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Groundwater potential to supply population demand within the Kompienga dam basin in Burkina Faso

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To my parents Simon-Pierre and Pauline,
my wife Thérèse Noélie and our twins, Elvis and Edwige

"C'est au plus profond de la nuit, qu'apparaît l'aube"

"We must treat each and every swamp, river basin, river and tributary, forest and field with the greatest care, for all these things are the elements of a very complex system that serves to preserve water reservoirs – and that represents the river of life." Mikhail Gorbatchev

"Water is the earth's eye, looking into which the beholder measures the depth of his own nature." Henry David Thoreau

"If the misery of our poor be caused not by the laws of nature, but by our institutions, great is our sin." Charles Darwin

ABSTRACT

Groundwater recharge is constrained by various factors with rainfall playing a key role. The Kompienga dam basin located in southeastern Burkina Faso displays semi-arid climatic conditions with rainfall occurring five months per year. The average long-term (1959-2005) mean annual rainfall amounted to 830.2 mm with high temporal and spatial variability. During the year, evaporation always exceeds rainfall, except for a few months in the rainy season when recharge can take place in the basin. In addition, the crystalline rocks of granites and amphibolites mainly underlying the basin have a poor water storage capacity. Therefore, groundwater recharge in the basin is estimated to be as low as 43.9 mm, which represents 5.3% of the rainfall in 2005 for a potential groundwater volume of 259.5 million m³. The estimation based on the water balance method, the chloride mass balance method and the water table fluctuation method shows that the basin recharge is mostly through matrix flow with considerable spatial variability based on soil textures, crystalline rock fracturing, land-use/land-cover and topography. Thus, preferential flow processes are dominant in the basin recharge in the southwestern part around Tanyélé, where the chloride concentration in the groundwater is about that in rainwater.

Annual recharge in the basin is determined by an annual rainfall threshold ranging between 314.3 mm and 336.6 mm reached during the first two to three months of the rains. This relationship provided the equation for deriving annual groundwater recharge in the basin. According to Eddy correlation measurements, actual evaporation in the basin depletes the aquifers at an average rate of 0.6 mm per day during the dry season. This situation contributes to the reduction of the groundwater resources and limits the possibilities of developing these resources to improve the population's livelihoods.

The basin population in 2005 was 270 000 inhabitants living in 15 departments in 5 provinces, and water withdrawal was estimated at an average rate of 76 l/c/d (including livestock watering) in the dry season period. This represents 5 million m³ of water, making up 2 % of the annual recharge to the aquifers. In anticipation of decreasing rainfall and increasing population in the Kompienga dam basin, scenarios of recharges against withdrawals show that the annual recharge will support the demand for water till 2030 at a supply rate of 25 l/c/d from 1260 functional boreholes operating 12 hours per day at an average unit yield of 1 m³ per hour. The nationally formulated norm for rural water provision of 20 l/c/d was found to respond to basic needs only, and 35 l/c/d is considered the required supply rate especially from March to May when the water demand is highest. Therefore, the revision of the national norm and policy target for rural water supply is recommended.

Grundwasserpotential zur Versorgung der Bevölkerung im Kompienga Staudammbecken in Burkina Faso

KURZFASSUNG

Grundwasseranreicherung wird durch verschiedene Faktoren bestimmt, wobei dem Niederschlag eine Schlüsselrolle zukommt. Das Kompienga Staudammbecken im süd-östlichen Teil Burkina Fasos weist mit seinen durchschnittlich fünf Regenmonaten pro Jahr und einem mittleren Jahresniederschlag (1959-2005) von 830,2 mm bei hoher zeitlicher und räumlicher Varianz. Im Laufe des Jahres übersteigt dort die Evaporation die Niederschlagsmengen, mit Ausnahme von wenigen Monaten während der Regenzeit, in denen die Grundwasseranreicherung im Becken stattfinden kann. Zudem haben die kristallinischen Granite und Amphibolite, die sich unter dem Becken befinden, nur eine geringe Speicherfähigkeit. Die Schätzung der Grundwasseranreicherung für das Becken ergibt darum einen niedrigen Wert von 5,3 % der jährlichen Niederschlagsmenge im Jahr 2005 für ein potenzielles Grundwasservolumen von 259,5 Mio. m³. Die auf der Wasserbilanz-Methode, der Chlorid-Mengenbilanz-Methode und der Grundwasserspiegel-Fluktuationsmethode basierende Schätzung zeigt, dass die Anreicherung hauptsächlich über *matrix flow* gespeist wird, mit einer hohen räumlichen Varianz je nach Bodenbeschaffenheit, Vorkommen von Frakturen im kristallinischen Gestein, Landnutzung und -bedeckung sowie Topografie. Dementsprechend dominieren *preferential flow* Prozesse im süd-westlichen Teil nahe Tanyélé, wo die Chloridkonzentration des Grundwassers ungefähr der des Niederschlagswassers entspricht.

Die jährliche Anreicherung im Becken wird durch den jährlichen Niederschlag (314,3 mm bis 336,6 mm), der während der ersten zwei bis drei Regenmonate erreicht wird, bestimmt. Den *Eddy correlation* Messungen zufolge führt die aktuelle Evaporation während der Trockenzeit zu einer Abnahme des in den Aquiferen gespeicherten Grundwassers um einem durchschnittlichen Wert von 0,6 mm pro Tag und damit zur Reduzierung der Grundwasserressourcen. Hierdurch sind die Möglichkeiten, diese Ressourcen zu entwickeln und so zu einer Verbesserung der Lebensgrundlage der Bevölkerung beizutragen, begrenzt.

Im Jahr 2005 lebten die 270 000 Bewohner des Beckens in fünfzehn Distrikten bzw. fünf Provinzen, und ihre Wasserentnahme in der Trockenzeit entsprach ca. 76 l/c/d (einschließlich Wasser für das Vieh). Das entspricht 5 Mio. m³ Wasser und 2 % der jährlichen Grundwasseranreicherungsmenge. Vergleichende Szenarien auf der Grundlage der zu erwartenden geringeren Niederschläge und steigendenden Bevölkerungszahlen im Kompienga Staudammbecken zeigen, dass die jährliche Grundwasseranreicherung ausreichen wird, um den Wasserbedarf bis 2030 bei einer Versorgung mit Wasser von 25 l/c/d durch 1260 funktionale Bohrlöcher im 12-stündigen Betrieb bei einer Pumprate von 1 m³ pro Stunde zu decken. Die auf nationaler Ebene formulierte Norm von 20 l/c/d für ländliche Gebiete kann lediglich die Grundversorgung sicherstellen, da tatsächlich 35 l/c/d benötigt werden, insbesondere in der Zeit von März bis Mai, wenn der Wasserbedarf am höchsten ist. Daraus ergibt sich die Empfehlung, die nationale Norm und politische Zielvorgabe für die ländliche Versorgung zu überprüfen und gegebenenfalls zu korrigieren.

Potentialités en eaux souterraines pour la satisfaction des besoins des populations du bassin versant du barrage de la Kompienga au Burkina Faso

RESUME

Les recharges des nappes d'eau souterraines sont conditionnées par divers facteurs dont les pluies jouent un rôle principal. Sur le basin versant du barrage de la Kompienga au Sud-est du Burkina Faso en conditions climatiques semi-aride, les pluies se caractérisent par une forte variabilité spatio-temporelle de 5 mois par an avec une hauteur pluviométrique moyenne interannuelle (1959-2005) de 830.2 mm. Tout au long de l'année, l'évaporation mensuelle sur le site dépasse généralement les pluies sauf durant quelques mois au cours de la saison des pluies où ont lieu les recharges des nappes. En plus de ces conditions défavorables, le site de Kompienga se trouve sur un socle cristallin de granites et d'amphibolites peu propice à la constitution d'aquifères importants. Une estimation de la recharge des nappes du bassin a conséquemment révélé un faible niveau de recharge de 43.9 mm représentant 5.3% de la pluie annuelle en 2005 et correspondant à un potentiel en eau de 259.5 millions de m³. Cette estimation faite à partir de la méthode des chlorures, la méthode du bilan hydrologique et celle de variations des niveaux statiques des nappes a montré que les recharges au niveau du bassin se faisaient principalement suivant des écoulements en nappe spatialement variables selon les textures des sols, le degré de fracturation des roches du socle, la végétation et l'utilisation des terres ainsi que la topographie. Relativement à cette variabilité spatiale des processus de recharge des nappes du bassin, les processus d'écoulements préférentiels se sont révélés dominants dans la partie sud-ouest du bassin autour de la zone de Tanyélé où les eaux souterraines présentent des teneurs en chlorures voisines de celles des eaux de pluies.

Un seuil de hauteur de pluie annuelle conditionne les recharges des nappes du bassin versant. Ce seuil varie entre 314.3 mm et 336.6 mm et n'est atteint qu'au bout des 2 ou 3 premiers mois de la saison des pluies. Cette relation a permis de formuler une équation pour l'estimation des recharges annuelles du bassin suivant les hauteurs pluviométriques moyennes annuelles. Les données climatiques de saison sèche de la station Eddy correlation ont montré que l'évaporation actuelle réduisait en moyenne les aquifères du bassin de 0.6 mm d'eau par jour. Ce qui réduit considérablement les possibilités de développement des ressources en eau souterraine du bassin pour l'amélioration des conditions de vie des populations.

En 2005, l'approvisionnement en eau des 270 000 habitants environ vivant dans les 15 départements des 5 provinces couvrant le bassin versant a été estimé à une moyenne de 76 litres d'eau par jour par personne (76 l/j/pers y compris l'abreuvement des animaux) durant la période sèche. Ce qui correspond à un volume de 5 millions de m³ d'eau prélevés des aquifères ; soit 2% de la recharge totale de l'année. En prévision de l'accroissement de la population du bassin et de scénarios de baisses de la pluviométrie, les recharges résultantes ont montré la capacité des nappes du bassin à supporter les besoins en eau des populations jusqu'en 2030 avec 25 l/j/pers à partir de 1260 forages d'eau fonctionnant continuellement chaque jour pendant 12 heures à un débit unitaire moyen de 1 m³/h par forage. La norme nationale de 20 l/j/pers en zone rurale s'est révélée juste pour la satisfaction des besoins de base et mérite donc d'être revue pour tenir compte du taux d'approvisionnement moyen utile de 35 l/j/pers observée au niveau du site pendant la période de fortes demandes en eau des mois de Mars à Mai.

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ACRONYMS AND ABBREVIATIONS

ARFA	Association de Recherche et de Formation Agro-écologique
BMBF	Bundesministerium für Bildung und Forschung (Germany)
BUMIGEB	BUreau des MInes et de la GEologie du Burkina
CD/MAHRH	Centre de Documentation du Ministère de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques
CIRD-Ouagadougou	Centre d'Information sur la Recherche et le Développement
CNRST	Centre National de la Recherche Scientifique et Technologique
DEP	Direction des Etudes et de la Planification (Ministère de l'Environnement et de l'Eau)
DGAEP	Direction Générale de l'Approvisionnement en Eau Potable
DGIRH	Direction Générale de l'Inventaire des Ressources Hydrauliques
DGRE	Direction Générale des Ressources en Eau (Ministère de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques)
EU	European Union
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product (in purchasing power parity)
GIRE	Projet Gestion Intégrée des Ressources en Eau
HDI	Human Development Index
HPIC	Heavily Poor Indebted Countries
IMF	International Monetary Fund
INERA	Institut de l'Environnement et de Recherches Agricoles
INSD	Institut National de la Statistique et de la Démographie
IWACO BV	Dutch consulting group of research/development on water resources
MAHRH/DRAHRH-Est	Ministère de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques/Direction Régionale de l'Agriculture, de l'Hydraulique et des Ressources Halieutiques de l'Est

MEF/DPD-Est	Ministère de l'Economie et des Finances - Direction Provinciale pour le Développement de l'Est
ONEA/Kpg	Office National de l'Eau et de l'Assainissement-Kompienga
OSS	Observatory of the Sahara and the Sahel. An organization composed of Arabic Maghreb Union (AMU) countries (Algeria, Egypt, Lybia, Mauritania, Morocco and Tunisia), Permanent Interstate Committee for Drought Control in the Sahel (CILSS) countries (Burkina Faso, Cape Verde, Chad, Gambia, Guinea-Bissau, Mali, Mauritania, Niger and Senegal) and countries of the Intergovernmental Authority on Development (IGAD) with Djibouti, Eritrea, Ethiopia, Kenya, Somalia, Sudan and Uganda.
PPB/Est	Projet Petits Barrages de la région de l'Est
PPIV	Projet Promotion de la Petite Irrigation Villageoise
SONABEL	SOciété NAtionale Burkinabé d'ELectricité
TUDelft	Technische Universiteit Delft (The Netherlands)
UNDP	United Nations Development Program
UNU-EHS	United Nations University - Institute for Environment and Human Security
US$	Dollar of United States of America
VINVAL	Project on the Impact of changing land cover on the production and ecological functions of vegetation in inland valleys in West Africa
WCED	World Commission on Environment and Development
WHO	World Health Organization
WMO	World Meteorological Organization
ZEF	Zentrum für Entwicklungsforschung (Germany)

1 INTRODUCTION

The planet earth is the only planet of the solar system to support living creatures mainly due to the presence of water in gaseous, liquid and solid form. “L’eau, c’est la vie” (water is life) is a common French saying to show how important water is for life. Pielou (1998, prologue) added that “living things depend on water but water does not depend on living things” as “it has a life of its own”. Hillel (1994) in the same reflexion, described the essence of water in human life, with our body composed of 90% of water at birth and “drying up” to 65% in old age.

Water’s importance on earth is therefore undeniable for human beings and is increasingly so, as water is becoming more and more scarce in major parts of the world. At the same time, in fewer areas, water availability is considered excessive (Hillel 1994) in addition to frequent floods occurrence. This dual characteristic of excess and scarcity of water on our planet seems unrealistic, since the global earth water budget has remained almost unchanged with only negligible inter-annual variation since the 1980’s (Pielou 1998). Global climate change has induced and even worsened the unequal spatial distribution of rains around the world with a drastic decrease in rainfall in African countries (Dale 1997, Arnell and Liu 2001, Agyare 2004 and www.news.bbc.co.uk). In these parts of the world and especially in West African countries, temporal and spatial rainfall variability has increased together with a decrease in amounts during the last decades (Somé 2002 and Paturel et al. 2002). Meanwhile, as lack of consensus among scientists on climate change impacts, Nicholson (2005) and Jung (2006) among others predicted a spatially complex pattern of increase in the annual rainfall in West Africa and especially in the Volta basin. Nevertheless, from the observations on this zone since the 1960’s and 1970’s, an overall decrease tendency in rainfall was agreed on (Lebarbé and Lebel 1997, Servant et al.1998, Hulme et al. 2001 and Amani 2001). Therefore, water availability within West African countries will mostly decrease (UNESCO 2004), and the growing population is going to face more frequent and severe shortages. Water supply to the populations in these countries using surface waters has shown to be limited due to high evaporative effects on such open-air water resources (Pouyaud 1985, 1986 & 1994, Milville 1991 and MEE 2001) and sedimentation (Lulseged 2005) due to considerable soil erosion in tropical zones (Vlek

1993, Vlek et al. 1997, Katyal and Vlek 2000). Shallow hand-dug wells also show limited efficiency due to low annual water recharge combined with high evaporation from such shallow aquifers close to soil surface. In addition, these aquifers are mainly laid in the regolith of the weathered crystalline basement rocks often of lesser thickness and unable of substantial water storage.

A relevant resource for sufficient water supplies in West Africa is considered to be deep groundwater. Deep aquifers of crystalline rocks sufficiently provided with fractures, fissures and joints storing substantial recharges are effectively providing water supply to the population through boreholes equipped with hand pumps and modern wells in addition to the existing traditional hand-dug wells. However, any or only little information related to these aquifers is available for planning their sustainable exploitation.

In Burkina Faso, groundwater studies by Savadogo (1984) and Geirnaert et al. (1984) proved the presence of tritium in the water samples, giving evidence of permanent seasonal recharge of the groundwater aquifers and therefore their annual renewability. However, the recharge level remains insufficiently investigated. As a main water source, groundwater needs to be durably managed based on information on aquifer quantities, seasonal and annual variability, characteristics, and response to intensive exploitation, etc.

The Glowa Volta project funded by the German Ministry of Education, Sciences and Technology (BMBF) is set *to develop a scientifically sound decision-support system for the assessment, development and sustainable use of water resources in the Volta basin by means of an integrated model of the basin* (Andreini et al.2000, p.2). In this project, groundwater and water resources management is one of the main objectives for supporting the people’s fight against water shortages. Land resources management under changing land use, rainfall reliability and water demands in the Volta basin is also part of the project objectives (ZEF 2000). Previous research within the framework of this project in Ghana and Burkina Faso has addressed various issues related to integrated water resources management in the Volta river basin. Among these can be mentioned Ajayi (2004), Martin (2005) and Amisigo (2005), whose studies focused on hydrological and hydrogeological aspects of the Volta Basin. Mainly based on modeling, this research addresses the basin rainfall-runoff relationship, riverflow predictions and groundwater recharge and baseflow evaluation. The present research in the Burkina Faso part of the basin pertaining to the research cluster Water Use, sub-project W1 titled Runoff and hydraulic routing (ZEF 2000), and following the previous research is a contribution to the achievement of the project objectives. The research addresses the following questions:

1. What is the groundwater resource potential in the Kompienga dam basin of 5911 km²?
2. What is the nature of this resource?
3. What is the resource capacity in supplying the population?
4. How much water does the population need/use?
5. What could be the supply capacity in the future be considering the erratic character of the rainfall and the growing population within the basin?

Answers to these questions were obtained through fieldwork with equipment installation and monitoring, data collection, survey of water sampling at boreholes and interviews among the basin dwellers. Data processing, analysis and interpretation provided clear answers to the questions mainly in chapters 6 and 7. The basin groundwater potential assessment to answer question 1 was done based on three methods (Chapter 6) providing the nature of the resource (question 2). The evaluation of the basin groundwater uses by the population against the evaluated potential (Chapter 7) provides answers to questions 3 and 4. Question 5 was answered using pessimistic scenarios of decreasing rainfall pattern along with increasing population in the basin (Chapter 7). Chapter 2 discusses some concepts and methods of groundwater resource evaluation and management, and the implications for the study area. Chapter 3 presents the state-of-the-art of the water resources in the study area in Burkina Faso and water management initiatives developed and practiced for the benefit of the population. Chapter 4 provides a description of the research site and the surrounding area in the Volta river basin. Chapter 5 describes the materials used during the 18 months of fieldwork within the basin and the analytical methodology used based on the collected data. The results are presented and discussed in chapters 6 and 7. Finally, Chapter 8 gives the conclusions on the research results and findings along with some recommendations for further research.

Research is never ended, never finished; as findings always raise questions to solve. There are only stops and pauses in research to evaluate what has been achieved and prepare for the following steps. The actual research therefore stops here to continue further on the induced recommendations presented at the “end” of this thesis.

May these results contribute to build sustainable management schemes for the basin groundwater resources and improve thereby the livelihood of the population living in the basin.

2 BACKGROUND AND LITERATURE REVIEW

2.1 Definition of basic terms

Before presenting the basin groundwater potential evaluation, basic terms used in the text are defined to provide an understanding of the theories and ideas developed in this thesis. An example is the evapotranspiration term, which is replaced by either evaporation or transpiration according to the situation in reference to Savenije (2004), except for expressions derived from references and theories explicitly cited.

River basin

A river basin at a given point represents the whole surface pertaining to this river on which any rainfall flows into the river and arrives at the given point. According to Pierre (1970), a basin is a geographical space providing water to a river and drained by it.

Recharge

Recharge is broadly defined by Lerner (1997) in Scanlon et al. (2002) as water that reaches an aquifer from any direction (down, up or laterally) while Freeze and Cherry (1979) in Gee and Hillel (1988, p.256) see it as "the surplus of infiltration over evapotranspiration drains from the root zone and continues to flow downward through the vadose zone (or unsaturated zone) toward the water table where it augments or replenishes the groundwater reservoir (aquifer)". In this study, the term recharge will be considered as defined by Freeze and Cherry (1979) as being all the water that moves downward to replenish the basin aquifers.

Aquifer

Pielou (1998, p.14) defines aquifer as "a body of rock or sediment that holds water in 'useful' amounts; that is, the water is abundant enough, and can flow through the ground fast enough for the aquifer to serve as a natural underground reservoir".

Saturated zone

The saturated zone of aquifers represents the portion of these aquifers saturated with water. For Fetter (1994), it is the zone in which, the voids in the rock or soil are filled with water at a pressure greater than the atmospheric pressure.

Unsaturated zone

The unsaturated zone above the saturated zone consists of water and air trapped in the voids of the soil materials. Also called vadose zone for its shallow position in the soil profile, the unsaturated zone is the zone closest to the ground surface. It encompasses the root zone, the intermediate zone and the capillary fringe (Fetter 1994).

Water table

The water table represents the level or the upper limit of the water, which permanently fills the aquifers in the saturated zone. Lerner et al. (1990) also define it as the position where the porewater pressure is equal to the atmospheric pressure.

Unconfined aquifer

An unconfined aquifer or water table aquifer is an aquifer saturated with water up to the water table (Pielou 1998) and free of a confining bed between the saturation zone and the surface (Fetter 1994).

Confined aquifer

A confined aquifer is an aquifer confined between two impermeable soil layers forming an aquifer under pressure, where any perforation of the top impermeable layer, called aquitard, (Rodhe and Killingtveit 1997) induces a rise of the water over the top of the aquifer consequently to the pressure release.

Regolith

The regolith is a common term for geologists characterizing the decomposed and weathered zone of crystalline basement aquifers (Nyagwambo 2006), including both soil and weathered bedrock (Fetter 1994).

Preferential flow process

Preferential flow is a flow process in groundwater recharge where water infiltration passes, by channels of deep roots, fissures, cracks or any pathway in the soil material to by-pass the bulk of the soil matrix and reach the water table in the saturated zone. It is also known as by-pass flow (Hoogmoed et al. 1991) inducing instant, rapid and localized recharge (de Vries and Simmers 2002, Gee and Hillel 1988).

Diffuse flow process

Diffuse flow process in groundwater recharge is mainly based on a progressive wetting of the soil layers. Here, the wetting front has an approximately uniform flow progressing downward, filling the soil pores and voids with water to their field capacity and then percolating to the water table. This flow process is also called matrix flow.

Indirect recharge

Also called focused or localized recharge, indirect recharge is a diffuse flow from lakes, streams and all the depressions collecting surface waters (Scanlon et al. 2002). It results from percolation to the water table following runoff and localization in joints as ponding in low-lying areas and lakes, or through the beds of surface-water courses (Lerner et al.1990).

Direct recharge

Direct recharge is a recharge from diffuse flow processes (Scanlon et al.2002). Lerner et al. (1990, p.6) also define it as "water added to the groundwater reservoir in excess of soil moisture deficits and evapotranspiration, by direct vertical percolation of precipitation through the unsaturated zone".

2.2 Review of groundwater resources evaluation and management: concepts, methods and implications

Groundwater is in the junction of various sciences mainly geology, hydrology, soils sciences and hydrodynamics. Also called hidden treasure or blue gold, groundwater is the biggest water resource volume estimated to range from 7 million km^3 (Nace 1971) to 23.4 million km^3 (Korzun 1978), not including polar glaciers and permanent snow

(UNESCO-WWAP 2003). Foster et al. (1997) and Burke and Moench (2000) estimated that more than 1.2 billion urban dwellers worldwide rely on groundwater with “70% of the European Union piped water supply, rural livelihood in sub-saharan Africa and the green agriculture revolution success in Asia” (UNESCO-WWAP 2003, p.78) also based on it. Groundwater science; hydrogeology, is considered young as stated by Aureli in the preface of Foster and Loucks (2006) and like all sciences, is still evolving with rapid progress due to the frequent occurrence of major droughts in the past decades and the increasing population, which has considerably increased water demands in the world.

Quantifying groundwater resources is worldwide a prerequisite to sustainable development (Lal 1991) and methods to satisfy this indispensable need have been developed by scientists. Applicable to the different parts of the soil profile from the soil surface to the unsaturated zone and the saturated zone, methods in estimating groundwater resources vary from physical and chemical methods to isotopic methods and mathematical models (Allison 1988). Physical methods range from direct measurements with seepage meters, lysimeters and baseflow discharge to water balance, zero-flux plane, thermal profile and water table fluctuation methods as well as empirical methods using physical measurement data for recharge estimation (Sammis et al. 1982, Allison 1988, Gee and Hillel 1988, Kumar 1996, Scanlon et al. 2002). Chemical methods encompass natural tracers and artificial tracers used in isotope methods of recharge estimation and mostly based on ^{2}H, ^{18}O, ^{3}H, ^{36}Cl, ^{3}He, ^{4}He, ^{60}Co, Cl and Br as showed in Chandrasekharan et al. (1988), Lerner et al. (1990) and Selaolo et al. (2000) among others. Mathematical models consist of all the numerical methods for recharge estimation simulating natural processes that lead to recharge and based on the various hydraulic and hydrodynamic laws governing water movements on the soil surface and in the unsaturated and saturated zones according to physical characteristics and climatic conditions. Examples are quoted in Scanlon et al. (2002) with the mathematical models of WaSiM-ETH, HYDRUS, MODFLOW, SWAT, etc based on Richards’s equations. Mathematical models always need field data from direct measurements for calibration refinement and results validation. An example is given in Puri et al. (2006) on the numerical model of the Western Jamahiriya Aquifer in Libya refined twice (1980 and 1990 from the original model built in 1970) using new hydrogeological data from additional exploration/observation wells, which served as a pillar of the Great Man-Made River Project - Phase II.

Particular techniques among the physical methods in groundwater recharge estimation are the recently developed techniques of remote sensing and its twin technique geographical information systems (GIS). More and more used worldwide alone or in combination with other techniques or methods, remote sensing techniques are described by Brunner et al. (2004), Van de Griend and Gurney (1988) in studies in Botswana and Klock and Udluft (2002) based on their research in Namibia as successfully deriving more accurate recharge estimates than conventional methods. Puri et al. (2006) describing aquifer characterization techniques also quoted the successful use by El Baz (1999) of digital satellite images including multi-spectral data from Landsat Thematic Mapper and radar images from the Spaceborne Imaging Radar to map the eastern Sahara groundwater basins.

According to Lerner et al. (1990), the choice of methods to investigate groundwater recharge is dependent on the objectives and the study area characteristics (including the flow mechanisms within the study area leading to the recharge), which determine the adequacy of the methods and the investigation time step. Scanlon et al. (2002) and Lerner et al. (1990) outlined furthermore the importance of the spatial and temporal scales of the recharge estimation in guiding the choice of the methods and techniques of groundwater recharge. In addition, subsidiary factors like the methods costs of remote sensing techniques and the required duration for deriving the parameters in the recharge estimation are also restrictive when selecting a method.

Besides the variety of methods aforementioned in the recharge estimation, none alone has enough accuracy to provide reliable recharge estimates. This is partly due to the hidden nature of groundwater resources, which implies that calculations be at best approximative, based on consistent assumptions on the components governing the resource occurrence as aquifer and known to be temporally and spatially variable and therefore likely to induce inaccuracies in the evaluation (Foster et al. 2000). Secondly, recharge estimation methods have their own limitations in terms of applicability and estimate reliability (Beekman and Xu 2003) and more than one should be used for recharge estimation as suggested by Lerner et al. (1990), Beekman et al. (1996), Scanlon et al. (2002), de Vries and Simmers (2002) and Risser et al. (2005). Van

Tonder and Bean (2003, p.19) quoting Simmers' preface of the proceedings of a conference on recharge estimation (1987 in Turkey), reported that "no single comprehensive estimation technique can yet be identified from the spectrum of methods available; all are reported to give suspect results". Based upon that consideration, combinations of different methods termed "hybrid methods" have been developed in order to improve recharge estimation accuracy as done by Sophocleous (1991) by combining the unsaturated zone water balance with the water table fluctuation method. Sophocleous and Perkins (2000) have also integrated SWAT and MODFLOW for a unique and optimized model that better constrains the parameters for recharge estimation (Scanlon et al. 2002).

Meanwhile, according to the location (climatic conditions) of the concerned aquifer, some methods are considered more relevant than others. Allison et al. (1994, p.12) demonstrated based on studies in Australia that "the greater the aridity of the climate, the smaller and potentially more variable the recharge flux" and better adapted to the estimate the chloride mass balance method (Allison 1988, p.66) which "concentration is inversely proportional to recharge rate and the estimation precision increasing with decrease in the recharge rate". Nevertheless, the suggested method cannot be considered as an all-purpose method or a panacea for recharge estimation, as limitations in a single method also apply to this method of chloride mass balance. Guidelines in choosing methods for recharge estimate exist, but no user-friendly framework or user manual of recharge estimation methods is available to date (Beekman and Xu 2003).

Despite the recommendation on using multiple methods to improve the recharge estimation reliability, the difference in recharge values derived from different methods applied to the same aquifer can remain high leaving no clue as to the precise recharge figure. Examples are given by Martin (2005) in estimating recharge to a northern Ghana site with 3 different methods from which, results were in the range of 20 to 147 mm/yr. 90 to 400 mm/yr deep percolation flow rates were estimated in Arizona (USA) using three different methods (Sammis et al. 1982) and a range of 45.4 to 81.3 mm/yr of recharge was also derived from three methods for a Tanzanian catchment in 1997 by Mkwizu (2002). The current arithmetic mean or average of the derived results is not always representative or significant nor does it reflect the realities that research attempts to figure out in groundwater recharge assessment. Therefore, it implies that the representative recharge value to consider among a range of recharge estimates to a given aquifer system does not depend only on the estimation methods but also on the objectives attached to the estimation with consideration of the various characteristics of the aquifer system. For example, if the objective in estimating the recharge is to know the extent of contaminant or pollutant effects on an aquifer system according to the recharge rate, the focus will be on the pollutant effects on the groundwater resource or the recharge flow process leading to the contaminant propagation in the aquifer. Therefore, an average of the estimates can be considered. In the contrast, when the recharge estimate leads to a water supply management according to the withdrawals, then the recharge accuracy is of crucial importance and additional considerations (like the geological and the unsaturated zone characteristics of the aquifer and the climatic conditions) are indispensable in the recharge estimate when the results of the different methods are too different. In such case, the principle of precaution recommends that the lower range of recharge be considered in order to avoid any water shortages likely to happen with the upper bounds recharge estimates.

Additional solutions to reduce uncertainties in estimation methods are suggested by Lerner et al. (1990) for permanent annual recharge estimations and comparison of estimates for aquifers with similar physical and climatic conditions. Indeed, groundwater recharge estimation according to the temporal variability of the components should neveur be done only once but in a continuing iterative process in order to update estimations and adjust management schemes (Lerner et al. 1990 and Puri et al. 2006).

Besides inaccuracy in groundwater recharge estimation, another considerable factor in groundwater management is the aquifer capacity to accept recharge. As stated previously, many factors contribute substantially to groundwater recharge, and rainfall is considered to play the predominant role. In effect, rainfall is an essential source inducing recharge and has considerable spatial and temporal variability in arid and semi-arid zones. Nevertheless, when rainfall becomes less constraining in groundwater recharge, the next limiting factor in recharge is considered to be the geological structures forming the aquifer. Indeed, when geological formation characteristics are less suitable for storing water, whatever the rainfall amount, the storage capacity will limit the recharge to such aquifers. Such situation is encountered in hard rock environments of crystalline basement aquifers where the unique secondary porosity acquired from fracturing, are generally of lesser storage capacity consecutively to the lack of primary porosity. In contrast, porous geological structures like unconsolidated sedimentary formations have considerable storage possibilities for satisfactory recharge acceptance. Rushton (1988) in Lerner et al. (1990, p.8) pointed out among others the "ability of aquifers to accept water" as important to consider.

Recharge estimation has rarely been, if not to say never, a final objective of research studies on an aquifer system but always an intermediary stage to a final step that is often the groundwater resource management. Lerner (2003, p.105) for this purpose stated that "recharge estimation is only part of the story of resource management. Not all recharge is available for abstraction by wells, for both technical and environmental reasons". Recharge is rarely estimated in isolation, but is usually just one aspect of a wider study such as on groundwater resources, pollution transport, subsidence or wellfield design (Lerner et al. 1990). Beyond groundwater recharge estimations, are the general objectives of resource sustainable management representing all the activities and initiatives toward a sustainable use of the available resources to supply actual population without compromising the possibility to correctly supply future generations (WCED 1987). This definition, applicable to all kind of resources, is restricted to water resources by Beek et al. (2003, p.31) as "the regulation, control, allocation, distribution and efficient use of existing supplies of water to offstream uses such as irrigation, power cooling, municipalities and industries as well as to the development of new supplies, control of floods and provision of water for instream uses such as navigation, hydro-electric power, recreation and environmental flow". Bogardi (1994) in introducing the system analysis approach has defined water resource management as the interface between and integration of different disciplines including technical, natural and social sciences. From these concepts, one can note that groundwater management mainly implies permanent use efficiency in all natural, social and technical aspects. As such, the implications for the Kompienga groundwater resources are their efficient use by the current population and future generations to satisfy their basic needs and generate as much income as possible for their well-being. In the Kompienga dam basin, water resource availability and population demands quantities are parameters varying along the year due to climatic conditions associated to spatial variations in the geophysical parameters. The monomodal rainfall regime governing the basin recharge is in contrast with the withdrawals. While during the recharge periods of the rainy season withdrawals by the population are low, the dry season without recharge is the period of high withdrawals and water demands. In addition, the geological structures of crystalline rocks with storage capacity and transmissivity are spatially variable and are coupled with uneven population density in the basin. For these reasons, successful management of the basin water resources requires that all the involved variables be well defined and evaluated.

Meanwhile very little has been done in this sense for evaluation and management of the basin water resources. Only the hydrological studies by Haskoning BV (Dipama 1997) for the dam construction and the "Bilan d'Eau" project activities of the Water Ministry for the whole country executed by IWACO BV under the financial assistance of the Dutch government in 1990 can be mentioned. These studies for establishing a national master plan for fresh water supply have provided regional results on groundwater potential, in which the Kompienga basin was included in Fada N'gourma region for a total renewable groundwater potential of 2.2 billion m^3 of water (MEE 1998). The study evaluated the potential of siting productive boreholes in the country and the Kompienga region was considered as having a good water potential (DEP/IWACO 1990). Martin (2005) drew the same conclusion in her studies at the whole Volta basin scale considering the Kompienga dam basin to be in the class with good to moderate groundwater potential (Figure 2.1). A groundwater potential in these studies was considered to be a function of accessibility (based on the success rate of drilling boreholes), exploitability in terms of yield and extraction depth and a function of supply reliability from the amount of the stored water in the aquifer, its mobility to wells and the amount of recharge in non-drought years (Martin 2005).

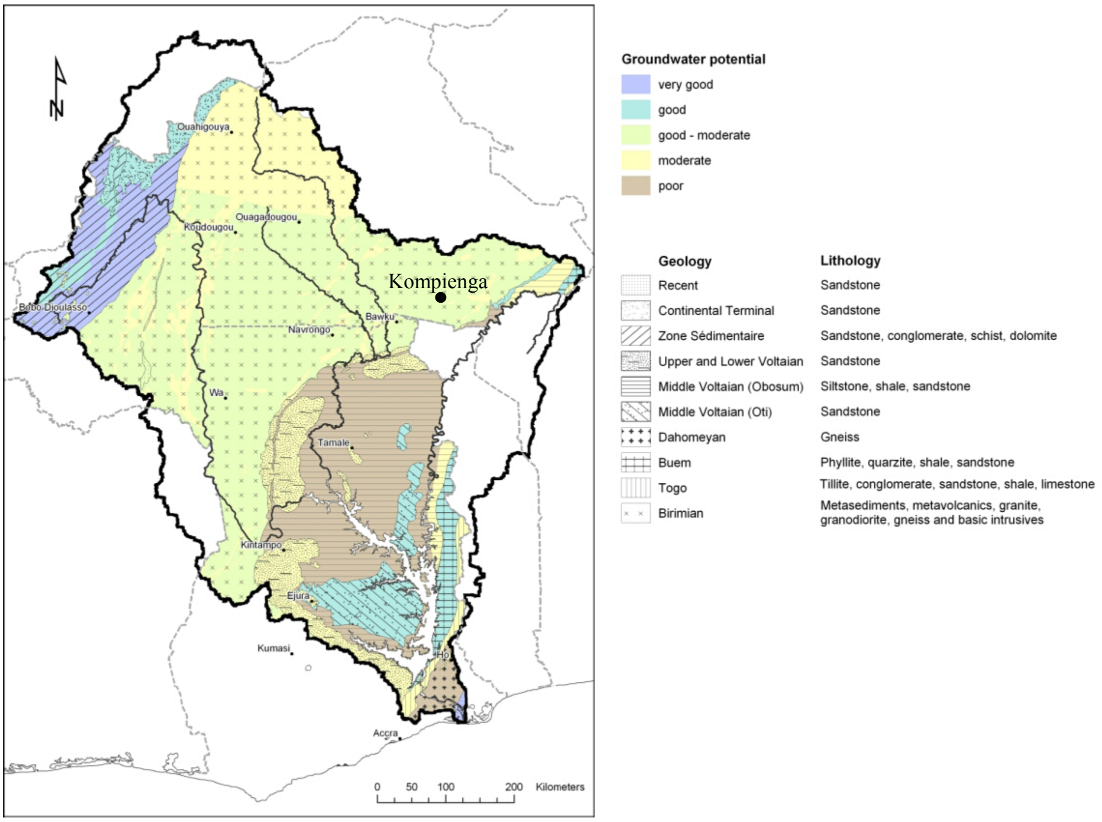

Figure 2.1: Geology and groundwater potential in the Volta river basin. Modified from Martin (2005)

In all these studies, the basin was considered to be provided with a good groundwater potential. However, no precise figure of this potential was given to allow sustainable management planning of these resources. Therefore, a need for complementary studies such as the present research on the basin was expressed.

3 OVERVIEW OF WATER RESOURCES IN BURKINA FASO

3.1 Introduction

Burkina Faso is a landlocked country in the center of West Africa surrounded by Mali in the north to west, Niger in the east and the coastal countries Côte d'Ivoire, Ghana, Togo and Benin south-west to southeast. Covering 274 000 km², the country is located between the north latitude of 9°30' and 15°00' and the longitudes 2°30' East and 5°30' West (Paturel et al. 2002, MEE 1998). With a total number of 10 313 511 inhabitants according to the 1996 census (INSD 2000), the population was estimated in 2004 at 13.5 million (13 393 000 inhabitants) according to FAO (2005) while the preliminary results of the 2006 census recently published by newspapers revealed a total population of 13 730 258 inhabitants (www.lefaso.net).

Burkina Faso is a flat country with altitudes mainly in the range of 250 to 300 m asl (above sea level) except for the Tenakourou peak in the west at 749 m asl. The 80% of the country is underlain by geological formations composed of Paleoproterozoic granitoids of the baoulé-mossi domain (Castaing et al. 2003) covered by Neoproterozoic sedimentary rocks in the west, north and southeast and Cenozoic Continental Terminal rocks in the northwest and extreme east.

The climatic conditions prevailing in the country are essentially the tropical climate with a monomodal rainfall pattern of variable duration and increasing from north to south from 3 to 7 months (MEE 2001). Eight 100-mm isohyets (period 1951-1980) with a maximum of 500 mm in the extreme north to 1200 mm in the southwest have been determined (Somé 2002) to cover the country. According to these isohyets, there are three climatic zones. The south Sudanean zone covering the southern part of the latitude 11°30'N from the isohyets 900 mm to 1200 mm, the north Sudanean zone occupying the central part of the country between the latitudes 11°30'N and 14°N including the isohyets 900 mm to 600 mm. The third climatic zone is the Sahelian zone including the region above the latitude 14°N with isohyets of 600 mm maximum (MEE 1998). Due to its geographical position, Burkina Faso shares three international river basins with the neighboring countries, namely the Comoé river basin, the Niger river basin and the Volta river basin, which is the object of this groundwater research under the framework of the GLOWA Volta project. At the national level, these basins are divided into four national basins, i.e., the Niger river basin, the Comoé river basin, the Mouhoun river basin and the Nakanbé river; the latter are subdivisions of the international Volta river basin. The national basins are subdivided into 17 sub-basins (MEE 2001) draining mainly surface waters during the rainy seasons and drying up in the remaining period of the year except for the Mouhoun and the Comoé (Comoé and Léraba rivers) basins with permanent runoff as baseflow from the sedimentary aquifers in the western part of the country. To these basins can be added the Nakanbé basin for the rivers downstream of the two hydropower dams of Bagré and Kompienga, which have almost perennial flows due to the electricity production from the reservoirs.

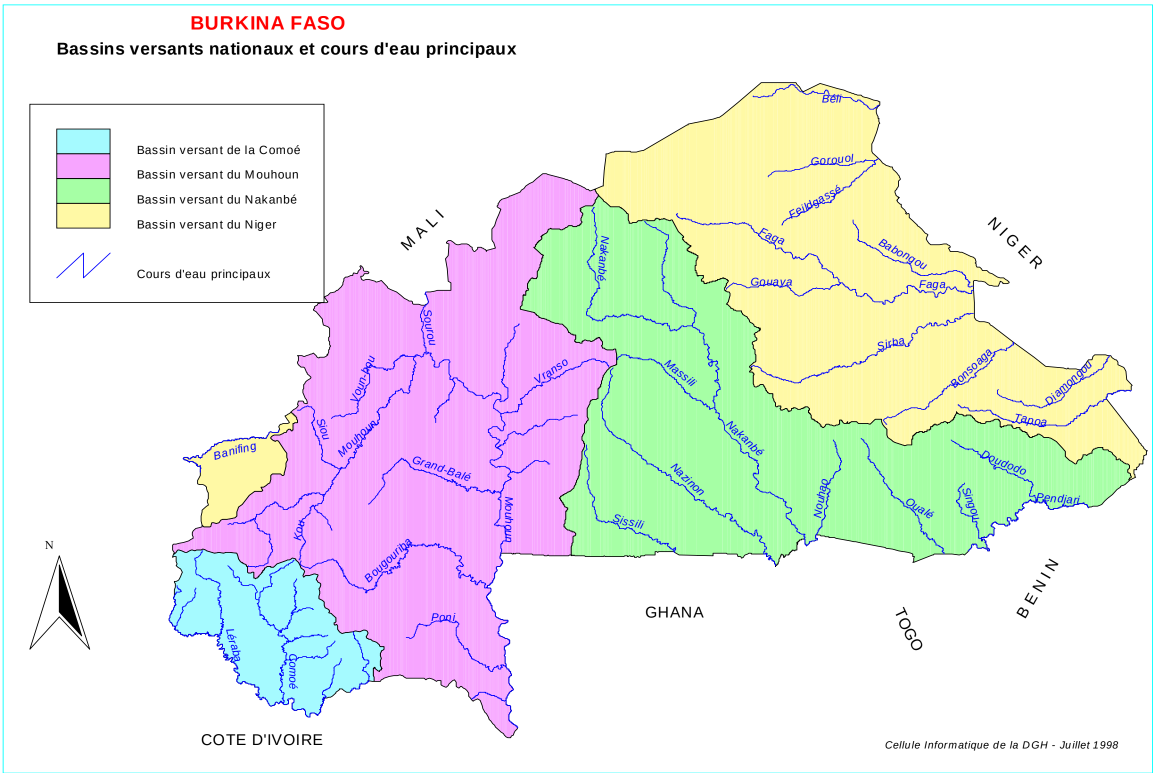

Figure 3.1: Main rivers in Burkina Faso and their drainage basins (MEE 1998)

3.2 Surface water resources

Water resources, whether surface or beneath the ground, are rainfed. Rainfall in Burkina Faso is characterized by the monomodal regime of the prevailing tropical climate. Two seasons, induced by the ITCZ (Inter Tropical Convergence Zone) front with its northward and southward oscillations, govern the water availability in the country: the rainy season of short duration with abundant rainfall during storm events inducing more runoff than infiltration, and the long dry season where no rainfall occurs but temperatures and evaporation are high. Faced with this situation, the governmental authorities decided to build reservoirs for accumulation of the runoff during the short rainy season for use in the dry season. In Burkina Faso, a number of 2000 reservoirs (MEE 2001) regulate water availability for population and livestock. The total volume of these reservoirs was estimated in 2001 by the GIRE project to be 2.66 billion m³ of water at their maximum capacity for an approximate total area of 100 000 ha. The average annual runoff volume (period 1961-1999) of the national river basins is estimated at 7.5 billion m³ and the average annual potential of surface water is 8.6 billion m³.

