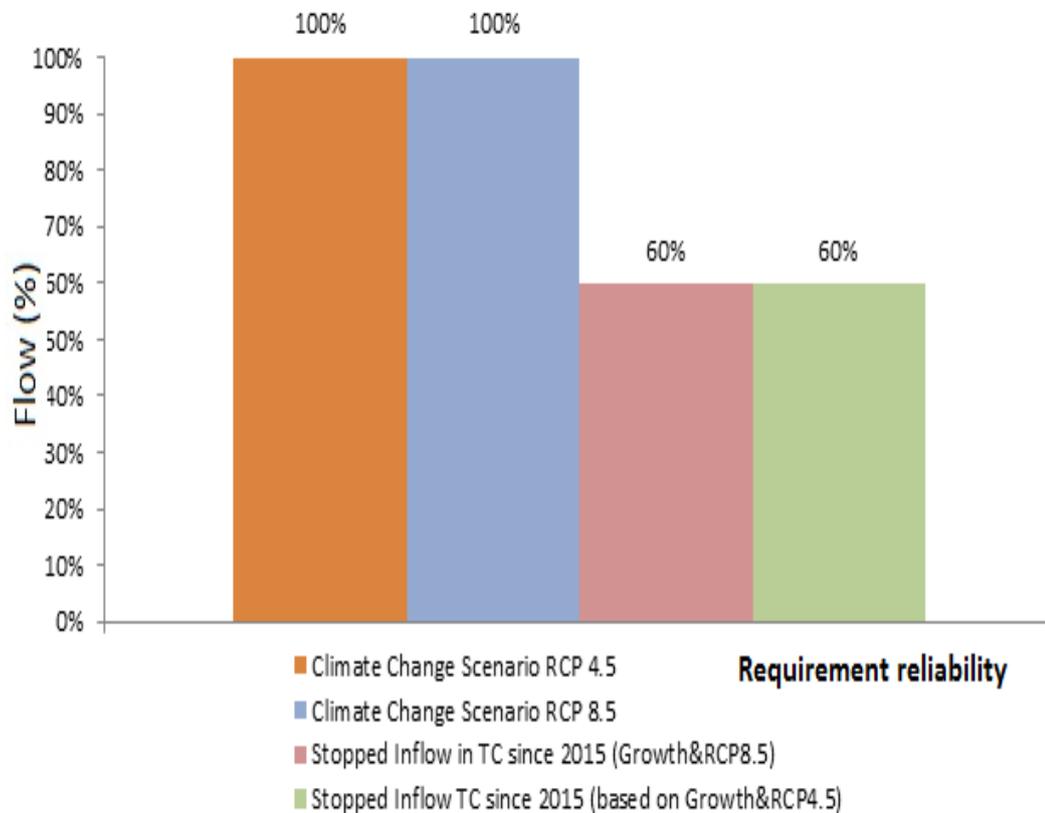
Figure 6.9: Flow requirement reliability in the Lower Ferlo region.

ios. Hereby, RCP8.5 shows the highest growth rates. Water demand particularly increases for the domestic demand sites and the irrigation sites. Another important user of water is Ndiael fauna reserve implemented as a diversion.

