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Integrated assessment of groundwater resources in the Ouémé basin, Benin, West Africa

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ABSTRACT

An integrated assessment of groundwater resources in Benin, West Africa was performed within the framework of the EC-funded research project RIVERTWIN (www.rivertwin.org). The assessment included a spatial analysis of groundwater relevant parameters taken from more than 4000 wells stored in a countrywide water database (BDI – Banque des Données Intégrée) and an estimation of the spatial and temporal distribution of groundwater recharge using a modified version of the hydrological model HBV. Additionally, a socio-economic assessment of the impacts of groundwater availability and accessibility on national health issues as well as an assessment of groundwater development costs was carried out.

The analysis revealed particularly unfavourable conditions for groundwater use in the northern part of the country where groundwater recharge during the wet season does not lead to the formation of persistent groundwater storage in its shallow, unconfined aquifers. Poor storage capacity and hydraulic properties of the deeper fractured aquifers additionally limit the capacity of individual wells to capture groundwater recharge. Including climate change scenarios forecasting less precipitation (generated from global climate models (GCM) based on IPCC scenarios) indicates that the situation in water scarce regions will worsen, as recharge volumes lessen and occur over a shorter time period. Drilling more wells may be a limited option to capture larger portions of the recharge, since the capture zone and therefore the regional influence of existing wells is rather small. In the south, deeper confined aquifers guarantee better and more reliable yields, yet the lack of long-term monitoring and groundwater age data does not allow an appraisal of the limits of the sustainable use of these aquifers.

Finally, it has been shown that access to suitable aquifers and diarrhea prevalence are spatially correlated. Access to groundwater is thereby not only a function of aquifer suitability and groundwater availability but a function of well development (mainly drilling) costs as well.

The present study can be seen as a first attempt of an integrated evaluation of the groundwater resources and the development options based on the BDI data set. However, it can clearly be seen that the amount, nature and reliability of the data currently available is not sufficient to come to a clear, spatially explicit description of groundwater resources in the country. Improved monitoring and the use of advanced data collection methods (isotopic analysis, remote sensing, fully coupled models of the hydrological cycle) are required to improve the understanding Benin's groundwater resources.

1. Introduction

Since groundwater is a major drinking water resource and critical for irrigation in many parts of the world, evaluating and predicting the availability and accessibility of groundwater under changing boundary conditions is one of the central tasks in *Integrated Water Resources Management* (IWRM) (Villholth, 2006; Holman, 2006). IWRM with respect to groundwater has two main objectives: to provide water in sufficient quantity and quality equitably to different consumers and at the same time to maintain and guarantee a sustainable qualitative and quantitative status of the groundwater resource itself (Hiscock et al., 2002). A 'good status' of groundwater refers to its function in water supply (drinking water, irrigation, industrial use etc.) but also to its role as a long-term reservoir to sustain aquatic ecosystems (wetlands) and to provide a source of discharge in dry periods (important for navigation, fisheries, and energy production). Water availability and

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accessibility must consider quantitative (volumes, fluxes, flow rates) and qualitative aspects (drinking water standards, minimum required quality for different uses).

The IWRM objectives are even more critical for the developing world. Equitable accessibility to safe drinking water is considered in the Human Development Report 2006 as a top development priority (UNDP 2006). Among the various Millennium Development Goals, infant mortality from water borne diseases and improvement in water accessibility are likely to be the largest challenges in developing countries, and often do not require major technological breakthroughs. Hence, it is important to identify effective IWRM strategies which improve water accessibility and combat water borne diseases, where the costs of these interventions can often be sponsored by private-public cooperation and further supported by donor agencies.

West Africa serves as a particular case in point. Diarrhea prevalence, which is seen as a good indication of water impurity in general, is considered the major cause of the high infant mortality in the region. Yet, efficient policies in the region that should coordinate improved water accessibility are largely absent, often due to weak institutions and inaccurate information systems on the exploitation of water resources. As the majority of suitable water sources are based on ground water exploitation, a spatial inventory and characterization of the aquifers will support efficient decision making and facilitate equitable access to safer sources of drinking water. For example, improving water accessibility for the poorest sections of the society has shown remarkable positive effects on their livelihood and might drastically reduce the irreversible effects of water borne diseases (loss in school attendance, adverse memory effects, poor analytical skills), which in turn may mitigate economic hardship for the poor in the future. Therefore, safe and secure groundwater is of paramount importance for the poor (Fewtrell et al., 2005; UNDP, 2006).

The European Community financed RIVERTWIN project (2004/03/01–2007/02/28; www.rivertwin.org, Gaiser et al., 2008) is based on the idea of IWRM and investigates Global Change effects on the hydrological cycle. The objective of RIVERTWIN is the development of tools for integrated water and land use management. The results of a model chain are loosely coupled by well-defined interfaces in MOSDEW (MOdel for Sustainable DEvelopment of Water Resources; Gaiser et al., 2008 www.rivertwin.org). Three river basins with contrasting ecological, social and economic conditions were selected (Fig. 1): (1) The Neckar basin (Germany, Central Europe); (2) The Ouémé basin (Benin, West Africa); (3) The Chirchik basin (Uzbekistan, Central Asia). Detailed results of RIVERTWIN plus the possibility to choose results from different models and scenario simulations are provided in further detail on the internet under http://mapserver.ilpoe.uni-stuttgart.de/rivertwin/index.php.