Table 3.1: Surface water resources in Burkina Faso (modified from MEE 2001)

National basin	Basin area (% of the country)	Flow volume downstream the basin (billion m³)	Volume in the reservoirs (billion m³)	Potential of surface water (billion m³)	Potential from modeling (billion m³)
Comoé	7	1.55	0.8	1.63	1.41
Mouhoun	30	2.64	0.29	2.75	2.94
Nakanbé	36	2.44	2.20	3.32	3.08
Niger	27	0.86	0.1	0.9	1.36
Total	100	7.5	2.66	8.6	8.79

3.3 Groundwater resources

Groundwater resources in Burkina Faso are closely linked to the geological structures and rainfall occurrence. The geological core formation is the Man-Leo shield of the West African craton from the Precambrian age (Ouédraogo et al. 2003). Mainly composed of crystalline rocks of low porosity in 82 % of the territory (MEE 1998) and based on fracturing and weathered regolith, they are overlain by Cambrian sedimentary rocks consisting of sandstones, schists or limestones with clay layers in the western parts of the country around the southeast of the Taoudeni basin. Recent Tertiary sedimentary rocks forming the so-called Continental Terminal are found in the north and the extreme southeastern parts. Based on these geological structures, the groundwater resources vary accordingly. Rainfall amounts and frequencies together with the land-cover and land-use changes are further factors. While in the sedimentary rocks, drilled boreholes can easily yield 10 m^3/h and more, in the crystalline basement rocks the average yield is around 2 m^3/h (MEE 2001). In these geological formations, the probability of siting positive boreholes depends on the thickness of the weathered zone; i.e., the regolith. The evaluation of the country's potential groundwater resources is based on careful assumptions on the specific yield of the geological structures known to be spatially highly variable (Table 3.2).

Table 3.2: Groundwater resources of Burkina Faso (MEE 2001)

National river basin	Estimated storage potential (Mm^3)	Annual renewal potential (Mm^3) [a]
Comoé	88080	2530
Mouhoun	175000	12400
Nakanbé	80000	8400
Niger	59000	9100
Total	402080	32430

[a] *This potential represents the infiltrated part of the rainfall in these river basins.*

3.4 Water resources management

Opoku-Ankomah et al. (2006) demonstrated that water resources management has been the population's concern since pre-colonial times. From traditional management under the responsibility of chiefs and priests to actual codifications with laws and rules, water resources have been permanently under careful management as they are considered as a common resource like land, which need to be shared equitably and in a sustainable way for long-term use. In Burkina Faso, since the independence, this need for water resources management by political authorities arose only after the droughts of 1973-1974 (MEE 1998). In the will to tackle the water problems that arose from this drought and its negative impacts, the first political decisions on water resources were elaborated in 1975. Since then, many other decisions and organizational structures have dealt with water resources management and development for equitable supply and livelihood improvement of the population. Among these decisions are the following (MEE 2001):

- Reconsideration of the first political decisions on water resources in 1982 in connection with the international decade of clean drinking water and sanitation (DIEPA 1981-1990);
- Creation in 1984 of a Ministry entirely and solely devoted to water resources, which later was restructured into the Water and Environment Ministry in 1995 integrating water as part of the environment to be consequently managed and now known as the Ministry of Agriculture, Hydraulic and Fisheries.
- Adoption in 1998 of the document on the national policies and strategies of water resources (Politique et stratégies en matière d'eau) considered as the final stage of the reconsiderations on the first political decisions. Together with this, the GIRE project was established in 1999 for the integrated aspects of water resources management as recommended in the Dublin and Rio international conferences on water and environment.

These developments depict the changes in the national concepts of water resources management with the adaptations in the organizational structures of public and private administrations in addition to laws and legal legislations codifying water resources management, usage and development. Among these laws are the national water code adopted in 1983 (MEE 1998), the land reform law (RAF) in 1996, the environmental code in 1997 and the water management law in 2001 (Youkhana et al. 2006). Governmental initiatives on national water resources management often attached to international decisions are locally supported by external partnerships and active national/international NGOs/institutions in the water sector. Youkhana et al. (2006) in their inventory of actors and institutions in the water sector of Burkina Faso listed 110 different actors including donor institutions (bilateral and multilateral, NGOs and international research projects), national corporate bodies, private companies, research and scientific institutions.

Table 3.3: Type and number of actors in the water sector in Burkina Faso (modified from Youkhana et al. 2006)

Structures	Donors and international actors	State and governmental structures	Assoc. struct.	National agencies, NGOs & corporate bodies	Local actors, org. and traditional authorities	Private companies & consultants	National research centers & scientific institutes
Number	40	17	18	11	9	8	7

All these efforts in the water sector have contributed to the construction of numerous hydraulic infrastructures for surface water retention, e.g., reservoirs, and boreholes for groundwater resources exploitation. Reservoirs alone have allowed irrigation of 15% of the potentially 165 000 ha of irrigable lands in the country (FAO 2005) for 20 000 tons of rice produced per year as the country's main crop. In addition to rice, maize production from irrigation has considerably improved food security in the country with more than 350 000 persons in the sector earning 242 US$ (for rice) to 1892 US$ (for potatoes) per ha.

Reservoirs also contribute to power generation and fresh water supply to the population. In 1999, it was estimated that 79% of the reservoir volume generated 35% of the electricity consumed in the country and supplied 36 towns and their population with 37 million m^3 of fresh water (MEE 2001). Hydraulic infrastructures for groundwater abstraction were evaluated in 2001 at 37 518 boreholes and modern wells supplying 90 % of the rural population in addition to 211 simplified tap water systems from boreholes with high yields of 10 m^3/h minimum. In 1998, the per capita water availability was evaluated at 1750 m^3 (MEE 1998), thus listing the country among those with sufficient water resources of more than 1000 $m^3/c/year$. In 2001, a re-evaluation gave a value of 852 m^3 as the annual per capita available water resources, predisposing the country to water shortages. UNESCO (2004) in its report foresaw the country to be part of the ten OSS (Observatory of the Sahara and the Sahel) countries with water shortages by 2025. Seckler et al. (1998) evaluated the available per capita world water resources and confirmed UNESCO predictions given 808 m^3 per capita for Burkina Faso by 2025.

In 1996, water use by agriculture was 55 % of the total water consumption in the country (UNESCO 2004). In 2000, of the total water demand of 2.5 billion m^3 (MEE 2001), 80% represent electricity generation and 20% for other activities. Of these, water demand for irrigation was 64%, for domestic needs 21% and for livestock 14%. The remaining 1% covered industrial demand, mines, environment, fishing and recreation.

3.5 Conclusion

Water resources in Burkina Faso are limited. Located in the heart of West Africa without access to sea, Burkina Faso water resources are constrained by the monomodal rainfall regime of the prevailing tropical climatic conditions. Underlain mostly by crystalline rocks, and thus poor aquifer conditions (unless they are enough provided with fractures and fissures), water resources are also limited by the fact that the country is the drainage zone and source of three transboundary river basins.

The severe droughts in the 1970’s just after independence revealed the country’s vulnerability to natural disasters due to insufficient preparedness. They led to plans and programs for water resources mobilization, conservation, protection and development in order to avoid future water shortages. Political and institutional reforms through laws and legislation have been developed and supported by international partners and local active organizations for numerous hydraulic infrastructures, water resources personnel training, water resources development programs, etc. Water supply to the rural population passed from 10 l/c/d to 20 l/c/d in 1990, and irrigation provided jobs for more than 350 000 people in addition to jobs for thousands of people involved in the transformation and commercialization of irrigation products. Irrigation development for vegetable and rainfed cotton production have substantially improved rural population income, with some people earning more than middle class public administration employees (MEE 2001).

Meanwhile, much remains to be done to secure water supplies in anticipation of negative impacts of the predicted climate change in the coming years. The weak economic situation[1] of the country is much constraining this possibility since it has limited investments in the water sector to a mere annual 16% of the required funds. Moreover, the lack of competent personnel in the water sector, equipment for data collection and reliable databases, office facilities and insufficient coordination between water actors (MEE 2001) remain also negative factors, which need to be eliminated in order to achieve water security for the population.

[1] Burkina Faso had a GDP of 314 US$/c in 2003 (FAO 2005) and ranked 162nd in the world in 2005 (IMF 2005) for its GDP at purchasing power parity of 1285 US$/c and 174th based on its HDI of 0.342 (UNDP 2006).

4 STUDY AREA

4.1 Introduction

In Burkina Faso, the name Kompienga refers at the same time to one of the 45 provinces, a department in this province and the biggest national hydropower dam built in 1988. The word derives from “Koul-péolgo” or “Kompiana”, which in the language of the Yana and Gulmatché communities living in the basin means “white river”, the color of the main river waters draining the basin (Dipama 1997, Koalaga/Onadja and Kano 2000). The Kompienga dam basin, in which the present research activities on groundwater potential for supplying the population’s water demand took place, is located in the Oti river basin.

4.2 Volta river basin

The Volta river basin is known as the 9th largest river basin in sub-saharan Africa (GEF-UNEP 2002) from the 63 transboundary river basins quoted by Opoku-Ankomah et al. (2006). It has an approximate watershed of 400 000 km² and covers six riparian countries in West Africa[2]. Almost 85 % of this area spans Burkina Faso (66.8% of the territory) and Ghana (63.7 %) and the remaining 15% stretch across Mali (0.8 %), Togo (47%), Benin (14.2%) and Cote d’Ivoire (2.2%). Located between the north latitudes of 5° 30’ and 14°30’ and the longitudes 5°30’W to 2°00’E (Amisigo 2005), the Volta river basin is drained by the lower Volta sub-basin in the south and the three main sub-basins in the north pertaining to the tributaries of Nakanbé (formerly White Volta), Mouhoun (formerly Black Volta) and Oti rivers (Andreini et al. 2000). The three tributaries flow southward to join each other at a confluence in the north central region of Ghana and flow downstream through a narrow gorge at Akosombo where a dam built in 1964 for hydropower generation has created the largest man-made lake in the world, Lake Volta (van de Giesen et al. 2001). All the rivers draining the basin are ephemeral and therefore dry up during the dry season except the Mouhoun river in Burkina Faso with baseflow mainly from the western sedimentary zone of the sandstone aquifers.

2 This watershed area varies greatly from one author to another. Niasse (2004) quoted 412 800 km² as the area of the basin, while van de Giesen et al. (2001) mentioned 398 000 km², Amisigo (2005) 394 196 km² referring to FAO (1997) and GEF-UNEP (2002) quoted 417 382 km² citing national reports from the basin countries. 400 000 km² is the average Volta basin area commonly used in literature.

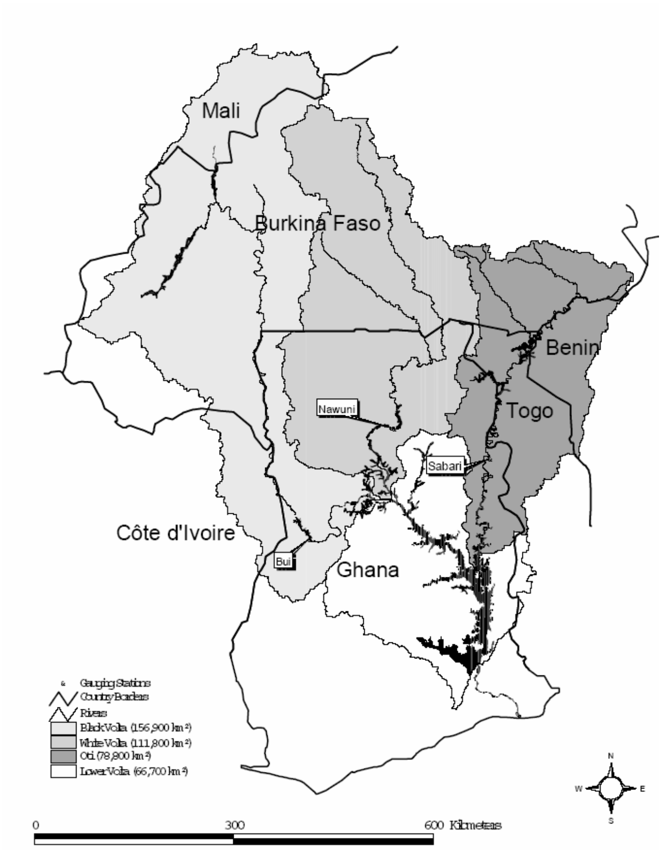

Figure 4.1: Volta river basin and its four sub-basins (Andreini et al. 2000)

The long-term average annual rainfall (1936-1963) of the basin (van de Giesen et al. 2001) varies between 1025 mm in the south and 600 mm in the north in the Sahel zone of northern Burkina Faso. The coefficient of variation of 7% from the mean rainfall for the whole basin in this period and 16% for Ouagadougou station (during the same period) depicts the temporal and spatial variability of the rainfall in the basin with a bimodal pattern in the south and a monomodal pattern in the north. Between the two zones exists a transition zone of 2 rainy seasons almost mingled. The major part of the basin going from the extreme northern Burkina Faso to the northern Ghana is under the monomodal rainfall regime of only 3 to 5 months duration. This situation consequently affects the Akosombo dam filling and energy production in Ghana as this upstream part of the basin is subject to recurrent droughts (Ofori-Sarpong 1985).

The climate in the basin as for all the West African countries is governed by the annual ITCZ oscillations from south to north and vice versa bringing rainfall to the southern parts between March and October and leaving the northern parts dry and hot with harmattan winds (GEF-UNEP 2002). The potential evaporation in the basin varies both temporally and spatially with the northern parts experiencing high annual potential evaporation of 2500 mm (Amisigo 2005), while in the south it is reduced to 1800 mm. Potential evaporation throughout the year usually exceeds rainfall in the basin with the exception of a few months in the rainy season. Water resources and agricultural activities in the basin are therefore unpredictable. However, 18.6 million people (Barry et al. 2005) with an annual growth rate of 2.4% (van de Giesen et al. 2001) rely on these activities for an average annual income of US$ 800 (Obeng-Asiedu 2004).

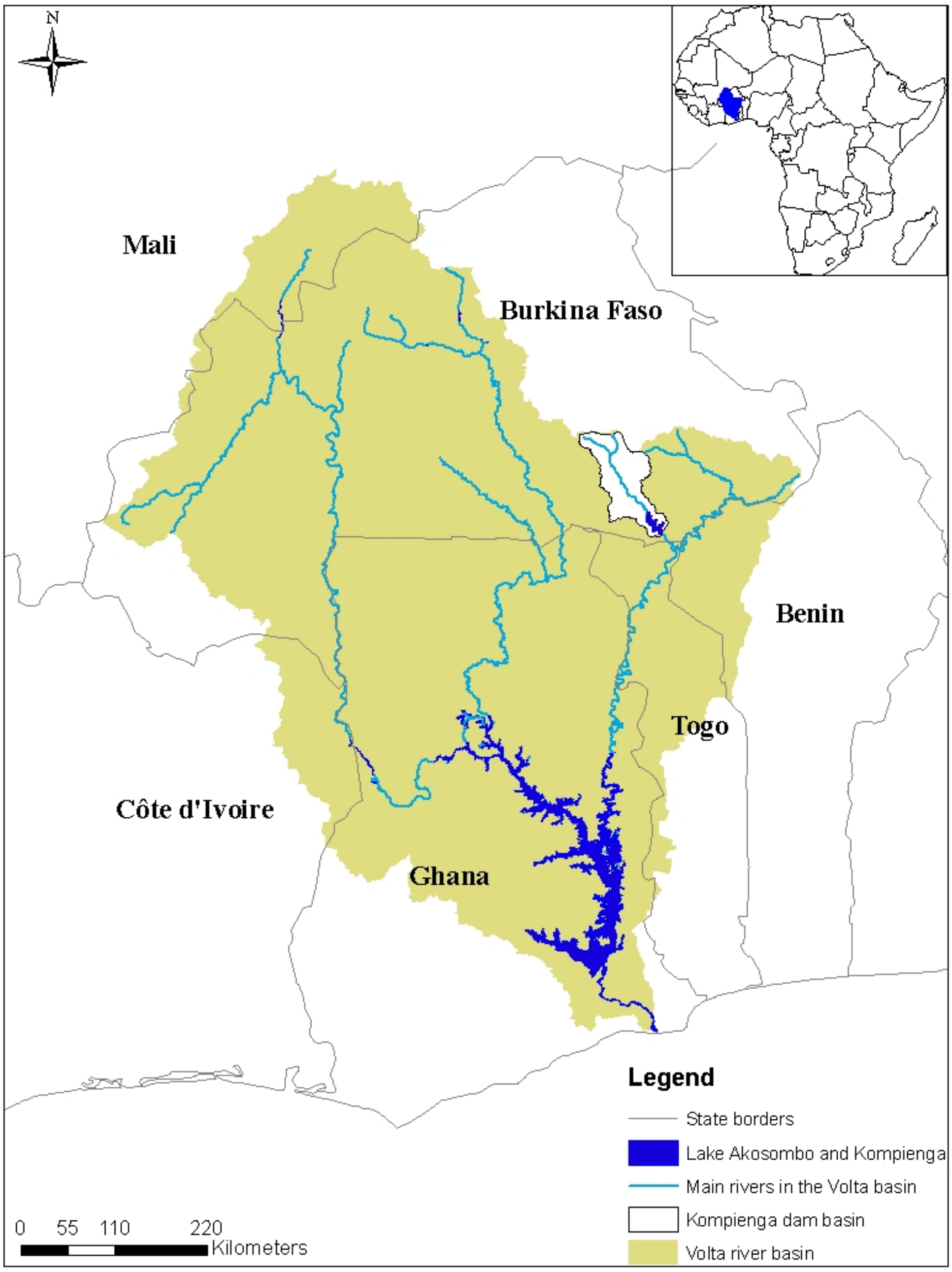

Figure 4.2: Kompienga dam basin within the Volta river basin in West Africa

Temperatures in the basin vary, from 27°C to 30°C with mean daily temperatures between 32°C to 44°C for daytime and 15°C for nighttime. Like temperatures, relative humidity in the basin varies according to locations and periods between 6% in the north during the dry season and 95% during the rainy season in the south of the basin (Oguntunde 2004).

The basin has a low relief with altitudes up to 972 m asl. Mountain chains are in the southern sub-basin, e.g., the Atakora ranges in the Oti sub-basin (GEF-UNEP 2002). The geological formations of the basin are dominated by the Voltaian system consisted of Precambrian to Paleozoic sandstones, shales and conglomerates. In addition, the basin comprises Buem formations, Togo series of sedimentary formations, Dahomeyan systems of metamorphic rocks and tertiary formations of the so-called Continental Terminal. The rock basement consists mainly of granites with Birrimian metamorphosed lavas and pyroclastic rocks, Tarkwaian quartzites, phyllites and schists. The Volta basin formations are mostly characterized by fractured porosity, thus a storage capacity and aquifer yield strongly depend on the density of fractures and fissures and the relative importance of the weathered zone induced by the water circulation and interactions with the rock materials.

Table 4.1: Hydrogeological characteristics of the Volta basin (GEF-UNEP 2002)

Sub-basin	Runoff coeff. (%)	Boreholes yield (m^3/h)	Mean yield boreholes (m^3/h)	Specific capacity ($m^3/h/m$)	Depth to aquifers (m)	Mean depth to aquifers (m)	Depth of boreholes (m)	Mean depth of borehole (m)
Nakanbé	10.8	0.03-24.0	2.1	0.01-21.1	3.7-51.5	18.4	7.4-123.4	24.7
Mouhoun	8.3	0.1-36.0	2.2	0.02-5.28	4.3-82.5	20.6	-	-
Oti	14.8	0.6-36.0	5.2	0.06-10.45	6.0-39.0	20.6	25.0-82.0	32.9
Lower Volta	17.0	0.02-36.0	5.7	0.05-2.99	3.0-55.0	22.7	21-129.0	44.5

Specific capacity is equivalent to transmissivity

Based on the four climatic zones (Figure 4.3) of Equatorial rain forest and Guinean savannah in the south of the basin, Sudanean savannah and Sahelian savannah in the north (Martin 2005), the basin vegetation and land-uses vary strongly. Amisigo (2005) referring to World Resource Institute (2003) report established the percentage of the land-cover/land-use of the basin depicting the high loss of the original forest zones which have been reduced to a very small area of 0.7% of the basin and therefore followed by the importance of the dry land areas as the consequence of the first observation.

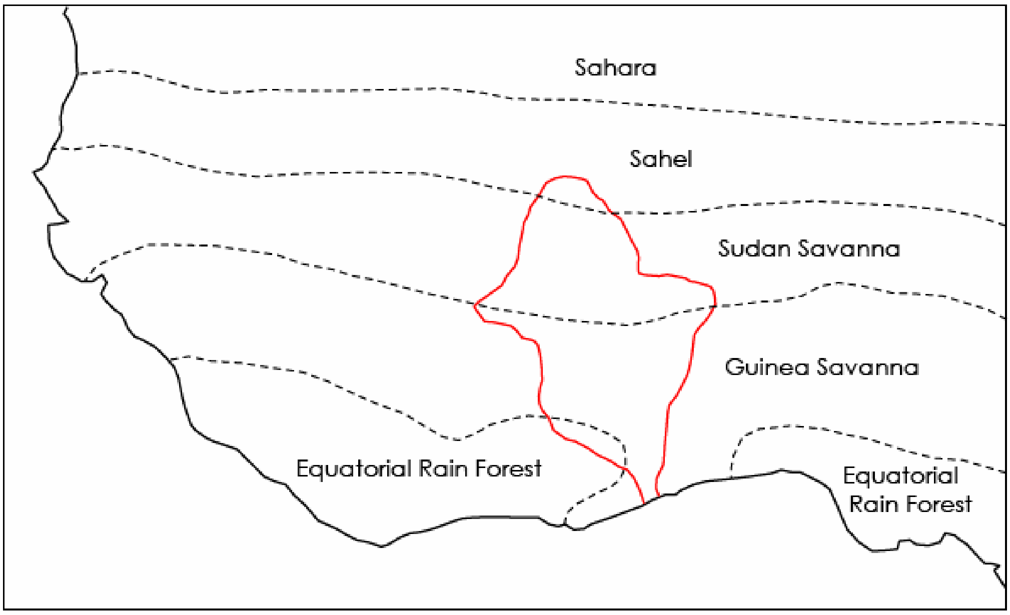

Figure 4.3: Climatic zones over the Volta river basin in West Africa (Martin 2005)

4.3 Kompienga dam basin

The study site is located in the eastern part of the country about 400 km southeast of Ouagadougou, the capital city of Burkina Faso. Kompienga hosts a hydropower dam built in 1988 on the Ouale (Kompiana) river and in 1995, provided 20% of the country's energy consumption (Dipama 1997). The dam's lake has an estimated area of 210 km² and a maximum capacity of 2 050 million m³ of water (SONABEL 2003) coming from the drainage of a watershed approximately covering 5911 km² over the provinces Kourittenga (northwest), Gourma (northeast and northwest), Boulgou (west), Koulpeologo (west and south), Kompienga (east and south) with Togo bordering the south (Figure 5.2). The basin is about 142 km long and 41 km wide.

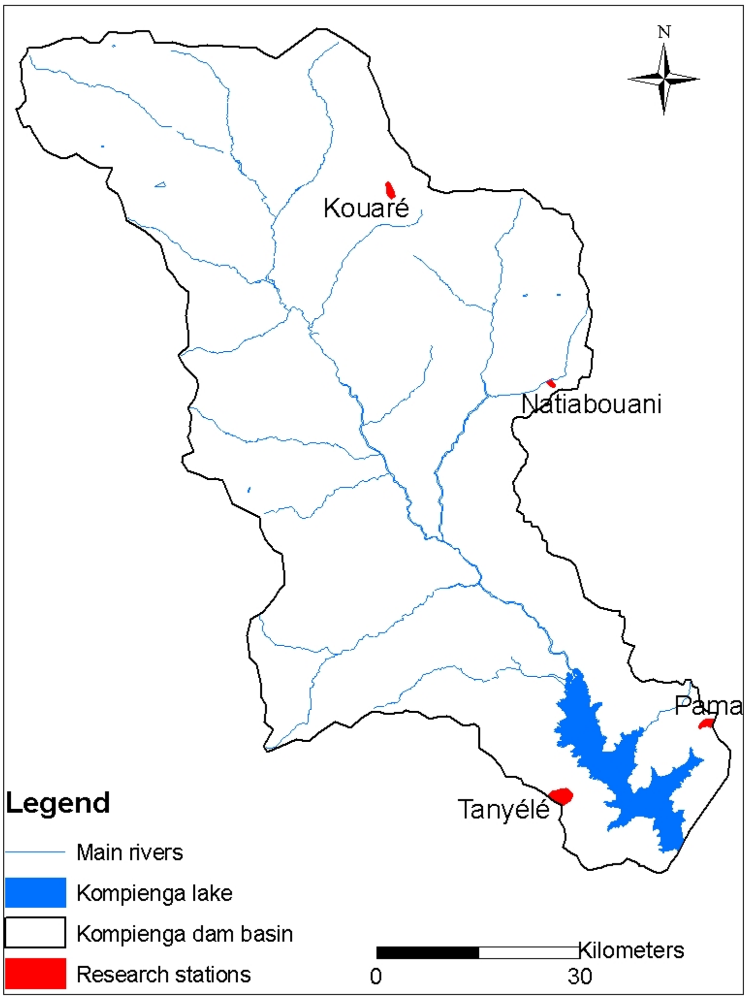

Figure 4.4: Kompienga dam basin and the four research stations

The tropical climate in the study area is characterized by two main seasons: a long dry season of 7 to 8 months (October/November to April) and a short rainy season of 5 months. The rainy season is characterized by heavy rainstorm events highly variable within time and space (Figure 4.7). The long-term mean annual precipitation (Thiessen polygon method) from 1959 to 2005 is 830.2 mm with a standard deviation of 126 mm, which illustrates the inter-annual variability of the rains. Within this period, a wet year with 1197 mm was observed in 1994 as well as a dry year with only 573 mm in 1984 (Figure 4.6). The area is therefore, considered as a semi-arid region with ephemeral rivers only flowing during the rainy season. In the dry season, they all dry up without any baseflow from aquifers. The Kompienga basin has a dendritic drainage system with an average drainage density of 0.6 km/km² around the main river Oualé (or Kompiana) and its two tributaries of Koul-peologo and Otabango (Dipama 1997).

Downstream of the dam, the Kompiana river discharges its waters into the Pendjari, which flows into Togo and becomes the Oti river flowing down to the Akosombo dam in Ghana. Since the Kompienga dam construction, a national water company station producing drinking water has been established. The station supplies treated water of negligible volumes from the dam's lake to the local population.

According to the rainfall pattern in the basin, it can be observed that the only favorable period of groundwater recharge is the rainy season, where rainfall can exceed potential evaporation for a few months (Figure 4.5) and induce runoff to fill the dam for energy production. Potential evaporation on the basin varies annually with an average of 2094.4 mm from the two years measurements (2004 and 2005) of the meteorological station at Tanyélé. Agricultural activities are mainly intensive during the rainy season period and no significant irrigation scheme exists in the basin.

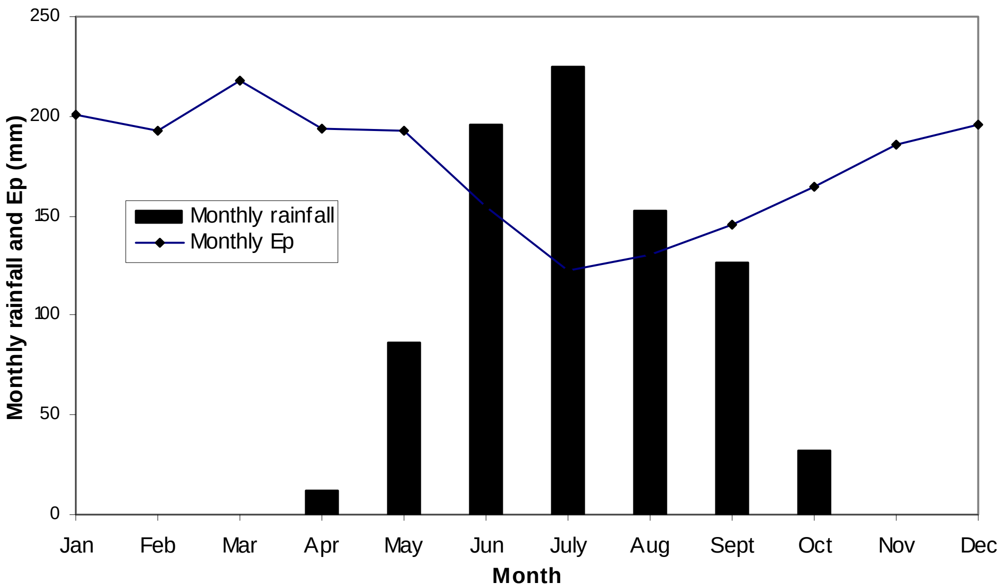

Figure 4.5: Monthly rainfall and evaporation (Ep) in the Kompienga dam basin in 2005

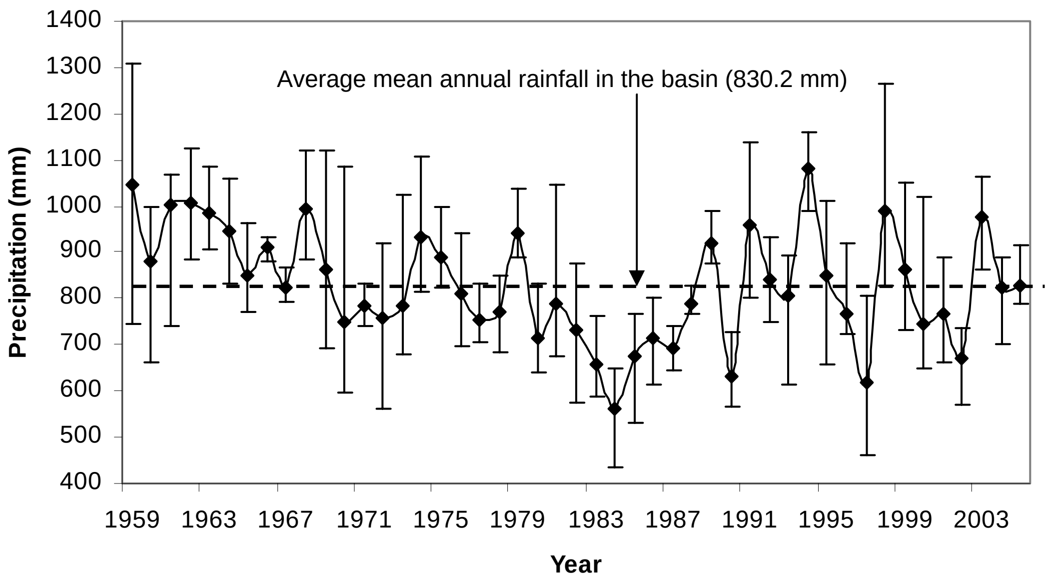

Figure 4.6: Inter-annual rainfall variability from long-term (1959-2005) weighted mean annual rainfall variability in the Kompienga dam basin from measurements at Koupéla, Fada, Pama and Ouargaye stations

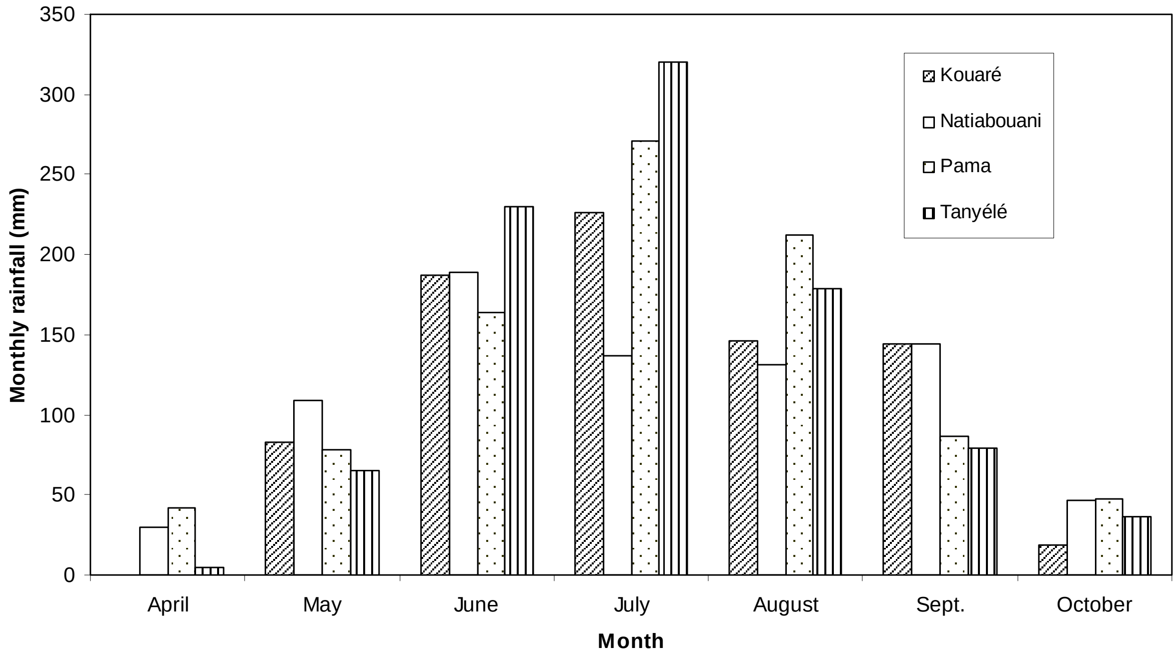

Figure 4.7: Temporal and spatial rainfall variability in the Kompienga dam basin in 2005

4.3.1 Geology and geomorphology

The revised geological map of Pama at scale 1:200 000 in digital and paper format combined with review of literature provided the geological and geomorphologic data of the Kompienga dam basin. The morphology is defined as a plateau with a flat topography on which a few hills exist mainly in the downstream area, where the dam is located. The highest elevation in the basin is about 328 m asl south of the Kouaré station and the lowest point is 140 m asl in a river bed downstream of the dam's spillway (Dipama 1997). The geological formations are paleoproterozoic or Precambrian (more than 2000 billion years old). The rocks mainly form the West African craton (Ouédraogo et al. 2003), which covers major parts of Burkina Faso and Côte d'Ivoire as the Man or Leo shield. This shield is made of volcanic sedimentary rocks and granitoids known as Birrimian rocks. Granitoids are the main (80%) components of the basement rocks forming around 60% of the Volta river basin (Martin 2005). They comprise migmatites, granodiorites and migmatic granites in combination with volcanic sedimentary rocks, mainly amphibolites. The other rocks are schists and quartzites in the center of the basin, partially covered by the dam's lake, orthogneiss in the northwestern part, green rocks (gabbro and diorite) in the south, and basalts and andesites in the southeast corner of the basin. Most of the structural faults in the basin are oriented NE-SW, sometimes with quartz veins as observed in the center of the basin from east to west. The basement rocks are often covered by lateritic soils resulting from weathering, which provide the sediments in the riverbeds and on the river banks as sands (Ouédraogo et al. 2003). The Tanyélé station is underlain by granite and leucogranite with biotite, the Pama station by granodiorite, tonalite and diorite with striped and folded quartzite dated from 2170 ± 6 million years. The Natiabouani station is underlain by granite with biotite and amphibole dated from 2143 ± 4 million years, and Kouaré is located on granite, granodiorite and quartziferous diorite with amphibole and biotite (2128 ± 4 million years).

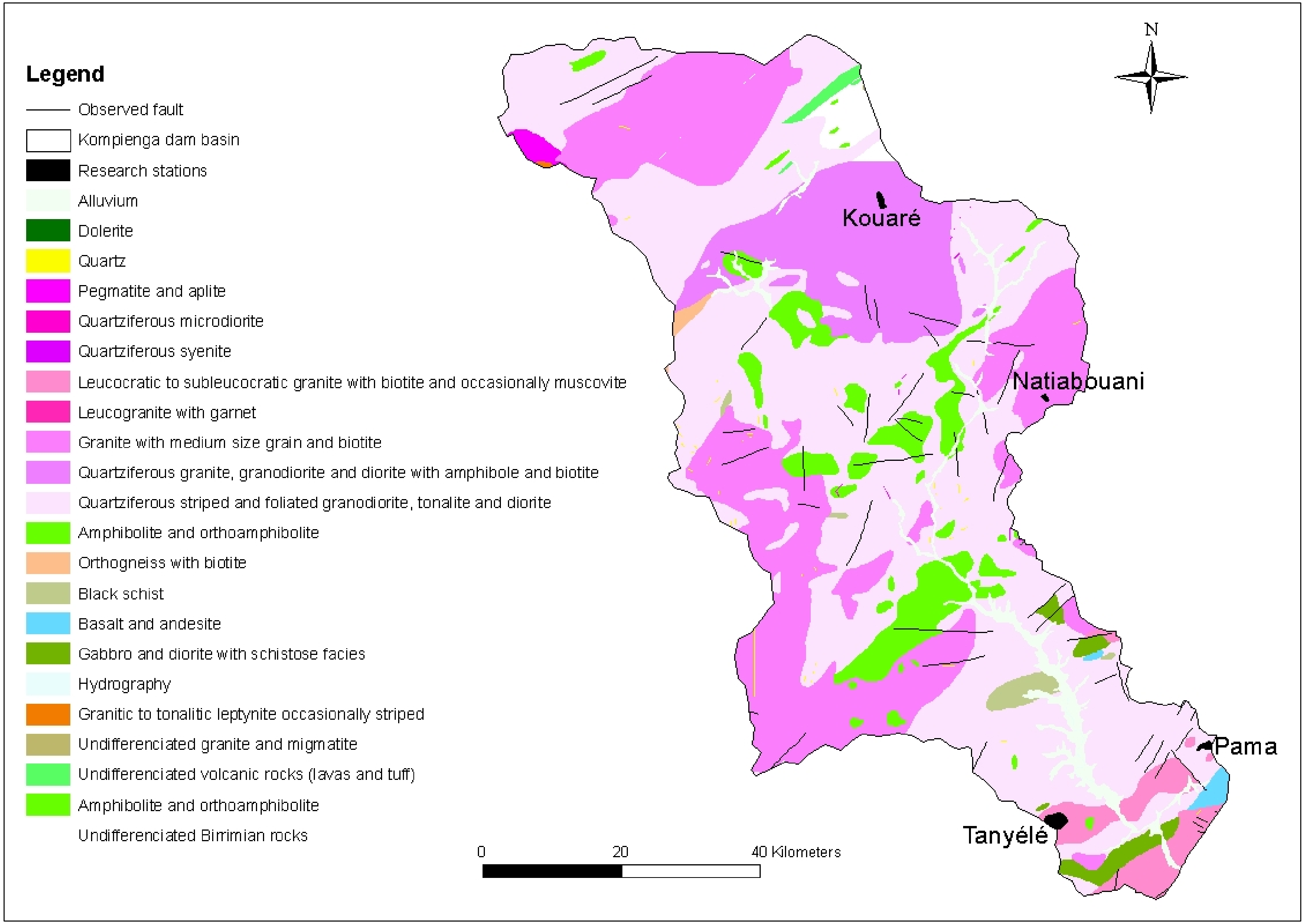

Figure 4.8: Geological map of the Kompienga dam basin

4.3.2 Hydrogeology

The basement rocks of the basin are known to be with fractured porosity, and they thus form poor aquifers for groundwater storage. Two hydrogeological domains are described by Ouédraogo et al. (2003) to be attached to the two main basement rocks of the basin, namely the granitoid aquifers and the volcanic sedimentary rocks aquifers. The former aquifers are called “early granitoids” aquifers often consisting of thin regolith with many fractures associated with successful boreholes siting. They are the only aquifers with exceptional yields of 10 m^3 of water per hour when the regolith is thick. The other granitoid aquifers are named “belated granitoids” aquifers with very thin regolith, less fractured and thus less productive boreholes siting. Meanwhile, the volcanic sedimentary basement aquifers with thick regolith have successful boreholes siting; however, the yield of these boreholes is often low.

4.3.3 Temperatures

The monthly average temperatures in the basin fluctuate between 25°C in January and 32°C in April. The daily mean maximum temperature is around 36°C in April with the highest maximum temperature observed in 1937 (44°C) and the daily mean minimum temperature is 20°C with 12°C in January 1936 (Dipama 1997). Recent observations on the temperatures indicate a rise in the daily mean minimum temperature of 1°C between 1960 and 1990 (Paturel et al. 2002) with 1.2°C for the Kompienga zone (from 20.9°C to 22.1°C between 1950 and 1999).

4.3.4 Soils

The crystalline basement rocks of the basin are generally covered by mineral soils mainly composed of leached ferruginous tropical soils found on most of the uplands of the basin (Dipama 1997). On the glacis, eutrophic brown soils associated to lithosols and hydromorphic soils exist while the lowlands are composed of alluvial plains of sandy and clayey soils under cultivation. The wetlands in the lowest topographical areas of the basin are composed of vertisols, hydromorphic soils and brown soils.

Boulet (1969) described the basin to be mainly composed of 6 soil textures: gravel in 46.57% of the basin area followed by clayey soil (26.67%), loamy sand (12.14%), sandy clay (6.62%), gravelly loamy sand (5.51%), alluvium (1.93%) and gravelly clay (0.57%). However, soil textures are subject to temporal and spatial (horizontally and vertically) variability, and peculiarities are likely to occur within the same environment, as was observed for the four research stations. In these stations, soil textures were described as being sandy loam at Tanyélé (Bagayoko 2006), gravelly clay at Pama, gravelly silt at Natiabouani and sandy clay at Kouaré.