However, water use by villages living around the Lake is rather small showing the lowest water use rates. According to the effects of the climate scenarios, water scarcity is highest in the study period. This becomes visible from increase in unmet demand in the period of 2015 to 2030, especially amongst demand sites relying on water from Taouey canal or Lake Guiers reservoirs. As the availability of the reservoir follows a monthly variation due to the rate of evaporation and pumping for irrigation and supply drinking water urban centres, the shortages solely occur during the dry season. Peaks of unmet demand occur from April to June. This
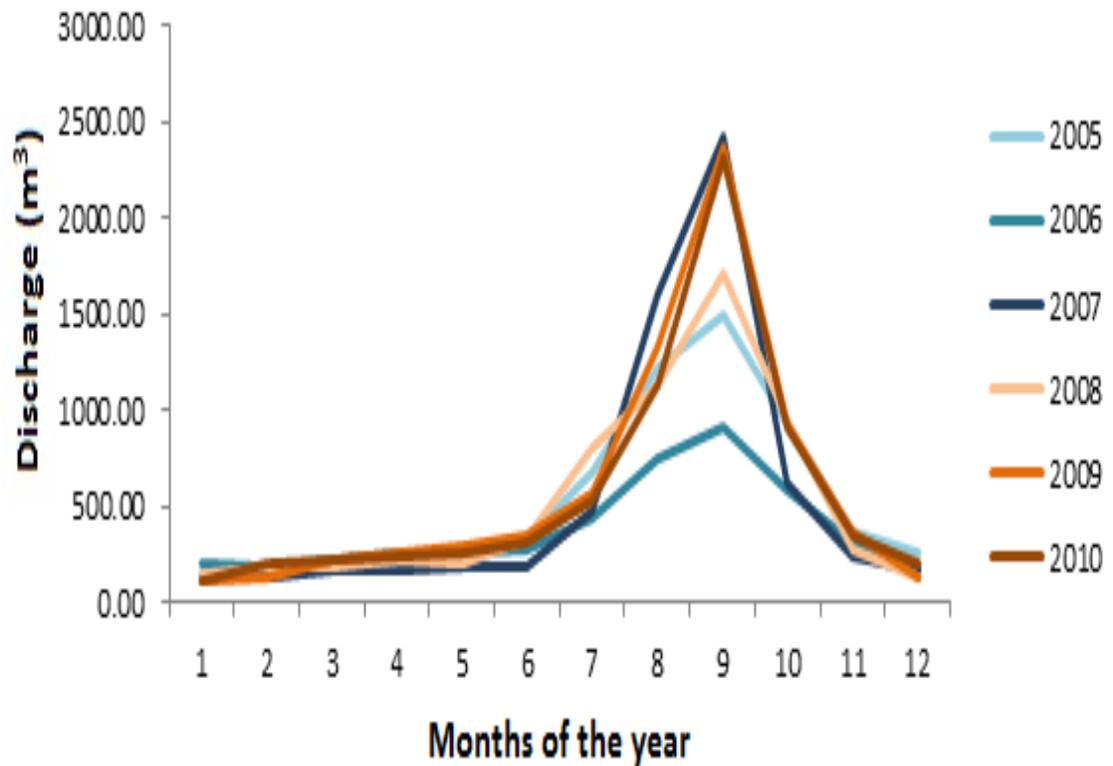
Figure 6.10: Observed discharge in Bakel 2005-2010

phenomenon is also a result of climate change affecting the reservoir.

6.4 Discussion on the water balance results

6.4.1 WEAP model uncertainties and constraints

WEAP is a water mass balance algorithm designed to support water resources manager and planner for IWRM [90]. Like most of modeling tools, WEAP requires a large number of input data. Therefore ,it faces uncertainties and constraints. One of the limits of the model is that it has not a quality assurance module [91]. Therefore, the challenge for a user applying WEAP model is to identify errors and

to judge of the model results accuracy. Information on uncertainties and constraints in model results is a key issue that should be given to policy makers before to deduce recommendation for future water resources management.

6.4.2 Data input uncertainities

Data input uncertainties and constraints apply to both water supply and water demand data. The CORDEX data (spatial resolution 0.25°; rasta data) has been used for simulating evapotranspiration. The modeled demand might be underestimated as we don't take account to ground water data, livestock watering, industrial water demand, due to the lack of data availability. However, to represent a reliable and realistic demand, literature has been carefully reviewed.

6.5 Conclusion

The water balance results of WEAP imply that the water supply security highly depends on supply from Touey canal, which in turn depends on Senegal River. The available amount of water volume in the Lake is potentially high enough to satisfy the demand, however,some water users experience shortages. These shortages occur in both climate scenarios with the decreasing of Taouey canal inflows.