4.3.5 Vegetation and land use

The climatic conditions in Kompienga have resulted in savannah vegetation of the Sudanian phytogeographic zone of the Guinko (1984) classification. This savannah vegetation is mainly composed of woody savannah made of large tree species of *Vitellaria paradoxum sp.*, *Parkia biglobosa*, *Lannea microcarpa*, *Adansonia digitata*, *Tamarindus indica,Sclerocarya birrea, Bombax costatum, Borassus aethiopium.* In the shrubby savannah, *Combretum glutinosum*, *Combretum nigricans*, *Ximenia Americana*, *Entada Africana*, *Anogeisus leiocarpus*, *Acacia gourmaensis*, *Strychnos spinosa* occur. The herbaceous savannah is made up of *Andropogon gayanus*, *Andropogon tectorium*, *Hyparrhenia rufa*, *Hyperthelia dissoluta*, *Hyparrhenia glabriuscula*. The Kompienga dam basin is one of the relatively well-vegetated parts of Burkina Faso due to restricted and protected zones developed by the authorities for wild animal protection and tourism purposes. However, since the dam construction, where part of the basin vegetation was destroyed, permanent threats to the remaining vegetation exist through new settlers needing lands for housing, agriculture, domestic and commercial purposes. In 1978, rainfed agriculture, mainly cereal crops, was estimated to be occupying 6% of the basin area (334.28 km^2) and practiced by 97% of the inhabitants (Dipama 1997), while the remaining area was covered by natural vegetation. In 1988, cropping areas were seen to be occupying 961.81 km^2 (17% of the basin area), i.e., an increase of 183 % to the detriment of the natural vegetation.

4.3.6 Population

The population in the Kompienga basin was estimated in 1985 to be 104 000 inhabitants living in 134 villages (Dipama 1997) with a density of 18 inhabitants/km^2, which is lower than the national density of 29 inhabitants/km^2 but more than the Gourma province population density (11 inhabitants/km^2). In 1975, the census revealed a total population of 63 000 inhabitants in the basin, while the census in 2005 (MAHRH 2006) depicted approximately 270 000 inhabitants living in about 215 villages in 15 departments in 5 provinces. Referring to Balk et al. (2005) formula, the population growth rate can be estimated at 4.8 %. This growth rate is higher than the rate of 3.2 % stated by Dipama (1997), which is certainly due to the difference in the considered boundaries of the basin in the two estimates. The latter estimate refers to the whole population in the basin and its vicinity, which is likely different from the first estimate in 1975, where the basin boundaries were different, as the dam in the south had not yet been built. Moreover, after the dam construction in 1988, the population of the basin significantly increased with the creation of new villages like those for settling fishermen and their families, who came sometimes from far away (Mali or Niger; Dipama 1997), mainly for fishing and sometimes agricultural purposes.

4.4 Conclusion

The Kompienga dam basin within the Volta river basin in the southeastern part of Burkina Faso is a hydropower dam basin in a watershed of about 6 000 km² where approximately 270 000 people live. Practicing mainly subsistence agriculture comprising rainfed cereal crops, they cultivate poor lands with gravelly and clayey textures in addition to fishing in the dam's lake. The originally dense vegetation in the basin was cleared for dam construction, and this has remained so due to an increasing population wishing to benefit from the dam. The monomodal rainfall pattern with a 5-month rainy season in addition to the geological formations of crystalline basement rocks consisting of granites and amphibolites, very much limit groundwater recharge to the basin aquifers. These aquifers, on which the population mainly rely for their supply through wells and hand pump boreholes are currently found in fractures and similar features of the basement rocks.

5 MATERIALS AND METHODS

5.1 Introduction

The research site Kompienga dam basin is located between the northern latitudes 11°00' and 12°10' and longitudes 00°50' east and 00°20' west. In this basin of 5911 km², four representative stations of 1 to 6 km² of mainly first order watersheds were selected. They are: the Pama station circa 5 km east of the dam's lake with a watershed of 2.19 km², the Tanyélé 5 km to the west with a second order watershed of 6.04 km², the Natiabouani station about 60 km north of Pama with a watershed of 0.86 km², and Kouaré located at the extreme upstream part of the dam basin in a 2.09 km² watershed (Figure 4.4). The stations were selected based on criteria of accessibility, areal importance of their geological formations in the basin, geographical position to the dam's lake, and the resources availability for the research activities.

5.2 Materials and methods

Three methods for estimating the groundwater potential were foreseen to be used, and accordingly on each of the four stations, the following instruments were installed:

- Rain gauges for measuring rainfall and collecting rainwater samples;
- Divers; Eijkelkamp Co. devices placed downstream of the station watershed for automatically recording rainfall runoff at fixed 3-minute intervals. The total runoff discharge of the basin was calculated using the data from the dam office administration; SONABEL (Société Nationale Burkinabé d'électricité);
- Piezometers set up with augers at a maximum depth of 5.5 m to monitor shallow groundwater level fluctuations during the seasons.

To evaluate the groundwater potential using the chloride mass balance approach, water samples were taken from boreholes, piezometers and rain gauges on a monthly basis. Water samples from rain gauges for each month were the mixed total of rainfall taken to the laboratory for chloride analysis. From piezometers, water was sampled upstream and downstream of the watersheds. All samples were separately collected in 100-cm³ plastic containers and transported to the laboratory for analysis of chloride concentration.

The Tanyélé station had a complete weather station and an Eddy Correlation (EC; Figure 5.1) station installed in November 2002 in the framework of a project funded by the European Union (VINVAL). This station consisted of two main devices: a Gill Windmaster Pro (3-dimensional) ultrasonic anemometer, and a Campbell Krypton KH2O hygrometer, which recorded in 10 Hz frequency, air temperature and humidity as well as wind velocity from 3 directions (Elbers 2002). Fluxes were averaged over hourly intervals to obtain moisture and heat fluxes. Recorded raw data were stored on a PCMCIA card via Palmtop computer using the Basic software Eddylogp. The data were processed using FORTRAN program named ALTEDDY to derive latent and sensible heat flux, friction velocity, Monin-Obukhov length, flux footprint and necessary error corrections (Bagayoko 2006).

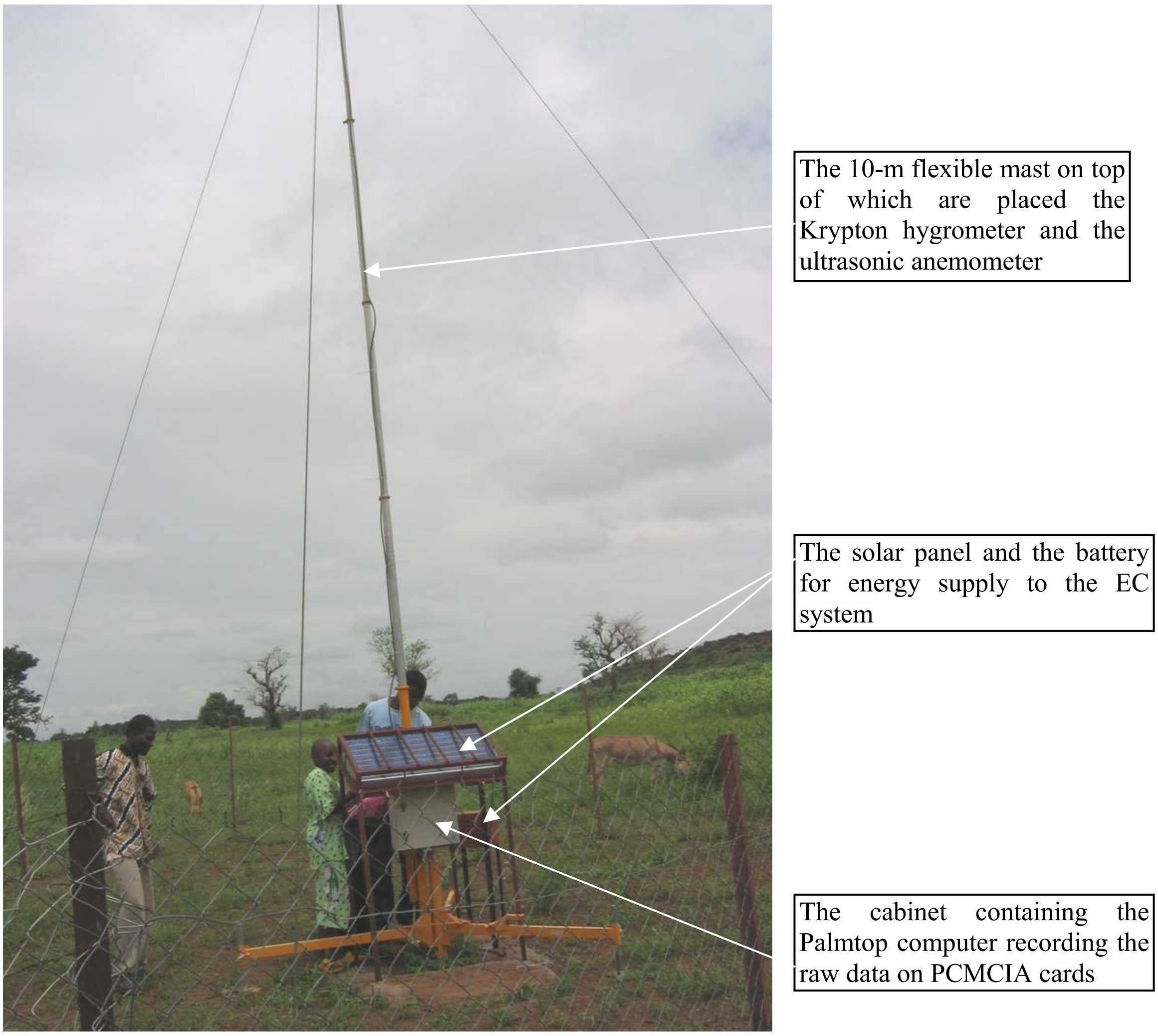

Figure 5.1: Eddy Correlation station at Boudtenga near Ouagadougou

The weather station was an Eijkelkamp Co. mini electronic meteorological station using a small solar panel. The station was equipped with an anemometer recording wind speeds and direction, a tipping bucket raingauge for rainfall monitoring and sensors measuring solar radiation, air temperature and humidity. All parameters were recorded every 20 minutes at 2-m height and stored in the main unit memory of the station. The data were periodically downloaded using the software HogWin. Within the whole research area, there are two national weather stations (Pama and Comin Yanga) with a relatively good dataset in addition to the synoptic weather station of Fada N'gourma and the stations of Ouargaye and Koupéla outside the research basin.

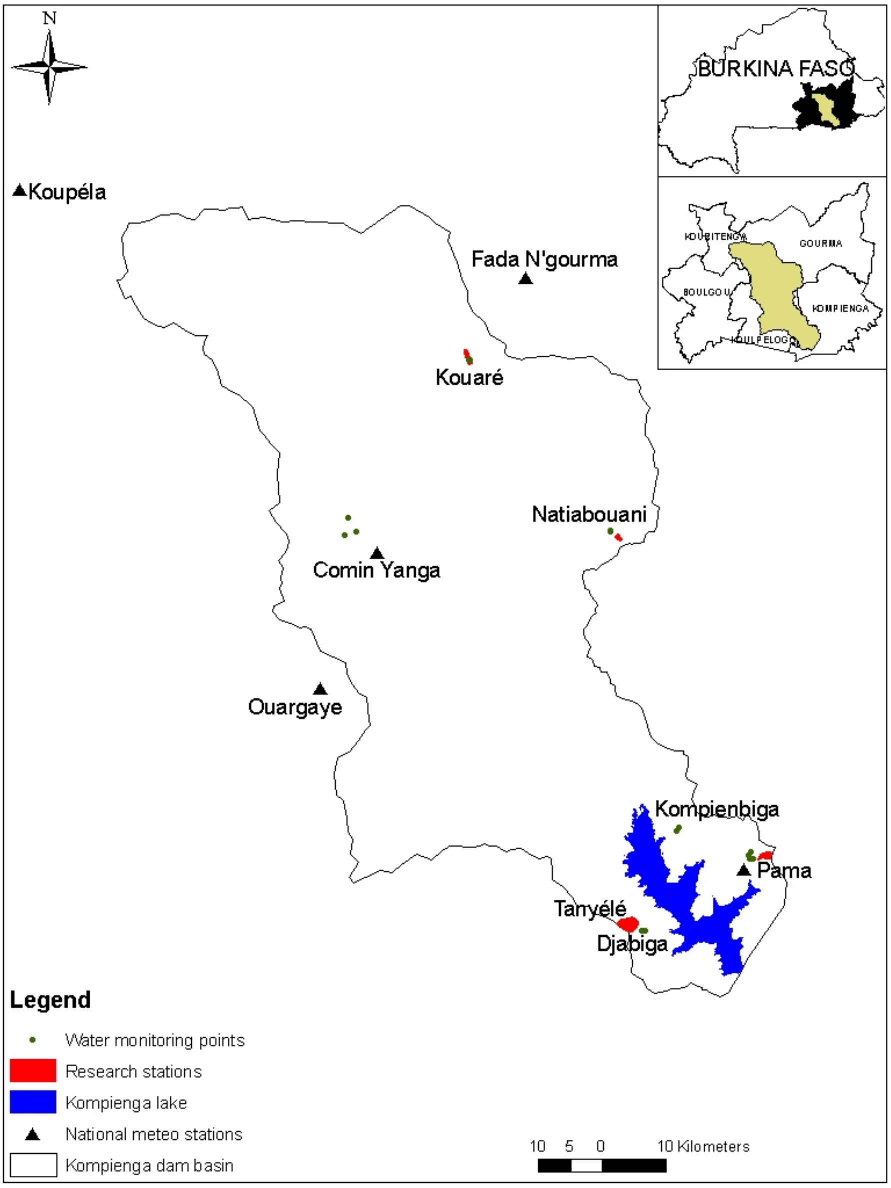

Figure 5.2: Kompienga dam basin within the 5 provinces in south-eastern Burkina Faso and the location of the stations that provided the research data

Additionally, river parameters (slope and transversal section dimensions) were measured to complement the runoff recorded by the divers and derive watershed discharge. Meanwhile, the whole basin runoff into the dam and the discharge from the dam for energy production as well as lake evaporation data were collected from SONABEL. Long-term rainfall data series and meteorological parameters (wind speed, relative humidity, air temperature and solar radiation) from weather stations near or within the study basin were also collected from the local administration of the Agriculture, Hydraulics and Fisheries Ministry (DRAHRH) and the national meteorology office in Ouagadougou.

Table 5.1: Instruments installed on the research stations

Instruments	Tanyélé	Pama	Natiabouani	Kouaré
Rain gauges	1	1	1	1
Piezometers	5	4	2	6
Divers	2	1	1	1
Weather station	1	1	0	0

Rainfall was measured daily with rain gauges during the same period at all the stations. Surveyors recruited from population were trained for recording rainfall in notebooks and collecting monthly water samples from rain gauges into 10-liter plastic containers for chloride analysis in the laboratory. For piezometers, recruited local surveyors monitored the daily water level fluctuations in the pipes at the same period of the day with bell-tape measurers (Figure 5.8) until water disappeared below the pipes. At the Natiabouani station, as it was not possible to find a suitable person, the author did the monitoring by collecting the water level data in the fieldwork period during the trips to the research stations.

To evaluate the groundwater potential with the water balance method, runoff, evaporation and rainfall recorded from the four stations were brought to the whole basin, and the infiltrated part of the rainfall recharging the research area was then deduced.

For the chloride mass balance approach, the station data were areally weighted using the Thiessen polygon method with ArcView software. Some well known prerequisites in the use of this approach and quoted in Bazuhair and Wood (1996), Bromley et al. (1997), Martin (2005) and McNamara (2005) were verified and found valid for using the method in evaluating the basin groundwater potential.

5.2.1 Chloride mass balance method

One of the methods used in this study on estimating the Kompienga dam basin groundwater potential is the Chloride Mass Balance method (CMB). As quoted by Gieske (1992), this method for groundwater recharge determination is based on the ratio of chloride concentration in rainwater to that in groundwater of a given water system. The equation for groundwater recharge estimation is derived from the application of the principle of mass conservation of chlorides in the water system. Prerequisites in the use of the method consist of the conservative state of chloride ions, rainfall considered as the sole source of chlorides in the water system, chlorides not taken up significantly by plants, no significant runoff out of the system or inflow from other water systems into the considered water system (Bromley et al. 1997). Considering these prerequisites fulfilled, the groundwater recharge of a water system is given by the equation:

$$R = P.\frac{Cl_P}{Cl_{gw}} \tag{5.1}$$

where R is the groundwater recharge flux $\left[LT^{-1}\right]$, P the average annual precipitation $\left[LT^{-1}\right]$, and Cl_p, the average rainfall-weighted chloride concentration $\left[ML^{-3}\right]$ and Cl_{gw}, the average groundwater-weighted chloride concentration. M represents mass, T is time and L is length, all in consistent units.

From this equation, the basin rainwater chloride concentration; Cl_p, was determined from weighting the unit rainwater chloride concentration of each station, Cl_{ps} derived from equation 5.2.

$$Cl_{ps} = \frac{\sum P_i Cl_i}{\sum P_i} \tag{5.2}$$

with $P_i[L]$, the i[th] precipitation in each research station having a chloride concentration $Cl_i\,[ML^{-3}]$ in its sample.

To obtain the groundwater chloride concentration of the whole basin, Cl_{gw}, the unit groundwater chloride concentration of the four stations, Cl_{gws} was first calculated using the harmonic mean of all monthly values of each station with equation 5.3 in order to reduce the differences between the unit values:

$$Cl_{gws} = N.\left(\sum_{1}^{N}\frac{1}{Cl_{gwi}}\right)^{-1} \tag{5.3}$$

with N the dimensionless total number of monthly values for each station, and Cl_{gwi} represents groundwater chloride concentration for the station in month i with consistent units of $[ML^{-3}]$.

The unit chloride concentrations in the groundwater of the stations, Cl_{gws}, were then spatially averaged to derive the chloride concentration in the groundwater of the whole study area termed Cl_{gw}. The areal weights of the stations (Table 6.5) were determined using the geographical coordinates of the stations with the Thiessen polygon method.

The data on the rainwater chloride concentrations in 2005 were thought to have major errors making them not valid for estimation of the annual basin recharge. For this reason, a second data collection during a short period of 3 weeks was realized in September 2006 (details in Section 6.2.2). This provided explanations for the shortcomings in the 2005 data, as well as additional data and ways to better re-evaluate the basin recharge. Given this opportunity, the basin long-term annual recharge was re-evaluated for 2005 and 2006 using the following procedures.

Basin recharge in 2005

According to the correlation observed between the chloride concentration in the groundwater data series in 2005 and 2006 (Figure 6.4), the first data were updated according to the correlation equation. The chloride concentrations in the groundwater for each station, Cl_{gws}, were calculated using equation 5.3 and the whole basin groundwater chloride concentration, Cl_{gw}, was the average of the areal weighted unit Cl_{gws}. Rainwater chloride data for 2005 were discarded for lack of correlation with the 2006 data series (correlation coefficient of -0.0048) and the basin rainwater chloride concentration, Cl_p, was determined by averaging the unit chloride concentration of the four stations in 2006 obtained from equation 5.2. The basin recharge in 2005 was then re-evaluated from equation 5.1 with Cl_p and Cl_{gw} as determined above and P was the annual precipitation in the basin in 2005.

Basin recharge in 2006

The parameter Cl_{gw} of the whole basin recharge estimation in 2006 was determined from averaging the of the unit areal weight of the groundwater chloride concentration measured at the stations in 2006, which was the average of the two values from the groundwater sample of the stations. Cl_p, the chloride concentration in rainwater of the whole basin in 2006, was the chloride concentration in the rainwater of the 3-week period of survey brought to the whole rainy season rainwater volume using equation 5.2. Finally, with the two parameters and the annual precipitation in the basin in 2006, the recharge was calculated.

Basin recharge using data from nearby sites

After discarding the rainwater chloride concentration of 2005, using the groundwater chloride concentration, a rough estimate of the basin recharge was made based on the rainwater chloride concentration of nearby sites (northern Ghana, southwest Niger and central Burkina Faso). The basin rainwater chloride concentration was the average of the rainwater chloride concentration of these sites and the groundwater chloride concentration for the basin was the same as determined previously from the average of the weighted harmonic mean value of the groundwater chloride concentration of the stations. The formula of equation 5.1 was used to derive the basin recharge for 2005 according to the precipitation.

5.2.2 Water balance method

This method is based on the knowledge of the hydrological balance parameters of the water system from which the recharge is calculated. Despite the uncertainties in the recharge estimate by this method for arid and semi-arid zones due to difficulties in obtaining reliable values of the balance components, the method remains valid in recharge estimation if time steps and spatial boundaries of the water systems are well defined (Sokolov and Chapman 1974, Gee and Hillel 1988 and Lerner et al. 1990). The method is based on the principle of mass conservation applied in hydrology (equation 5.4):

$$I - O = \frac{dS}{dt} \tag{5.4}$$

where $I\left[LT^{-1}\right]$ represents the input flows, $O\left[LT^{-1}\right]$ the output flows, $dS[L]$ the change in storage, and $dt[T]$ the time increment.

Considering the Kompienga dam basin, the equation can be stated as:

$$P + Q_{on} = E + Q_{off} \pm \Delta S + \eta \tag{5.5}$$

where P is precipitation, Q_{on} the flow in the basin, Q_{off} the flow from the basin, E the evaporation in the basin, and ΔS the change in the stock including recharge. All the parameters are in consistent units of $\left[LT^{-1}\right]$. η is an error term accounting for discrepancies due to errors in component measurement or estimation and is used in order to obtain a water balance that is as accurate as possible.

Applying the water balance method to the Kompienga dam basin recharge estimates requires definition of spatial and temporal boundaries. The spatial boundaries are the limits of the Kompienga dam basin, and temporal boundaries are the time scale (year) of the recharge assessment so that the estimate can be compared with other methods. To assess the annual recharge of the basin with the known parameters of the water balance, the spatial boundaries will be divided into two parts with the dam as one unit and the other parts of the basin considered as a second unit. It is assumed that no external surface water or groundwater is flowing into the basin. Using equation 5.4 for each part yields:

- For the dam part, parameters involved in the balance are :

P_d = precipitation to the reservoir (lake) surface;

E_0 = lake evaporation;

L = water withdrawn from the lake for drinking water and energy production;

R_1 = recharge from the lake;

ΔS_1 = stock variations in the lake reservoir;

r_1 = basin runoff into the lake;

All the parameters are in consistent units of $\left[L^3T^{-1}\right]$. The equation of the mass conservation principle in hydrology implies that:

$$P_d + r_1 = R_1 + E_0 + L \pm \Delta S_1 \quad (5.6)$$

From equation 5.6, r_1 can be inferred as:

$$r_1 = R_1 + E_0 + L \pm \Delta S_1 - P_d \quad (5.7)$$

- For the basin part, the balance parameters are:

P_b = precipitation in the basin;

Ea = actual evaporation over the basin;

r_2 = runoff in the basin;

R_2 = recharge in the basin;

ΔS_2 = stock changes in the basin

The parameters are in consistent units of $\left[L^3T^{-1}\right]$.

The application of equation 5.4 to the basin part yields:

$$P_b = r_2 + R_2 + Ea \pm \Delta S_2 \quad (5.8)$$

From equation 5.8, r_2 can also be inferred as:

$$r_2 = P_b - R_2 - Ea \pm \Delta S_2 \quad (5.9)$$

As can be seen, r_1 and r_2 are the same parameters of the balance and express the runoff from the basin into the lake. Therefore, equalizing equations 5.7 and 5.9 yields equation 5.10 for annual groundwater recharge in the whole basin:

$$R = P - Ea - E_0 - L \pm \Delta S_1 \pm \Delta S_2 \quad (5.10)$$

with R = annual recharge under the whole Kompienga basin comprising R_1 and R_2;

P = annual precipitation in the basin;

Ea = annual (actual) evaporation on the basin;

E_0 = annual evaporation of the lake;

ΔS_1 = annual change in storage within the lake according to input (rainfall and run-on) and output (energy and drinking water production);

L = annual water withdrawn from the dam for drinking water and energy production;

ΔS_2 = annual stock flux in the basin (the unsaturated zone soil moisture). This flux at an annual time scale is considered zero. This implies that equation 5.10 becomes 5.11 for the annual time scale recharge estimation:

$$R = P - Ea - E_0 - L \pm \Delta S_1 \quad (5.11)$$

At shorter time steps, in addition to the lake fluxes, one should also consider the stock variations according to soil moisture storage and retention capacity in the unsaturated zone, ΔS_2 .

All parameters involved in the recharge estimate with the water balance method are measured at the basin scale with the exception of rainfall measurements done from the four stations and brought to the basin level using areal weights of the Thiessen polygons. In addition, complementary data were collected from local institutions of the Agriculture, Hydraulics and Fisheries Ministry (DRAHRH), SONABEL, ONEA/Kpg and the national meteorology office for precipitation, runoff in the basin, lake evaporation, lake level fluctuations and water quantities withdrawn from the lake for energy and drinking water production.

Actual evaporation (Ea) data were inferred from the EC station in correlation with rainfall amounts and Ep (potential evaporation) derived from the 2-m high meteorological station. The Ea derivation procedures are described below. For runoff in the basin, the correctness of the SONABEL data was verified by means of the daily records of the lake level fluctuations, the withdrawals from the lake and the tare curves of the lake volume and surface against water heights (Figure 5.3). In the same way, the estimated lake evaporation data by SONABEL were corrected when necessary, according to interpolated values from Pouyaud's (1985) studies on evaporation of Lake Bam (Burkina Faso) and Lake Tchad (Chad).

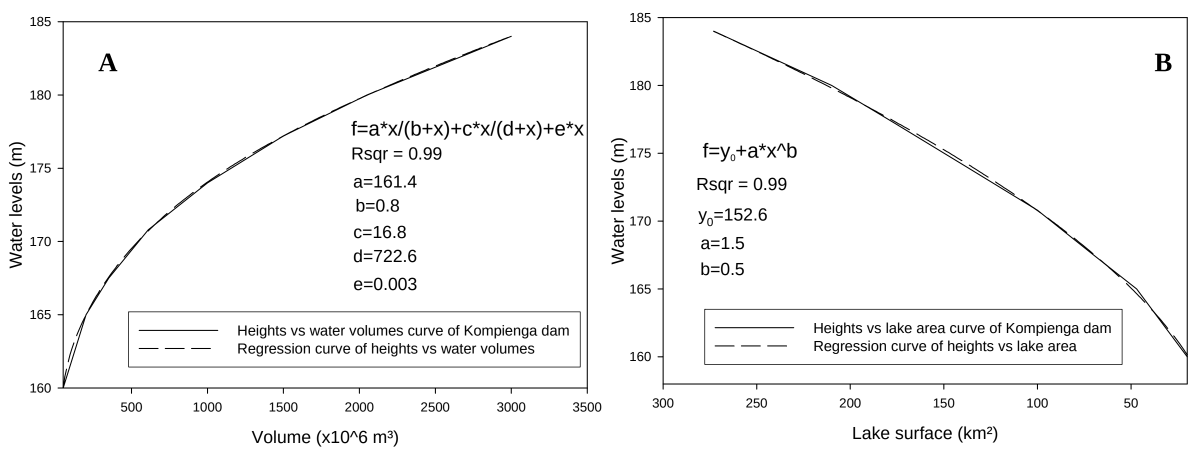

Figure 5.3: Fitted regression curves for Kompienga dam water levels versus volumes (A) and levels versus lake area (B)

Actual evaporation derivation procedures

The EC station located near the dam's lake at the Tanyélé station measured latent and sensible heat fluxes. The raw data retrieved from the EC station were in ASCII format and were processed with Alteddy software producing three different files. One file from the three (Appendix 1, Elbers 2002) was made of latent heat flux and daily mean temperature parameters used to derive hourly actual evaporation in combination with the latent heat of vaporization (λ) as in the equations below (Monteith and Unsworth 1990):

$$E = 3600.\frac{LE}{\lambda} \text{ and} \tag{5.12}$$

$$\lambda = 2500300 - 2359.T \tag{5.13}$$

with $E[mm/h]$, as actual evaporation, $LE\ [W/m^2]$ the latent heat flux, and $\lambda[J/kg]$ the latent heat of vaporization derived from hourly temperature $T[°C]$ as in equation 5.13.

The daily actual evaporation from the basin was obtained by adding up the hourly Ea values of a day. Meanwhile, the actual evaporation (Ea) data series derived from the equations above and the daily potential evaporation (Ep) series derived from the FAO Penman-Monteith equation (FAO 1990) were made of gaps of one day to 10 or even 15 consecutive days. In addition, Ea data of the whole year 2005 were lacking due the EC station transfer in January 2005 to Boudtenga near Ouagadougou.

In order to validate the basin recharge for 2005 using the water balance method, the existing data series were generalized. The daily short Ea and Ep gaps were first filled by averaging the values of the three consecutive days surrounding each gap. The large gaps were filled using regressive fitted exponential (R^2=0.87) and logarithmic (R^2=0.46) curves for scatter plot graphs (Figure 5.4) of Ea 2004 against relative humidity and Ep 2004 against Ep 2005. This resulted from good correlations (86 %) between relative humidity and Ea 2004, and 67 % between Ep 2004 and Ep 2005. Full data series of Ea and Ep were hence obtained for 2004 in addition to 2005 for Ep data as the weather station remained in operation on the site.

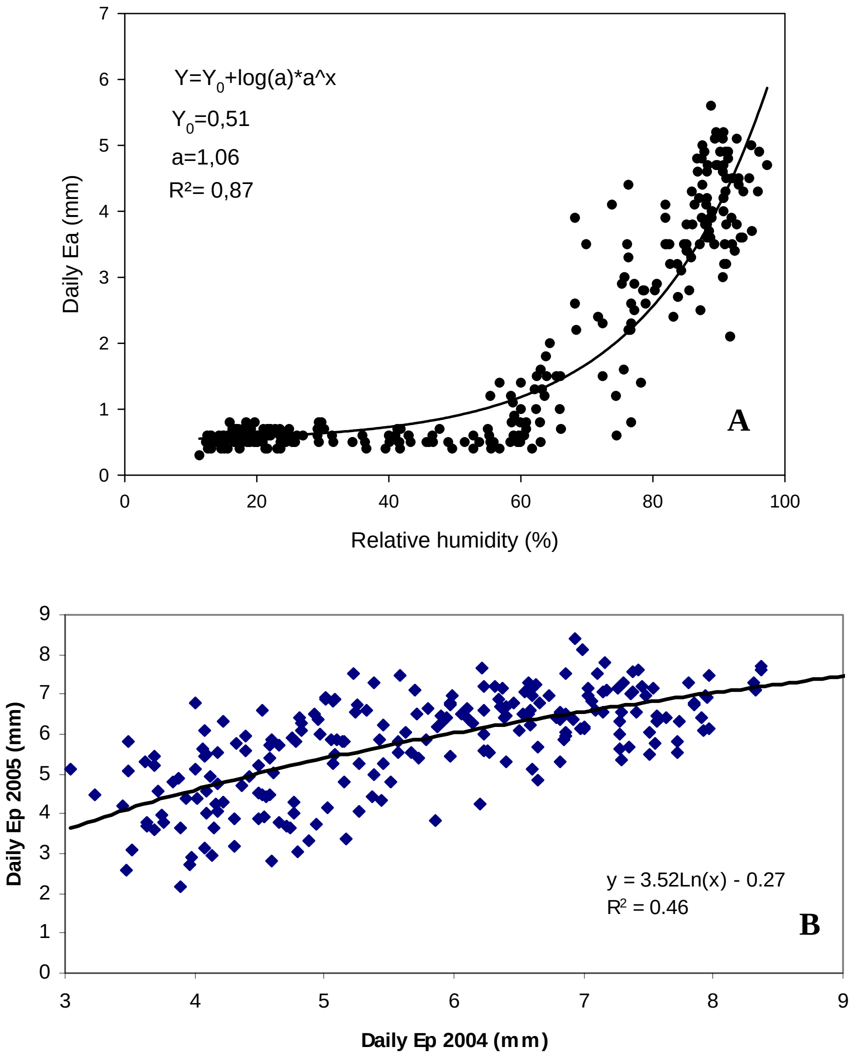

Figure 5.4: Regressive exponential curve (A) and logarithmic curve (B) for fitting actual evaporation (Ea) and potential evaporation (Ep) long series data gaps

To obtain the indispensable Ea data for 2005 in the water balance computation, a module of the WaSiM-ETH model was used with Ep and rainfall as required input data (Schulla and Jasper 2001). The first step consisted of computing 2004 Ep and rainfall to derive Ea 2004 as simulated values for comparison to the observed values from the EC measurements. The plotted graph of the ratio of the observed Ea/Ep versus rainfall 2004 quite depicted the seasonal variations of the two parameters (Ea and Ep) following the rainfall events in the basin (Figure 5.5) showing that Ea 2005 could be derived from Ep 2005 according to the soil moisture induced by rainfall. The topmodel-approach module of WaSiM-ETH for estimating Ea was therefore used with the following equations considered as simple reduction of Ep to derive Ea when soil moisture storage drops below a specified level η:

$$Ea = Ep \cdot SB/(\eta \cdot SB_{\max}) \text{ if } SB < \eta \cdot SB_{\max} \tag{5.14}$$

$$Ea = Ep \qquad \text{if } SB \geq \eta \cdot SB_{\max} \tag{5.15}$$

with Ea = real or actual evaporation (mm);

Ep = potential evaporation (mm);

SB = actual content of soil water storage (mm);

$SB_{\max}$ = maximum capacity of soil water storage (mm);

η = threshold value for soil moisture, below which the evaporation is reduced compared to the potential evaporation ($\eta \approx 0.6$ after Menzel 1997)

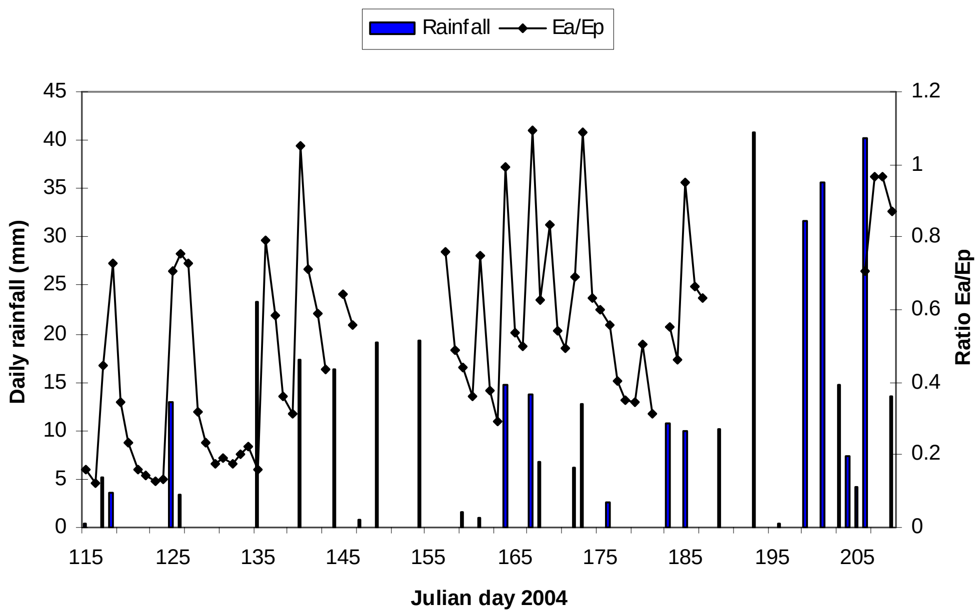

Figure 5.5: Daily Ea/Ep ratio variations according to rainfall amounts in the Kompienga dam basin during the rainy season 2004 (Day 115; i.e., April 17, 2004 to July 20, 2004; Day 209)

Using daily Ep and rainfall in the basin, the simulation derived Ea values through the Solver module of Excel according to the conditions in the above equations with the soil water storage, SB, evolving to its maximum capacity of $SB_{\max}$. To evaluate the simulation quality, a Nash-Sutcliffe Efficiency coefficient NSE (Nash and Sutcliffe 1970) was calculated using equation 5.16:

$$NSE = 100 \cdot \left(1 - \frac{\sigma_r}{\sigma_o} \right) \tag{5.16}$$

with σ_r the variance of the residuals (difference of observed and predicted Ea values) and σ_o the variance of the observed values.

A NSE close to 1 or 100% obtained after a trial with different values of maximum soil water storage using the unit residuals square sum and the initial soil water storage as target values gives the simulation efficiency. The lower the sum of the unit residuals square, the higher the NSE and better the simulation with the derived target values conserved as the basin characteristics to infer the 2005 Ea values. The simulation derived good results with a NSE of 97% showing a perfect fit of the predicted values to the observed ones for the rainy season 2004 (Figure 5.6). Nevertheless, the NSE for the dry season period appears low (64%) as an indication of the simulation weakness for periods without soil moisture and substantiated by the occurrence of the two exceptional rains (light showers) in November 2004 (the 5th and 13th) bringing the two parameters to close values.

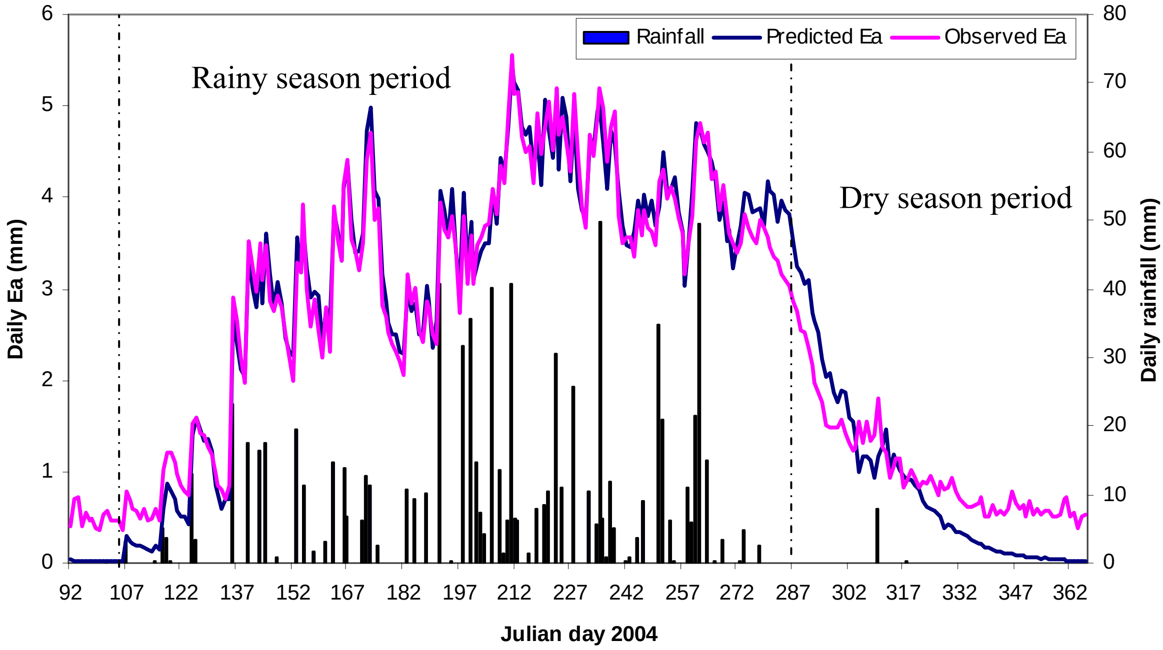

Figure 5.6: Predicted and observed actual evaporation (Ea) values in 2004 using WaSiM-ETH Topmodel-approach module

Considering the basin initial soil moisture SB to be 0.4 mm (equivalent to the first Ea value of the simulation), the simulation gave at NSE = 97%, SB_{max} of 139.5 mm. Keeping these parameters constant, the Ea 2005 values were derived by replacing Ep and rainfall of 2004 by those of 2005. The derived Ea were compared to values of previous years in order to find possible correlation and use the regressive equation to fill the dry season period Ea. Finally, a full data series of 2005 daily Ea values were obtained by completing with the observed January data from the EC before its removal. Estimating the basin recharge for 2005 with the water balance method implies disposal of the balance parameters for the period of the corresponding hydrological year of April 2005 to March 2006. The daily Ea values in 2006 for the 3-month period in the dry season to complete the available Ea 2005 data were obtained by averaging the daily first quarter Ea values of the three previous years.

5.2.3 Water table fluctuation method

The water table fluctuation method used the daily data of water levels inside the piezometers installed at the four stations in the Kompienga dam basin. Piezometers are plastic pipes with strainers/liners for water to flow in from the aquifer. Closed at their bottom, piezometers were installed in augered holes on the banks of the rivers according to Philippe and Nicolas (1998). They were longer than the depth of the hole inside which they were placed in order to prevent surface water inflow and the part above ground is used as reference to the water level measurements (Figure 5.7).

Figure 5.7: Piezometer with the pipe above the ground surface

Figure 5.8: Bell tape measurer for monitoring the water levels inside the piezometer

The piezometers were monitored daily with a bell-tape measurer (Figure 5.8) to record the water level fluctuations till water disappeared below the piezometer's bottom. Based on the recorded water levels and the respective soil texture, the water recharging the basin was evaluated according to the formula developed in Healy and Cook (2002):

$$R = S_y \cdot dh/dt = S_y \cdot \Delta h / \Delta t \qquad (5.17)$$

where R is the recharge, S_y the specific yield of the aquifer, Δh the water table rise, and Δt the time period within which the rise occurred. S_y is a dimensionless parameter, while R and Δt are consistent units of $\lfloor LT^{-1} \rfloor$ and $[T]$, respectively. $\Delta h[L]$ is expressed as the difference between the peak of the water level rise and the extrapolated antecedent recession curve at the time of the peak (Figure 5.9). The specific yield S_y is defined as the "volume of water released from a unit volume of saturated aquifer material drained by a falling water table" (Sophocleous 1991, p.236).

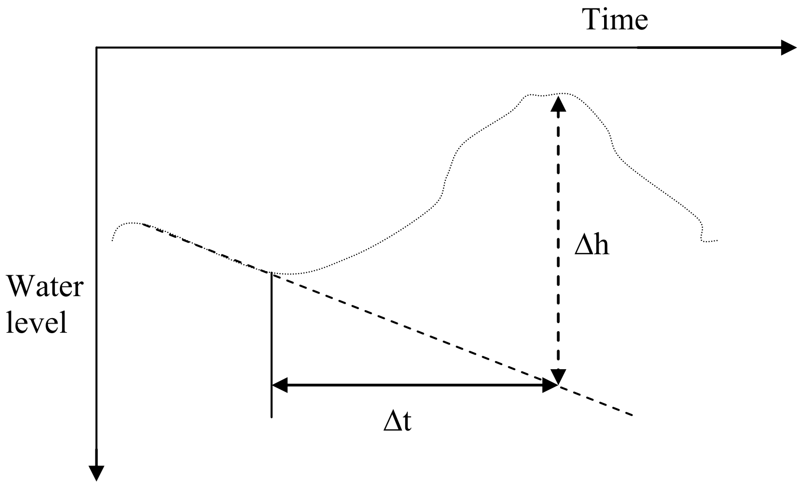

Figure 5.9: Graphic representation of Δh as used to compute groundwater recharge by the water table fluctuation method

It has to be noted that the piezometers installed in the mid rainy season 2004 were mostly damaged during the dry season period without monitoring, and from the total of 18 piezometers, 11 were re-installed in the early rainy season of 2005 for the continuity of the water level monitoring.