Water availability and water supply situation could be ensured and achieved by using different management methods. A stronger development of reservoir water availability includes measures such as increasing reservoir capacities to meet growing domestic demand and demand for irrigation. Therefore the inflow from upstream would be sufficient to fill the reservoir. Taouey canal should be therefore adjusted in order to mitigate or anticipate unmet demand. In addition to increasing the reservoir capacities, other efficiency measurements should be applied: Adopt a basin approach, taking into account the adjacent ecosystems. This option incorporates the development of the lake's former outlets, to enable free water circulation, thereby preventing the growth of aquatic plants and improving water quality. Another efficiency measure is to establish water laws and allocations. This option imply water pricing and other market-based incentives to motivate further improvements in water use efficiency in agriculture dominated by private agro-industrial unit. Water

evaporation mitigation is also another efficiency measure that could be used. Reducing the amount of water lost to evaporation would improve water security for Lake Guiers and lead to increased irrigation production. Substantial research and commercial testing on practical methods to reduce evaporation in a reservoir were completed recently [92] [93]. These methods use new technologies. Some of these new technologies are cost-efficient solution to reduce evaporation each year and to maintain the highest quality drinking water.

Such measures especially gain importance when bearing in mind that the inflow into the Lake decreases due to climate change and that the water demand increases due to population growth and a change in water demand patterns.

General Conclusion

CONCLUDING REMARKS

The goal of this study was to provide reliable and practical information about water availability and demand under the patterns of recent and future of population growth and climatic change in the basin of Lake Guiers, and to use these information to stimulate further research, informed planning, and adaptive management that can help residents of the basin to adapt and/or mitigate to future changes.

Results has shown that the basin of Lake Guiers has a long and varied environmental history that include rainfall deficit, warmer temperatures, floods and drought. Significant climatic changes are already under way in the Basin.

Increasing temperature and potentially dryer conditions during the rest of this century will affect Lake Guiers water resources significantly. However, climate is not the only factor to consider in predicting future change in Lake Guiers. How people influence the resource and the landscape will be at least as important.

The development of water demand and supplies in Lake Guiers depends on a large number of factors such as socio-economic developments, population growth, infrastructure improvements, impact from climate change or the quality of water management on a local, regional and countrywide scale. The scenario analysis with WEAP reveal potential conflicts about water shortage. These shortages occur in both climate scenarios RCP 4.5 and RCP 8.5 with the decreasing of Taouey canal inflows.

DEDUCTION OF RECOMMANDATIONS TO ASSURE WATER SUPPLY SECURITY

How water resources manager and land-use planners prepare for and respond to changes in population growth and climate change will help to mitigate or anticipate futures impacts?

As we seek to understand the likely balance between water inputs and outputs specific to Lake Guiers and its tributaries in a warmer, potentially dryer future,

comprehensive hydrological modeling and monitoring in the basin will become more important than ever.

Rigorous monitoring of the physical conditions in local hydrologic systems, in particular, will be needed to provide early warnings of change as well as baseline information with which to support future management decisions, especially in light of the limitations of local-scale and seasonal climate model projections. Besides these general statements, following are more specific recommendations for research and data needs and for management, planning and policy strategies.

An improvement of input data for different areas such as industrial demand, irrigation demand and domestic demand would also be valuable achievements. For water resources manager we encourage the implementation of the six necessary components of any effectives management response(Appendix B 2) on water resources and landscapes to reduce non-point sources of phosphorus transport in the Lake. Also we recommend that water resources manager work with municipalities to protect the lake shorelines and floodplains in order to better accommodate their natural processes as well as to improve resilience to flooding and to improve water quality.

Finally water resources managers should increase public education and provide resources for local residents regarding impacts of fertilizer use on water quality and the benefits of vegetated buffers.

Therefore the statement refers to the recommendation to integrate the results in a Driving forces-Pressure-State-Impact-Response Framework (DPSIR) as an analyzing tool. It offers the possibility to unite aspects of water quality and supply in a single management approach.

While IWRM is becoming increasingly accepted as an appropriate framework for managing water resources in river basin, it is essential that Lake Guiers's managers applied its principles (Appendix B 1) recommanded at the Third World Lake Forum in 2003 for an effective management response.

PERSPECTIVES (Further studies)

Water quality in Lake Guiers require further observations. Even though WEAP offers water quality modeling, this study could not include this aspect due to a lack of reliable data. As discussed in section 4.5 eutrophication and salinization are already a serious problem in Lake Guiers. Therefore studies on water quality modeling would benefit to water resources managers to know how climate change will affect Lake Guiers water quality and how to prepare and response.

Furthermore WEAP allows groundwater modeling using either MODFLOW or the integrated groundwater surface water model. However, both methods were not applied in this study because of the lack of information on groundwater. Therefore a major research on dynamical relationship between Lake Guiers and aquifers is needed to track either the ground water supply the lake or the lake supply ground water.

The study already paid attention to administrative levels and scales by disaggregating the demand on commune level. While this approach allows statements down to commune level, additional recommendations or analysis on specific hotspots within these scales are not feasible. It would be the task of further studies to analyze the situation on a more local scale and to identify problems and developments in the reservoir.

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Appendix

A.1   Streamflow characteristics, indicators, and assessment criteria

Methods to calculate hydrologic indicators and assessment criteria for flow regimes described in Chapter 3 are provided below.Given hydrological data are typically neither independent nor normally distributed and often contain extreme values, non-parametric statistics have been selected to characterise the central tendency (indicators) and variability (assessment criteria) in the data. In (**Figure** A.1), measures of dispersion around the median are shown as percent exceedances a common convention used by hydrologists when analysing flow duration curves (FDCs).

The percent exceedance is obtained by subtracting the percentile scale value from 100 percent. For example, a discharge at the 75 percent exceedance is the same as a discharge at the 25th percentile (100-25=75). In keeping with this convention, percent exceedance will be used to describe values associated with a flow duration curve while percentiles will used to describe all other data. (**Figure** A.1) also shows the associated levels of alteration with increasing distance from the median. The values demarcating the boundaries between the alteration levels have been rounded to simplify assessment criteria calculations.