5.2.4 Groundwater use quantities and water supply rate estimation

Apart from the evaluation of the basin groundwater potential, the present research on the Kompienga dam basin also quantified the actual water use by the population. This objective was fulfilled by daily monitoring of the water use at selected points within the basin. A total number of 15 boreholes were selected within six localities of the basin for the survey (Table 5.2). The 15 boreholes were the two to three most frequented water withdrawal points within each of the six localities selected for daily monitoring of the containers used by the population for their water supply. The monitoring was done by surveyors recruited from the local population and consisted of recording the number of containers and their type (big, small or medium capacity) brought to the monitoring points for taking water during the daytime from 6.00 am to 6.00-6.30 pm. Following the daily tally of the containers, the unit volume of the various types of containers at a sampling point was measured in addition to the unit volume of water delivered by a unit action on the boreholes pumps called strokes. This latter measure was suggested by the various uses of the hand pump boreholes by the population. Among these kinds of uses, one consisted of watering livestock at boreholes by pumping the water to directly flow to an appointed area next to the borehole (Figure 5.10). The quantitative water use survey for the whole basin lasted the dry season period of high water demand between November 2004 and June 2005.

Figure 5.10: Sheep watering at hand pump borehole in Comin Yanga

Table 5.2: Location of 15 water monitoring points in the Kompienga dam basin

Site	Nature of the water monitoring point	UTM coordinates X	Y	Altitude (m asl)
Djabiga	Borehole 1	0233642	1231984	215
	Borehole 2	0233113	1232024	219
Pama	Modern well	0250228	1244500	211
	Borehole 1	0250651	1243334	199
	Borehole 2	0249913	1243857	200
	Borehole 3	0250050	1243286	193
Kompienbiga	Borehole 1	0238839	1248178	208
	Borehole 2	0238576	1247781	201
Natiabouani	Borehole 1	0228079	1294782	258
	Borehole 2	0228186	1295084	258
Kouaré	Borehole 1	0206059	1321983	347
	Borehole 2	0205861	1321866	349
Comin Yanga	Modern well	0188111	1294806	267
	Borehole 1	0186826	1297130	270
	Borehole 2	0186194	1294214	283

For various reasons (pump breakdown, wells drying up, etc.), temporary interruptions were observed at some monitoring points. For these points, the preceding water volume was considered as the actual month volume to fill the gap. The reason is that the population who collected water at these points moved due to the breakdown to other nearby points in order to satisfy their water demand, which led to a temporary increase in the withdrawal quantities at these points. At Pama, in addition to the monitoring points, tap water from a local piped distribution system using a power-driven pump taking water from a borehole to a reservoir also supplied fresh water to the population. The supply was estimated at an approximate rate of 6200 m^3 per year according to fuel availability for the motor pump. Taking into account all these parameters, the monthly water volumes from the 15 monitoring points were determined.

Supply rate estimation

In order to evaluate the future water supply quality to the population, scenarios were built based on available information for forecasting rainfall, population increase and recharge to the basin aquifers. The daily water volume (V_1) to supply the basin population was determined according to the population of a given year of projection and a fixed supply rate. This volume is compared to the real water volume (V_2) that can be delivered by the functional boreholes in the basin according to their unit yields, their number and the daily withdrawal. For a given year and a fixed supply rate, V_1 and V_2 are calculated as follows:

Let P $[c]$ be the total number of inhabitants in the basin in that year,

s be the fixed supply rate in units of $\left[m^3 c^{-1} d^{-1}\right]$ (cubic meter per capita per day), then :

$$V_1 = s \cdot P \tag{5.18}$$

with V_1 in units of $\left[m^3 d^{-1}\right]$ (cubic meter per day) and P in $[c]$ units (capita).

V_2 is obtained from the following equation:

$$V_2 = n \cdot q \cdot t \tag{5.19}$$

with V_2 in consistent units of $\left[m^3 d^{-1}\right]$; n the total number of functional boreholes in the basin $[b]$ (borehole), q the unit borehole yield $\left[m^3 h^{-1} b^{-1}\right]$ (cubic meter per hour per borehole), and t the daily withdrawal duration $\left[h d^{-1}\right]$ (hour per day).

For a satisfactory supply, V_2 is supposed equal to V_1. If this is not the case, the number of boreholes to satisfy this condition is calculated according to the fixed supply rate, the borehole yield and the daily duration of withdrawals using an equation from equalizing equations 5.19 and 5.18 as follows:

$$n = \frac{s \cdot P}{q \cdot t} \tag{5.20}$$

According to equation 5.20, the higher the population within the basin, the higher the number of functional boreholes for a satisfactory supply. In contrast, an increase in the borehole yields and the daily duration of withdrawal contributes to reduce the number of functional boreholes necessary to supply the population.

5.3 Conclusion

The groundwater potential for the Kompienga dam basin was evaluated based on three methods: the water balance method, the chloride mass balance method and the water table fluctuation method. To assess the basin groundwater potential with these methods, various qualitative and quantitative data from hydrologic to climatic data were collected from equipment installed in the basin or from public administration offices. The hydrological data were composed of piezometric measurements, lake level fluctuations, runoff heights in rivers, and water volumes for electricity and fresh water production. Climatic data were from the Eddy Correlation station and the weather station in addition to rain gauge measurements in the basin and precipitation data from the national meteorology office.

The collected data varied with respect to measurement time scale and spatial representation. Therefore, they were consequently brought to the whole basin level for the recharge estimation. Indispensable but unavailable data of a given period were generalized from known data using adequate and proven tools. An example is the geological map resulting from four different maps composed of 3 recent numerical formats (Ouédraogo et al. 2003) of the maps of Tenkodogo, Boulsa and Pama (thanks to BUMIGEB) combined with a paper map of Fada N'gourma (Bos 1967) scanned, digitalized and updated according to the numerical maps.

To evaluate the groundwater use quantities and estimate the population water demands and the supply quality according to pessimistic scenarios, daily monitoring of the water withdrawal at boreholes was carried out. The measurements supported sound processing procedures to derive results for analysis and suggestions for sustainable schemes of the basin groundwater resources management.

6 GROUNDWATER POTENTIAL EVALUATION

6.1 Introduction

Providing enough water to meet demands is a major concern of decision makers worldwide. In Africa, and especially in Burkina Faso, the situation is worsening due to prevailing climatic conditions. The tropical climate in Burkina Faso with 3 to 5 months of rainfall per year and a long dry season highly limits water supplies for the population. This supply limitation is aggravated by the high spatial and temporal variability in rainfall in addition to the observed annual downward trend in its quantities since last decade (Somé 2002 and Paturel et al. 2002). The geological formations in the country, mainly granitic rocks basement do not form good aquifers and the high potential evaporation in this semi-arid zone representing 2 to 10 times the annual rainfall (Pouyaud 1994), are additional unfavorable factors with respect to local water resources. Although in the same time, evaporation is also considered useful (Savenije 1997) as it has preserved West African sahelian zones from not yet being totally covered by desert. Quantifying water resources and especially groundwater resources is a prerequisite for sustainable water management (Foster 1988). Hence, this study evaluates the groundwater potential in the Kompienga dam basin in the southeastern part of Burkina Faso.

The evaluation is based on the methods chloride mass balance, basin water balance and water table fluctuation. Difficulties in obtaining accurate data for groundwater recharge assessment, and uncertainties and limitations in the methods (Martin 2005), have led to the recommendation that these assessments be based on multiple methods (Risser et al. 2005) for cross-checking the results to improve their reliability, as no single method can provide enough reliable results (Scanlon et al. 2002).

6.2 Groundwater potential evaluation using chloride mass balance method

6.2.1 Background

Simmers (1988), Lerner et al. (1990), Sophocleous (1991), Bromley et al. (1997), Scanlon et al. (2002), de Silva (2004), Martin (2005), McNamara (2005) and other authors described techniques for groundwater recharge assessment that vary in their complexity and cost (Risser et al. 2005). In the wide range of these methods, the chloride mass balance method used in this study has been recognized as simple (Ayers 1985, Bazuhair and Wood 1996, Martin 2005), of low cost, and straightforward for use in semi-arid and arid zones. This tracer method based on chloride ion conservation appears relevant for these zones due to its insensitivity to evapotranspiration, a parameter generally difficult to quantify accurately. Evapotranspiration does not transport chloride but increases its concentration in the soils (Bromley et al. 1997). Wood (1999) and Scanlon et al. (2002) state that the increasing effect of evapotranspiration on chloride concentration in the soils is directly proportional to the depth within the root zone, below which it remains relatively constant. This limits the suitability of the chloride method to deep groundwater as done in this study with the groundwater samples taken from boreholes drilled in the fractured crystalline rocks at an average depth of 20 to 40 m (Ouédraogo et al. 2003).

The chloride mass balance method relies on the assumption that the chloride ion is stable and conservative (non-reactive and the downward concentration not decreased by interactions with the solid phase; Phillips 1994) and not taken up significantly by plants (Allison 1988, Edmunds et al. 1988, Gieske 1992 and Bromley et al. 1997). Rainfall from the atmosphere is also considered as the sole source of chloride in the water flow system, and no net change in chloride storage is observable below the unsaturated zone due to plants, soil fauna or water-rock interaction (Bromley et al. 1997). The implication of these assumptions is that for any existing chloride sources apart from rain like mineralogical weathering, industrial pollution or fertilizers, the basic formula for the recharge evaluation has to be readapted (Nyagwambo 2006). For the study area Kompienga, these assumptions are considered valid, as these other sources of chloride are rare or even non-existent. However, some commencing but as yet negligible fertilizing practices within the basin for cash crop production, especially cotton, under government incentives can be mentioned. Another possible source of chloride is weathering due to water or external groundwater source enriched with chloride and flowing into the basin. The latter is unlikely as in granitic rock like in the Kompienga dam basin; the hydrological boundaries are almost equivalent to the hydrogeological ones, implying that no external groundwater is likely to flow into the basin. For the first assumption, without any chemical investigations on the geological formations, it can be assumed that the granitic rocks, which are free of halide minerals, are unlikely to provide chloride to the aquifers.

Another assumption from Bromley et al. (1997) on the use of the chloride method stated that no significant net surface run-on or run-off should occur on the site. The watershed has a relatively flat geomorphology (mean slope of 0.12 %) and relatively important vegetation (Mihin 1984) during the rainy seasons, which slow down the surface run-on in the basin creating ponds and marshes. Moreover, with the dam's spillway downstream, the entire surface runoff is collected to infiltrate in the basin as focused, localized or indirect groundwater recharge (Scanlon et al. 2002). The run-off from the basin is thus under control, with only periodical and negligible releases (8.4% of the annual rainfall on average of 18-year period, Table 6.1) for national energy production by the company in charge of the dam and for drinking water.

McNamara (2005) referring to Allison and Hughes (1978) stated that the chloride mass balance was first developed as a one-dimensional estimation of point recharge in desert soils and called chloride profiling method. Due to regional specificities (mountainous and semi-arid regions), this method was later modified by Detinger (McNamara 2005) to be applied to watersheds in Nevada, hence the watershed chloride mass balance approach integrating the spatial variability of soil parameters of the chloride profiling method. This method was also preferred to chloride profiling in this study due to previous studies in the research zones showing the spatial recharge character of the groundwater resources preferably to point-based recharge through individual soil profiles (Martin 2005).

Considering all the assumptions valid for the Kompienga dam basin, the groundwater potential is estimated using equation 5.1.

Table 6.1: Percentage of annual rainfall in the Kompienga dam basin as run-off used for energy and drinking water production

Year	Average annual rainfall (mm)	Volume for electricity (hm³)	Volume for drinking water (x10^{-6}hm³)	Total volume out of the dam (hm³)	% of annual rainfall flowing out of the dam
1989	921	36.84	40000	36.88	0.68
1990	633	140.86	40000	140.90	3.77
1991	962	177.75	56000	177.81	3.13
1992	795	289.45	56000	289.51	6.16
1993	807	306.39	56000	306.45	6.42
1994	1197	361.11	56000	361.17	5.10
1995	850.4	561.55	56000	561.61	11.17
1996	768.5	586.55	56000	586.61	12.91
1997	613.4	387.5	56000	387.56	10.69
1998	991.4	541.68	56000	541.74	9.24
1999	862.7	729.58	56000	729.64	14.31
2000	746.3	694.97	56000	695.03	15.75
2001	765.8	477.32	56000	477.38	10.55
2002	671.1	297.47	56000	297.53	7.50
2003	976.3	332.92	56000	332.98	5.77
2004	823.7	528.98	61572	529.04	10.87
2005	829.6	573.8	65277	573.87	11.70
2006	804.0	285.47	68933	285.54	6.01
Total	(834.3)	**7310.19**	**1003782**	**7311.19**	(8.43)

Numbers between brackets are average of the columns. Source: SONABEL (water quantities for electricity) and ONEA/Kpg (water quantities for drinking water production).

6.2.2 Results and discussion

Chloride in rainwater

The chloride concentration in water samples from rainfall and groundwater collected during the rainy season 2005 from the research stations in the Kompienga dam basin were analyzed (Table 6.2).

Table 6.2: Chloride concentration in rainwater and groundwater samples along with monthly weighted precipitation in the Kompienga dam basin in 2005

Month		Chloride concentration (mg/l)				Average basin precipitation (mm)
		Kouaré	Natiabouani	Pama	Tanyélé	
April 05	Rain	-	27	10	20	11.7
May	Rain	7.5	8.5	10	8.5	86.1
	Groundwater	27.5	24.3	27.0	13.0	
June	Rain	10	6	9	7	195.7
	Groundwater	28.8	24.3	27.5	11.3	
July	Rain	2.6	5	2	4.2	224.4
	Groundwater	27	20.2	23.2	9	
August	Rain	4.6	5.8	4.8	5.8	153.1
	Groundwater	28	19.4	-	1.8	
September	Rain	5	5	27.5	7.5	126.3
	Groundwater	30	22	-	10	
October	Rain	7.5	10	7.5	20	32.1
	Groundwater	32.5	18	27.5	12.5	
November	Groundwater	30	-	30	15	-
January 06	Groundwater	32.5	27.5	32.5	15	-
March 06	Groundwater	30	25	27.2	12.5	-

A comparison of these data with those of previous studies on nearby sites (Table 6.3) in central Burkina Faso, Ghana and Niger, shows that the chloride concentrations in rainwater are remarkably high. They ranged from 2 mg/l to 27.5 mg/l compared to 0.1 mg/l to 3.7 mg/l observed in northern Ghana in 2004 close to the study site (Martin 2005). The average rainwater chloride concentration was 6.37 mg/l, and 22.63 mg/l for the basin average groundwater chloride concentration.

Table 6.3: Chloride concentration in rainwater and groundwater in previous study sites

Authors	Site location	Cl-1	Cl-2	Average concentration	
				Cl-1	Cl-2
Roose (1981)	Central Burkina Faso	1	0.5-7.8	1	2.3
Turner et al. (1996)	Central Ghana (Kumasi)	1.9	-	1.9	-
Bromley et al. (1997)	Southwest Niger	0.12-10.2	5-150	0.62 (0.42)	36.4 (27)
Martin (2005)	Northern Ghana	0.1-3.71	0.8-39	0.20	6.2 (3)

Cl-1 (mg/l) represents chloride concentration in rain, Cl-2 (mg/l) represents chloride concentration in groundwater and numbers between brackets are average chloride concentration without high values of the range.

Monthly chloride concentrations in rainwater measured in 2005 at the research stations (Figure 6.1) showed an exponential decay trend with high concentration at the beginning and end of the rainy season (19 mg/l and 11.3 mg/l respectively for the average concentration). Low average concentration of 3.5 mg/l was observed mid season, and the negative correlation coefficient of -0.83 between rainfall and chloride concentration in the rainwater depicts an inverse trend of the two parameters throughout the rainy season. High rainfall values of 195.7 mm to 153.1 mm observed in the mid season period of June to August 2005 correspond to the lowest monthly average chloride concentration of 3.5 mg/l and vice versa (Figure 6.1). For the same periods of beginning and end of the season, the chloride concentration is highly variable between stations (Figure 6.2) with large standard deviation of 6.9 to 9.4 mg/l in April and September respectively and October (5.2 mg/l).

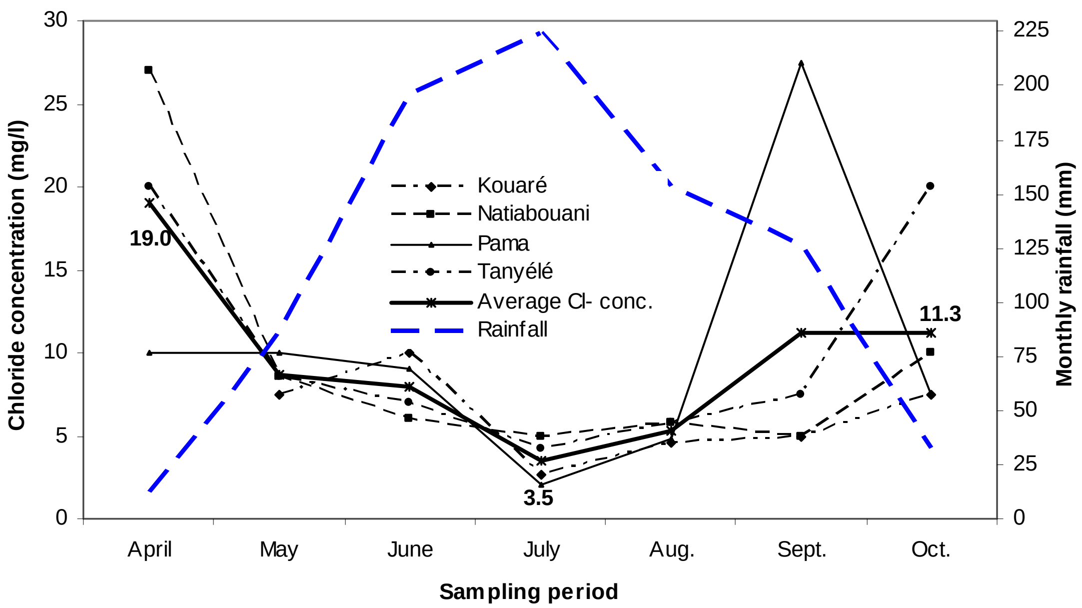

Figure 6.1: Monthly chloride concentration (mg/l) in rainwater compared to average chloride concentration for the basin and rainfall variation during the rainy season 2005

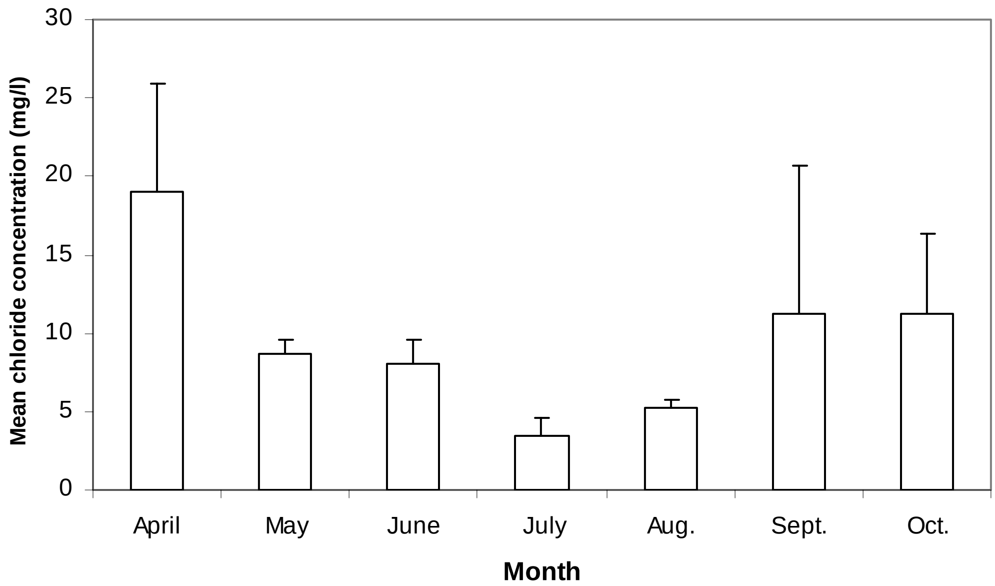

Figure 6.2: Standard deviation (bars on top of columns) of chloride concentration in rainwater for the Kompienga dam basin in 2005

The high chloride concentration at the beginning of the rainy season can be explained by the antecedent long dry season where the atmosphere gained chlorides through sea winds and harmattan dusts (Nyagwambo 2006). In Burkina Faso, Koné (1992) effectively evaluated the harmattan content of aerosols to be about 15 to 20 mg/cm³ and Muller (1985) found it fluctuating between 30 and 100 mg/cm³, which suggest variations depending on climatic conditions from one year to another. These high contents of chlorides in the atmosphere have probably influenced the chloride concentration of the first rainfall while in the following rainfall events; sea was the only source of chloride and therefore lower chloride concentration. This is especially marked in the successive months till the end of the rainy season (October), where the chloride concentration slightly increased for all the sampling stations compared to the previous months (Figure 6.1). This situation could be due to the following reasons:

- Rainfall origin. Nyagwambo (2006) in estimating groundwater recharge in Zimbabwe catchments with the chloride mass balance method revealed the influence of the origin of rainfall on chloride content in rainwater. Cyclonic rainfall are described to have higher chloride concentrations while this is lower in convectional rainfall from the ITCZ. Burkina Faso is a landlocked country like Zimbabwe.

Cyclonic rainfalls from the south at the end of the 2005 rainy season, could have affected Kompienga site at the borders of the coastal countries of Togo and Benin. It could be supposed that all the rains of the season were of cyclonic origin, hence the high chloride concentration measured in the rainwater. It is known that the seasons and thus the climatic conditions in Burkina Faso, as in the whole of western Africa, are governed by the oscillations of the inter-tropical front (ITCZ) which moves from 5° latitude north in January to 20° in August and back (Dipama 1997, Leroux 2001), describing thus the season's succession. The inter-tropical front formed by the convergence of two marine air masses of the northern anti-cyclonic dry air of the Azores and the humid southern anti-cyclonic air of St Helene is a zone where the surrounding southern parts are rainy and humid while the northern parts are dry and hazy. The surrounding zones are associated with heavy rainfall storms and thunder, while the southern parts of the front have light rain and mainly continuous showers.

- Shortcomings in sampling the rainwater. The rainwater samples were taken by field surveyors taught and committed to manually record the daily rainfall amounts from the rain gauges and collect the rainwater in plastic containers. Some errors in sample collection and neglected precautions during the sample storage could have possibly led to such high chloride concentrations, thus explaining the generally high chloride content observed in season rainwater. Furthermore, independent from surveyors, other possible errors occurring during rainwater sampling at the rain gauges or at the laboratory level when analyzing the samples could also explain the high chloride content.

Chloride in groundwater

The chloride concentration in the groundwater samples was more or less homogenous all along the rainy season 2005 for all the four sampling stations. Exceptions were observed with some extremely low concentrations likely to be outliers like the 1.8 mg/l recorded in August at Tanyélé. Meanwhile, slightly increasing trends were also observed (Figure 6.3) throughout the season for all the stations (monthly average of 20.16 mg/l in May 2005 to 24.31 mg/l in January 2006) with a decreasing trend at the beginning of the dry season (March 2006).

The Tanyélé station had the lowest groundwater chloride concentration, which indicates higher recharge at this site compared to the others (Figure 6.3). This can be explained by the location of the sampling borehole close to a riverbed highly contributing to groundwater recharge. Bagayoko (2006) described the soil texture of Tanyélé to be sandy loam, an additional factor favoring local water infiltration at the site in comparison to the other sites, which are composed of gravelly clay (Pama), gravelly silty (Natiabouani) and sandy clay soils (Kouaré). In addition, Tanyélé located near the dam's lake at about 5 km distance like the Pama station had received more precipitation in the preceding month of July (Figure 4.7) and could have benefited from the lake due to favorable hydraulic gradient.

Besides the noticeably low chloride concentration in the Tanyélé groundwater samples along the season suggesting higher recharge at this station than at the others, a general decreasing trend of all the curves is also remarkable in the July-August period (Figure 6.3). This situation indicates that the basin aquifers seemed to be responding relatively well to rainfall events and suggests the occurrence of preferential flow processes at that period within the basin. These flows prevailing in the basin recharge processes confirm the conclusions from previous studies quoted in Martin (2005) on similar granitic basement aquifers within the West African region. For this reason, the Tanyélé station, which showed higher recharge, could have more preferential pathways than the other stations. However, it cannot be excluded that the flow process be also diffuse, as the first noticeable recharge effect was only observed in July-August after 3 rainy months. During these months, rain is supposed to have sufficiently wetted the topsoil to meet the soil moisture deficit as well as evaporation and transpiration demands and percolate through the wet unsaturated zone to reach the water table and dilute the groundwater. Meanwhile, for a diffuse flow process, once the recharge takes place it is reasonable to expect a continuous process when rains are still falling in the basin (Figure 4.7). After the supposed recharge of the aquifers in July-August (Figure 6.3), the chloride concentration increased again in the groundwater. This suggests that the observed recharge in July-August resulted from preferential flow through the soil cracks and fissures. Later, these preferential paths, due to swelling of clay soil particles as suggested by Lloyd (1986) and Nyagwambo (2006) are blocked and the subsequent rainwater therefore percolate through diffuse flow processes to recharge the basin groundwater after the rainy period depending on the depth to the water table. This conception is substantiated by the decrease in the curves observed between January and March (Figure 6.3). The remarkable increase in the groundwater chloride concentration of all the stations after the preferential flow recharge process is likely to be the result of transpiration of trees, which extracted the recharged water and left the aquifer with more chloride resulting from the preferential flow recharge. This is confirmed by the actual evaporation values observed from the EC measurements in the basin, which never tended to zero during the dry season (Figure 5.6). Authors like Adar and Leibundgut (1995), Haase et al. (1996) and de Vries et al. (2000) also mentioned upward fluxes of groundwater by deep-rooted vegetation from 15 m to 50 m in semi-arid and arid zones amounting to 1 mm/a (Nyagwambo, 2006).

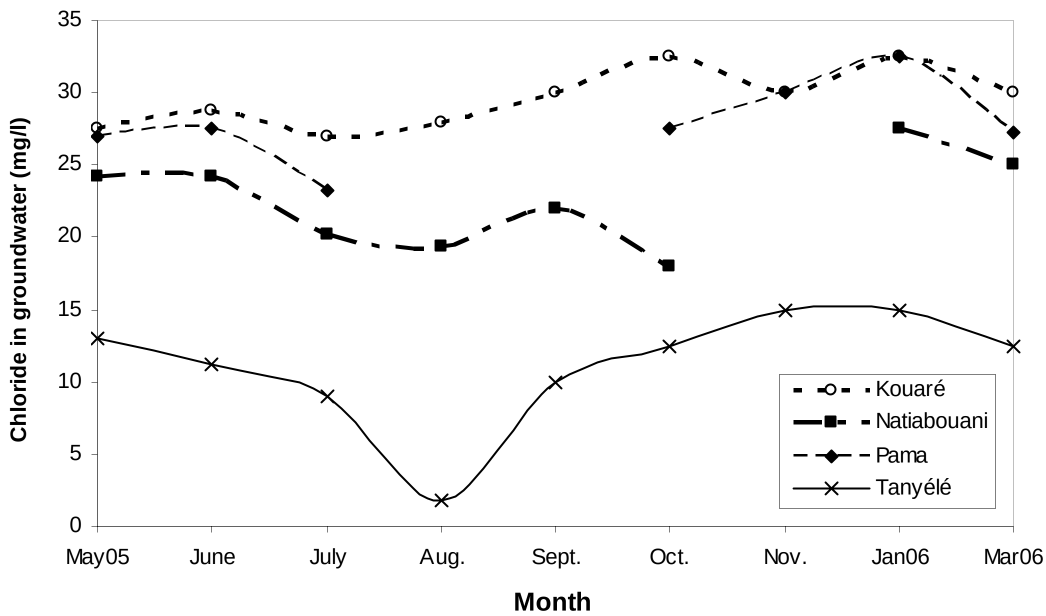

Figure 6.3: Monthly chloride concentration in groundwater from boreholes of the study stations from May 2005 to March 2006

Comparing the groundwater monthly chloride concentration values of the stations to those of nearer sites (Table 6.3), the data appear to be in the range of those from Niger (5-150 mg/l) and Ghana (0.8-39) with the same geological formations of West African crystalline basement. The groundwater chloride values in the study are therefore acceptable for the basin recharge estimation. The difference between these data and the rainwater data can be mainly attributed to shortcomings in the rainwater sampling method by the local surveyor as the author sampled the groundwater every month from the boreholes.

Basin recharge estimation

In the light of the shortcomings that led to the high chloride content in the rainwater, a second rainwater sampling was realized in September 2006. This time, trained staff did the rainwater sampling for three of the stations while the author collected the samples at the fourth station. During three weeks, rainwater was recorded and sampled in individual plastic bottles for each rainfall event. In addition, two samples were taken from boreholes at each site at the beginning and end of the 3-week period. Finally, the samples were divided into two parts when it was possible, and taken to laboratories in Burkina Faso (the same laboratory that in 2005 analyzed the rainwater and groundwater samples) and Germany (Bonn) for chloride analysis. The same analysis method (ion chromatography) was applied by the two laboratories. It can be seen from the results that the laboratory analysis in Burkina Faso was the reason for the high chloride content in the rainwater in 2005. Apparently, unsuitable equipment was used to analyze the rainwater samples likely to have low chloride contents. Weaver and Talma (2005) and Beekman and Sunguro (2002) in their studies on analysis of chloride concentration in water samples underlined that not all laboratories are equipped for measuring low chloride content of water samples (chloride concentration below 5 mg/l with a precision of less than 0.5 mg/l). They therefore, suggested that samples be duplicated and sent to at least two reputable laboratories. The unsuitability of the laboratory equipment in Burkina Faso for measuring the rainwater chloride concentration as stated above is substantiated by the weak correlation coefficient of -0.0048 between the analysis results of this laboratory and those of the Bonn laboratory. In contrast, the chloride concentration in the groundwater samples from the two laboratories correlates with a coefficient of 0.99, when excluding the second value of groundwater chloride concentration of Pama, considered an outlier in comparison to the data series from the Burkina Faso laboratory. The strong correlation between the two data series of groundwater chloride concentration gave a linear regressive equation with R^2=0.98 (Figure 6.4). The suppression of the outlier value of 10 mg/l at the Pama station is based on the values from all four stations, where Tanyélé received more recharge than the three other showed. Comparing the data of all stations during the 3-week sampling, the Pama station showed the lowest precipitation of 69.9 mm while Tanyélé, Natiabouani and Kouaré received 74.4 mm, 78.5 mm and 136.5 mm, respectively. At the same time, the two groundwater samples of each station analyzed by the laboratory in Burkina Faso always showed to have the same chloride concentration despite the 3-week time lag separating the two sampling dates, except for Pama where a significant difference can be observed (Table 6.4). If a recharge occurred at the Pama station as indicated by the decrease in the chloride concentration of the groundwater samples, the favorable difference in the precipitation in addition to the sandy loam texture should have also led to a recharge at Tanyélé. As that was not the case, the second groundwater chloride value at Pama is therefore likely to be erroneous.

Table 6.4: Chloride concentration in rainwater and groundwater from the four research stations in the Kompienga dam basin in 2006 analyzed in Burkina Faso and German (Bonn) laboratories

Sample nature	Rainwater																					
Station	Kouaré								Pama								Natiabouani					
Sampling date in Sept. 2006	07	08	09	12	15	18	21	22	09	12	15	16	19	20	23	24	09	10	13	16	17	19
Sample code	K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	P8	N1	N2	N3	N4	N5	N6
Bonn laboratory (mg/l)	9.49*	1.41	2.69	0.76	1.64	1.77	0.93	0.51	2.31	0.89	0.69	0.59	288.44*	2.28	0.57	0.73	0.45	0.38	0.74	0.56	0.55	0.41
Burkina Faso laboratory (mg/l)	5.0	10.0	10.0	5.0	10.0	5.0	5.0	5.0	28.0	-	10.0	-	-	10.0	10.0	10.0	8.0	8.0	8.0	8.0	8.0	8.0

Table 6.4 continued

Sample nature	Rainwater										Groundwater							
Station	Tanyélé										Kouaré		Pama		Tanyélé		Natiabouani	
Sampling date in Sept. 2006	9	11	12	15	16	19	21	22	24	24	07	25	11	25	08	25	07	25
Sample code	T1	T2	T3	T4	T5	T6	T7	T8	T9	T9’	K1F	K2F	P1F	P2F	T1F	T2F	N1F	N2F
Bonn laboratory (mg/l)	0.96	0.74	1.55	0.50	1.15	0.67	579.17*	6.67*	1.29	0.47	22.87	22.92	20.80	20.50	3.90	3.38	15.49	15.99
Burkina Faso laboratory (mg/l)	8.0	8.0	-	8.0	-	-	-	-	8.0	-	30.0	30.0	28.0	10.0	10.0	10.0	25.0	24.0

* *High chloride content samples discarded from the analysis*

Considering the above analysis, it appears that laboratory equipment in Burkina Faso was suitable for analyzing the high chloride contents in the groundwater samples but not the low ones, as it was the case for the rainwater samples. Therefore, using the regressive equation of the correlation between the groundwater chloride concentration analyzed in the two laboratories (Figure 6.4), the groundwater chloride concentration data from the Burkina Faso laboratory in 2005 were corrected and used in combination with the rainwater chloride concentration analyzed in 2006 to re-evaluate the Kompienga dam basin annual groundwater recharge with the methodology described in section 5.2.1.

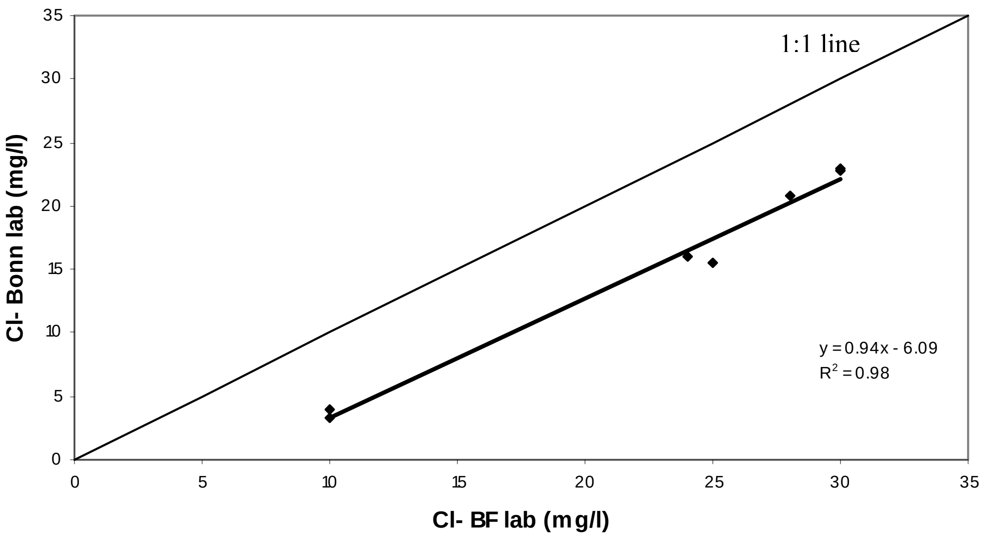

Figure 6.4: Relationship between chloride concentration in rainwater analyzed in Burkina Faso and German laboratories

The average chloride concentration in rainwater Cl_p was estimated equal to 0.87 mg/l and Cl_{gw} was 15.91 mg/l for the groundwater chloride concentration in 2005. For 2006, Cl_p was equal to 0.88 mg/l and Cl_{gw}, 16.52 mg/l. The average chloride concentration in rainwater from nearby sites was estimated to be 0.61 mg/l. The results therefore show the annual recharge of the basin in 2005 to be 45.4 mm representing 5.5% of the annual rainfall and in 2006, 42.9 mm equivalent to 5.3% of the annual precipitation of 804 mm. With the nearby sites rainwater average chloride concentration, the recharge in 2005 is shown to be approximately 31.6 mm, i.e., 3.8% of the annual rainfall. Initially, with the average groundwater chloride concentration without regression, this estimate was 22.2 mm, representing 2.7 % of the annual precipitation in 2005.

Table 6.5: Areal weights and groundwater chloride concentration for estimating recharge in the Kompienga dam basin

Stations	Kouaré	Natiabouani	Pama	Tanyélé
Areal weights	0.44	0.28	0.06	0.22
$Cl_{gws} \left[mgl^{-1}\right]$	21.6	15.0	19.8	4.7

It can be observed that these estimations fall within the range of previous estimates of 2 to 16% of the total annual precipitation quoted in van der Sommen and Geirnaert (1988) for natural groundwater recharge in Burkina Faso using water balance method, water table fluctuation and isotope analysis. The main observation deriving from the different estimations, except for the evaluation using rainwater chloride concentrations of the nearby sites, shows that the annual recharge roughly represents 5% of the annual precipitation, although the observations in 2006 were too short to be representative. The recharge estimated from the average rainwater chloride concentration of the nearby sites can be considered as a rough estimate for preliminary results of the basin recharge in the absence of valid observed data.

6.3 Groundwater potential evaluation using water balance method

6.3.1 Background

Among the variety of methods existing for groundwater recharge estimation, the water balance method is a method applicable to any water system. Sokolov and Chapman (1974) described the method as providing an indirect evaluation of an unknown water balance component from the residual unexplained by the known components. For this reason, the method was defined as the application in hydrology of the principle of conservation of mass with the implication that:

- for any arbitrary control volume and during any period of time, the difference between total input and output has to be balanced by the change of water storage within the volume;
- time and spatial boundaries of the water system must be well-defined;

- measurements of storage and fluxes of water at appropriate time scales must exist or be expected.

The application of this method provides a groundwater recharge estimation as a residual of all the other fluxes (Lerner et al. 1990). Therefore, the method is considered flexible with a wide range of space and time applicability without any presuppositions except the availability of the balance terms (Scanlon et al. 2002) and the advantage of using readily available data. Meanwhile, a disadvantage of the method, which reduces its usefulness, is that recharge being residual, errors and uncertainties in measuring other water balance components affect its estimation. Gee and Hillel (1988) noted that calculating small figures such as recharge in semi-arid and arid regions from large figures like precipitation and potential evaporation in these regions is likely to induce a high level of uncertainty in the evaluation. Recharge estimation with the water balance method is therefore considered inappropriate for semi-arid and arid regions where potential evaporation, a key component of the method, amounts to 60% or 80% of the annual water budget (Martin 2005), and 60% of the global annual precipitation (Seckler et al. 1998 and Compaoré 2006). This shortfall prompted Gee and Hillel (1988), Lerner et al. (1990), and Hendrickx and Walker (1997) to question its usefulness in such parts of the world where runoff is often low. Indeed, the water balance method was developed for temperate climates where, in general, annual rainfall exceeds potential evaporation (Lerner et al. 1990, Martin 2005). In arid and semi-arid zones, rainfall occurs during storm events within short periods of time, and recharge mechanisms are rather through ponding and preferential flow than through the matrix flow process as in the temperate zones. Nevertheless, the method remains useful in providing preliminary insight for any groundwater system recharge when estimation time steps are adapted.

6.3.2 Results and discussion

Annual time step water balance recharge estimation

The application of the water balance method to the Kompienga dam basin was based on available data for the components of equation 5.11 collected from different field measurements and from SONABEL and ONEA/Kpg in volume units, which were converted into millimeters according to the basin watershed area. An exception is made for actual evaporation over the basin, Ea, restricted to the basin excluding the lake area to which the E_0 (evaporation over the lake) estimation refers. The recharge evaluation is based on the hydrological year of the basin starting in April and ending in March, assuming no significant irrigation schemes. In the Kompienga dam basin of 6000 km², the parameter of rainfall in the water balance estimation of the basin recharge proved to be difficult to estimate accurately. Using a two-sample T-Test at 90% confidence interval for pair-wise comparison between the data from the four national meteorological stations (1959-2004) in estimating the average annual rainfal in the basin, it was shown (Table 6.6) that annual rainfall at Koupéla (just outside the northwestern boundary of the basin, Figure 5.2) were significantly lower than the corresponding figures at Pama (south of the basin and close to the dam). Thus, the Kompienga lake is likely to receive more precipitation according to the Pama station data than the average annual rainfall over the entire basin. The difference in the average annual precipitation of 67.4 mm (i.e., 8% more rain in the south close to the lake) over the basin based on the Pama station data accounts, therefore, for the rainfall in the lake in Kompienga proportionally to its surface, i.e., 2.4 mm in the storage changes.

Table 6.6: Two-sample pair-wise T-Test (α=0.05) for differences in long-term annual rainfall (1959-2004) data series of four stations for estimation of the average annual rainfall in the Kompienga dam basin

Stations		Fada N'gourma	Pama	Koupéla	Ouargaye
Average (mm)		844.0	904.7	768.3	831.2
Standard deviation (mm)		153.9	170.3	139.5	161.1
P(t)	Fada N'gourma	-	0.0761	0.0153	0.6983
	Pama	-	-	0.0002	0.0601
	Koupéla	-	-	-	0.0996

Table 6.7: Annual recharge of the Kompienga dam basin in 2005 estimated with the water balance method

Parameters	(hm³)	(mm)	% of P
P	4903.7	829.6	100
ΔS_1	85.8	14.5	1.8
Ea	4286.9	725.2	87.4
E_0	254.4	43.0	5.2
L	438.3	7.1	0.9
R	9.9	1.7	0.2

with R = annual groundwater recharge in the whole Kompienga dam basin; P = annual precipitation in the basin; ΔS_1 = annual change in storage within the lake; Ea = annual (actual) evaporation over the basin; E_0 = annual evaporation of the lake water; L = annual water withdrawn from the dam for drinking water and energy production.

The groundwater recharge in the Kompienga dam basin in 2005 with the water balance method is therefore equal to 1.7 mm (Table 6.7), which represents almost 0.2% of the annual rainfall of the basin in that year. Taking into account the favorable difference of rainfall over the lake as suggested by the T-Test between the meteorological stations, the annual recharge can then be estimated to be 4.1 mm, representing 0.5% of the annual rainfall in the basin. This recharge, nevertheless, remains lower than the recharge estimated using the chloride mass balance method. The difference in the estimate between the two methods can be attributed to the main problem of the water balance method of recharge estimation in arid and semi-arid environments quoted by many authors (Sokolov and Chapman 1974, Gee and Hillel 1988, Lerner et al. 1990). Indeed, parameters like evaporation (Ea and E_0) and rainfall (derived from spatially variable sample measurements) used in this water balance were an additional source of inaccuracy in the final estimation as demonstrated in the following section.