In some cases, indicators and assessment criteria will be calculated using preliminary assessments, primarily desk-top methods, and refined, or in some cases replaced, with field-based assessments when such data can be collected. Most indicator metrics and assessment criteria can be obtained using the Streamflow Analysis and Assessment Software (SAAS) (http://people.trentu.ca/rmetcalfe/SAAS.html) to analyse either an altered or natural reference streamflow time series.
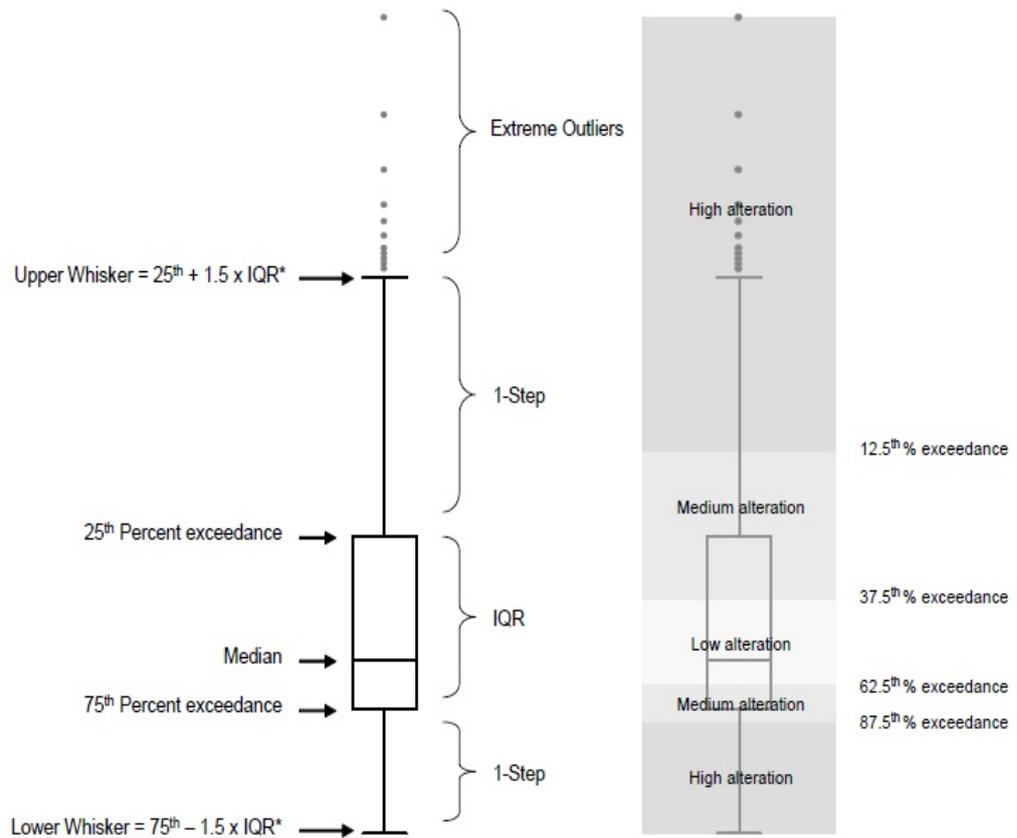
Figure A.1: Anatomy of a box plot and how it is used to assess alteration. *M*easures of dispersion around the median are shown as percent exceedances, a common convention in hydrology when analysing flow duration curves (FDCs).(Metcalfe et al,2013)

A.1.1 Baseflow

A.1.0.1   Description

Streamflow is maintained by a combination of surface runoff and baseflow components. Baseflow is defined as the streamflow portion contributed by persistent, slowly varying sources (i.e. groundwater, lakes, wetlands) between precipitation

events. Temporally variable baseflow conditions in rivers are important for maintaining ecosystem function. Baseflow provides a relatively stable supply of high quality water, relatively constant in temperature, which is important to stream biota that have become adapted to the timing and quantity of these inputs. The role of baseflow in maintaining streamflow between episodic flow events has resulted in it being considered an important 'ecological reserve' flow .

The magnitude of baseflow relative to total streamflow is often used to characterise the relative importance of contributions from these sources. These contributions define a river's baseflow regime, and are influenced by a number of natural factors including the rate, frequency, and amount of groundwater recharge and discharge, soil characteristics, topography, hydrogeology and hydraulic characteristics of aquifers, evapotranspiration rates, area of surface water storage, and climatic variability.

A.1.0.2 Indicators

Baseflow indicators include the monthly median baseflow (m3 sec-1). This indicator is calculated using the median of all daily or hourly baseflow values for each month for the period of record (e.g. the median baseflow of all Januaries in the period of record, etc.). The median baseflow is the most appropriate measure because it is less influenced by extreme events (i.e. high and low baseflows) and therefore, better represents typical streamflow conditions. Summarising the data on a monthly time-scale is sufficient to characterise the annual variability in baseflow. The ecological importance of intra-annual variation in baseflow would be dampened considerably if baseflow values were aggregated by seasons and its importance eliminated entirely if only an annual value was estimated.

A.1.0.3 Information requirements

Calculation of baseflow indicators for the reference condition requires a baseflow time series extracted from a natural flow simulation at the site of the flow alteration.If the initial reference condition time series was improved using streamflow monitoring from the site, the baseflow separation and calculation of assessment criteria indicator values should be repeated.

A.1.0.4   Assessment criteria

Assessment criteria for baseflow indicators include the monthly baseflow values associated with the the 13th, 38th, 62nd, and 87th percent exceedances, calculated using the reference condition baseflow time series (**Figure** A.2).