Error estimation on the annual time step water balance recharge in the basin

In order to quantify the likely uncertainty associated with the annual time step water balance estimate of the basin recharge, a basic error propagation exercise was conducted. The annual time step estimation of the basin recharge is based on equation 5.11 with all the parameters in units of $\left[L^3T^{-1}\right]$:

$$R = P - Ea - E_0 - L \pm \Delta S_1 \qquad (5.11)$$

For $E = Ea + E_0$, then R becomes:

$$R = P - E - L \pm \Delta S_1 \qquad (6.1)$$

Equation 6.1 is a function of the general form of:

$$\Psi = \alpha X_1 + \beta X_2 \qquad (6.2)$$

in which, terms are separable, additive and linear (Bevington and Robinson 1992). The variance of such form of function is given by:

$$\sigma_\Psi^2 = \alpha^2 \sigma_{X_1}^2 + \beta^2 \sigma_{X_2}^2 + 2\alpha\beta\sigma_{X_1 X_2}^2 \qquad (6.3)$$

In equation 6.1, the parameters L and ΔS_1 are, in absolute value, greatly inferior to P and E which represent point samples from a spatially extensive random field, very accurately measured and not sampled; therefore their variance is considered negligible compared to the variance of P and E. Assuming that errors in R are controlled by errors in P and E, eliminating L and ΔS_1 in equation 6.1 yields an error analysis:

$$R = P - E \qquad (6.4)$$

which shows that annual recharge precision highly relies on precision in estimating P and E. Evaluating the recharge variance from equation 6.4 based on equation 6.3 yields:

$$\sigma_R^2 = \sigma_P^2 + \sigma_E^2 + 2\sigma_{PE}^2 \qquad (6.5)$$

The latter in this equation is the covariance between errors in P and E. Since P and E are derived by independent methods, there is no basis to assume that errors are correlated, thus the term $2\sigma_{PE}^2 = 0$. Assuming also that error variance in E (σ_E^2), which is unknown, is at the same magnitude as σ_P^2 (the error variance in P) based on the fact that P and E are of same order of magnitude in the estimation of R (Table 6.6), then $\sigma_P^2 = \sigma_E^2$ and:

$$\sigma_R^2 = 2\sigma_P^2 \tag{6.6}$$

To simplify the analysis, annual precipitation totals at the four research stations are assumed unbiased samples from the "true" but unknown basin precipitation field. The variance of the sample mean is used as the estimate of error in P; therefore, equation 6.6 in 2005 resulted in $\sigma_R = 46$ mm. At 90% confidence interval for $\sigma_R = 46$ mm, the precision for R is ±75 mm. This depicts how much the precision in the rainfall and evaporation terms in the annual water balance determines the precision in the annual recharge estimation for the basin. Considering that the lake close to Pama receives 8% more rain than the average of the basin, the error interval in estimating the basin recharge can be considered to be, at 90% confidence interval, in the theoretical range of -72.6 mm and 77.4 mm, i.e., -72.6 < R (mm) ≤ 77.4. This means in practice, a minimum of zero annual recharge, which is very unlikely according to previous studies from Savadogo (1984) and Geirnaert et al. (1984) proving the annual renewability of groundwater resources in Burkina Faso, and a maximum of 77.4 mm, i.e., 0 < R (mm) ≤ 77.4.

Daily time step water balance recharge estimation

To improve the recharge estimation with the water balance method, scientists suggest reducing the time steps of the estimation for semi-arid environments. For this reason, the recharge estimate was re-evaluated on a daily time step basis using equation 5.10 with the following assumptions:

- Only the available data were used and the computation done with volume components from the first rainfall in the basin;
- The storage variation ΔS_2 in the basin that is assumed to be zero in annual time step evaluation is considered changing over the estimation period. ΔS_2 is evaluated through the daily SB (basin soil moisture) variations. The daily negative values of ΔS_2 symbolize increase in soil moisture deficits and positive values represent the

groundwater recharge when SB is above field capacity of SB_{max} as in Rushton and Ward (1979);

- The daily changes in the lake storage, ΔS_1, are derived from the lake level fluctuations and the tare curve of water levels versus lake volume using the attached regressive equation;
- A maximum soil water storage capacity of the unsaturated zone is considered equal to SB_{max} determined in the Ea 2005 derivation with WaSiM-ETH topmodel module;
- At the end of the rainy season, where no input water was available and after SB_{max} was exhausted, groundwater depletion by upward circulation was considered and limited to extraction alone by deep-rooted vegetation depicted by the daily Ea measurements from the EC station (Figure 5.6);
- The daily lake evaporation values E_0 used in the simulation were interpolated daily values from Pouyaud (1985) studies on Lake Bam and Lake Tchad;
- The withdrawals of groundwater by the population of the basin are considered negligible in the water balance as observed by Martin and van de Giesen (2005) from their estimation of groundwater potential of the whole Volta river basin.

The main principle of the annual recharge estimate through daily time step evaluation is based on the consideration that the unsaturated zone of the basin is a reservoir with a maximum storage capacity of SB_{max} representing the soil moisture SB at field capacity over the depth of the unsaturated zone profile. The estimates consider that according to its intensity, the first rainfall contributes to the generation of runoff in the basin, satisfies plants transpiration demands and evaporation as well as infiltration for recharge. When the sum of the infiltrated part of the daily rainfall reaches the threshold value of the unsaturated zone storage capacity of SB_{max}, then all additional infiltrated rainfall is considered to percolate to the water table as recharge. Once the unsaturated zone reaches the maximum storage capacity, the following dry days with a negative balance are considered to deplete this unsaturated zone storage, and the subsequent rainfall refills this storage to SB_{max} for new recharge occurrence.

From the above assumptions, and using equation 5.10 as daily recharge estimation, the total basin recharge in 2005 from 15 rains amounted to 59.8 mm with a maximum recharge of 33 mm on July 10, 2005, and a lowest recharge of 0.5 mm on September 3, 2005. It can be observed that this recharge, like those derived from the chloride mass balance method, fall within the interval of the predicted annual recharge quantity in the basin with the error estimation. The estimated recharge period appears to have lasted the 2 months between July 10 and September 8, 2005. The estimate, which represents 7.2% of the annual basin rainfall in 2005, is considerably higher than the annual time step estimation at 0.5% of the annual rainfall with the same method. The difference in recharge between the two methods lies solely in the water storage change ΔS_2 within the basin with the sum of all the other components over the year equal to the corresponding cumulative water balance components. Assumed to be zero over the whole year in the annual time step recharge estimation, the water storage change is considered to be changing along the year in the daily time step recharge estimate. This result of the daily time step water balance recharge estimate substantiates somewhat the results of Rushton and Ward (1979) in Northern Lincolnshire Chalk aquifer (United Kingdom) that show 10% underestimates of recharge from weekly input data and 25% from monthly data. This thus shows the appropriateness of adapting the recharge evaluation time steps to natural processes occurrence (Howard and Lloyd 1979) in semi-arid zones like the Kompienga region in Burkina Faso, where potential evaporation often exceeds rainfall for most of the year (Figure 4.5) leaving in general hardly any little possibility for recharge. Nevertheless, this does not mean that the method is more reliable than any other method, but only expresses the adequacy of the recharge evaluation with time steps close to real and natural occurrence of events. The recharge occurrence details provided by the estimation process (Figure 6.5) provide better possibilities for groundwater resource management in the basin.

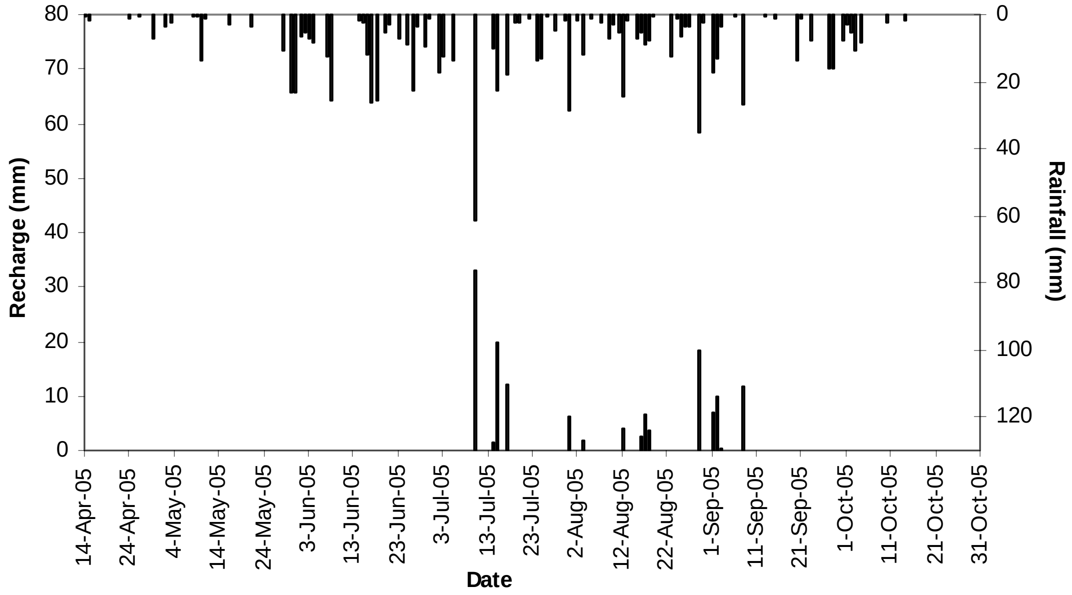

Figure 6.5: Daily recharge (upward bars) in Kompienga dam basin compared to daily rainfall depths (downward bars)

From the daily simulated groundwater recharge graph (Figure 6.5), the following can be observed:

- There is a time lag between begin of rainfall and begin of recharge. The first rainfall was observed on April 14, while the first recharge was 3 months later on July 10 after the highest rainfall of the season. This delay in recharge is due to many factors. One factor is the recharge process assumed in the water balance method with the daily processing time steps to be the matrix or diffuse flow. In this flow process, rain first has to wet the unsaturated zone to its field capacity before deep percolation starts. Therefore, depending on the unsaturated zone field capacity and its thickness, i.e., the depth to the water table, the delay between rainfall occurrence and recharge can be short or long. Other factors are soil characteristics (partially involved in the previous factor) and rainfall characteristics combined with the basin land cover and topographical aspects. Indeed, as explained by Ajayi (2004), water infiltration to induce recharge is a complex process involving rainfall, soil matrix, terrain topography and morphology as well as land covers. In the Kompienga dam basin with its flat terrain without significant slopes (van de Giesen et al. 2001), the topography and morphology have less influence on the infiltration processes than the rainfall-soil matrix interrelations. Indeed, rainfall intensities in addition to heterogeneity according to structure and texture and land use in relation to hydraulic properties as quoted in Spaan and Stroosnijder (1997), van de Giesen et al. (2000), Stomph et al. (2002) and Ajayi (2004) are the main influences of surface runoff and infiltration processes. Nyagwambo (2006) studies on a small catchment in Zimbabwe with similar geological characteristics and climatic conditions like those in Kompienga confirm this fact, pointing out that a threshold rainfall depth exists for the commencement of any detectable recharge to aquifer independent of the recharge flow process. The level of the threshold, meanwhile, depends intrinsically on the flow process. For the Kompienga dam basin in 2005, this threshold rainfall according to the results from the water balance is estimated at 336.6 mm, representing 41% of the annual rainfall, which is used during the time lead to satisfy evaporative demands and soil moisture deficits in the basin.

- After the first recharge takes place in the basin, the following rains easily produce recharge proportional to their amount (Figure 6.5). The highest daily recharge (33 mm) in the basin was observed to correspond to the highest precipitation (61.2 mm) in the year. It appears that after the threshold rainfall for the recharge is reached, the subsequent rainfall recharges the basin according to the wetness of the soil and the rainfall amount. According to this observation, the daily recharge rates following the first recharge of the season vary from 13% to 87% of the daily rainfall. The lowest recharge rate (13%) is derived from 10.4 mm rainfall on July 14, 2005 and the highest recharge rate (87%) from 22.5 mm rainfall on July 15, the day following the highest rainfall in the basin. While almost the same precipitation of 26.8 mm on September 8 following 4 dry days only produced a recharge rate of 44% (half of that derived from the rainfall on July 15), a precipitation of 9.1 mm in a wet spell of 7 rainy days contributed to 71% as recharge. Despite the strong correlation (correlation coefficient of 89%) between daily rainfall and daily recharge in the basin once the unsaturated zone is above field capacity, it remains difficult to generalize in predicting from the derived results, the exact pattern of the daily recharge according to daily rainfall. This is partly due to the high erratic behaviour in the daily rainfall, which supposes that dry spells appearing within the rainy season compromise all possibility of recharge as the unsaturated zone wetness has to be refilled before new recharge occurrence; depending on the rainfall depth and the level of lowering of the unsaturated zone wetness. Nevertheless, it can be stated that during the recharge period and without dry spell, the daily rainfall threshold for recharge is approximately equal to the daily actual evaporation in the basin.

- From cumulative rainfall and cumulative recharge within the basin, a strong relationship was observed and made it possible to derive the rainfall-recharge relation for the annual recharge estimation based on the annual rainfall amount. This relationship, similar to the daily rainfall-recharge relation depicts a threshold of rainfall for commencement of recharge to the basin. From the linear relationship of R^2=0.94 (Figure 6.6), this rainfall threshold is equal to 314.3 mm, and the equation for the annual recharge estimation using the precipitation is:

$$R = 149.05 \cdot (Ln(P) - 5.75) - Ea \qquad (6.7)$$

with $R[L]$ as the annual water recharge in the basin, $P[L]$ the annual precipitation, and $Ea[L]$ the total actual evaporation calculated for the period between the end of the rainy season and the end of the hydrological year of the recharge estimation. As depicted by the Eddy correlation measurements (Figure 5.6 and Appendix 3), Ea in the basin is never zero during the dry season period, most likely due to transpiration of deep-rooted trees.

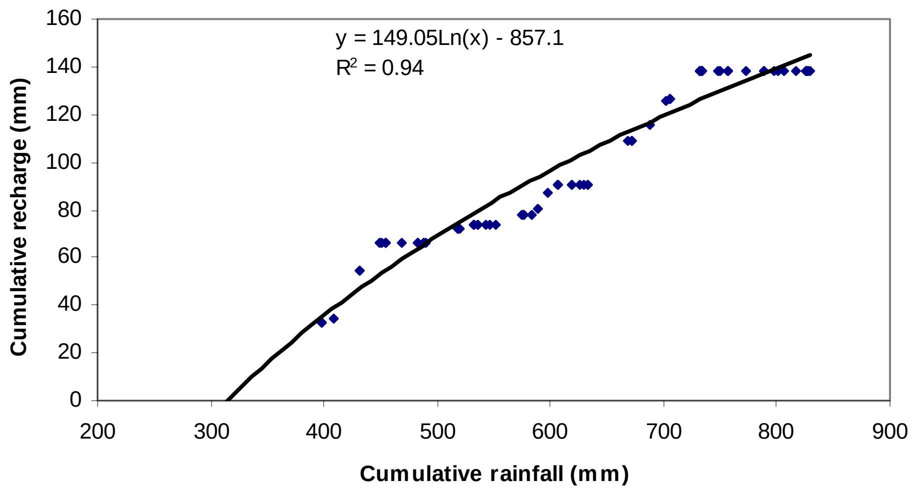

Figure 6.6: Relationship between cumulative rainfall amount and recharge in the Kompienga dam basin in 2005

- The last recharge occurred in the basin on September 8, while rains continued falling until October 14 (Figure 6.5), more than a month later. The cumulative rainfall of this period amounts to 97.6 mm (12% of annual rainfall) with two consecutive days receiving the highest precipitation of 16 mm without any recharge occurrence. This situation substantiates the previous conclusions indicating that recharge is strongly dependent on soil wetness memory. Indeed, temperature and consequently evaporation in the research area of Kompienga are described (Bagayoko 2006) to be increasing at the end of the rainy season. This situation observed in the comparative trend of rainfall and E_p (Figure 4.5) in 2005 depicted in October where E_p was considerably higher, being 5 times the precipitation. Therefore, little possibility is given to the decreasing rainfalls to induce recharge. In addition, spatial variability in rainfall and soil characteristics may influence recharge evaluation at the whole basin scale and be a source of bias in the interpretation of the results. For example, rainfall amount recorded by only one of the four stations in a given period will be considered through the Thiesen polygon to have occurred over the whole basin at a lower rate of 50% to 30% or only 25% of that at the given station. Therefore, while insufficient for recharge at the whole basin scale, it could have been sufficient at the local station. It seems thus advisable to consider carefully the recharge results derived at the whole basin scale, which tend to mask local specificities of rainfall as revealed by the T-Test results, soils, land cover and topography that are likely to exist for a basin covering 5911 km². An example is the basin recharge derived from the two methods of water table fluctuation and water balance. While the last recharge is estimated by the water balance to have occurred at the whole basin scale on September 8, the water levels fluctuations in a piezometer at Pama for example (Figure 6.8), show that it was on October 8, 2005, i.e., one month later.

6.4 Groundwater potential evaluation using water table fluctuation method

6.4.1 Background

The variations of the water table within the saturated zone express the groundwater level fluctuations under recharge and discharge processes. The water table fluctuation (WTF) method for groundwater recharge evaluation is one of the most widely used methods due to current availability of groundwater level data, the method's simplicity and insensitivity to mechanisms of water movements through the unsaturated zone (Healy and Cook, 2002). From the water table definition, it is obvious that the WTF method is solely applicable to unconfined aquifers and best fits to shallow groundwater where sharp water level rises and declines can be observed. The main assumption in the WTF method is that rise in the water table is an indication of recharge of water arriving in the groundwater (equation 5.17). From the assumption and the derived equation, some remarks need to be made regarding the limitations of the method:

- Not all water table rises can be solely attributed to recharge. Groundwater recovery from pumping or extraction, evapotranspiration, barometric pressure effects and many other causes (entrapped air in the unsaturated zone, changes in groundwater flow processes from adjacent aquifers, temperature variation, etc.) independent of input of water to the water table can lead to rises in groundwater levels (Sophocleous 1991, Healy and Cook 2002). Therefore, a clear distinction should be made between the effects of water input and other possible factors on water table rise for a better groundwater recharge evaluation with the WTF method. These effects are assumed to be minimal.
- For shallow groundwater, a time scale evaluation longer than a rain event period in semi-arid and arid zones is likely to underestimate the recharge (Healy and Cook 2002). Indeed, the evaporation effects on shallow groundwater and discharges to streams are considerable in long time lag and tend to reduce the effects of individual rain events on the water table, and thus lead to underestimation of the recharge.
- The specific yield in equation 5.17 for the recharge estimation is a parameter known to be difficult to estimate accurately. Some authors (Lerner et al. 1990) even suggest considering standard soil texture values from literature rather than field test measurements when values from laboratories are unavailable. The recharge accuracy of the WTF method critically relies on the specific yield defined by

Sophocleous (1991, p.236) as the "volume of water released from a unit volume of saturated aquifer material drained by a falling water table". It reflects the difference between the porosity and the specific retention of the soil materials as quoted in Healy and Cook (2002).

6.4.2 Results and discussion

Groundwater levels in the Kompienga dam basin were measured daily in 2005 from piezometers installed at the four main research stations. These measurements provided evidence of groundwater recharge within the basin during 2005 rainy season by means of the water table fluctuation method (Figure 6.7).

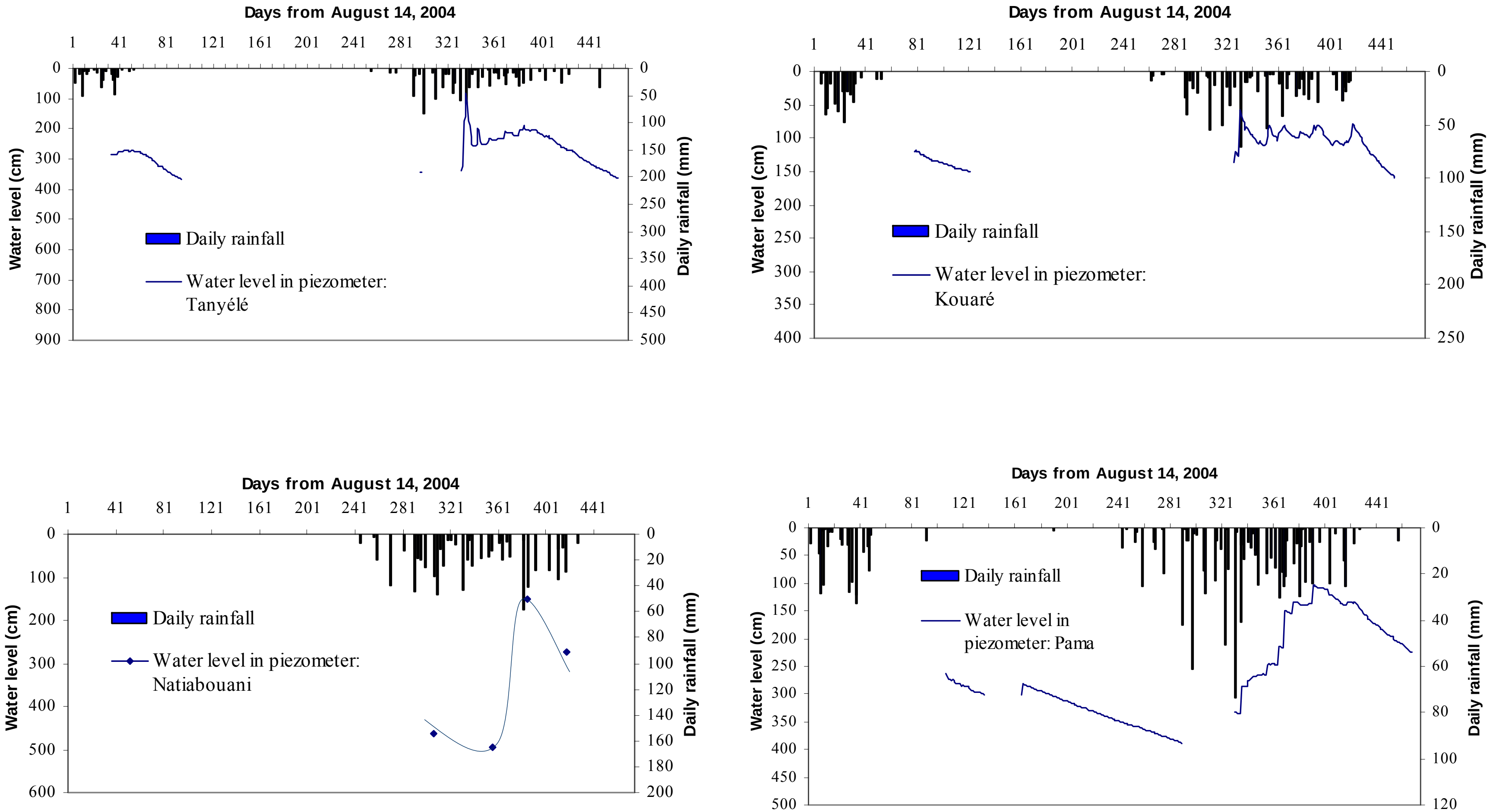

Figure 6.7: Water levels in piezometers and daily rainfall (vertical bars) at four stations in the Kompienga dam basin from August 14, 2004 to November 21, 2005

The water levels fluctuations showed that the water levels rose and fell according to rainfall events till the end of the rainy season where, in the absence of input of water, they continuously fell. This pattern is only observed after a certain period in the rainy season. It is remarkable that all the curves, despite the gaps between the two rainy seasons, show that all rainfall events of the first 2 to 3 months of the season failed to induce recharge, while the water balance in the same period showed the occurrence of the highest recharge of the season (Figure 6.5). This situation describes the delay in groundwater recharge as similarly observed with the water balance method at daily processing time steps and suggests complex relations between the rainfall, soil matrix, terrain topography and morphology as well as land cover to be the main causes. It should be stressed that the piezometers do not represent the deeper aquifers.

Comparing the water level fluctuation curves to those of the chloride concentration in the groundwater along the rainy season 2005 (Figure 6.8), a shift in the trends can be observed. While the water levels in the piezometers of the research stations started to decline mostly after the last recharge on September 18, 2005 (day 401 from August 14, 2004) following the end of the rainy season, the CMB method only showed the same recharge in January-February 2006 (Figure 6.8). At the same time, the preferential flow recharge in the basin observed with the CMB method in July-August is only visible on the WTF curves for the Tanyélé station. Sudden and exceptional peaks of the water table normally depict the preferential flow considered as localized, instant and fast recharge flow process (Gee and Hillel 1988, de Vries and Simmers 2002). For these reasons, the two methods seem to have monitored two different aquifers in the basin. Considering the shallow depths (5.5 m maximum) of the piezometers compared to the drilled hand pump boreholes of 40-70 m depth in the granite bedrock (Ouédraogo et al. 2003) where the groundwater samples were taken for the chloride analysis, the two methods are likely to have evaluated two different aquifers. In this case, the WTF method estimates recharge to perched aquifers whilst the CMB method estimates recharge to deep aquifers. Therefore, it took four months (from September to January) for the perched aquifer recharge to pass through the unsaturated zone by percolation and reach the water table of the deep basin aquifer depending on the hydraulic conductivity of the confining bed. Meanwhile, two exceptional peaks can be observed at the Tanyélé station on 15 and 25 July 2005 with the WTF method (Figure 6.7) as observed with the

CMB method (Figure 6.3). It can also be seen that the preferential flow at Tanyélé was more important than at the three other stations. Consequently, and considering the gaps in the monitoring water levels due to the piezometers shallowness, the suggested difference in the basin aquifers monitored by the two methods has to be reconsidered. As the CMB method shows that the preferential flow recharge was relatively low for the three stations, due to the shallowness of the piezometers such low peaks are likely to have occurred below the piezometers and therefore remained undetected. Hence, the impression that the recharge at these stations was to perched aquifers different from the deep water table aquifers exploited by the hand pump boreholes. At the actual stage of the study, no conclusion can be drawn on the exact figure of the aquifer structure in the basin and the importance of the suggested perched aquifers.

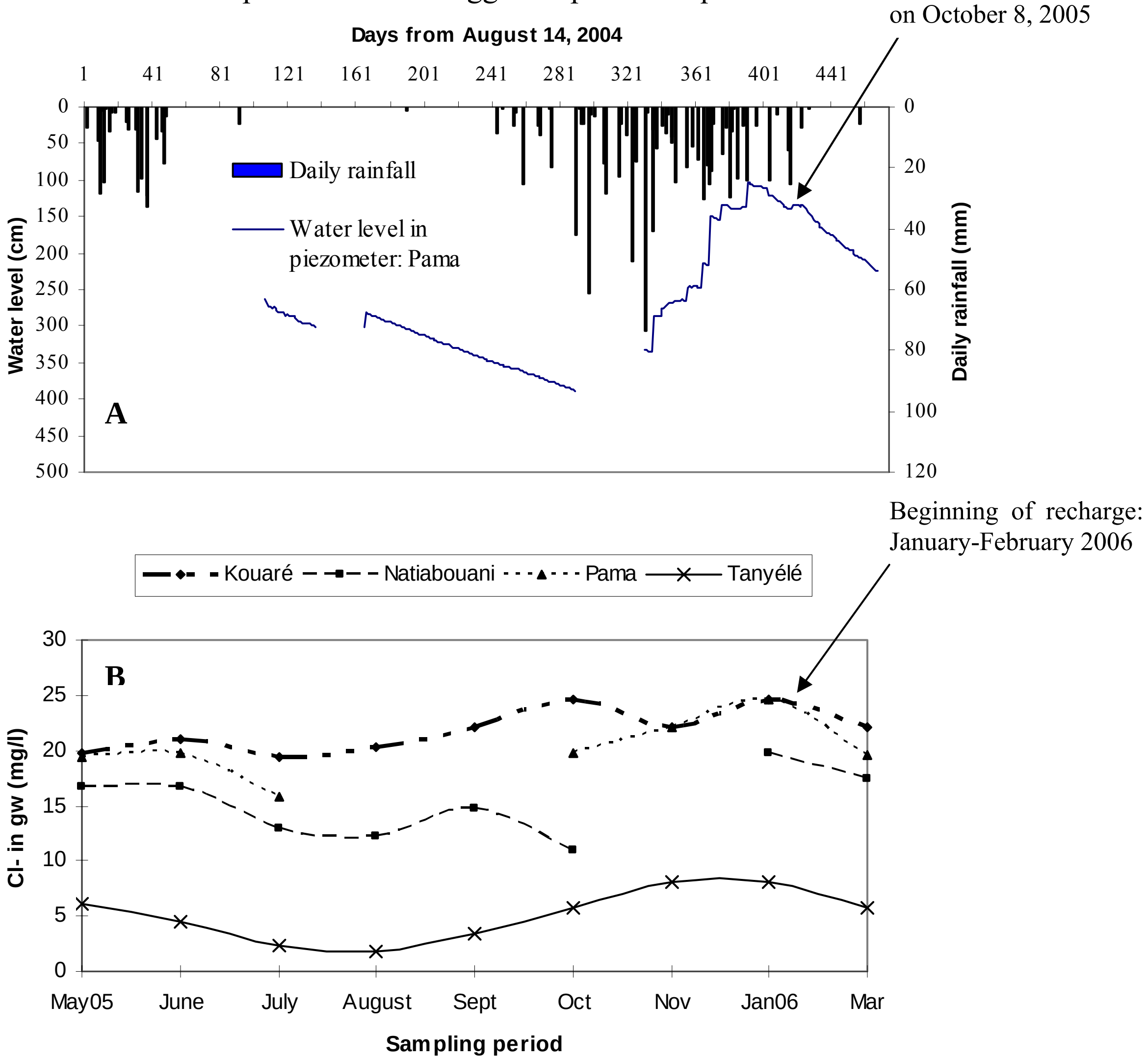

Figure 6.8: Water levels fluctuation at Pama station (A) and variation of chloride concentration in groundwater (B; regression data) along the rainy season 2005 showing the shift in the recharge occurrence

From the water level fluctuation figures, the water recharge depths were determined. Considering the soil textures at the four research stations and standard values of soil specific yields from Johnson (1967), Prickett (1965), Castany (1982), Todd (1980), and Sinha and Sharma (1988), annual groundwater recharge at the stations was derived (Table 6.8). The specific yields in the recharge estimation were the average values of the specific yields of the soil texture at each station considering the vertical variability of the soil layer textures and the corresponding specific yields from the surface to the granite bedrock.

Table 6.8: Specific yield (S_y) according to soil texture and the recharge in 2005 using the WTF method

Station	Soil class	S_y		Δh	Recharge (mm)				
		Min	Max	(mm)	Min	Max	Average	Stdev	CV(%)
Tanyélé	Sandy loam	0.005	0.10	3950	19.8	395.0	207.4	187.6	90
Pama	Gravelly clay	0.01	0.12	2800	28.0	336.0	182.0	154.0	85
Natiabouani	Gravelly silt	0.02	0.13	2410	48.2	313.3	180.8	132.6	73
Kouaré	Sandy clay	0.03	0.06	1850	55.5	111.0	83.3	27.8	33

CV = Coefficient of Variation; Stdev = Standard deviation

The overall basin recharge in 2005 varied between 43.9 mm and 243.6 mm using the weights determined with the Thiessen polygon method (Table 6.5). Compared to the annual rainfall of 829.6 mm, the recharge fluctuated between 5.3% and 29.4% with an average of 17% representing 143.8 mm. The reason to this wide range of recharge is most certainly the soil specific yield. Indeed, the reference values in the literature are given in wide ranges of specific yields according to the soil textures in the basin. The lack of laboratory data on the soils of the stations and the prohibitive cost of long-duration pumping tests to derive adapted in situ data meant that standard values from literature had to be used. However, although the aforementioned field measurements were done, nothing predicts that they would have been better than the standard values quoted in Healy and Cook (2002) due to intrinsic shortcomings attached to such field measurements. Likewise, the graphical determination of Δh (station recharge heights) suggested by the method, is an additional source of uncertainty in recharge estimation.

Nevertheless, according to the average recharge values (Table 6.8), it can be remarked that the WTF method depicts the highest groundwater recharge estimates in the basin in 2005 (CV of 33% to 90%) compared to the two other methods. Effectively, the results of these methods in the opposite of the WTF method, fall within the interval of probable recharge in the basin derived by the error estimation in the annual time step water balance recharge (Section 6.3.2). Considering the gaps in the water level monitoring from the piezometers due to their shallowness, the hydraulic heads (Δh) determination according to the WTF method are likely to be overestimated, as the observed preferential flow with the CMB method was undetected by most of the piezometers. Hence, the basin recharge could have been overestimated by the WTF method. At the Tanyélé station, where preferential flow was detected, recharge can be separated into two parts from the curve (Figure 6.7), with one part pertaining to the preferential flow and the other to the matrix flow, and the recharge estimated accordingly. The preferential flow recharge then varies between 2.1 mm and 82 mm, while the matrix flow recharge fluctuates between 1.6 mm and 62 mm for a maximum of 144 mm as total recharge instead of 395 mm (Table 6.8).

6.5 Conclusion

The first groundwater recharge assessment ever undertaken in the Kompienga dam basin using the chloride mass balance method, water balance method and water table fluctuation method is presented. According to the estimation results from the three methods (Table 6.9), the basin recharge in 2005 can be considered equal to 43.9 mm (the lowest recharge of the range out of the extreme recharge values of 4.1 mm and 243.6 mm) corresponding to 5.3% of the annual rainfall. This recharge represents 259.5 milllion m^3 of groundwater potential in the basin in 2005.

Table 6.9: Groundwater recharge in the Kompienga dam basin in 2005 estimated from the methods of chloride mass balance, water balance and water table fluctuation

Recharge estimation method	Recharge (mm)	Recharge (% of annual rainfall)
Chloride mass balance	45.4	5.5
Water balance (min-max)	4.1 – 59.8	0.5 – 7.2
Water table fluctuation (min-max)	43.9 – 243.6	5.3 – 29.4

The estimation is in line with previous evaluations within the research area of West African crystalline basement aquifers quoted in van der Sommen and Geirnaert (1988), Bromley et al. (1997) and Martin (2005) and varying between 2% and 16% of the annual rainfall.

Table 6.10: Recharge rates from previous studies within West African crystalline basement aquifers

Site	Pann. (mm)	Recharge (mm)	Recharge (% of Pann)	Method	Source
Southwest Niger	564	10-19	1.8-3.4	Chloride profiling	Bromley et al. (1997)
Central Burkina Faso	690	23-45	3.3-6.5	Modeling	Thiery (1988)
Northern Ghana	910-1138	59	6	Chloride mass balance	Martin (2005)
Central north Burkina Faso	517	10-37	1.9-7.2	Soil moisture profiling	Milville (1991)
	515-1000	10-250	-	Modeling	Milville (1991)
West African region	850	17-136	2.0-16.0	WB, WTF & isotope analysis	van der Sommen and Geirnaert (1988)

WB = Water Balance method; WTF = Water Table Fluctuation method; Pann. = annual precipitation

Meanwhile, the recharge estimates from the three methods depicted differences for reasons additional to the fact that they were evaluated using different methods and are expected, *a priori,* to be different. Uncertainties in the determination of the parameters are one of the main reasons for these differences as showed with the water balance annual time step recharge estimation. For example, in the process of estimating the water balance components (Chapter 5) for the basin recharge evaluation, errors are likely to arise and reduce the reliability of the estimate (Lerner et al. 1990 and Gee and Hillel 1988) by as much as 100%. Howard and Lloyd (1979) at this purpose, observed from studies on Northern Lincolnshire Chalk aquifers (United Kingdom) that an overestimation of the potential evaporation by 10% in the water balance method can result in underestimating the recharge by 5%. Another important reason is the intrinsic nature of the methods. The recharge estimations with the CMB and the WTF methods integrate large areas 200 m to several kilometers from the measurement points (Wood and Sanford 1995). Using this property, the results from the four stations were brought to the whole basin level, while the water balance method derived the recharge of the whole basin in one step and directly from the parameters observed at the outlet of the dam without considering spatial specificities likely to influence the whole basin recharge. According to the precedents, precision in groundwater recharge estimation whatever the method, remains limited by the accuracy level of the estimation components.

The CMB method proved the existence of fractures and similar features all over the whole Kompienga dam basin inducing preferential flow recharge prior to the diffuse flow processes. In line with the WTF method, the CMB method showed that the Tanyélé station received more recharge than the three other stations, mostly due to the existence of preferred flow pathways, favorable soil texture and the proximity to the dam's lake. The Kouaré station at the upstream part of the basin with low recharge suggests unfavorable soil textures as well as probable discharge of the aquifer downstream to the dam's lake and surrounding aquifers. The latter assumption is substantiated by the station's groundwater recharge levels (Table 6.8), where an increase following the watershed slope is observed. The suggested preferential flow impact in the whole basin recharge processes seems to be of little importance as groundwater samples depicted a relatively high chloride content in comparison to that in rainwater. Effectively, for a dominant preferential flow process of recharge in the basin, the groundwater chloride content would have been closer to that of rainwater as observed for the Tanyélé station, where this flow process of recharge appeared predominant due to the low groundwater chloride content of less than 10 mg/l (Figure 6.8).

The daily time step evaluation of the basin recharge with the water balance method shows strong relationship between rainfall and recharge through the soil moisture. The equation derived from this relationship shows that annual recharge in the basin can only start after a threshold of cumulative rainfall of approximately 314.3 mm. The annual recharge directly proportional to the annual rainfall is derived from this relation with reduction of the total Ea measured at the end of the rainy season till the end of the annual period due to transpiration of the deep-rooted trees in the basin.

With the WTF and the water balance methods, a time lag of approximately 2 to 3 months was observed between the rainfall events and the commencement of the recharge to the basin aquifers. This time lag depends on various factors (Spaan and Stroosnijder 1997, van de Giesen et al. 2000, Ajayi 2004 and Nyagwambo 2006) and is a key factor in any sustainable planning scheme for groundwater resource management in the basin. The results of the study on the basin recharge suggest the existence of perched aquifers at three of the four research stations, probably induced by the weathering of the basin crystalline rocks, which are known to lead to formation of clay in the soil profile and therefore reduce hydraulic conductivity (Dubois 2002 and Nyagwambo 2006).

Although the results of this study can be considered substantial for preliminary steps in the basin water resources management, additional studies need to be carried out for their validation and for planning of sustainable water management. The recommended studies are mainly:

- Analysis of satellite images of the basin area to detect the preferred flow pathways and similar features suggested by the CMB method;
- One or two years more of rain and groundwater sampling for chloride analysis as suggested by Bromley et al. (1997) for validating the basin groundwater recharge estimate using the CMB method.

7 GROUNDWATER USE AND WATER SUPPLY RATE

7.1 Introduction

Water resource management and especially groundwater management requires knowledge on the aquifer characteristics in terms of quantity, quality, renewability, withdrawal and temporal and spatial variability. Following the basin groundwater potential evaluation, the withdrawal quantities were evaluated as a complementary parameter in setting up the groundwater management plans for the Kompienga dam basin. Based on the annual renewability of the basin resources according to climatic conditions and the geophysical characteristics of the basin, management planning will basically aim at ensuring a reliable water supply for the population and improving their livelihood by adding economic value to the basin water productivity whenever possible.

7.2 Results and discussion on the basin groundwater use

From the survey of the 15 water monitoring sites in the basin and in accordance with the considerations to fill the gaps in the non-survey periods, the monthly withdrawal volumes from the monitoring sites were determined (Table 7.1). For extrapolation of these monthly volumes to the whole Kompienga dam basin, additional calculations were done to determine the total number of boreholes within the basin and the average monthly withdrawal volumes for each borehole.

Table 7.1: Groundwater withdrawal volumes (m³) in the dry season 2005 derived from 15 monitoring points within six localities in the Kompienga dam basin

Locality	Comin Yanga	Kouaré	Natiabouani	Kompienbiga	Pama	Djabiga	Total
No. of survey pts	3	2	2	2	4	2	15
Population	5373	5990	11565	4745	6204	1878	35755
Nov 04	1022.04	184.17	825.52	591.32	2853.39	1401.55	6877.99
December	1159.40	221.46	823.31	440.62	6185.27	2006.59	10836.65
January 05	1353.35	698.87	891.94	611.68	5845.96	1621.74	11023.54
February	1547.29	1176.27	960.57	782.74	5506.65	1236.90	11210.42
March	1589.39	1334.23	1045.71	916.95	5538.13	1246.92	11671.33
April	1655.34	2624.32	930.14	1083.92	3972.97	2554.72	12821.41
May	1840.41	2023.49	884.81	1353.63	3972.97	1899.56	11974.87
June	1486.70	1748.06	614.95	1262.75	3972.97	1700.93	10786.36
Total vol. until April 2005	8326.81	6239.32	5477.19	4427.23	29902.37	10068.42	

the total volume is calculated till April 2005 to evaluate the relationship between the survey parameters. After April, the monthly volumes at Pama were mostly estimated and less representative of the real situation at this site.

According to the data, the localities seemed to cluster except for Pama and Djabiga (Figure 7.1).

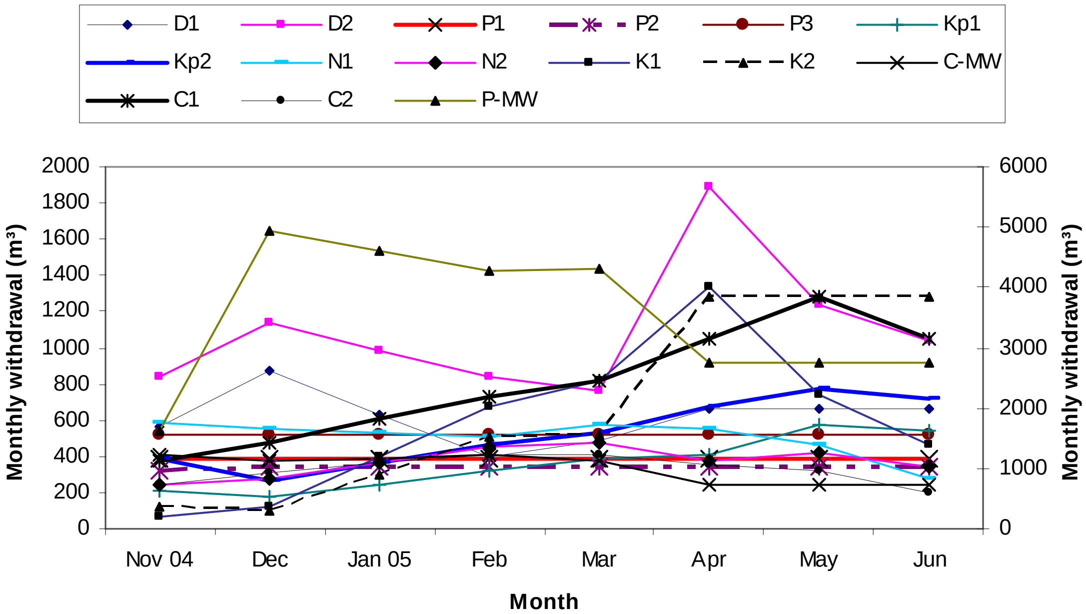

Figure 7.1: Monthly groundwater withdrawal quantities during the dry season 2005 from 15 water monitoring points in the Kompienga dam basin.
D1 and D2 represent hand pump boreholes in Djabiga; P1, P2 and P3, hand pump boreholes in Pama; Kp1 and Kp2, hand pump boreholes in Kompienbiga; N1 and N2, hand pump boreholes in Natiabouani; K1 and K2, hand pump boreholes in Kouaré; C1 and C2, hand pump boreholes in Comin Yanga; and P-MW and C-MW, modern wells in Pama and Comin Yanga respectively. The curve P-MW refers to the secondary axe of monthly withdrawal (0-6000 m³).

It can be seen that the monitoring points are mostly separated into two groups. One group has a minimum withdrawal rate of 3000 m³/month, while the second group, where most of the sites are found, has a maximum withdrawal rate of 2000 m³ per month. Most of the monitoring points depicted an expected pattern of increasing withdrawal quantities with increasing heat till the heat peak period of April, typical of the climatic conditions in the country. Meanwhile, at Pama and Djabiga (curves P-MW, D1 and D2), an almost reverse trend is observable with a decrease in the withdrawal volumes between December and April. One reason is that the main water monitoring point at Pama that is a modern concrete well was drying up, as it gets far deep in the dry season with heat increasing. Another reason was the breakdown of the two monitoring boreholes pumps, which led to an extrapolation of the previous withdrawal quantities in March for the periods of April till June; these values are therefore underestimated. In Djabiga, the trend is due to temporary malfunction in the borehole pump leading to a lower yield of withdrawal.

When comparing the survey parameters of the localities, it appears that Pama had the highest withdrawal quantities due probably to more survey points at this site (4 points including the volumes of the local pipe distribution system; Figure 7.2). It can be seen that the withdrawal quantities are well correlated to the number of monitoring points (graph A with R^2=0.79) than the number of inhabitants around the survey site (graph B with R^2=0.007). The withdrawals should be correlated to the population size of the localities, but because the survey did not include all the water monitoring points in the localities, there is no correlation.

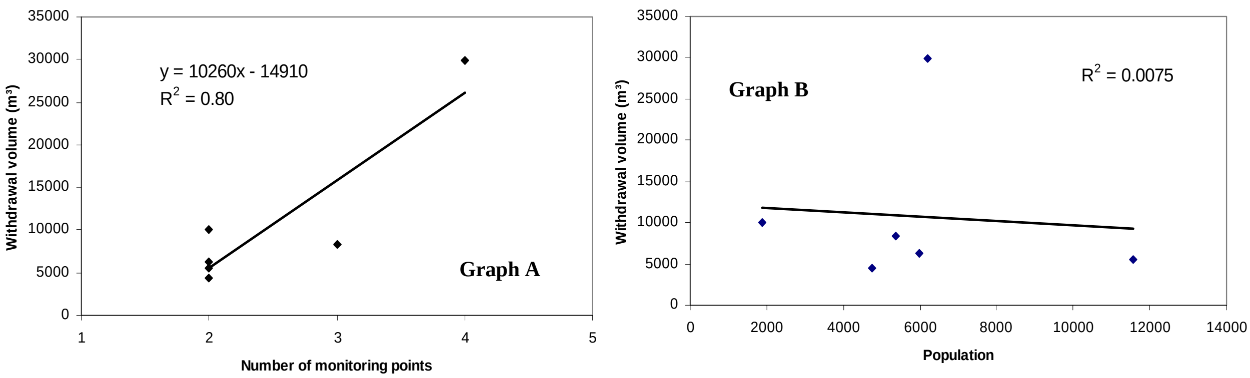

Figure 7.2: Correlation of withdrawal volumes versus number of survey points (graph A) and withdrawal versus population per locality (graph B) during the dry season 2005 in the Kompienga dam basin

From this analysis and the considerations above, the monthly withdrawal volumes per monitoring point to be considered for evaluating the whole basin withdrawal volume in 2005 was taken to be the mean monthly withdrawal volume of the 15 monitoring points (Table 7.2).

Table 7.2: Mean monthly withdrawal volumes per water monitoring point in the Kompienga dam basin

Period	Nov 04	Dec	Jan 05	Feb	Mar	April	May	June
Unit water monitoring point volume (m^3)	458	723	736	749	779	856	799	720

To determine the total number of water withdrawal points within the whole Kompienga dam basin, the BNDT-BF database (Topographic database of Burkina Faso) with all the villages in the country was used in ArcView to locate the position of the water withdrawal points in the Kompienga dam basin. This database was combined with the data of the recent national inventory of the hydraulic infrastructures (MAHRH 2006) to determine the number of water withdrawal points inside the basin and the population within the basin and in the villages surrounding the basin limits. The populations in the surrounding areas of the basin were taken into account based on the assumption that they are likely to use the basin water withdrawal points according to their accessibility (distance and easiness of fetching water, water demand intensity, pump breakdown or even preferences in terms of quality and taste). The same behavior applies to the population inside the basin toward the water withdrawal points surrounding the basin. When counting the water withdrawal points, those outside the basin limits were not considered, as they do not tap the basin aquifer. This consideration supports the assumptions for the basin recharge estimation with the water balance method stating that the basin aquifers are limited inside the boundaries only and no inflow from adjacent aquifers exist. All water withdrawal points in the MAHRH's inventory period were considered whatever their nature, whether modern wells, traditional hand-dug wells or permanent hand-pump boreholes or those drying up temporarily. Meanwhile, new boreholes without equipment for water abstraction and abandoned wells and boreholes were not included as they were unable to allow water withdrawal from the basin aquifers. The number of water withdrawal points and the population number were determined with updated data of the national census of the population in 1996 (INSD 2000) according to the local growth rate.

The estimation of the hydraulic infrastructures inside the basin area based on the MAHRH's inventory revealed a total number of 1223 water withdrawal points including all the intermittent traditional hand-dug wells as stated above. The total monthly withdrawal volumes of these points were determined (Table 7.3).

Table 7.3: Monthly water volume (m³) withdrawn from the Kompienga dam basin aquifers in 2005

Period	Nov 04	Dec	Jan 05	Feb	Mar	April	May	June	Total
Mean vol. of water withdrawal points	458	723	736	749	779	856	799	720	-
Monthly withdrawal	560786	884751	900131	915511	953091	1046860	977840	880937	7119907
Standard deviation	365.5	1161.7	1052.1	954.2	956	679.1	620.7	626	-
Coefficient of Variation-CV (%)	79.7	160.6	142.9	127.5	122.7	79.3	77.6	86.9	-

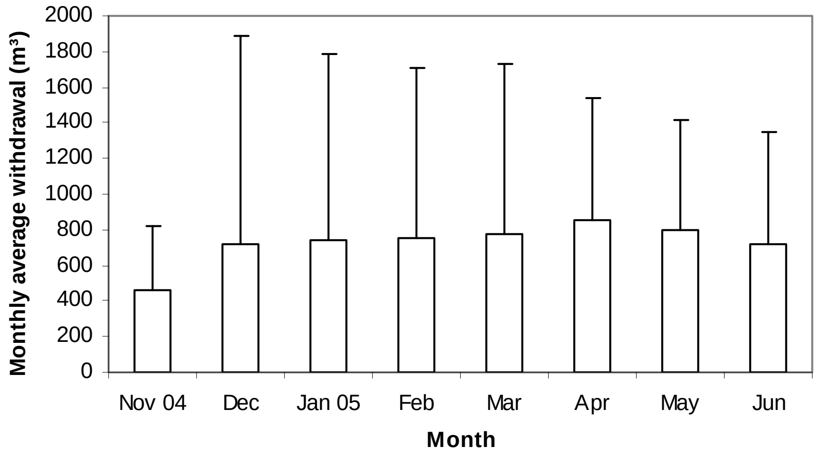

Figure 7.3: Standard deviation (top bars) from monthly withdrawals per water monitoring point in the Kompienga dam basin in 2004-2005

According to the monthly withdrawals, the volume in November was relatively low compared to that of December. The difference in volume between these two months (323 966 m³) is higher than that between the other months (Figure 7.3). Variability in the monthly withdrawals from one monitoring point to another was high (CV>100%) due to factors like the yield of the water monitoring points, the nature of these water points (well or borehole) and their density in the localities in relation to the density of the population. Another factor explaining the high level of the coefficient of variation in the monthly withdrawals is the quality of the monitoring by the surveyors likely to be different and thus influencing the recorded withdrawal quantities. The low withdrawal volume in November is probably because the rainy season had just ended and many ponds and marshes in the basin were still holding surface water for livestock watering, laundry and even for bathing. People, therefore, only use boreholes and wells for part of their supplies (drinking and cooking). Moreover, two exceptional rains were recorded in the basin at Tanyélé on 5 November (36 mm) and on 13 November at Pama (5.3 mm), which significantly reduced the need for water from boreholes.

The average monthly withdrawal volumes per borehole seem inconsistent with the hand pump yields reported by UNDP/World bank (1986) which varied between 5 and 36 l per minute, i.e., 0.3 m³/h and 2.16 m³/h with 0.7 m³/h as a currently observed yield for most of boreholes. Indeed, with a maximum daily pumping duration of 18 hours, which implies uninterrupted pumping from 4.00 am till 10.00 pm, a borehole could yield only 391 m³ of water in a month. But in this study, the survey involved modern wells that were sometimes the main source of water, e.g., in the urban zone of Pama where most of the hand pump boreholes had broken down during the dry season of the survey in 2005. The very modern well in Pama (Figure 7.5) was rectangular (6 m x 4 m and 17 m deep) with more or less permanent water throughout the year. The volumes of such wells increased the overall basin volume. Moreover, the hand pump boreholes could have been yielding more than the suggested 0.7 m³/h in the UNDP/World bank report (1986). Nevertheless, excluding the withdrawal volumes of these two wells in the survey (Table 7.1) gives an average monthly volume per water monitoring point of 321 m³ in November and 628 m³ in April (Figure 7.4). This corresponds to a maximum withdrawal volume for the whole basin of 770 000 m³ of water in April for a monthly unit borehole yield fluctuating between 0.7 m³/h in

November and 1.5 m³/h in April; this is the range of yields reported by UNDP/World bank (1986).

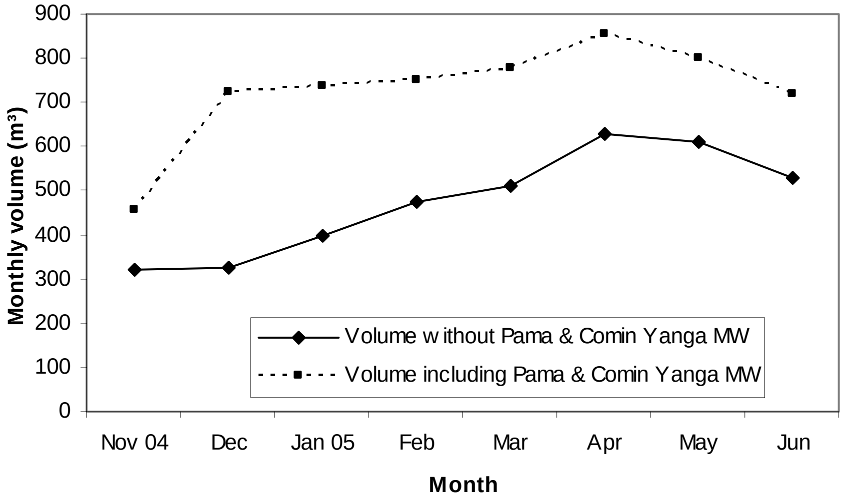

Figure 7.4: Variation of monthly withdrawal volumes per water monitoring point in the Kompienga dam basin based on the volumes of modern wells

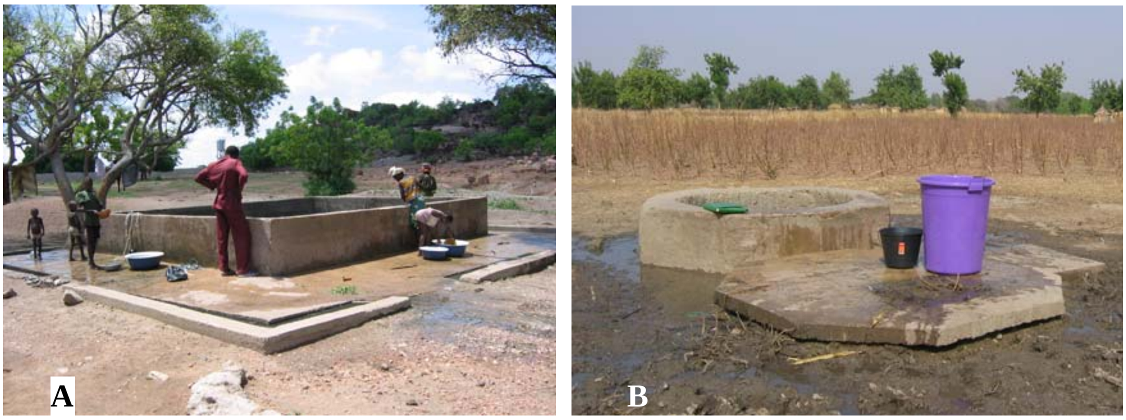

Figure 7.5: Monitoring modern wells in Pama (A) and Comin Yanga (B)

Based on this evaluation, the total water volume withdrawn from the basin during the dry season 2005 represents approximately 7 million m³ (Table 7.3) equivalent to 1.2 mm of water according to the basin area. It corresponds to 3 % of the annual recharge evaluated at 43.9 mm. A similarly low groundwater withdrawal of 0.7 % of the annual recharge was reported by Martin and van de Giesen (2005), who evaluated the groundwater potential in the Volta basin parts of Burkina Faso and Ghana. Martin (2005) also reported an abstraction rate of 4 mm/a in the Atankwidi catchment in northern Ghana for a recharge of 60 mm/a. Therefore, the actual evaluation is considered acceptable and consistent with the assumption made for the daily time step recharge estimation of the basin using the water balance method (Section 6.3.2).

From this evaluation, it can be concluded that the water withdrawals within the basin are very unlikely to deplete the groundwater aquifers in the Kompienga dam basin. Considerable opportunities, therefore, exist for improving the population's livelihood through development of the basin's water resources if the estimations elsewhere are considered reliable. Meanwhile, if for any reason (e.g., underestimation of the monthly withdrawal volumes or existing withdrawal points in the basin or not considered nighttime withdrawals reported by the surveyors, or even inconsistent assumptions in the withdrawal estimation), an estimation error of 100% of the withdrawal volume is considered, a correction will merely bring it to 2.4 mm, which is still remarkably low compared to the 43.9 mm of recharge.

7.3 Water demand and supply within the basin

The previous results show the low importance of the withdrawals compared to the recharge. Now the supply level should be examined in order to ensure that the withdrawals satisfy the population demands as suggested by the positive difference between recharge and withdrawals. Groundwater resource management assumes that the population demands are satisfied at all times and for all people everywhere in the basin. Before evaluating the supply quality, the question arises what happened to the large remaining part of the annual recharge to the basin in 2005? Was there no carry-over of the aquifer's water from one year to another if it is considered that withdrawals are nearly negligible compared to recharge? Answers to these questions can be found in the study of van der Sommen and Geirnaert (1988) on the continuity of the aquifer systems in the crystalline basement in Burkina Faso. The study proved that within such aquifers, lateral discharge flow is of the same magnitude as recharge and the authors concluded the existence of continuity in the regional lateral flow of the basin recharge within the crystalline basement aquifers. Thus, the observed extensive recharge to the Kompienga dam basin aquifer is mainly for discharge to adjacent aquifers due to the favorable hydraulic gradients, toward the downstream parts. Therefore, there is no carry-over of water from one year to another. This conclusion provides opportunities for substantial planning schemes in groundwater resource management to satisfy water demands in the basin. For this reason, the water supply has to be evaluated, as the recharge appears enough to support more than the population demands.

7.3.1 Actual water supply

To evaluate the supply rate, monthly withdrawal volumes are compared to the volume of recharge to the basin. It can be seen that the recharge within the basin corresponds with the rainy season, while the withdrawals are mainly in the dry season period where no recharge takes place; the withdrawals are from the last rainy season recharge. The daily basin recharge estimation with the water balance method shows that from November 29 (Appendix 2), the basin soil moisture started to deplete and the recharged water then started to contribute to the daily water balance at the rate of the transpiration of deep-rooted trees and the withdrawals. From this period, the total withdrawals of about 560 000 m^3 of water (Table 7.3) in addition to actual evaporation and the following dry season withdrawals of 6.5 million m^3 are considered normally satisfied by the recharged water volume of 259.5 million m^3. Before this period, losses through withdrawals and tree transpiration are supposed to be compensated by inputs through rainfall. However, in reality the supply satisfaction from the basin recharge is not as simple as presented. Indeed, the suggested regional lateral flow is occurring simultaneously with evaporation, transpiration and withdrawals to deplete the recharged water resources. With such considerations and depending on aquifer transmissivity spatially variable, the water levels of the aquifers can drop too fast or too slowly, resulting in rapid or slow drying up of some wells and boreholes. Hence, subsequent low withdrawal volumes and low supply to the population. The storage capacity of the crystalline basement aquifers, spatially variable, is therefore an important parameter to take into consideration for the supply estimation. According to the degree of fracturing of the rock materials, the storage capacity will be more or less considerable, as the induced secondary porosity will vary accordingly (Kellgren and Sander 2000). This parameter highly influences success of borehole siting in hard rocks terrain, boreholes yields and the abstraction rate. For the Kompienga dam basin, studies in the area revealed the success of borehole siting to be related to the thickness of the weathered layer of the geological formations (Ministère de l’Eau 1990). The thicker the weathered layer, the more successful are the boreholes sitings. This spatial variability of the basin aquifer storage will thus play a major role in the water supply quality, which is likely to differ, as the geological formations in the basin are mainly crystalline. Related to the spatial variability of the supply quality is the distribution of the hydraulic infrastructures all over the basin according to the population density. For a good water supply, every inhabitant in rural areas should receive a minimum of 20 l of water per day (MEE 2001 and WHO 2003). This standard rate of supply is the basis for evaluating the supply quality within the Kompienga dam basin. Using inventory data (MAHRH 2006) with the above assumptions on the local population and the number of hydraulic infrastructures, the estimate shows (Table 7.4) that the water supply quality is satisfactory when compared to standard norms of supply mentioned by Gleick (1996) as ranging between 27 and 200 liters per capita per day (l/c/d).

Table 7.4: Water supply rate for the administrative departments in the Kompienga dam basin based on population and estimated withdrawal quantities in 2005

Department	Inhabitants	Hydraulic infrastructures	Annual withdrawal volume (m^3)	Water supply rate (l/c/d)
Diabo	48947	305	1 773 119	149.7
Diapangou	21960	124	720 875	135.6
Comin Yanga	34401	168	976 669	117.3
Yondé	24931	102	592 977	98.3
Gounghin[b]	19859	158	918 534	191.1
Bissiga	213	1	5 814	112.8
Dourtenga	2692	31	180 219	276.6
Ouargaye	7954	13	75 576	39.3
Sangha	9821	25	145 338	61.2
Soudougui	18737	29	168 592	37.2
Kompienga	8324	36	209 286	103.9
Pama	13802	89	517 402	154.9
Tibga	2280	17	98 830	179.1
Fada	56435	125	726 688	53.2
Total	**270 356**	**1 223**	**7 109 916**	**(122.2)**

[b] Total population of this department includes that of the 15th department (Yorgo)
Number between brackets is the average of the column

Meanwhile, the derived results should be read with caution as:

- The supply rate refers to the whole water volume taken from all withdrawal points and for all purposes including livestock watering. The supply rates reflect thus household uses and livestock watering, while the WHO standard refers to household uses only, comprising consumption and hygiene, i.e., drinking, cooking and personal hygiene; laundering is not included.
- The supply volumes were estimated considering that all the water withdrawal points are permanently bearing water and have functioned so, during the whole dry season in 2005. For the estimation of the basin water abstraction, such assumption was tolerable but for the effective water supply rate to the population it has to be reconsidered as some of these water-bearing points dry up before the next rainy season starts. For this reason, the water supply to the basin population was re-estimated based only on the number of effectively permanent water-bearing points within the basin listed in the official inventory report (MAHRH 2006).

Table 7.5: Water supply rate per administrative department in the Kompienga dam basin according to the number of functional hand pump boreholes and the population in 2005

Department	Hydraulic infrastructures	Annual withdrawal volumes (m^3)	Water supply rate (l/c/d)
Diabo	220	1 278 971	108.0
Diapangou	90	523 215	94.9
Comin Yanga	73	424 389	51.0
Yondé	71	412 759	68.4
Gounghin	142	825 518	171.8
Bissiga	1	5 814	112.8
Dourtenga	11	63 949	98.2
Ouargaye	11	63 949	33.2
Sangha	19	110 457	46.5
Soudougui	17	98 830	21.8
Kompienga	19	110 457	54.8
Pama	46	267 421	80.1
Tibga	14	81 389	147.5
Fada	94	546 469	40.0
Total	**828**	**4 813 582**	**(80.6)**

Number between brackets is the average of the column

From this re-evaluation, it can be seen that the supply rate per administrative department in the basin seems acceptable as the lowest rate of 21.8 l/c/d observed for Soudougui department equals the standard norm value of 20 l/c/d suggested by Water and Environment Ministry (MEE 2001) and WHO (2003). Meanwhile, considering that the estimated supply comprises livestock watering, it can be concluded that it will probably be insufficient in some areas. Comparing these results to the first evaluation, there is a reduction of 32 % of the number of hydraulic infrastructures, which induced a reduction of the withdrawals to the same order of magnitude. According to this new situation, the total withdrawal quantity is about 0.8 mm, which is 2 % of the annual recharge in 2005 representing a 40% reduction of the previous evaluation. Considering this re-evaluation to be based on the functional hand pump boreholes in the basin, it appears possible, therefore, to develop the basin resources for the population livelihood improvement. Meanwhile, the acceptable water supply quality for the basin population seems contradictory to the interviews carried out among the monitoring surveyors of the water withdrawal points. In these interviews, it appeared that in the families where the supply was considered acceptable, the supply rate ranged between 20 and 54 l/c/d, while for those who found it insufficient, the supply rate fluctuated between 29 and 48 l/c/d. Based on these results, which are, however, statistically insufficient to draw valid conclusions for the whole basin population, it can nevertheless be noted that the supply rate of 20 l/c/d is only for basic needs. Therefore, the daily water requirements need to be reconsidered as requested by most of the interviewees, and increased to an average supply of 35 l/c/d.

Table 7.6: Summary of interviews with families on the water supply quality in the dry season within the Kompienga dam basin

Interviewee/site	Daily water demand–dry season (liters)	No. of persons in the family	Supply rate (l/c/d)	Appreciation of the supply
S. Ouahabou/Comin Yanga	875	30	29	Never satisfied
G. Issa/Natiabouani	420	13	32	Hardly satisfied
O. Roucky/Natiabouani	105	3	35	Satisfied
K. Harouna/Kompienbiga	950	20	48	Not satisfied
O. Oumpougla/Pama	360	8	45	Satisfied
C. Kalenli/Djabiga	862	16	54	Satisfied
T. Baridja/Djabiga	630	32	20	Satisfied

7.3.2 Future water supply

According to the previous scenarios, it appears that the actual water supply was satisfactory. Thus, considerable possibilities are open for resources development. However, will this situation last in the basin considering the erratic rainfall conditions in this semi-arid zone of Kompienga in addition to the so-called climatic change and its forecasted side effects, as well as the growing population in the basin? What should sustainable water resources development in the basin look like?

Such questions are vital for decision makers, who need to know how to proceed without delay in order to secure the population welfare for years ahead. Martin (2005) evaluating the recharge to the Atankwidi catchment in northern Ghana with a monomodal rainfall pattern, realized that a 20 % reduction in the annual rainfall reduces the annual groundwater recharge by 30 to 60 %. Nyagwambo (2006) made the same observation in his research on the small Nyundo catchment in Zimbabwe under tropical climate conditions, where he noted that a reduction of 40 % in the annual rainfall has induced a 30 to 60 % reduction in the catchment annual recharge of the aquifers. Based on these results where the characteristics of the aquifers are similar to those in the Kompienga dam basin, similar conclusions can be made with regard to the rainfall and groundwater recharge relationship. Moreover, the analysis of the long-term rainfall data series (1959-2005) in the basin showed that 24 years over 46 recorded on average 11.8 % reduction of the average mean annual rainfall of 830.2 mm. From these years, only 4 years (1983, 1984, 1990 and 1997; Table 7.7); i.e. 17 %, recorded rainfall lower than 20 % reduction (664.2 mm) of the average long term mean annual rainfall; which is nearly the basin average rainfall depth in 2005 (829.6 mm). Therefore, considering 20% reduction in the basin average precipitation in 2005 as basis for the simulation scenarios appears reasonable and consistent.

Table 7.7: Reduction rate of average annual rainfall in the Kompienga dam basin according to the average mean annual rainfall (830.2) of the long term rainfall data series (1959-2005)

Year	Average annual rainfall (mm)	Reduction rate (%) according to average mean annual rainfall	Year	Average annual rainfall (mm)	Reduction rate (%) according to average mean annual rainfall
1970	748.1	9.9	1985	673.9	18.8
1971	785	5.4	1986	716.2	13.7
1972	756.6	8.9	1987	692.6	16.6
1973	783.3	5.7	1988	789.2	4.9
1976	808.3	2.6	**1990**	632.2	**23.8**
1977	754.5	9.1	1993	806.2	2.9
1978	771.8	7.0	1996	768.5	7.4
1980	715.5	13.8	**1997**	620.3	**25.3**
1981	789.2	4.9	2000	746.3	10.1
1982	729.7	12.1	2001	765.8	7.8
1983	657.6	**20.8**	2002	671.1	19.2
1984	561.8	**32.3**	2004	823.7	0.8

Somé (2002) and Paturel et al. (2002) reported an almost cyclic 20-year dynamism pattern of the rainfall in Burkina Faso with consequent impacts on the groundwater recharge as observed by Thiery (1988) with piezometric measurements from a site in Ouagadougou. It was observed for example, that low precipitations occurred in the periods 1972-1973 and 1983-1984 with consequent droughts, while the 1950's, 1960's and 1990-1999 were reported to have higher precipitation (Somé 2002, Paturel et al. 2002). In reference to such results and according to the results of this study, realistic scenarios of rainfall variations can be simulated to derive the basin recharges and determine adequate water supply rates in relation to projected withdrawal volumes from standards of water supply rates and the population size.

According to the long-term annual rainfall pattern in the basin region (Figure 4.6), the 2005 precipitation of 829.6 mm ranged within the average precipitations. Within this long-term annual rainfall, the years 1983-1987, 1990, 1997 and 2002 which fall almost within the low rainfall periods reported in Somé (2002), showed amounts fluctuating between 500 and 750 mm, which represents a 19% to 32% reduction of the 2005 rainfall. Considering the observed rainfalls patterns, the decades 2010 to 2020 are likely to be dry or at best with annual average rainfall, as the decades since 1990's can be considered rainy or with average rainfall. In the simulation scenario for assessing the water supply to the population, five important parameters are considered:

1. Annual rainfall depth influencing the recharge;
2. Population size;
3. Number of water withdrawal points (wells and boreholes);
4. Average daily withdrawal duration at each water point
5. Average unit yield of the water withdrawal points.

From these parameters, the scenarios will be built around the two first parameters and the derived supply rates will be improved if necessary by refining the other parameters. Subsequent assumptions for the basis of the simulation are therefore:

- The annual population growth rate considered equal to 3.2% (Dipama 1997);
- The total number of 828 boreholes in the basin considered unchanged despite the population increase for the reason that, maybe new boreholes have replaced some broken down ones or no new borehole has been added to the existing functioning boreholes;
- The water demand by population will be determined based on the national standard of water supply in rural areas (20 l/c/d) and on Gleick's (1996) estimations reported in Seckler et al. (1998) and consistent with the survey results (Table 7.3) for 20 m^3/c/year which corresponds to 55 l/c/d;
- The average unit borehole yield will be taken equal to 0.7 m^3/h; the minimum drilling yield that a borehole in Burkina Faso should have to be equipped with pump for water abstraction;
- The dry season period of November to June (242 days) will be the period of the simulations as in the estimation of the actual supply rate to the population.

First scenario: 20 % reduction in the actual annual rainfall amount with population size unchanged or negligibly changed. A possible scenario in 2007.

In this case, and considering the proximity of the study area to the Atankwidi catchment in northern Ghana with similar geological formation, the recharge reduction will be considered proportional to that at this site (Martin 2005). The unchanged population size or negligible change implies that the withdrawals also remain more or less the same as the actual withdrawal quantities with slight increase during the rainy period due to the rainfall reduction, which will be compensated by subsequent rainfalls. Moreover, this period is not included in the withdrawals evaluation.

Second scenario: 20 % reduction in the actual annual rainfall amount and increase in the population

This is a scenario likely to happen in the coming decades according to Somé (2002) and Paturel et al. (2002). The population increase will induce an increase in the water demand that will be estimated based on the assumptions above.

Third scenario: No reduction in the annual rainfall but increase in the population

This scenario is likely to occur anytime from 2005 onward. The recharge is here considered equal to the actual recharge of 259.5 million m^3 of water for supplying more people than the actual population.

Considering these scenarios, the simulations will first evaluate the capacity of the recharge to support the corresponding water demands. Second, the feasibility of the demand satisfaction will be examined according to the existing number of boreholes and their unit yield associated with the possible daily duration of abstraction (Section 5.2.4). Finally, suggestions will be made on how to satisfy the water demand by increasing the number of boreholes (equation 5.20), the daily withdrawal duration, or even limiting the supply rate.

Table 7.8: Water demand satisfaction in the Kompienga dam basin according to projected scenarios

<table>
<tr><th rowspan="2">Scenario</th><th rowspan="2">Year</th><th rowspan="2">Population</th><th rowspan="2">Annual rainfall 2005 (mm)</th><th rowspan="2">Annual recharge 2005 (mm)</th><th rowspan="2">20% reduction rainfall (mm)</th><th colspan="2">Annual recharge (mm)</th><th colspan="2">Water demand[c] (mm)</th><th rowspan="2">Demand satisfaction rate (%)</th></tr>
<tr><th>30% reduction</th><th>60% reduction</th><th>20 l/c/d</th><th>55 l/c/d</th></tr>
<tr><td>Scenario 1</td><td>2007</td><td>288224</td><td rowspan="9">829.6</td><td rowspan="9">43.9</td><td rowspan="4">663.7</td><td rowspan="4">30.7</td><td rowspan="4">17.6</td><td>0.2</td><td>0.6</td><td rowspan="9">>100</td></tr>
<tr><td rowspan="3">Scenario 2</td><td>2015</td><td>372315</td><td>0.3</td><td>0.8</td></tr>
<tr><td>2025</td><td>512725</td><td>0.4</td><td>1.2</td></tr>
<tr><td>2030</td><td>601688</td><td>0.5</td><td>1.4</td></tr>
<tr><td rowspan="4">Scenario 3</td><td>2007</td><td>288224</td><td rowspan="4">-</td><td colspan="2" rowspan="4">43.9</td><td>0.2</td><td>0.6</td></tr>
<tr><td>2015</td><td>372315</td><td>0.3</td><td>0.8</td></tr>
<tr><td>2025</td><td>512725</td><td>0.4</td><td>1.2</td></tr>
<tr><td>2030</td><td>601688</td><td>0.5</td><td>1.4</td></tr>
</table>

[c] *The water demand refers to the population needs only using equation 5.18 brought to the basin area. The projections didn't take into account livestock's needs and it was therefore remarkable that the actual withdrawal in 2005 estimated from the 15 boreholes survey was higher than the projected demands till 2025 with the supply rate of 55 l/c/d. Meanwhile, livestock demands volume can be projected equal to that of the population as unit supply rate is reported equivalent to 35 l/UBT/d (MEE, 2001). These demands are considered satisfied with modern and traditional wells in addition to natural lakes and the Kompienga dam Lake discarded from the water demands scenarios. UBT= unité de bétail tropical; approximately unit tropical livestock.*

Table 7.9: Water demand satisfaction based on possible withdrawal quantities in the Kompienga dam basin

<table>
<tr><th rowspan="3">Scenarios</th><th rowspan="3">Year</th><th rowspan="3">Population</th><th colspan="2">Water demand (mm)</th><th colspan="3">Possible withdrawal quantities[d] (mm)</th><th colspan="6">Satisfaction rate (%)</th></tr>
<tr><th rowspan="2">20 l/c/d</th><th rowspan="2">55 l/c/d</th><th rowspan="2">12 h/d
06:00-18:00</th><th rowspan="2">14 h/d
05:00-19:00</th><th rowspan="2">18 h/d
04:00-22:00</th><th colspan="3">20 l/c/d</th><th colspan="3">55 l/c/d</th></tr>
<tr><th>12h</th><th>14h</th><th>18h</th><th>12h</th><th>14h</th><th>18h</th></tr>
<tr><td>Scenario 1</td><td>2007</td><td>288224</td><td>0.2</td><td>0.6</td><td rowspan="4">0.28</td><td rowspan="4">0.33</td><td rowspan="4">0.43</td><td>140</td><td>165</td><td>215</td><td>47</td><td>55</td><td>72</td></tr>
<tr><td rowspan="3">Scenario 2</td><td>2015</td><td>372315</td><td>0.3</td><td>0.8</td><td>93</td><td>110</td><td>143</td><td>35</td><td>41</td><td>54</td></tr>
<tr><td>2025</td><td>512725</td><td>0.4</td><td>1.2</td><td>70</td><td>83</td><td>108</td><td>23</td><td>28</td><td>36</td></tr>
<tr><td>2030</td><td>601688</td><td>0.5</td><td>1.4</td><td>56</td><td>66</td><td>86</td><td>20</td><td>24</td><td>31</td></tr>
</table>

[d] *These quantities refer to the limitations of the hand pump yield of the boreholes and the daily duration of abstraction during the whole dry season period of 242 days. Their calculation refers to equation 5.19 brought to the dry season period duration and the basin area. h/d = hours per day.*

Table 7.10: Number of hand pump boreholes necessary to improve the water supply rate within Kompienga dam basin based on the projected scenarios

Projected water supply rate to population	Daily borehole functioning duration	Satisfaction rate (%)				Number of boreholes in 2005	Necessary number of boreholes				Number of additional boreholes			
		2007	2015	2025	2030		2007	2015	2025	2030	2007	2015	2025	2030
20 l/c/d	12h/06:00-18:00	140	93	70	56	828	828	886	1221	1433	0	58	393	605
	14h/05:00-19:00	165	110	83	66		828	828	1046	1228	0	0	218	400
	18h/04:00-22:00	215	143	108	86		828	828	828	951	0	0	0	123
55 l/c/d	12h/06:00-18:00	47	35	23	20		1887	2438	3355	3940	1059	1610	2527	3112
	14h/05:00-19:00	55	41	28	24		1618	2090	2878	3377	790	1262	2044	2549
	18h/04:00-22:00	72	54	36	31		1252	1618	2227	2614	424	790	1399	1786
25 l/c/d	12h/06:00-18:00	95	73	53	45		858	1108	1526	1791	30	280	698	963
	14h/05:00-19:00	112	87	63	54		828	950	1308	1535	0	122	480	707
	18h/04:00-22:00	146	113	82	70		828	828	1013	1188	0	0	185	360

The main results of the simulations (Table 7.10) can be summarized as followed:

- The option of 55 l/c/d as a water supply rate to be achieved for the population can only be considered as an ideal target as the necessary installation of the large number of new boreholes is hardly feasible;
- The 18 hours as a daily pumping duration for water abstraction at the basin boreholes appears to be extremely high and not to be recommended due to the predictable frequent breakdown of the borehole pumps that are supposed to be repaired by the population as reported by the interviewees (Appendix 6);
- Two options are relevant and feasible for achieving an acceptable water supply rate to the basin population within the next years whatever the scenario: the 12-hour and at most the 14-hour options of daily borehole pumping duration at 0.7 m^3/h;
- The supply rate of 20 l/c/d as used by decision makers in Burkina Faso (MEE 2001) for water supply in rural areas is hereby seen to be acceptable for supplying basic needs as described by WHO (2003). Otherwise, there would be a need for improvement according to the interview results (Table 7.6) and in reference to the water use quantities in 2005 (Table 7.4).

The non-relevance of the 55 l/c/d option is due to the induced high number of boreholes required and can be considered economically and technically unrealistic and hence less feasible. One consequence of this option would be the addition by 2030 of at least 3100 boreholes to the current functional boreholes in the basin. Considering one borehole installation costs around US$11 000 (MEE 2001) and the number of years it took to install the existing 1000 boreholes in the basin, installing 3100 boreholes in 20 years is practically impossible, as this will be unaffordable for the basin community. Moreover, adding 3100 boreholes to the existing ones will imply at least 4000 boreholes within the basin area of 6000 km^2, i.e., almost 1 borehole per km^2 considering the existing wells. The consequence would be that such density of boreholes would likely reduce the productivity of each borehole by lowering the yield due to interferences in the recharge and abstraction sources even the withdrawals revealed low. Thus, a rapid depletion of the aquifers would occur and hence the boreholes would dry up. Moreover, not all the basin areas are suitable for siting boreholes due to the crystalline nature of the basement rocks, where aquifers are mainly found in the fractured zones. However, as the number of necessary boreholes is inversely proportional to borehole yield and the daily abstraction duration (equation 5.20), if good sites for installing boreholes were to be found providing excellent yields for withdrawals, the supply rate of 55 l/c/d could be satisfied with less boreholes. In addition, the supply rates described by the interviewees and close to 55 l/c/d are considered as an indispensable supply rate for the 3-month period of March to May. While during the other months, less water is needed and the daily borehole functioning duration is far less than 12 hours (Appendix 6).

The simulation results of the scenarios to determine the basin capacity in supporting the population water demands show that a 20 % reduction in the rainfall amounts cannot considerably affect the supply quality as the water demands remain lower than the subsequent recharge rates, and when an adequate number of functional boreholes is available for withdrawal. Meanwhile, the general situation depicting a high capacity of the recharge to support the population demands needs to be verified with substantial monitoring of the deep groundwater level fluctuations throughout the whole basin.

The simulations also reveal the need of additional boreholes according to the increasing population along the years and the subsequent water demand increase. These new boreholes should be installed according to the supply rate of the different localities in the basin if the hydrogeological context is favorable. Therefore, localities with a low supply rate like the Soudougui, Sangha and Ouargaye departments as observed in the 2005 estimations (Table 7.5) should be first provided.

7.4 Conclusions

The actual water withdrawals from the Kompienga dam basin aquifers in 2005 were relatively low compared to the annual recharge. Estimated at 2% of the annual recharge to the basin, these low withdrawals mean much possibility for water resources development. The withdrawal estimations based on assumptions and data for 2005 may, however, not remain valid, as the situation is always changing with probably new boreholes thanks to projects or previously broken down boreholes now functioning.

Scenarios for decreasing rainfall in the basin and increasing population with subsequent increasing water demands reveal that it will be possible to supply the population with sufficient water if the required number of functional boreholes is available. Meanwhile, the recharge sufficient to supply the population demands needs to be substantiated by long-term deep groundwater level monitoring due to the nature of the basin crystalline basement rocks characterized by spatial variability in the hydrogeological parameters in addition to the concave morphology of the basin favoring unequal distribution of the recharge. It is also likely that in the long term, rainfall decrease will induce a higher reduction in the aquifer recharge than expected due to a probable reduction in the basin vegetation, which will result in higher runoff in the basin than infiltration for recharge as observed by Kincaid and Williams (1966), Albergel (1988), Lane et al. (1997) and Bagayoko (2006). In such case, the derived acceptable supply rates could be compromised and the population suffers from water shortages. Meanwhile, results from Gee et al. (1994) show that recharge is higher in non-vegetated than in vegetated areas (Scalon et al. 2002), higher in grasslands and under annual crops than in areas with trees and shrubs (Prych 1998) as observed by Allison et al. (1990) in Australia. They effectively noted a significant increase in recharge of two orders of magnitude after replacement of deep-rooted native eucalyptus trees by shallow-rooted crops. Nevertheless, and whatever the situation in the Kompienga dam basin, the existence of the dam is likely to contribute to accumulation of the whole basin runoff for indirect recharge to the aquifers. Therefore, only negligible changes in the supposed recharge rate might be observed and maybe even an increase in the recharge.

The supply rate of 20 l/c/d for 12 to 14 hours per day of withdrawal is considered as a reasonable option to satisfy the population's water demands. Nevertheless, there is a real need for improvement at least temporarily during the high demand in the heat period (March till May). This improvement, of course, should not target the rate of 55 l/c/d shown to be unfeasible (Table 7.10), but 25-30 l/c/d in order to fulfill the demand expressed through the interviews. Considering the unequal distribution of the boreholes in the basin due to the spatial variability in the aquifers suitability for siting boreholes, low supply rates may exist in some localities while in some others, they may be high as suggests GEF-UNEP's (2002) report (Table 4.1) indicating average boreholes yield of 5.2 m^3/h in the Oti sub-basin where the Kompienga dam basin is located.

Recharge within the basin mainly occurs during the rainy season period of low water demand while in the dry season of high water demand no recharge exists. The estimated general satisfaction of the supply according to the annual recharge can therefore be hindered, as in the natural context sub-lateral flow processes and transpiration from deep-rooted trees take place simultaneously with the withdrawals.

The simulations for the quality of the water supply to the population assumed that all recharge water to the basin is of good quality. Any poor quality of these waters would reduce the predicted possibilities and therefore induce water shortages. This situation cannot be completely discarded, as intensive cotton production has developed on the basin under the government incentives that in the long term, will lead to groundwater pollution due to pesticides as well as fertilizers (Morris et al. 2003).

The projected scenarios revealed considerable possibilities for developing the basin water resources. Within such possibilities, small-scales irrigation schemes from boreholes are considered suitable for cropping vegetables during the dry season if local markets and neighboring countries can absorb the production. This will provide additional income to the population for livelihood improvement and therefore reinforce the government's initiatives. Indeed, in January 2007 through a financial agreement with the Islamic Development Bank (IDB) for a project on development of agricultural activities downstream of small dams in the eastern part of Burkina Faso, a dam is planned by the government at Kouaré in the upstream part of the Kompienga dam basin (www.lefaso.net).

8 GENERAL CONCLUSIONS AND RECOMMENDATIONS

8.1 General conclusions

In this study, the first groundwater potential evaluation was made for the Kompienga dam basin in Burkina Faso. The basin hosts a national hydropower dam of 2.05 billion m³ of water at its maximum capacity mainly used for generating electricity and marginally for fresh water production to supply the Kompienga population.

The geographical position of the basin in the southeastern part of the country between the isohyets 900 and 1000 mm (Somé 2002) provided a relatively favorable annual rainfall to the site estimated at 830.2 mm in the period 1959-2005. However, as is the case for the whole country with its tropical climate, rainfall is characterized by seasonal and inter-annual variability with a standard deviation of 126 mm in the inter-annual rainfall amount. During the year, potential evaporation exceeds rainfall for most of the periods except for a few months in the rainy season. Therefore, only a daily or weekly water balance can be applied to estimate satisfactorily the basin groundwater recharge, as these time steps are closer to the natural occurrence of rainfall and recharge events. The basin groundwater recharge was estimated using three methods: the water balance, the chloride mass balance (CMB) and the water table fluctuation (WTF) methods. They provided different values for the basin recharge due to their intrinsic limitations and uncertainties in the measurements. However, the overall basin annual recharge was evaluated at 43.9 mm; i.e., 5.3% of the annual rainfall in 2005. This estimate appears to be in line with the results of previous studies within the West African region of crystalline basement rocks as underlying the Kompienga dam basin depicting the general low level of aquifer recharge in these semi-arid zones.

With the water balance method at daily time step estimation, it was shown that:

- in accordance with the WTF method, an approximate 2- to 3-month period exists as a time lag between the commencement of rainfall relative to the recharge. This period therefore represents the required duration for the basin soil moisture to be restored after the long dry season period before deep percolation starts;
- during the aforementioned time lag, the corresponding annual threshold rainfall was evaluated ranging between 314.3 mm and 336.6 mm.

Appropriate for estimating temporal variability of the basin recharge, the water balance method, however, is less adapted for estimating spatial variability of recharge.