A.1.0.5   Evaluating alteration

The degree of alteration in individual indicators can be evaluated as follows:

Low alteration : A monthly median baseflow indicator that lies between the 38th and the 62nd percent exceedance baseflow for the reference condition.

Medium alteration: A monthly median baseflow indicator that lies between the 13th and 38th or 62nd and 87th percent exceedance baseflow for the reference condition.

High alteration:A monthly median baseflow indicator less than the 13th or greater than the 87th percent exceedance baseflow for the reference condition.

Total baseflow alteration should be evaluated by assessing the suite of monthly indicators together. For instance, low alteration would be associated with monthly indicator values distributed equally above and below the median monthly baseflow in 'average' flow years, biased toward the 62nd percent exceedance in 'dryer' years and toward the 38thpercent exceedance in 'wetter' years. Thus, monthly indicator values that lie between the 38th and the 62nd percent exceedance baseflow of the reference condition but constantly in the lower range (i.e. close to the 62nd percent exceedance) might warrant an adjustment from low to medium alteration. Transitions from one monthly baseflow magnitude to the next should avoid rapid changes that may harm biota (e.g. stranding of fish).

A.1.0.6   Methods

To determine the flow magnitudes associated with the baseflow indicators and assessment criteria, the 13th, 38th, 62nd, and 87th percent exceedance values are calculated for each month of the period of record. That is, for twenty years of a simulated flow regime a baseflow separation is performed and used to calculate the daily baseflow magnitudes that are then aggregated into their respective months

(e.g all daily values for each January for 20 years = 620 values) and a single period-of-record baseflow duration curve produced for each of the 12 months of the year. Values for indicators and assessment criteria are obtained from the baseflow duration curve for each month (**Figure** A.2).
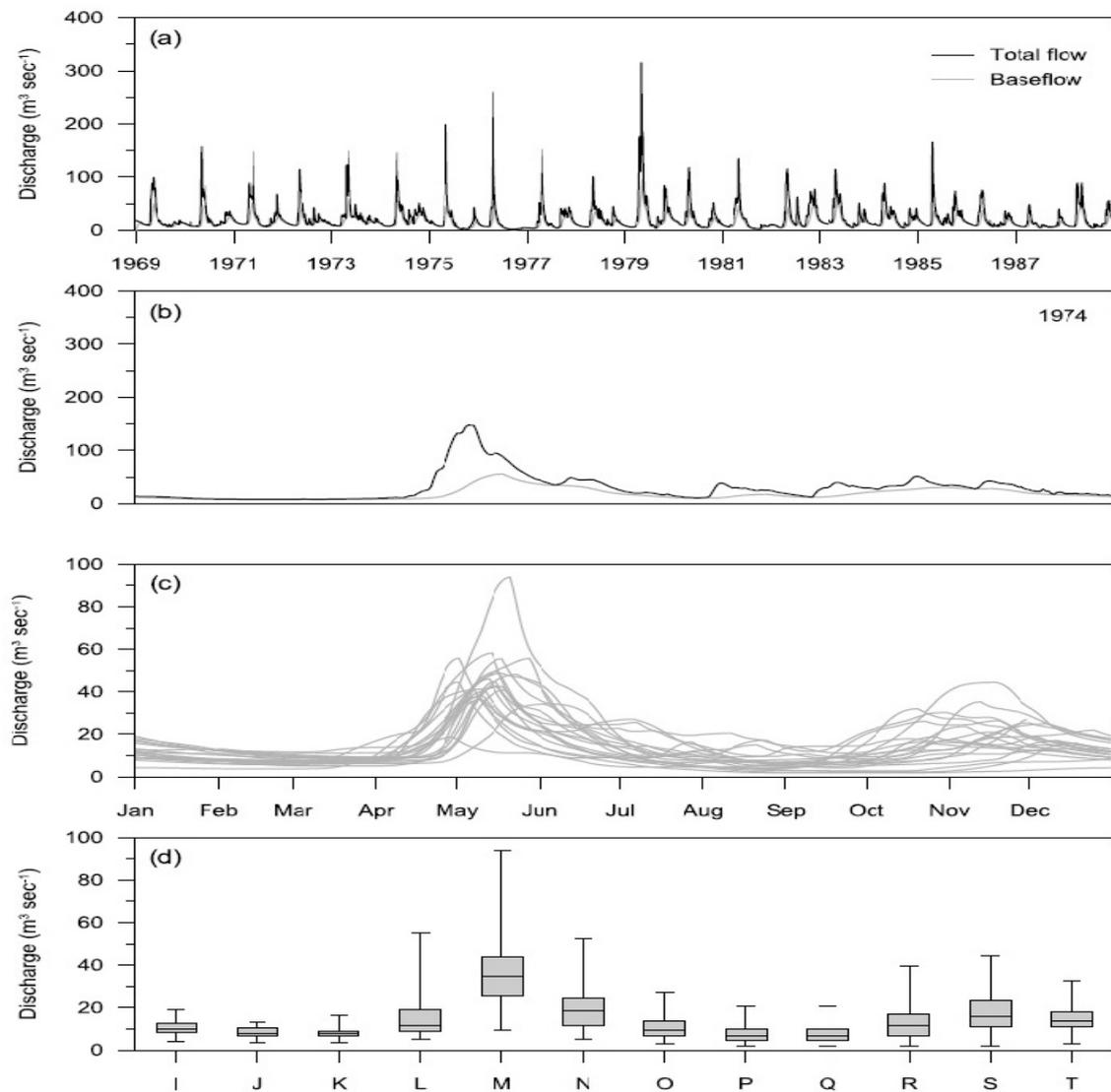
Figure A.2: Baseflow separation process and calculation of indicators