The CMB method of recharge estimation provided the basin long-term annual recharge estimate and moreover, depicted in accordance with the WTF method, the flow processes governing the recharge. The preferential flow was shown to have occurred earlier and during a short period in the rainy season within the basin with variable importance according to the location, i.e., the geological characteristics. Meanwhile, the CMB method's high reliance on the chloride analysis of the samples as a prerequisite to its successful use has to be noticed. The CMB and WTF methods are appropriate to depict both spatial and temporal variability of recharge to aquifers. They revealed that three of the four research stations likely had perched aquifers due to the weathering of the crystalline rocks into clay layers of low permeability and hence leading to a low recharge to the deep basin aquifers of these stations compared to the fourth station, which had a high preferential flow recharge. In addition, the results from the WTF method suggest some sublateral flows following the topographical gradient of the basin for discharge of the upstream parts to the downstream parts.

The evaluation of the basin annual recharge potential provides a basis for planning the water resources according to the population demands and the annual and spatial variability in the aquifer characteristics. A further step is to determine the water demands within the basin, which have to be satisfied with the evaluated water potential.

These demands were projected based on the actual water uses quantities determined from daily water sampling campaigns at selected boreholes in the basin. The water use quantity by the population in 2005 was estimated at about 5 million m^3 of water for the dry season period of high water use of November 2004 to June 2005. This represents an average monthly volume of 725 m^3 of water per functional hand pump borehole in the basin for 18 m^3 per inhabitant and livestock during the whole dry season period as the survey took into account all the water use types in the basin (from domestic use to livestock watering and brick making).

Simulations were also used to determine the future basin population supply quality based on pessimistic scenarios of reduction in the annual rainfall amount by 20% with a concurrent increase in the population size. They showed that the resulting 70% to 40% of the long-term average annual recharge is still sufficient to adequately supply the population demands at 20 l/c/d. Considering that this supply rate is to be achieved by hand pump boreholes with an average yield of 0.7 m^3/h during 12 to 14 hours maximum per day of withdrawal, it can be seen that by 2030, 1200 to 1450 functional boreholes are necessary in the basin (Appendix 5.1). According to the unequal distribution of the actual number of boreholes in the basin, the new boreholes should be installed in the areas with the lowest density of boreholes like the Soudougui, Ouargaye and Sangha departments if favorable hydrogeological conditions exist there.

Interviews of the monitors of the water withdrawal points revealed that the supply rate of 20 l/c/d as assumed satisfactory for basic needs has to be slightly improved to ensure easy supply during the very high water demand period of March to May. This increase in the supply rate is seen to be possible through the increase in the daily withdrawal duration already practiced by the population and good organization of the water withdrawal in addition to good internal organization in the families regarding enough containers for water provision during the day. However, as the supply is directly proportional to the pumps yield, considering an average hand pump yield of 1 m^3/h as quoted in Ouédraogo and Ilboudo (1996) for Burkina Faso, there is no need for additional boreholes to adequately supply the basin population till 2015 at 25 l/c/d if the existing boreholes remain functional. To maintain the supply rate at 25 l/c/d with 12-hour daily withdrawal duration, by 2025 only 240 additional boreholes from the actual number will be needed and by 2030, 425 boreholes are necessary. Increasing the pumps average yield; which is reasonable as 0.7 m^3/h is the lowest possible yield for hand pump boreholes, was revealed therefore, to be highly beneficial as the 43% increase from 0.7 m^3/h to 1 m^3/h made it possible to improve the supply rate by 25% with a 40% reduction in the number of new boreholes.

Numerous scenarios remain to test the basin groundwater capacity for supplying the population demands. For example:

- What can be the supply rate to the population if the annual rainfall depth drops below the 20% reduction in the long-term average annual rainfall in the basin?
- What can the supply be when two consecutive years record rainfall less than or equivalent to the 20% reduction in the long-term average annual rainfall?

These worst-case scenarios cannot be discarded in reference to periods 1972-1973 and 1982-1984 (Table 7.7). However, consistent answers are not possible to draw, as reliable databases do not exist. Therefore, the endless character of the research sciences once again demonstrated.

8.2 Recommendations

In order to draw consistent and sustainable water resources management and development schemes it is essential to develop and maintain a reliable database of the basin groundwater potential through continual evaluations with improved methods such as modeling.

Additional to these activities is the necessity to evaluate the importance of the preferential flow pathways and similar features in the basin for early recharge occurrences that are substantial in the basin resources renewal and facilitate management.

Monitoring deep groundwater level fluctuations and the existing boreholes drillers logs are essential to evaluate the basin aquifer’s capacity to support all the abstractions during the long dry season period without recharge and to obtain the exact pattern of the aquifer structuring.

Further research studies need to be carried out for estimation of the spatial variability of the recharge according to the geophysical (geology, land cover and land use, topography) and hydrogeological (hydraulic conductivity, transmissivity and storativity) characteristics of the basin in order to guide through a clear pattern, boreholes siting for the groundwater resources development for the benefit of the population.

Studies on the future groundwater quality are necessary to prevent pollution of the basin resources as foreseeable from the existing cotton production intensification. The newly installed factory for shelling the cotton shows the central role that the basin zone will play in the future for cotton production in the country. An intensification of pesticides and fertilizers (generally chemical fertilizers) use and negative side effects for groundwater resources are to be expected (Morris et al. 2003).

Installation of adequate pumps in term of production yield can contribute to better supply the population and be beneficial for the investors.

According to the possibilities depicted by the high recharge potential to supply the population demand, the basin water resources development should be carried out. These resources development should be done with small-scale irrigation schemes, as successfully developed since 2001 by the PPIV project (small irrigation scheme promotion at the community level) of the Water and Environment Ministry under HPIC (Heavily Poor Indebted Countries) financial assistance (Youkhana et al. 2006) to procure income for the population. Such developments are more feasible at the administrative entities level such as departments, provinces and regions than at the uncommon basin level. Therefore, decision makers at those levels are invited to undertake such initiatives and improve the livelihood of the population.

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10 APPENDICES

Appendix 1: Example of .fmv file datasheet processed by the Alteddy software from Eddy correlation raw data file

Yr	Doy	DecTim	Flx_Tsonic	Flx_Krypto	Mea_WINDSP	Mea_Tsonic	Mea_Krypto	U-star	Z-over-L	Wind-Dir	80PercFlux	Var_U-Wind	Var_V-Wind	Var_W-Wind	Var_Tsonic	Var_Krypto
4	333	10	1.15E+02	3.81E+01	3.98E+00	2.64E+01	9.04E+00	4.07E-01	-2.05E-01	1.08E+02	4.40E+01	1.08E+00	1.05E+00	2.75E-01	5.84E+01	6.53E-02
4	333	11	1.84E+02	6.18E+01	4.45E+00	2.88E+01	8.29E+00	4.98E-01	-1.81E-01	8.84E+01	4.20E+01	1.38E+00	1.31E+00	3.34E-01	1.21E+02	1.88E-02
4	333	12	2.03E+02	5.08E+01	4.53E+00	2.97E+01	8.17E+00	5.29E-01	-1.66E-01	9.29E+01	4.00E+01	1.52E+00	1.33E+00	3.20E-01	1.08E+02	1.19E-02
4	333	13	2.30E+02	5.37E+01	3.73E+00	3.08E+01	8.40E+00	4.61E-01	-2.79E-01	9.50E+01	3.80E+01	1.48E+00	1.26E+00	3.29E-01	1.16E+02	1.03E-02
4	333	14	1.79E+02	4.96E+01	3.27E+00	3.19E+01	8.37E+00	3.90E-01	-3.59E-01	9.72E+01	3.60E+01	9.50E-01	1.28E+00	2.84E-01	1.03E+02	1.18E-02
4	333	15	9.15E+01	4.15E+01	3.08E+00	3.23E+01	8.63E+00	3.95E-01	-1.80E-01	1.17E+02	3.80E+01	7.09E-01	1.01E+00	2.14E-01	6.96E+01	1.95E-02
4	333	16	2.61E+01	4.21E+01	3.17E+00	3.22E+01	8.82E+00	3.49E-01	-8.18E-02	1.15E+02	4.60E+01	6.49E-01	3.88E-01	1.58E-01	3.02E+01	3.20E-02
4	333	17	-5.96E+00	2.60E+01	2.60E+00	3.16E+01	9.68E+00	2.73E-01	2.18E-02	1.05E+02	5.80E+01	4.21E-01	1.88E-01	1.00E-01	3.20E+01	5.16E-02
4	333	18	-1.15E+01	1.00E+01	2.29E+00	3.02E+01	9.93E+00	1.51E-01	3.60E-01	9.99E+01	1.52E+02	1.13E-01	5.93E-02	3.15E-02	-2.75E+01	1.05E-02
4	333	19	-1.81E+01	5.46E+00	2.45E+00	2.85E+01	1.06E+01	1.55E-01	5.47E-01	1.07E+02	1.86E+02	1.65E-01	1.09E-01	3.95E-02	-2.75E+01	3.00E-02
4	333	20	-2.29E+01	1.81E+01	2.34E+00	2.70E+01	1.21E+01	1.54E-01	6.86E-01	1.23E+02	2.00E+02	2.34E-01	3.84E-01	4.25E-02	-2.66E+02	1.19E-01
4	333	21	-1.61E+01	9.65E+00	2.38E+00	2.62E+01	1.18E+01	1.43E-01	6.15E-01	1.18E+02	2.06E+02	1.14E-01	6.04E-02	3.34E-02	-3.75E+01	4.52E-02
4	333	22	-2.18E+01	1.42E+01	2.63E+00	2.56E+01	1.17E+01	1.88E-01	3.60E-01	1.05E+02	1.42E+02	2.83E-01	1.32E-01	5.74E-02	-5.33E+01	4.19E-02
4	333	23	-2.45E+01	7.99E+00	2.36E+00	2.48E+01	1.14E+01	1.88E-01	4.12E-01	9.06E+01	1.40E+02	2.06E-01	1.28E-01	5.63E-02	-4.05E+01	1.46E-02
4	333	24	-2.49E+01	9.84E+00	2.02E+00	2.43E+01	1.13E+01	1.81E-01	4.70E-01	1.18E+02	1.34E+02	2.03E-01	1.68E-01	5.70E-02	-8.11E+01	3.73E-02
4	334	1	-1.90E+01	4.52E+00	1.61E+00	2.34E+01	1.15E+01	1.31E-01	9.61E-01	1.20E+02	1.96E+02	1.61E-01	1.24E-01	4.28E-02	-5.24E+01	1.00E-02
4	334	2	-1.70E+01	7.11E+00	1.55E+00	2.28E+01	1.17E+01	1.34E-01	7.92E-01	1.19E+02	1.72E+02	1.25E-01	7.82E-02	3.28E-02	-3.75E+01	2.36E-02
4	334	3	-2.56E+01	1.02E+01	1.76E+00	2.20E+01	1.12E+01	1.77E-01	5.20E-01	1.27E+02	1.28E+02	2.33E-01	1.21E-01	5.82E-02	-6.10E+01	1.57E-02
4	334	4	-2.52E+01	7.39E+00	1.87E+00	2.18E+01	1.08E+01	2.01E-01	3.50E-01	1.34E+02	1.04E+02	2.95E-01	2.03E-01	6.72E-02	-9.71E+01	3.11E-02
4	334	5	-3.06E+01	1.43E+01	1.58E+00	2.13E+01	1.08E+01	2.18E-01	3.29E-01	1.16E+02	8.40E+01	4.64E-01	2.71E-01	7.75E-02	-8.42E+01	1.79E-02
4	334	6	-6.65E+00	6.36E-01	1.26E+00	2.12E+01	1.08E+01	9.20E-02	9.74E-01	1.15E+02	2.14E+02	1.67E-01	7.90E-02	2.56E-02	-5.81E+00	1.27E-02
4	334	7	-1.31E+01	8.29E+00	1.61E+00	2.06E+01	1.11E+01	1.29E-01	6.76E-01	1.38E+02	1.72E+02	1.17E-01	1.35E-01	2.96E-02	-6.14E+01	1.72E-02
4	334	8	4.96E+00	1.71E+01	1.82E+00	2.07E+01	1.09E+01	1.65E-01	-1.52E-01	1.36E+02	4.80E+01	2.50E-01	1.46E-01	6.21E-02	-1.42E+02	8.52E-02
4	334	9	6.44E+01	4.46E+01	2.92E+00	2.25E+01	9.79E+00	3.43E-01	-1.96E-01	1.17E+02	4.00E+01	5.65E-01	4.67E-01	1.69E-01	4.14E+01	2.15E-02
4	334	10	1.33E+02	5.26E+01	4.08E+00	2.49E+01	9.01E+00	4.91E-01	-1.37E-01	9.78E+01	4.00E+01	1.20E+00	9.13E-01	2.84E-01	6.99E+01	4.49E-02
4	334	11	1.44E+02	3.59E+01	5.93E+00	2.69E+01	8.26E+00	5.48E-01	-1.09E-01	9.13E+01	5.00E+01	1.76E+00	1.46E+00	4.20E-01	6.09E+01	1.15E-02
4	334	12	2.03E+02	2.88E+01	4.74E+00	2.80E+01	8.48E+00	5.38E-01	-1.57E-01	8.51E+01	4.20E+01	1.42E+00	1.72E+00	3.73E-01	5.58E+01	1.13E-02

Appendix 1 (continued): Meaning of the columns headings in the datasheet table

Column's heading	Indication	Units
Yr	Year	-
Doy	day of year (Julian day)	-
DecTim	time	hour
Flx_Tsonic	sensible heat flux from Sonic temperature	W m^{-2}
Flx_Krypto	H_2O flux from Krypton hygrometer	W m^{-2}
Mea_WINDSP	mean wind speed U	m s^{-1}
Mea_Tsonic	mean temperature from Sonic	°c
Mea_Krypto	H_2O mean from Krypton hygrometer	g m^{-3}
U-star	u*	m^2 s^{-2}
Z-over-L	z/L	
Wind-Dir	wind direction	degrees
80PercFlux	distance of 80% integration of flux	m
Var_U-Wind	variance wind speed U	m^2 s^{-2}
Var_V-Wind	variance wind speed V	m^2 s^{-2}
Var_W-Wind	variance wind speed W	m^2 s^{-2}
Var_Tsonic	variance temperature from Sonic	$°c^2$
Var_Krypto	H_2O variance from Krypton hygrometer	g m^{-3}

Appendix 2: Daily time step recharge resulting from the water balance method

Day	Daily electri. volume-hm³	Daily vol. ONEA- 10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
1-Apr-05	2.36	238	0.71	-2.72	0.00	3.30	-1.54	0.00	0.0
2-Apr-05	1.08	259	0.71	-2.71	0.00	3.16	-1.30	0.00	0.0
3-Apr-05	1.28	228	0.70	-0.90	0.00	4.15	-1.19	0.00	0.0
4-Apr-05	2.83	207	0.70	-2.70	0.00	4.16	-1.76	0.00	0.0
5-Apr-05	2.66	257	0.70	-2.69	0.00	4.21	-1.74	0.00	0.0
6-Apr-05	2.39	254	0.70	-2.68	0.00	4.22	-1.69	0.00	0.0
7-Apr-05	2.35	221	0.70	-5.33	0.00	2.65	-1.86	0.00	0.0
8-Apr-05	2.89	224	0.69	-5.29	0.00	3.31	-2.06	0.00	0.0
9-Apr-05	3.21	240	0.69	-2.63	0.00	3.63	-1.72	0.00	0.0
10-Apr-05	1.03	241	0.69	-4.37	0.00	2.75	-1.49	0.00	0.0
11-Apr-05	2.25	240	0.68	-1.74	0.00	2.69	-1.25	0.00	0.0
12-Apr-05	3.05	248	0.68	-5.20	0.00	4.24	-2.23	0.00	0.0
13-Apr-05	2.74	261	0.68	-2.59	0.00	2.64	-1.46	0.00	0.0
14-Apr-05	2.60	253	0.67	-6.00	2.98	2.97	-1.57	0.00	0.0
15-Apr-05	2.86	194	0.67	-2.56	11.59	2.75	0.46	0.46	0.0
16-Apr-05	1.88	250	0.67	-2.55	0.00	3.60	-1.47	-1.01	0.0
17-Apr-05	1.21	236	0.66	-3.38	0.28	3.13	-1.37	-2.38	0.0
18-Apr-05	2.40	233	0.66	-3.37	0.00	3.11	-1.62	-3.99	0.0
19-Apr-05	1.65	249	0.66	-2.52	0.00	3.91	-1.48	-5.47	0.0
20-Apr-05	2.71	236	0.66	-3.34	0.00	2.50	-1.56	-7.03	0.0
21-Apr-05	1.41	288	0.65	-2.50	0.00	4.29	-1.50	-8.53	0.0
22-Apr-05	3.04	300	0.65	-4.14	0.00	4.45	-2.08	-10.61	0.0
23-Apr-05	1.58	264	0.65	-3.30	0.00	2.90	-1.43	-12.03	0.0
24-Apr-05	0.72	186	0.65	0.00	7.85	3.42	0.52	-11.51	0.0
25-Apr-05	2.84	275	0.64	-4.10	0.57	3.00	-1.70	-13.21	0.0
26-Apr-05	2.63	263	0.64	-3.26	3.97	2.23	-0.81	-14.02	0.0
27-Apr-05	2.76	198	0.64	-3.25	0.00	2.13	-1.48	-15.51	0.0
28-Apr-05	2.56	235	0.64	-4.04	0.00	1.89	-1.54	-17.05	0.0
29-Apr-05	2.74	200	0.63	-3.21	42.11	1.63	5.73	-11.32	0.0
30-Apr-05	2.02	246	0.63	-3.20	0.00	1.69	-1.27	-12.59	0.0
1-May-05	0.35	206	0.62	-0.80	0.00	1.59	-0.57	-13.16	0.0
2-May-05	1.16	187	0.62	-2.39	21.85	1.43	2.75	-10.41	0.0
3-May-05	2.29	223	0.62	-2.38	12.48	0.87	1.07	-9.34	0.0
4-May-05	2.59	199	0.62	-3.94	0.00	1.07	-1.39	-10.73	0.0
5-May-05	0.65	118	0.61	-1.57	0.00	1.02	-0.65	-11.38	0.0
6-May-05	1.83	280	0.61	-2.35	0.00	0.90	-0.96	-12.35	0.0
7-May-05	1.37	193	0.61	-2.34	0.00	1.03	-0.90	-13.25	0.0
8-May-05	0.31	149	0.61	0.00	2.20	0.89	0.07	-13.18	0.0
9-May-05	1.38	189	0.61	0.00	3.33	0.78	0.10	-13.09	0.0
10-May-05	0.75	165	0.61	0.00	82.14	3.32	13.10	0.02	0.0
11-May-05	1.49	157	0.61	-0.78	6.24	3.40	0.00	0.01	0.0
12-May-05	1.22	222	0.61	-3.11	0.00	3.45	-1.42	-1.41	0.0
13-May-05	1.40	215	0.60	0.00	0.00	3.41	-0.92	-2.32	0.0
14-May-05	0.24	214	0.60	-0.77	0.00	3.18	-0.81	-3.13	0.0
15-May-05	0.00	144	0.60	-0.77	0.28	2.81	-0.66	-3.79	0.0
16-May-05	2.23	214	0.60	-2.31	16.65	5.64	0.99	-2.80	0.0

Appendix 2 (continued)

Day	Daily electri. volume-hm³	Daily vol. ONEA- 10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
17-May-05	1.91	197	0.60	-3.07	0.00	5.31	-1.84	-4.65	0.0
18-May-05	1.21	179	0.60	-1.53	0.00	4.99	-1.41	-6.06	0.0
19-May-05	1.38	212	0.60	-2.29	0.00	4.74	-1.52	-7.58	0.0
20-May-05	2.47	208	0.59	-3.04	0.00	3.78	-1.67	-9.25	0.0
21-May-05	0.57	211	0.59	-1.51	22.18	3.90	2.64	-6.61	0.0
22-May-05	0.06	185	0.59	-0.76	0.00	4.01	-0.92	-7.53	0.0
23-May-05	1.60	210	0.59	-2.26	0.00	3.60	-1.36	-8.89	0.0
24-May-05	1.73	273	0.59	-3.75	0.00	3.31	-1.59	-10.48	0.0
25-May-05	1.62	214	0.58	-3.73	0.00	2.87	-1.49	-11.97	0.0
26-May-05	2.40	199	0.58	-2.23	0.00	2.10	-1.24	-13.20	0.0
27-May-05	2.63	206	0.58	-3.69	0.07	2.53	-1.58	-14.79	0.0
28-May-05	1.49	198	0.58	-2.20	65.02	2.37	9.88	-4.91	0.0
29-May-05	0.11	182	0.57	-0.73	0.00	2.04	-0.59	-5.50	0.0
30-May-05	1.37	188	0.57	2.94	138.43	1.43	23.35	17.85	0.0
31-May-05	0.83	149	0.57	2.21	138.24	17.25	20.61	38.46	0.0
1-Jun-05	1.35	152	0.54	3.71	39.22	23.77	2.92	41.38	0.0
2-Jun-05	1.48	181	0.54	0.74	32.04	22.61	1.38	42.76	0.0
3-Jun-05	1.71	192	0.54	1.49	41.59	18.65	3.75	46.51	0.0
4-Jun-05	0.25	139	0.54	0.00	48.00	22.74	4.14	50.65	0.0
5-Jun-05	0.02	152	0.54	0.75	0.00	21.39	-3.59	47.06	0.0
6-Jun-05	1.81	162	0.54	-2.24	0.00	21.85	-4.47	42.59	0.0
7-Jun-05	1.71	167	0.54	12.03	74.76	20.02	10.91	53.50	0.0
8-Jun-05	1.07	160	0.55	2.28	151.04	30.82	20.45	73.95	0.0
9-Jun-05	1.57	147	0.55	1.53	0.00	27.16	-4.70	69.26	0.0
10-Jun-05	1.60	182	0.55	0.00	1.06	25.60	-4.52	64.74	0.0
11-Jun-05	0.30	164	0.56	-2.29	1.30	27.10	-4.90	59.85	0.0
12-Jun-05	0.03	127	0.55	0.00	0.00	26.68	-4.61	55.23	0.0
13-Jun-05	1.51	136	0.55	-1.52	0.00	26.04	-5.01	50.22	0.0
14-Jun-05	2.06	169	0.55	-1.52	10.40	25.54	-3.26	46.96	0.0
15-Jun-05	0.73	155	0.55	0.00	15.60	25.75	-1.93	45.03	0.0
16-Jun-05	1.33	128	0.55	3.04	72.25	28.45	7.61	52.63	0.0
17-Jun-05	2.11	145	0.55	6.12	154.75	28.65	21.92	74.55	0.0
18-Jun-05	0.22	148	0.56	2.31	150.21	31.27	20.38	94.93	0.0
19-Jun-05	0.00	147	0.56	34.81	0.00	30.81	0.58	95.52	0.0
20-Jun-05	1.29	150	0.57	0.00	32.77	29.92	0.17	95.68	0.0
21-Jun-05	0.75	170	0.59	4.07	18.87	29.03	-1.26	94.43	0.0
22-Jun-05	0.86	163	0.59	0.00	0.00	27.65	-4.92	89.50	0.0
23-Jun-05	2.07	130	0.59	4.92	41.05	27.37	2.69	92.20	0.0
24-Jun-05	1.67	128	0.59	0.82	0.00	27.26	-4.86	87.34	0.0
25-Jun-05	0.39	123	0.60	3.30	54.12	28.92	4.66	92.00	0.0
26-Jun-05	0.44	170	0.60	1.66	133.00	26.42	18.13	110.13	0.0
27-Jun-05	1.30	120	0.60	5.83	21.14	27.81	-0.46	109.67	0.0
28-Jun-05	0.65	153	0.60	0.00	0.00	26.29	-4.66	105.01	0.0
29-Jun-05	0.51	119	0.61	-3.33	55.28	27.20	4.00	109.00	0.0
30-Jun-05	0.38	131	0.60	-1.66	8.61	25.61	-3.33	105.68	0.0

Appendix 2 (continued)

Day	Daily electri. volume-hm³	Daily vol. ONEA-10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
1-Jul-05	0.45	160	0.52	-0.83	0.00	21.99	-4.03	101.65	0.0
2-Jul-05	0.18	190	0.52	9.18	100.72	21.16	14.89	116.55	0.0
3-Jul-05	0.00	138	0.53	10.14	72.94	27.47	9.32	125.87	0.0
4-Jul-05	1.00	128	0.53	4.27	0.00	26.01	-3.94	121.93	0.0
5-Jul-05	1.81	139	0.54	0.00	80.32	27.60	8.52	130.45	0.0
6-Jul-05	1.86	119	0.54	2.57	0.00	25.62	-4.31	126.14	0.0
7-Jul-05	1.90	150	0.54	0.86	0.00	25.03	-4.50	121.64	0.0
8-Jul-05	1.69	119	0.54	0.00	0.00	24.25	-4.48	117.16	0.0
9-Jul-05	0.25	141	0.54	6.04	0.00	23.19	-3.04	114.13	0.0
10-Jul-05	0.45	78	0.54	12.23	361.86	28.03	58.38	172.50	**33.0**
11-Jul-05	0.86	147	0.55	21.41	0.57	25.38	-0.81	138.69	0.0
12-Jul-05	1.38	136	0.56	10.92	0.00	24.43	-2.61	136.07	0.0
13-Jul-05	2.08	132	0.57	6.44	0.00	24.21	-3.46	132.62	0.0
14-Jul-05	1.46	99	0.58	13.02	61.21	23.32	8.27	140.89	**1.4**
15-Jul-05	0.36	119	0.58	12.27	133.26	28.43	19.65	159.15	**19.7**
16-Jul-05	0.24	134	0.59	10.52	0.99	27.85	-2.90	136.60	0.0
17-Jul-05	1.63	133	0.60	13.56	107.39	29.61	15.08	151.67	**12.2**
18-Jul-05	0.94	124	0.61	7.84	0.00	28.17	-3.70	135.80	0.0
19-Jul-05	1.10	157	0.61	4.93	13.00	26.96	-1.82	133.98	0.0
20-Jul-05	0.49	115	0.62	0.00	15.20	27.34	-2.24	131.74	0.0
21-Jul-05	1.03	189	0.62	0.00	0.00	27.02	-4.85	126.89	0.0
22-Jul-05	0.00	120	0.62	0.99	6.88	27.60	-3.44	123.45	0.0
23-Jul-05	0.00	146	0.62	1.98	0.92	25.77	-3.97	119.48	0.0
24-Jul-05	0.63	138	0.62	8.98	79.84	28.11	10.06	129.54	0.0
25-Jul-05	1.42	121	0.62	10.07	79.18	29.29	9.80	139.34	0.0
26-Jul-05	2.09	119	0.63	0.00	3.62	27.91	-4.57	134.76	0.0
27-Jul-05	1.99	137	0.63	-5.05	0.00	26.76	-5.83	128.94	0.0
28-Jul-05	1.37	125	0.63	-2.01	29.79	27.70	-0.32	128.61	0.0
29-Jul-05	0.57	132	0.63	-1.00	0.00	26.31	-4.82	123.79	0.0
30-Jul-05	0.36	171	0.63	0.00	10.40	24.76	-2.59	121.20	0.0
31-Jul-05	0.00	146	0.63	0.00	168.58	23.22	24.48	145.68	**6.2**
1-Aug-05	0.94	141	0.51	0.00	0.00	23.01	-4.14	135.36	0.0
2-Aug-05	1.16	117	0.51	3.02	11.18	23.34	-1.83	133.53	0.0
3-Aug-05	0.94	128	0.51	5.05	71.07	29.63	7.62	141.15	**1.7**
4-Aug-05	0.00	143	0.52	1.01	0.00	27.48	-4.57	134.93	0.0
5-Aug-05	1.24	135	0.52	0.00	6.76	25.72	-3.50	131.43	0.0
6-Aug-05	0.00	139	0.52	3.05	0.00	24.39	-3.70	127.73	0.0
7-Aug-05	0.20	136	0.52	-1.02	13.90	27.34	-2.57	125.16	0.0
8-Aug-05	0.54	114	0.52	-1.02	0.00	24.34	-4.47	120.70	0.0
9-Aug-05	0.50	156	0.52	0.00	43.79	24.12	3.15	123.85	0.0
10-Aug-05	0.53	122	0.52	0.00	17.17	26.51	-1.76	122.09	0.0
11-Aug-05	0.45	152	0.52	1.02	30.62	27.80	0.49	122.58	0.0
12-Aug-05	0.26	115	0.52	8.16	142.85	27.09	20.83	143.41	**3.9**
13-Aug-05	0.15	129	0.52	9.26	10.64	26.61	-1.25	138.25	0.0
14-Aug-05	0.06	132	0.53	0.00	0.00	26.10	-4.51	133.74	0.0
15-Aug-05	0.00	139	0.53	10.39	41.61	23.17	4.79	138.52	0.0

Appendix 2 (continued)

Day	Daily electri. volume-hm³	Daily vol. ONEA- 10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
16-Aug-05	0.16	109	0.53	15.79	31.54	24.76	3.70	142.22	**2.7**
17-Aug-05	0.04	135	0.54	10.66	54.00	26.00	6.44	145.94	**6.4**
18-Aug-05	0.14	119	0.54	4.29	45.02	27.93	3.50	143.00	**3.5**
19-Aug-05	0.77	150	0.55	2.15	2.06	27.35	-4.14	135.36	0.0
20-Aug-05	0.23	149	0.55	0.00	0.00	25.60	-4.46	130.90	0.0
21-Aug-05	0.18	124	0.55	2.16	0.00	25.29	-4.04	126.86	0.0
22-Aug-05	0.95	142	0.55	-2.16	0.00	22.84	-4.48	122.38	0.0
23-Aug-05	0.60	123	0.55	1.08	73.08	23.69	8.34	130.72	0.0
24-Aug-05	0.67	155	0.55	0.00	5.53	22.92	-3.15	127.58	0.0
25-Aug-05	0.73	159	0.55	1.08	40.05	21.41	3.12	130.70	0.0
26-Aug-05	0.16	161	0.55	1.08	22.11	25.49	-0.51	130.19	0.0
27-Aug-05	0.00	133	0.55	0.00	20.55	24.36	-0.74	129.45	0.0
28-Aug-05	0.15	160	0.55	5.42	0.00	23.19	-3.12	126.32	0.0
29-Aug-05	0.03	122	0.55	4.36	207.83	26.13	31.38	157.70	**18.2**
30-Aug-05	0.23	148	0.56	3.28	13.38	26.07	-1.72	137.78	0.0
31-Aug-05	0.56	138	0.56	1.09	0.14	25.78	-4.34	133.43	0.0
1-Sep-05	0.55	122	0.58	3.29	102.99	27.70	13.10	146.54	**7.0**
2-Sep-05	0.00	154	0.59	11.04	76.16	28.10	9.90	149.40	**9.9**
3-Sep-05	0.16	131	0.59	10.03	20.29	26.79	0.47	139.97	**0.5**
4-Sep-05	0.12	143	0.59	12.38	0.00	25.70	-2.37	137.13	0.0
5-Sep-05	1.04	120	0.60	7.95	0.00	24.44	-3.07	134.06	0.0
6-Sep-05	0.38	171	0.60	8.01	2.27	23.80	-2.45	131.60	0.0
7-Sep-05	0.92	139	0.61	5.75	0.00	23.36	-3.24	128.37	0.0
8-Sep-05	0.19	126	0.61	5.78	158.25	28.43	22.80	151.17	**11.7**
9-Sep-05	0.48	144	0.61	2.32	0.00	27.08	-4.37	135.13	0.0
10-Sep-05	0.63	158	0.62	2.32	0.00	26.38	-4.28	130.85	0.0
11-Sep-05	0.58	145	0.62	0.00	0.00	25.50	-4.52	126.33	0.0
12-Sep-05	1.04	140	0.62	0.00	0.00	24.98	-4.51	121.82	0.0
13-Sep-05	1.46	159	0.62	-2.32	2.13	24.39	-4.51	117.31	0.0
14-Sep-05	1.36	201	0.62	-1.16	0.00	24.59	-4.69	112.62	0.0
15-Sep-05	1.78	145	0.62	-2.32	7.28	25.72	-3.92	108.71	0.0
16-Sep-05	1.19	173	0.62	-1.16	0.00	24.54	-4.65	104.05	0.0
17-Sep-05	0.26	169	0.62	-1.16	0.00	23.40	-4.30	99.75	0.0
18-Sep-05	0.11	158	0.61	1.16	0.00	22.96	-3.81	95.94	0.0
19-Sep-05	1.51	177	0.61	-2.31	0.00	21.91	-4.46	91.48	0.0
20-Sep-05	0.63	123	0.61	0.00	82.68	27.12	9.19	100.67	0.0
21-Sep-05	1.14	160	0.61	-1.15	8.65	26.76	-3.56	97.12	0.0
22-Sep-05	1.70	151	0.61	-1.15	0.00	26.07	-5.00	92.12	0.0
23-Sep-05	1.61	130	0.61	-2.30	46.29	24.79	2.87	94.99	0.0
24-Sep-05	0.31	144	0.61	-1.15	0.00	23.13	-4.26	90.73	0.0
25-Sep-05	0.07	143	0.61	0.00	0.92	21.48	-3.59	87.13	0.0
26-Sep-05	1.41	122	0.61	-1.15	0.00	18.99	-3.75	83.39	0.0
27-Sep-05	0.17	96	0.61	0.00	96.92	21.58	12.61	96.00	0.0
28-Sep-05	0.93	111	0.61	4.60	94.53	20.84	12.98	108.98	0.0
29-Sep-05	1.45	118	0.61	2.31	0.00	20.42	-3.41	105.57	0.0
30-Sep-05	1.97	133	0.61	-2.31	47.33	19.71	3.85	109.41	0.0

Appendix 2 (continued)

Day	Daily electri. volume-hm³	Daily vol. ONEA- 10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
1-Oct-05	0.25	145	0.74	-3.45	17.87	19.63	-1.05	108.36	0.0
2-Oct-05	0.36	132	0.74	1.15	31.75	17.94	2.34	110.71	0.0
3-Oct-05	1.64	93	0.74	4.61	64.93	23.35	7.41	118.12	0.0
4-Oct-05	1.56	114	0.74	11.60	48.33	23.47	5.78	123.90	0.0
5-Oct-05	1.60	114	0.75	-2.33	0.00	22.01	-4.52	119.38	0.0
6-Oct-05	1.61	105	0.75	2.33	0.00	20.71	-3.51	115.87	0.0
7-Oct-05	1.59	157	0.75	-3.49	0.00	19.21	-4.24	111.64	0.0
8-Oct-05	0.20	118	0.75	0.00	0.00	18.53	-3.30	108.34	0.0
9-Oct-05	0.01	143	0.75	1.16	0.00	17.14	-2.83	105.51	0.0
10-Oct-05	2.04	94	0.75	-1.16	15.23	20.86	-1.62	103.89	0.0
11-Oct-05	1.88	134	0.75	-5.80	0.00	20.06	-4.82	99.07	0.0
12-Oct-05	1.84	154	0.75	0.00	0.00	19.50	-3.74	95.33	0.0
13-Oct-05	1.96	88	0.75	-2.31	0.00	18.10	-3.91	91.42	0.0
14-Oct-05	1.79	167	0.74	-3.46	11.87	16.70	-1.83	89.59	0.0
15-Oct-05	0.56	146	0.74	0.00	0.00	16.09	-2.94	86.64	0.0
16-Oct-05	0.12	138	0.74	-1.15	0.00	15.81	-3.02	83.63	0.0
17-Oct-05	1.81	149	0.74	-1.15	0.00	14.19	-3.03	80.60	0.0
18-Oct-05	1.81	138	0.74	-3.44	0.00	13.84	-3.35	77.25	0.0
19-Oct-05	1.65	142	0.74	-2.29	0.00	14.18	-3.19	74.06	0.0
20-Oct-05	1.93	126	0.74	-2.28	0.00	12.97	-3.03	71.02	0.0
21-Oct-05	1.66	152	0.74	-2.28	0.00	11.78	-2.78	68.24	0.0
22-Oct-05	1.07	147	0.74	-2.27	0.00	10.44	-2.46	65.78	0.0
23-Oct-05	1.68	101	0.73	-2.27	0.00	8.29	-2.20	63.59	0.0
24-Oct-05	2.84	132	0.73	-2.27	0.00	7.16	-2.20	61.39	0.0
25-Oct-05	2.28	133	0.73	-5.65	0.00	5.97	-2.47	58.91	0.0
26-Oct-05	2.18	146	0.73	-3.37	0.00	4.29	-1.79	57.13	0.0
27-Oct-05	2.54	23	0.73	-2.24	0.00	3.98	-1.61	55.52	0.0
28-Oct-05	2.74	177	0.72	-2.24	0.00	4.70	-1.76	53.76	0.0
29-Oct-05	2.53	169	0.72	-3.35	0.00	2.71	-1.58	52.18	0.0
30-Oct-05	2.27	217	0.72	-4.45	0.00	2.43	-1.67	50.51	0.0
31-Oct-05	2.90	195	0.72	-4.43	0.00	4.01	-2.04	48.47	0.0
1-Nov-05	1.96	147	0.69	-3.31	0.00	3.27	-1.56	46.91	0.0
2-Nov-05	2.44	164	0.69	-4.40	0.00	4.98	-2.12	44.79	0.0
3-Nov-05	1.81	157	0.69	-3.29	0.00	3.03	-1.49	43.30	0.0
4-Nov-05	2.59	149	0.69	0.00	0.00	4.41	-1.30	42.00	0.0
5-Nov-05	1.30	111	0.69	-2.19	0.00	3.99	-1.38	40.62	0.0
6-Nov-05	1.33	136	0.69	-3.27	0.00	3.82	-1.54	39.08	0.0
7-Nov-05	2.71	148	0.68	-2.18	0.00	3.85	-1.59	37.49	0.0
8-Nov-05	2.82	155	0.68	-5.42	0.00	3.28	-2.07	35.42	0.0
9-Nov-05	2.80	156	0.68	-3.24	0.00	3.12	-1.67	33.76	0.0
10-Nov-05	2.54	116	0.68	-4.31	0.00	4.84	-2.09	31.66	0.0
11-Nov-05	2.63	172	0.68	-3.22	0.00	4.10	-1.80	29.87	0.0
12-Nov-05	2.21	73	0.67	-3.21	0.00	3.89	-1.69	28.18	0.0
13-Nov-05	1.69	218	0.67	-2.13	0.00	3.21	-1.30	26.88	0.0
14-Nov-05	2.89	157	0.67	-4.26	0.00	2.75	-1.79	25.09	0.0
15-Nov-05	3.05	140	0.67	-4.24	0.00	4.26	-2.07	23.02	0.0

Appendix 2 (continued)

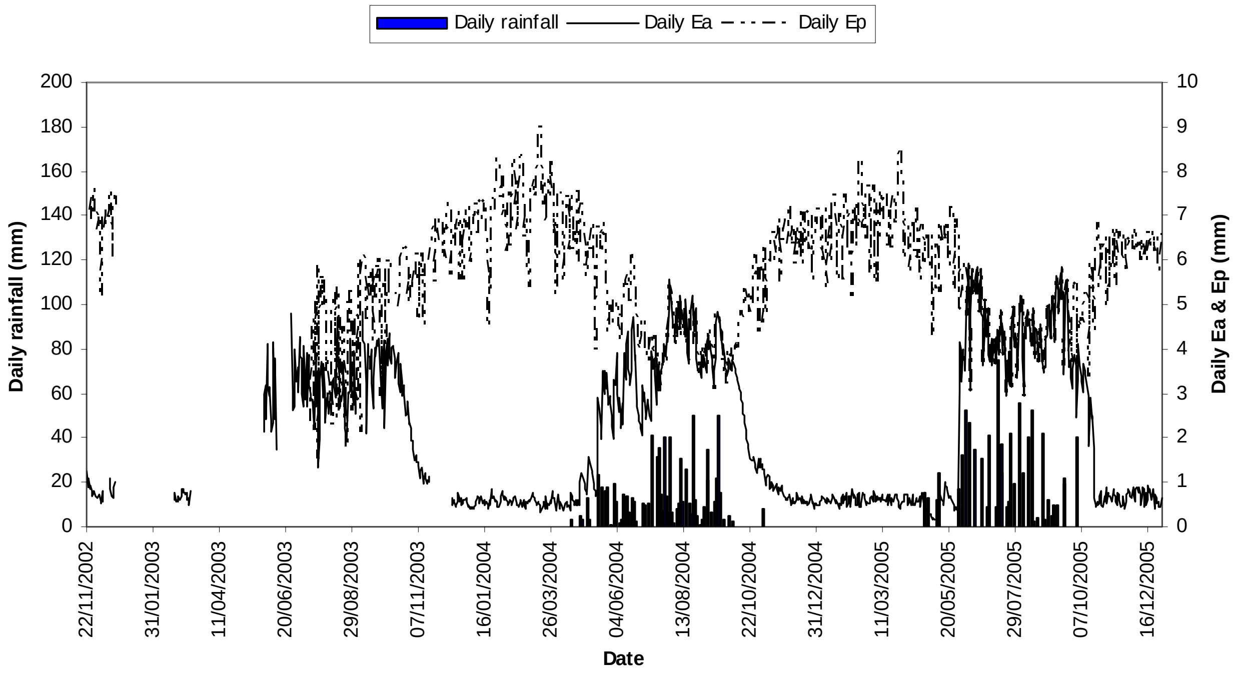
Day	Daily electri. volume-hm³	Daily vol. ONEA- 10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
16-Nov-05	2.99	148	0.66	-3.17	0.00	4.18	-1.86	21.16	0.0
17-Nov-05	2.85	141	0.66	-4.21	0.00	3.52	-1.90	19.26	0.0
18-Nov-05	2.49	149	0.66	-4.19	0.00	2.50	-1.66	17.60	0.0
19-Nov-05	1.13	125	0.66	-2.09	0.00	2.74	-1.12	16.48	0.0
20-Nov-05	1.28	148	0.66	-1.04	0.00	3.85	-1.15	15.32	0.0
21-Nov-05	2.98	163	0.65	-3.12	0.00	2.42	-1.55	13.77	0.0
22-Nov-05	2.76	141	0.65	-4.15	0.00	2.39	-1.68	12.09	0.0
23-Nov-05	2.31	135	0.65	-3.10	0.00	3.28	-1.58	10.51	0.0
24-Nov-05	2.78	158	0.65	-4.12	0.00	4.12	-1.97	8.53	0.0
25-Nov-05	2.58	161	0.65	-3.08	0.00	4.28	-1.79	6.74	0.0
26-Nov-05	2.14	169	0.64	-3.07	0.00	4.94	-1.83	4.92	0.0
27-Nov-05	1.16	156	0.64	-2.04	0.00	4.35	-1.39	3.53	0.0
28-Nov-05	2.76	186	0.64	-4.07	0.00	3.90	-1.92	1.61	0.0
29-Nov-05	2.59	159	0.64	-3.04	0.00	3.76	-1.70	-0.09	0.0
30-Nov-05	2.65	186	0.64	-3.03	0.00	3.98	-1.74	-1.83	0.0
1-Dec-05	2.50	129	0.53	-4.03	0.00	5.16	-2.07	-3.90	0.0
2-Dec-05	2.36	156	0.53	-3.01	0.00	4.24	-1.72	-5.61	0.0
3-Dec-05	1.52	166	0.53	-3.00	0.00	3.18	-1.39	-7.00	0.0
4-Dec-05	1.11	165	0.53	-1.00	0.00	4.90	-1.27	-8.28	0.0
5-Dec-05	2.33	169	0.53	-3.98	0.00	5.04	-2.01	-10.29	0.0
6-Dec-05	2.31	152	0.52	-0.99	0.00	4.41	-1.39	-11.68	0.0
7-Dec-05	2.11	164	0.52	-3.96	0.00	5.17	-1.99	-13.67	0.0
8-Dec-05	2.28	171	0.52	-1.97	0.00	4.24	-1.52	-15.20	0.0
9-Dec-05	2.53	200	0.52	-2.95	0.00	2.77	-1.48	-16.68	0.0
10-Dec-05	2.33	169	0.52	-3.92	0.00	4.15	-1.85	-18.53	0.0
11-Dec-05	1.82	180	0.52	-3.90	0.00	4.94	-1.89	-20.42	0.0
12-Dec-05	1.85	195	0.52	-0.97	0.00	4.81	-1.38	-21.80	0.0
13-Dec-05	2.17	190	0.51	-3.88	0.00	2.52	-1.54	-23.34	0.0
14-Dec-05	1.83	171	0.51	-2.90	0.00	4.43	-1.64	-24.97	0.0
15-Dec-05	2.06	192	0.51	-2.89	0.00	2.75	-1.39	-26.37	0.0
16-Dec-05	1.89	164	0.51	-1.92	0.00	3.49	-1.32	-27.69	0.0
17-Dec-05	0.89	217	0.51	-0.96	0.00	5.29	-1.29	-28.98	0.0
18-Dec-05	0.00	161	0.51	-0.96	0.00	4.44	-1.00	-29.98	0.0
19-Dec-05	1.14	157	0.51	-1.92	0.00	4.93	-1.44	-31.42	0.0
20-Dec-05	1.54	182	0.51	-2.86	0.00	3.48	-1.42	-32.84	0.0
21-Dec-05	1.38	175	0.50	-3.81	0.00	3.53	-1.56	-34.40	0.0
22-Dec-05	0.49	181	0.50	-3.79	0.00	4.90	-1.64	-36.04	0.0
23-Dec-05	0.93	190	0.50	-0.94	0.00	2.39	-0.81	-36.84	0.0
24-Dec-05	0.97	246	0.50	-0.94	0.00	4.18	-1.12	-37.96	0.0
25-Dec-05	0.24	198	0.50	-0.94	0.00	3.62	-0.90	-38.86	0.0
26-Dec-05	0.34	177	0.50	0.00	0.00	2.89	-0.63	-39.49	0.0
27-Dec-05	0.55	205	0.50	0.00	0.00	3.22	-0.72	-40.21	0.0
28-Dec-05	0.57	165	0.50	-0.94	0.00	2.53	-0.77	-40.98	0.0
29-Dec-05	0.86	197	0.50	-0.94	0.00	2.53	-0.82	-41.79	0.0
30-Dec-05	0.26	204	0.50	-0.94	0.00	2.53	-0.72	-42.51	0.0
31-Dec-05	0.00	173	0.50	0.00	0.00	3.72	-0.71	-43.22	0.0