The continuous baseflow separation process and calculation of indicators showing: a) continuous baseflow separation versus total flow using the reference condition period of record; b) one calendar year of data illustrating the baseflow separation; c) daily baseflow hydrographs for the period of record; d) monthly baseflow box plots showing the interquartile range (IQR) (shaded box) and one step from the IQR (whiskers also referred to as the upper and lower adjacent values). (Metcalfe et al, 2016)

Appendix

B.1   The Seven Principles of the World Lake Vision

- **Principle1:** A harmonious relationship between humans and nature is essential for the sustainability of lakes.

- **Principle2:** A lake drainage basin is the logical starting point for planning and management actions for sustainable lake use.

- **Principle3:** A long-term, proactive approach directed to preventing the causes of lake degradation is essential.

- **Principle4:** Policy development and decision making for lake management should be based on sound sciences and the best available information.

- **Principle5:** The management of lakes for sustainable use requires the resolution of conflicts among competing users of lake resources, taking into account the needs of present and future generations and of nature.

- **Principle6:** Citizens and other stakeholders should be encouraged to participate meaningfully in identifying and resolving critical lake problems.

- **Principle7:** Good governance, based on fairness, transparency and empowerment of all stakeholders, is essential for sustainable lake use.

Source: ILEC(http://www.ilec.or.jp).

B.2 The six necessary components of any effectives management response

1. Adequate **institutions** for implementing change;

2. Efficient, effective and equitable **policies**;

3. Meaningful **participation** of all stakeholders involved;

4. **Technical measures** to ameliorate certains problems;

5. Appropriate **information** about current and future conditions;and,

6. Sufficient **financing** to allow all the above to take place.

Source: ILEC(http://www.ilec.or.jp).

B.3   Published articles in peer review journal

1- Sambou, D., Diekkruger, B., Gaye, A., Gaye, A. T. (2017). Assessment of Hydrologic Alteration within Ecosystem in a Sahalian Shallow Lake: Lake Guiers, Senegal. Modern Environmental Science and Engineering, 3(03), 184-199. https://doi.org/10.15341/2581)/03.03.2017/007