Appendix 2 (continued)

Day	Daily electri. volume-hm³	Daily vol. ONEA-10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
1-Jan-06	0.00	196	0.48	-0.94	0.00	2.78	-0.71	-43.93	0.0
2-Jan-06	0.00	207	0.48	0.00	0.00	2.67	-0.53	-44.47	0.0
3-Jan-06	0.16	196	0.48	0.00	0.00	2.81	-0.58	-45.05	0.0
4-Jan-06	0.35	182	0.48	-0.94	0.00	2.83	-0.78	-45.83	0.0
5-Jan-06	0.38	189	0.48	-0.94	0.00	3.11	-0.83	-46.66	0.0
6-Jan-06	1.39	181	0.48	-1.87	0.00	3.38	-1.20	-47.87	0.0
7-Jan-06	0.00	191	0.48	-0.93	0.00	3.69	-0.86	-48.73	0.0
8-Jan-06	0.00	216	0.48	0.00	0.00	4.05	-0.77	-49.50	0.0
9-Jan-06	0.88	193	0.48	-0.93	0.00	4.06	-1.08	-50.57	0.0
10-Jan-06	0.08	237	0.48	-0.93	0.00	3.80	-0.90	-51.47	0.0
11-Jan-06	1.58	202	0.48	-1.86	0.00	3.22	-1.21	-52.68	0.0
12-Jan-06	1.11	179	0.48	-1.86	0.00	4.05	-1.27	-53.95	0.0
13-Jan-06	1.17	225	0.48	-2.78	0.00	3.47	-1.34	-55.28	0.0
14-Jan-06	0.91	157	0.48	-1.85	0.00	3.51	-1.14	-56.42	0.0
15-Jan-06	0.27	221	0.48	-0.92	0.00	3.57	-0.89	-57.31	0.0
16-Jan-06	1.72	203	0.48	-1.84	0.00	2.96	-1.18	-58.49	0.0
17-Jan-06	1.51	209	0.48	-2.75	0.00	3.66	-1.42	-59.91	0.0
18-Jan-06	1.06	217	0.47	-0.92	0.00	3.74	-1.05	-60.96	0.0
19-Jan-06	1.06	185	0.47	-1.83	0.00	3.26	-1.12	-62.08	0.0
20-Jan-06	2.14	266	0.47	-1.82	0.00	2.76	-1.22	-63.30	0.0
21-Jan-06	0.75	234	0.47	-2.73	0.00	3.65	-1.29	-64.59	0.0
22-Jan-06	0.51	198	0.47	-0.91	0.00	3.11	-0.85	-65.43	0.0
23-Jan-06	1.81	248	0.47	-2.72	0.00	4.47	-1.60	-67.03	0.0
24-Jan-06	1.55	155	0.47	-1.81	0.00	3.46	-1.23	-68.26	0.0
25-Jan-06	1.75	249	0.47	-2.70	0.00	3.77	-1.47	-69.73	0.0
26-Jan-06	2.20	204	0.47	-2.69	0.00	3.77	-1.54	-71.28	0.0
27-Jan-06	1.90	252	0.46	-2.68	0.00	3.71	-1.48	-72.76	0.0
28-Jan-06	1.03	217	0.46	-1.78	0.00	3.95	-1.22	-73.98	0.0
29-Jan-06	0.51	199	0.46	0.00	0.00	3.38	-0.74	-74.72	0.0
30-Jan-06	2.07	215	0.46	-2.67	0.00	3.19	-1.42	-76.14	0.0
31-Jan-06	1.19	223	0.46	-2.66	0.00	3.06	-1.25	-77.39	0.0
1-Feb-06	0.73	178	0.54	-0.88	0.00	3.84	-1.01	-78.40	0.0
2-Feb-06	1.65	224	0.54	-1.77	0.00	3.67	-1.29	-79.69	0.0
3-Feb-06	0.91	225	0.54	-1.76	0.00	4.36	-1.28	-80.97	0.0
4-Feb-06	0.39	187	0.54	0.00	0.00	4.42	-0.90	-81.87	0.0
5-Feb-06	0.00	229	0.53	-1.76	0.00	3.86	-1.04	-82.91	0.0
6-Feb-06	1.21	211	0.53	-0.88	0.00	3.72	-1.07	-83.99	0.0
7-Feb-06	1.45	201	0.53	-2.63	0.00	4.29	-1.51	-85.49	0.0
8-Feb-06	1.64	271	0.53	-1.75	0.00	3.86	-1.31	-86.81	0.0
9-Feb-06	1.05	197	0.53	-2.61	0.00	3.84	-1.36	-88.17	0.0
10-Feb-06	0.22	224	0.53	-0.87	0.00	3.25	-0.82	-88.99	0.0
11-Feb-06	0.04	220	0.53	0.00	0.00	3.26	-0.65	-89.64	0.0
12-Feb-06	0.00	242	0.53	-0.87	0.00	3.49	-0.83	-90.46	0.0
13-Feb-06	1.04	220	0.53	-1.73	0.00	3.81	-1.20	-91.67	0.0
14-Feb-06	1.03	263	0.53	0.00	0.00	3.45	-0.85	-92.51	0.0
15-Feb-06	2.26	214	0.53	-1.73	0.00	3.46	-1.35	-93.86	0.0

Appendix 2 (concluded)

Day	Daily electri. volume-hm³	Daily vol. ONEA-10^{-6}hm³	Daily lake evap-hm³	Daily lake flux-hm³	Daily rain hm³	Daily Ea hm³	SB (ΔS_2) mm	ΔS_2/SBmax mm	Rech. mm
16-Feb-06	2.06	166	0.53	-1.73	0.00	3.57	-1.33	-95.20	0.0
17-Feb-06	0.45	228	0.52	-0.86	0.00	3.84	-0.96	-96.16	0.0
18-Feb-06	0.00	211	0.52	-1.72	0.00	3.63	-0.99	-97.15	0.0
19-Feb-06	0.00	228	0.52	-0.86	0.00	3.56	-0.84	-97.99	0.0
20-Feb-06	0.22	189	0.52	-0.86	0.00	3.39	-0.85	-98.83	0.0
21-Feb-06	0.22	227	0.52	-0.86	0.00	3.14	-0.80	-99.63	0.0
22-Feb-06	0.32	249	0.52	0.00	0.00	3.14	-0.67	-100.31	0.0
23-Feb-06	0.30	231	0.52	-0.86	0.00	3.66	-0.90	-101.21	0.0
24-Feb-06	0.02	182	0.52	-0.85	0.00	2.98	-0.74	-101.95	0.0
25-Feb-06	0.00	270	0.52	0.00	0.00	3.06	-0.61	-102.56	0.0
26-Feb-06	0.00	231	0.52	-0.85	0.00	3.46	-0.82	-103.37	0.0
27-Feb-06	0.66	200	0.52	-0.85	0.00	3.50	-0.94	-104.31	0.0
28-Feb-06	0.72	249	0.52	-1.70	0.00	3.18	-1.04	-105.35	0.0
1-Mar-06	2.06	220	0.61	-2.55	0.00	3.46	-1.47	-106.81	0.0
2-Mar-06	2.03	237	0.60	-3.38	0.00	3.83	-1.67	-108.48	0.0
3-Mar-06	1.69	263	0.60	-0.84	0.00	4.02	-1.21	-109.69	0.0
4-Mar-06	0.06	248	0.60	0.00	0.00	3.84	-0.76	-110.45	0.0
5-Mar-06	0.00	224	0.60	-0.84	0.00	3.74	-0.88	-111.33	0.0
6-Mar-06	0.70	253	0.60	-1.68	0.00	4.01	-1.18	-112.51	0.0
7-Mar-06	0.37	234	0.60	-1.68	0.00	3.94	-1.11	-113.62	0.0
8-Mar-06	0.23	264	0.60	-0.84	0.00	3.91	-0.94	-114.56	0.0
9-Mar-06	0.00	200	0.60	0.00	0.00	3.63	-0.71	-115.28	0.0
10-Mar-06	0.00	202	0.60	-0.84	0.00	3.45	-0.83	-116.11	0.0
11-Mar-06	0.00	308	0.59	-0.84	0.00	3.33	-0.81	-116.91	0.0
12-Mar-06	0.00	236	0.59	-0.83	0.00	3.62	-0.85	-117.77	0.0
13-Mar-06	0.24	217	0.59	-0.83	0.00	3.52	-0.88	-118.64	0.0
14-Mar-06	0.55	259	0.59	-0.83	0.00	3.37	-0.90	-119.55	0.0
15-Mar-06	0.18	231	0.59	0.00	0.00	3.32	-0.69	-120.24	0.0
16-Mar-06	1.24	229	0.59	-0.83	0.00	2.84	-0.93	-121.17	0.0
17-Mar-06	0.35	304	0.59	-3.32	0.00	2.65	-1.17	-122.34	0.0
18-Mar-06	0.00	244	0.59	0.00	0.00	3.15	-0.63	-122.97	0.0
19-Mar-06	0.00	303	0.59	0.00	0.00	3.36	-0.67	-123.64	0.0
20-Mar-06	0.78	241	0.59	-1.65	0.00	3.26	-1.06	-124.70	0.0
21-Mar-06	0.75	226	0.59	-0.82	0.00	2.90	-0.86	-125.56	0.0
22-Mar-06	0.50	249	0.59	-0.82	0.00	3.94	-0.99	-126.55	0.0
23-Mar-06	0.77	332	0.59	-1.64	0.00	2.85	-0.99	-127.54	0.0
24-Mar-06	1.21	246	0.59	-1.64	0.00	3.61	-1.19	-128.73	0.0
25-Mar-06	0.47	258	0.58	-1.64	0.00	3.40	-1.03	-129.76	0.0
26-Mar-06	0.00	253	0.58	0.00	0.00	3.84	-0.75	-130.51	0.0
27-Mar-06	1.63	252	0.58	-2.45	0.00	3.49	-1.38	-131.89	0.0
28-Mar-06	1.00	263	0.58	-1.63	0.00	4.35	-1.28	-133.17	0.0
29-Mar-06	0.62	242	0.58	-1.62	0.00	3.57	-1.08	-134.25	0.0
30-Mar-06	0.00	230	0.58	-0.81	0.00	3.51	-0.83	-135.08	0.0
31-Mar-06	0.00	224	0.58	-0.81	0.00	3.46	-0.82	-135.90	0.0



Appendix 3: Daily Ea and Ep fluctuations along with the daily rainfall in the Kompienga dam basin from 2002 to 2005

Appendix 4: Results of the daily water sampling survey in the basin

Appendix 4.1: Monthly number of containers at each water monitoring point and number of strokes or buckets (others) according to their size of big (B), small (S) or medium (M)

Month	Survey site	Buckets			Pans			Cans			Barils			Canaris			Others		
		B	S	M	B	S	M	B	S	M	B	S	M	B	S	M	B	S	M
Nov 15-30	Comin Yanga	3186	1797	1012	4108	2060	1659	3656	2001	1191	194	25	8	479	180	209	6385		
	Kouaré	683	245	408	479	175	303	803	369	568	41	0	4	87	31	36	1019		
	Natiabouani	2181	201	451	4845	479	597	2300	1908	202	389	0	13	2	0	0	1752		
	Kompienbiga	364	113	51	1524	333	182	701	114	110	0	0	0	18	0	0	4719		
	Pama	2954	2048	1971	7202	3578	4337	3764	1847	3271	1854	10	153	0	0	0	6178	531	178
	Djabiga	2401	1545	1607	9346	3362	3959	2884	1750	1580	0	0	0	0	0	0	8512		
Dec 01-14	Comin Yanga	3681	2389	1264	4143	2765	1810	3886	2542	1436	210	13	11	593	259	279	8209		
	Kouaré	716	474	477	712	355	420	1000	445	605	17	2	0	76	20	48	1269		
	Natiabouani	2036	244	522	4441	564	720	2444	2166	209	402	0	6	2	0	0	2763		
	Kompienbiga	603	307	287	2981	808	854	1146	246	177	2	0	1	13	0	0	6794		
	Pama	8374	3775	3616	11524	8217	6581	8197	5550	4624	6412	0	19	0	0	0	3405	543	201
	Djabiga	3119	2175	2546	11376	5582	6991	5380	3658	2134	0	0	0	0	0	0	7611		
Feb 14-28	Comin Yanga	4027	2848	2667	5090	3915	3547	4855	3494	2979	323	22	5	568	185	277	17225		
	Kouaré	3656	1720	1118	5967	2558	1130	5779	2119	886	19	0	0	64	17	5	34095		
	Natiabouani	2031	369	390	6112	556	657	1715	3411	335	394	0	0	0	0	0	4049		
	Kompienbiga	611	320	227	5657	1310	1188	2718	232	138	12	0	0	17	0	0	7878		
	Pama	3835	2512	1871	7263	4611	4915	5197	4684	4207	6223	0	0	0	0	0	2083	1098	563
	Djabiga	1350	727	865	7799	3151	5469	2590	1293	1343	0	0	0	0	0	0	8721		

Appendix 4.1 (continued)

Month	Sites	Buckets			Pans			Cans			Barils			Canaris			Others		
		B	S	M	B	S	M	B	S	M	B	S	M	B	S	M	B	S	M
March 01-15	Comin Yanga	4492	3259	2887	5301	4175	3590	4947	3885	3510	249	2	0	331	86	189	18987		
	Kouaré	4127	1817	1150	6868	2648	1312	7423	1501	842	29	0	1	36	4	1	32836		
	Natiabouani	2414	644	640	6236	803	903	1764	3761	654	439	0	0	0	0	0	4429		
	Kompienbiga	453	308	240	7107	1833	1324	2474	242	118	8	0	0	6	0	0	9738		
	Pama	4448	2605	2123	7146	4970	5933	5162	5111	4793	6099	0	0	0	0	0	1679	1342	552
	Djabiga	1778	822	1131	7648	3144	4920	2674	1085	1639	0	0	0	0	0	0	11904		
April 01-30	Comin Yanga	9381	8128	7475	10565	9194	8546	9577	8257	7843	382	78	6	640	224	384	47034		
	Kouaré	13063	12534	12517	13481	12381	12323	14485	8824	8561	1268	11	100	1338	590	644	199235		
	Natiabouani	4666	595	714	10666	867	838	4613	6291	307	861	35	0	6	0	0	6161		
	Kompienbiga	1185	1094	620	15619	4612	3196	6965	871	445	46	0	0	48	0	1	25511		
	Pama	4997	3020	2261	10374	6275	7775	8170	5608	5978	7388	0	0	0	0	0	3135	2537	1736
	Djabiga	10387	8376	9004	23792	14799	17019	12548	8609	9166	2	0	0	0	0	1	55643		
May 16-31	Comin Yanga	4769	4469	4383	4779	4872	4530	4897	4615	5212	23	0	0	62	2	65	17912		
	Kouaré	1816	1766	1785	1729	1755	1730	2035	1000	995	176	0	0	143	97	130	26410		
	Natiabouani	1870	268	270	5119	448	429	1927	3036	156	430	27	34	0	0	0	3275		
	Kompienbiga	1054	911	530	9249	2601	2186	4514	925	542	44	0	0	6	0	0	16726		
	Pama	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Djabiga	3436	1999	2664	5020	2930	3937	3560	2190	2783	0	0	0	0	0	0	17731		
June 01-14	Comin Yanga	3867	3663	3438	3796	3712	3500	3822	3690	3616	18	0	0	45	9	49	11028		
	Kouaré	1229	1201	1202	1185	1205	1111	1311	453	453	33	0	0	48	34	39	15925		
	Natiabouani	1272	255	191	3656	360	277	1298	2746	111	215	11	38	0	0	0	2873		
	Kompienbiga	1003	843	444	8438	2611	2036	4185	937	511	58	0	0	0	0	0	15409		
	Pama	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Djabiga	2724	2190	2431	3699	2924	3280	2709	2218	2492	0	0	0	0	0	0	24391		

Appendix 4.2: Unit volume (liters) of the containers types inventoried at the water monitoring points in 2005 in the Kompienga dam basin

Site	Surveyor's name	Canaris			Barils			Cans			Buckets			Pans			Others		
		S	B	M	S	B	M	S	B	M	S	B	M	S	B	M	B	M	S
Kouaré	Bapougouni	15	24	20	42	210	-	4	20	10	11	20	15	20	35	30	0.5		
	Pougoumba	15	25	20	105	210	210	5	20	10	11	20	15	22	45	35	0.3		
Comin-Yanga	S. Ouahabou	5	22	18	50	210	210	10	50	20	11	20	15	7	48	16	0.3		
	Salembere/well	11	20	13	20	210	5	5	20	10	20	20	15	12	35	15	7		
	Z. Awa	-	-	-	-	210	-	10	20	4	17	20	10	28	35	17	0.3		
Natiabouani	G. Issa	-	20	-	-	210	-	20	30	10	11	23	10	20	35	10	0.3		
	O. Hamado	-	-	-	45	210	105	5	23	10	7	20	10	8	35	18	0.7		
Pama	K. Malendi	10	-	-	80	210	150	5	20	10	11	22	18	17	35	27	0.4		
	M/O. Bibata	-	-	-	-	280	210	10	25	20	11	22	15	22	50	35	0.5		
	Oumpougla/well	-	15	-	-	210	-	10	20	5	15	20	10	26	40	16	11	7	11
Kompienbiga	Th. Mandia	6	-	23	-	210	143	10	20	5	10	18	16	23	45	27	0.4		
	K. Harouna	-	15	-	-	210	-	10	20	5	18	25	11	30	40	17	0.5		
Djabiga	C. Djabouado	-	-	8	-	210	-	4	20	10	4	20	15	21	37	27	0.3		
	Th. Baridja	-	-	-	-	210	-	5	20	10	13	22	24	18	35	27	0.5		

Examples of pan types used to fetch water at the monitoring points in the basin

Appendix 4.3: Monthly withdrawal volumes at the 15 water monitoring points in the Kompienga dam basin from 2004 to 2005

Site	Djabiga		Pama				Kompienbiga		Natiabouani		Kouaré		Comin Yanga			Average mthly withdrawal volume (m³)
Survey point	B1	B2	MW	B1	B2	B3	B1	B2	B1	B2	B1	B2	MW	B1	B2	
November 2004	566.2	835.3	1626.2	383.2	325.9	518.1	208.2	383.2	584.6	240.9	67.3	116.9	411.9	371.7	238.4	458.5
December	872.8	1133.8	4954.6	383.2	344.1	518.1	171.5	269.1	548.3	275.0	125.3	96.2	371.1	478.0	310.2	723.4
January 2005	633.4	988.3	4617.0	383.2	344.1	518.1	244.3	367.4	528.0	364.0	397.1	301.8	389.4	603.3	360.7	736.0
February	394.1	842.8	4279.4	383.2	344.1	518.1	317.0	465.7	507.6	453.0	668.9	507.4	407.6	728.5	411.2	748.6
March	487.1	759.9	4310.9	383.2	344.1	518.1	381.8	535.2	575.0	470.7	819.8	514.5	371.0	814.4	404.0	779.3
April	661.4	1893.4	2745.8	383.2	344.1	518.1	408.9	675.0	550.6	379.5	1338.8	1285.5	243.2	1054.3	357.9	856.0
May	661.4	1238.2	2745.8	383.2	344.1	518.1	574.7	779.0	462.3	422.6	738.0	1285.5	243.2	1280.0	317.3	799.5
June	661.4	1039.6	2745.8	383.2	344.1	518.1	541.4	721.3	272.9	342.1	462.6	1285.5	243.2	1049.9	193.6	720.3
Mean monthly volume (m³) per survey point	617.2	1091.4	3503.2	383.2	341.8	518.1	356.0	524.5	503.7	368.5	577.2	674.1	335.1	797.5	324.2	

MW = modern well, B = borehole and B3 (Pama) represents the borehole of the tap water system.

Appendix 5: The necessary number of boreholes for a reasonable groundwater supply to the population

Appendix 5.1: The necessary number of boreholes to supply the population according to the years and the supply rate, borehole's yield and daily functioning duration

Supply rate (l/c/d)	Year	12 hours		14 hours	
		0.7 m³/h	1 m³/h	0.7 m³/h	1 m³/h
		No. boreholes	No. boreholes	No. boreholes	No. boreholes
20	2007	686	480	588	412
	2010	755	529	647	453
	2015	886	621	760	532
	2025	1221	855	1046	732
	2030	1433	1003	1228	860
25	2007	858	600	735	515
	2010	944	661	809	567
	2015	1108	776	950	665
	2025	1526	1068	1308	916
	2030	1791	1254	1535	1074
30	2007	1029	721	882	618
	2010	1133	793	971	680
	2015	1330	931	1140	798
	2025	1831	1282	1570	1099
	2030	2149	1504	1842	1289
40	2007	1372	961	1176	823
	2010	1511	1058	1295	906
	2015	1773	1241	1520	1064
	2025	2442	1709	2093	1465
	2030	2865	2006	2456	1719
55	2007	1887	1321	1618	1132
	2010	2077	1454	1781	1246
	2015	2438	1706	2090	1463
	2025	3357	2350	2878	2014
	2030	3940	2758	3377	2364

Appendix 5.2: The number of boreholes for water supply to the population of the Kompienga dam basin according to the pump's yield and the daily withdrawal duration

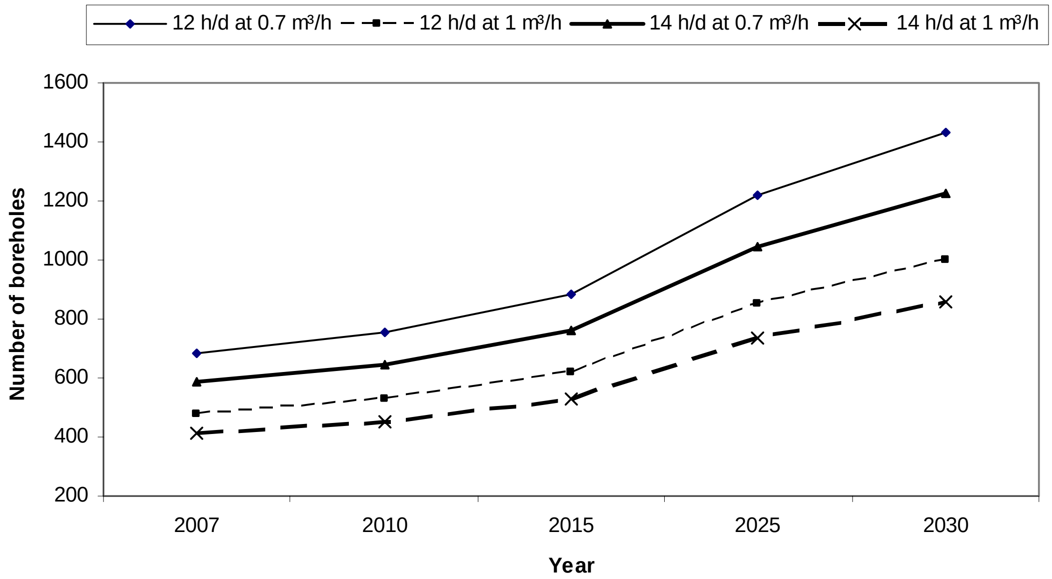


Figure 5.2a: Number of boreholes for a supply rate of 20 l/c/d

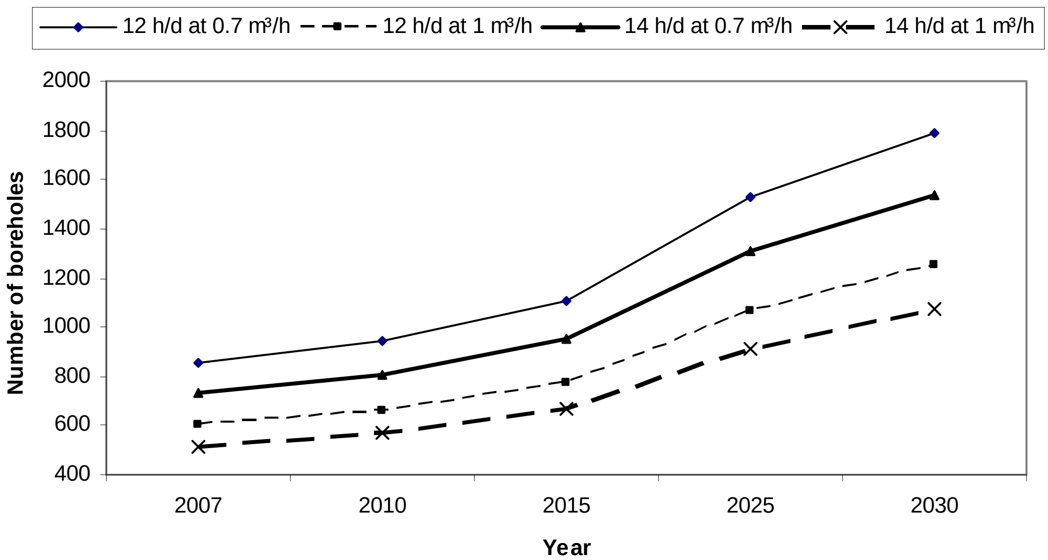


Figure 5.2b: Number of boreholes for a supply rate of 25 l/c/d

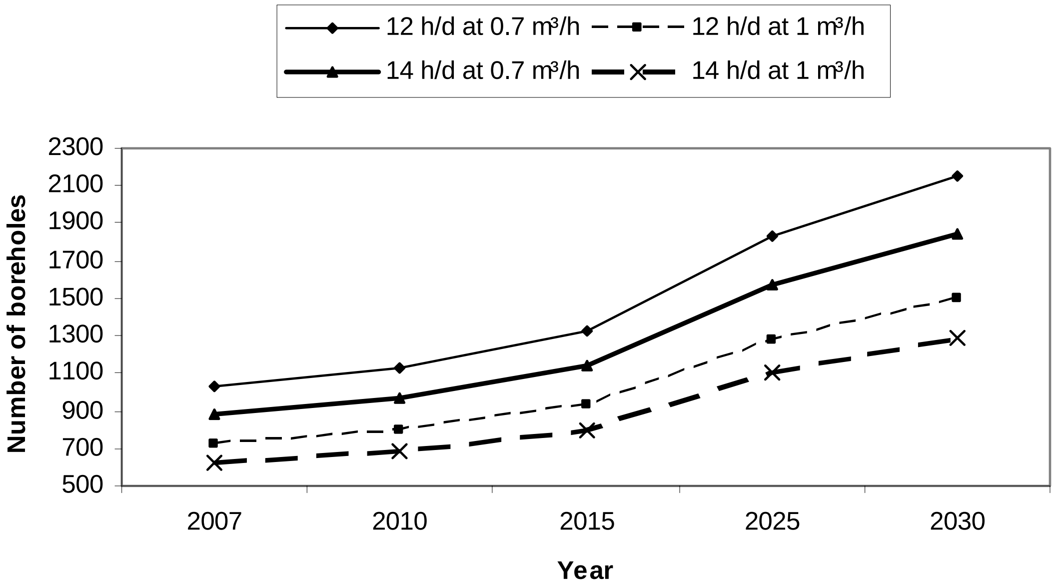


Figure 5.2c: Number of boreholes for a supply rate of 30 l/c/d

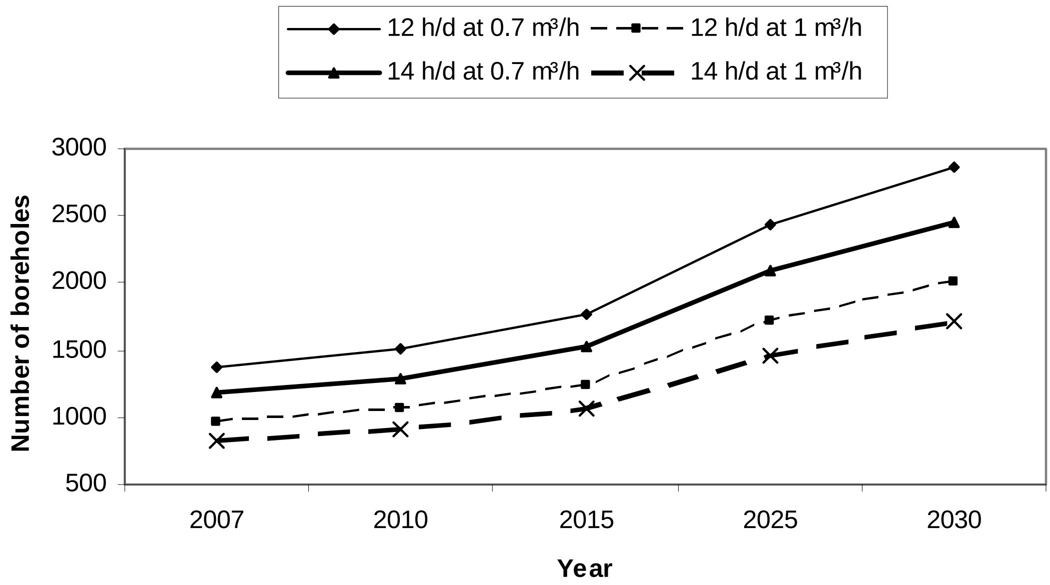


Figure 5.2d: Number of boreholes for a supply rate of 40 l/c/d

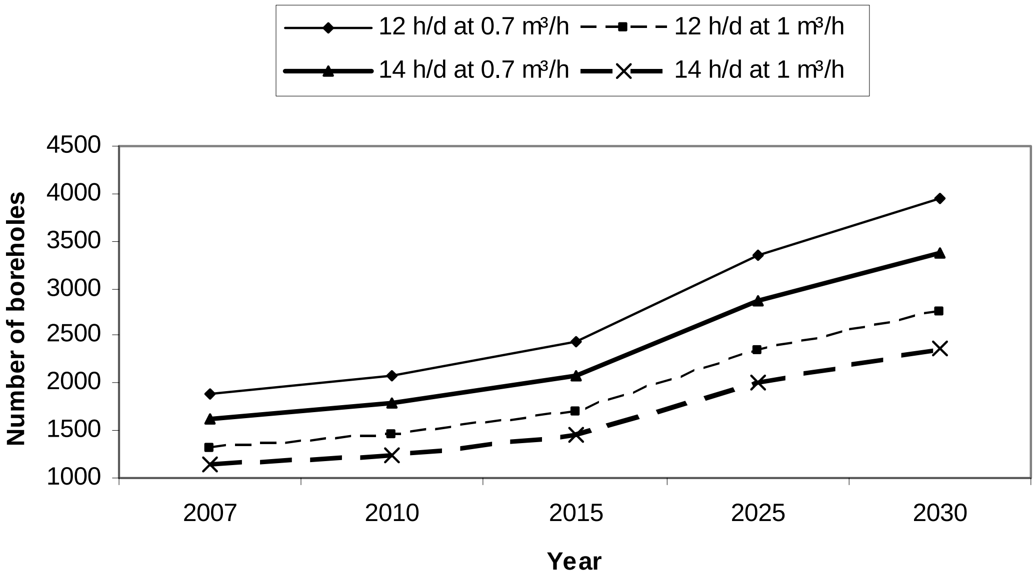


Figure 5.2e: Number of boreholes for a supply rate of 55 l/c/d

Appendix 6: Interviews on the water supply quality in the Kompienga dam basin among the surveyors of the water monitoring points

1. La période la plus exigeante des 4 en suivi des prélèvements d'eau

Thiombiano Bapougouni (Kouaré)

Période Mai Juin car début des travaux champêtres et dilemme avec le suivi des prélèvements d'eau.

Zoumboudre Awa (Comin Yanga)

Même réponse que le précédent.

Sana Ouahabou (Comin Yanga)

Période d'Avril en raison de la très forte chaleur ayant induit une forte affluence des populations aux points d'eau ; ce qui signifie plus de prélèvements et donc de sollicitations en terme de suivi ; spécialement les prélèvements « autres ».

Guiguemkoudre Issa (Natiabouani)

Aucune des périodes de suivi n'a été plus exigeante que l'autre.

Kiemkodogo Harouna (Kompienbiga)

Période Nov/Dec due à la non maîtrise et non discernement du travail demandé.

Thiombiano Mandia (Kompienbiga)

Période de Mars car forte affluence des femmes aux forages et difficultés à bien suivre les prélèvements.

Onadja Oumpougla (Pama)

Période Fev/Mars avec les fortes affluences des populations aux points d'eau.

Combary Kalenli (Djabiga)

Période d'Avril

Sanfo Pougoumba (Kouaré)

Période d'Avril car beaucoup de prélèvements et donc plus de suivi.

Thiombiano Baridja (Djabiga)

Période Mai/Juin en raison de forte affluence des populations.

2. Les prélèvements nocturnes d'eau et leur ampleur par rapport aux prélèvements diurnes

T. Bapougouni

Ils sont apparus seulement durant la période Mai/Juin en raison du démarrage des travaux champêtres sinon inexistants durant les autres périodes en raison de la fermeture de la pompe chaque jour à partir de 19h.

Z. Awa

Pas de prélèvements nocturnes excepté les enfants qui s'y amusent la nuit à se laver.

S. Ouahabou

Prélèvements nocturnes existent mais moindres par rapport aux prélèvements journaliers. Les prélèvements nocturnes vont de 18h à 22h et reprennent à partir de 4h du matin le jour suivant.

G. Issa

Les prélèvements nocturnes existent fortement et sont surtout l'œuvre des hommes. Ils sont estimés à 1,5 fois les prélèvements journaliers en terme de quantité.

K. Harouna

Les prélèvements existent mais inférieurs à ceux diurnes.

T. Mandia

Les prélèvements nocturnes sont permanents au niveau de ce forage.

O. Oumpougla
Ils existent et ont été très élevés (>à ceux de jour) en Avril lorsque bon nombre de forages de la ville étaient en panne pendant que les besoins en eau étaient très élevés.
C. Kalenli
Prélèvements nocturnes inexistants en général. C'est lorsque certains forages tombent en panne qu'apparaissent les prélèvements nocturnes. Le village est suffisamment doté de points d'eau.
S. Pougoumba
Les prélèvements nocturnes existent surtout en Mars/Avril (période de fortes sollicitations en eau) mais de moindre quantité par rapport aux prélèvements de jour.
T. Baridja
Ils existent et sont même permanents mais restent de moindre quantité par rapport aux prélèvements journaliers.

3. Coût de l'eau puisée (FCFA)
T. Bapougouni
Couple du village : 750 F/an dont 250 F/femme et 500 F/homme.
Avant 2003 : paiement en argent ou en nature (céréales) suivant les possibilités.
En 2003 : 500 F/femme/an, 1500 F/homme/an et 500 F/tête de bœuf/an (petits ruminants exemptés)
2004 : année sabbatique
2005 : 250 F/bœuf/an, 500 F/homme/an et 250 F/femme/an
Z. Awa
100 F/femme/mois
G. Issa
1800 F/femme/an
S. Ouahabou
600 F/femme/homme/an
1000 F/an/propriétaire d'animaux domestiques
K. Harouna
300 F/mois/personne prélevant l'eau au forage, 1000 F/personne confectionnant des briques.
T. Mandia
200 F/femme/mois
O. Oumpougla
Point d'eau à grand diamètre ; eau gratuite.
C. Kalenli
150 F/femme/mois puis 100 F/femme/mois depuis 2004.
S. Pougoumba
1500 F/femme/an et 1000 F/homme/an
T. Baridja
100 F/femme/mois

4. Durée journalière moyenne de suivi des prélèvements d'eau
T. Bapougouni
6h-18h sans discontinuité dès l'ouverture de la pompe dont je suis le détenteur de la clé.
Z. Awa
6h-18h

S. Ouahabou
6h-18h, chaque jour.
G. Issa
6h ou 7h à 18h ou 19h.
K. Harouna
6h-19h et rupture de 10h à 11h pour déjeuner pendant 15-20 mn.
S. Pougoumba
6h-18h/19h
T. Baridja
Du lever au coucher du jour.

5. Périodes journalières de prélèvements d'eau

T. Baridja
A tout moment sans discontinuité durant les périodes chaudes de l'année. Alors que pendant le froid et les pluies les fortes fréquentations vont de 11h à 13h ; le reste de la journée est à faible fréquentation.
S. Pougoumba
Pendant la période de chaleur : 6h-10h puis 14h-17h.
Pendant la période du froid : matin et midi.
C. Kalenli
Grande affluence : 6h-11h et 15h-17h/18h
Faible affluence : 12h-14h
O. Oumpougla
Pendant la période de chaleur (Février-Mars) : affluence sans discontinuité.
Autres périodes de l'année : du matin jusqu'à 11h puis 14h-18h/19h.
T. Mandia
Période de chaleur : du matin jusqu'à la nuit sans discontinuer
Autres périodes : du matin à 10h puis de 15h à la nuit.
K. Harouna
Pompage permanent sans discontinuer quelque soit le jour.
G. Issa
A toutes les périodes de l'année, affluence des femmes au forage sans discontinuité du matin au soir mais périodes de chaleur encore très affluente.
S. Ouahabou
5h-11h et 14h-18h : très forte affluence journalière.
11h-14h : légère affluence.
Z. Awa
8h-12h puis 14h-18h.
T. Bapougouni
6h-11h et 15h-18h/19h, forte affluence ;
11h-15h, faible affluence mais considérable en période de chaleur.

6. Quantité d'eau prélevée suivant le nombre d'éléments dans la famille et les périodes de l'année

S. Ouahabou
L'eau du forage est insuffisante. En saison sèche, notre famille de 30 personnes environ n'est jamais complètement satisfaite à hauteur de ses besoins journaliers de 20 à 25 grands plats.

G. Issa
Pour une famille de 13 personnes utilisant 2 grandes barriques d’eau par jour, il est difficile d’obtenir ces quantités durant les périodes chaudes de l’année (Février à Avril).
Roucky (Natiabouani)
Notre famille de 3 personnes est largement satisfaite tous les jours avec 3 grands plats d’eau.
K. Harouna
Pour notre famille de 20 personnes, 20 grands plats et 5 petits plats environ sont nécessaires pour nos besoins journaliers. Il est difficile de pouvoir satisfaire ces besoins dans les mois de Novembre à Mars : baisse alors des quantités à 15-18 grands plats par jour.
O. Oumpougla
Famille de 8 personnes avec des besoins quotidiens en eau de 7 grands plats environ satisfaits à chaque moment de l’année avec quelque fois une augmentation des quantités journalières passant à 9 grands plats.
C. Kalenli
Les besoins journaliers peuvent être estimés à environ 16 grands plats + 6 plats moyens et 6 grands bidons pour notre famille de 16 personnes. Ces volumes sont facilement acquis chaque jour sans difficulté.
S. Pougoumba
Notre famille de 25 personnes arrivent difficilement a satisfaire ses besoins en Avril (période de grande chaleur) et se contente des quantités disponibles.
T. Baridja
Famille de 32 personnes environ, nos besoins journaliers en eau de 3 grandes barriques sont toujours satisfaits tout au long de l’année sans problème.

7. Les pannes des pompes et les réparations
T. Baridja
Forage de 3 ans d’age, n’est pas encore tombé en panne.
S. Pougoumba
Forage de 15 ans d’age environ et 1 panne par mais 3 pannes certaines années. Les réparations sont payées à hauteur de 20 000 à 25 000 FCFA parfois 50 000 FCFA à partir des ressources des cotisations collectées par 3 personnes différentes.
C. Kalenli
Forage en panne pour la première fois depuis 2003, année de son implantation.
O. Oumpougla
Puits à débits faibles à partir de Mars jusqu’en Mai. Il n’y a donc pas de panne ni de réparations quelconques.
T. Mandia
Forage implanté en 2001, il n’y a encore pas de panne.
K. Harouna
Les redevances mensuelles collectées et gérées par un vieux à sa guise (sans contrôle) sont sensées servir aux réparations des pompes du village. Mais un forage en panne depuis un mois demeure ainsi sans réparation jusqu'à nos jours.
G. Issa
Le forage du village a été réalisé en 2002 et est tombé en panne pour la première fois en Juin 2005 et réparé à 99000 FCFA sur les cotisations annuelles collectées.
S. Ouahabou

Forage réalisé en 1992 avec 3 pannes enregistrées et réparées sur les cotisations collectées annuellement.

Z. Awa

Forage de 2001, pas de panne jusqu'à ce jour.

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