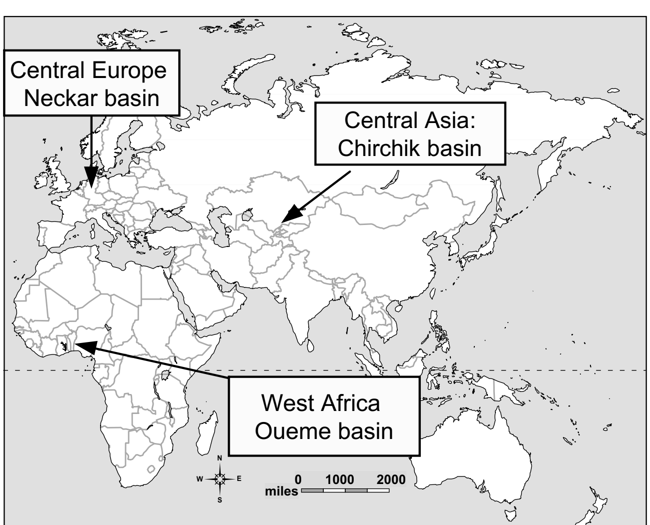

Fig. 1. Study areas of RIVERTWIN.

This article deals exclusively with the groundwater resources of the Ouémé basin. This selection is motivated by social relevance as the Ouémé basin hosts the poorest population of the three basins, which is also reflected in the statistics on water accessibility. Nation-wide only 37.4% of households have a piped water source, 43.2% obtain their water from wells; and the vast majority have poor sanitation facilities (Balk et al., 2003). Poor access to safe water sources is also reflected in the persistent problem of high diarrhea prevalence, especially amongst children. Diarrhea prevalence increased from 105 cases per 1000 children in 1995 to 121 cases in 1999, with as most vulnerable group the children below one year with prevalence rates going as high as 250 per 1000 children. The percent of children with diarrhea that were given oral rehydration solution stands at 32 (DHS, 2001). Furthermore, the present environmental endowments and sparse population makes the Ouémé basin an important settlement area that will increasingly absorb migration flows from North and South in response to environmental degradation and mounting population pressure. Migration is likely to continue in the coming decades and, therefore, groundwater resources will be of particular relevance for the future inhabitants of the Basin (see also Doevenspeck (2004). Hence, technical support for the decision making process on the allocation of the investments is urgently needed.

Currently, information on groundwater sources in Benin is scarce. The aggregated statistics of the annual AQUASTAT[1] database reveal that groundwater is largely underutilized as only 2% of the yearly internally produced water is being harvested. Yet these data do not reveal the temporal and geographic dimensions of the water availability and possibilities for its sustainable exploitation. Therefore the main goals of the groundwater related work in the Ouémé basin in the RIVERTWIN project were:

1) a spatial characterization of groundwater resources that supports decision makers in their future investment policies,
2) provide spatially explicit information on
   (a) a relation between diarrhea prevalence and groundwater accessibility
   (b) a cost assessment for groundwater exploitation

This article addresses these research topics and is structured as follows: Section 2 discusses the nature and role of groundwater resources in Benin and specifies the open science questions related to the availability and management of groundwater. Section 3 describes the methodology used to tackle the study's goals and presents the analysis results. Section 4, sums up the outcomes and extracts the recommendations for future activities from both the research and policy perspectives.

2. Groundwater resources in Benin – current situation and research demand

2.1. Climate, hydrology and geography

About 89% of the Ouémé catchment is located in Benin, ~10% in Nigeria and ~1% in Togo. The Ouémé catchment makes up roughly 43% of the country of Benin (Fig. 2). Although the RIVERTWIN pro-

[1] http://www.fao.org/nr/water/aquastat/dbase/index.stm.

ject was focused on the Ouémé catchment only, the groundwater analysis presented here investigated the conditions of the country as a whole mainly because the most important data sets used covered Benin entirely.

The climate of Benin is of typical monsoon type which is characteristic for the large sub-humid Savannah zones of the world. Average annual temperatures are approximately 27 °C, with temperature amplitudes of 5–6 °C (Fig. 2). However, different climatic zones can be found throughout the country: the Southern Sudan Savannah zone tends to be semi-arid and there is a single summer rainy season in Northern and Central Benin; a subequatorial moist savannah zone (Guinea-Savannah) can be found in Central and Southern Benin, and the humid subequatorial zone in the South, which both show bimodal rainfall patterns (Stahr, 2000) (Fig. 2). The mean annual aerial precipitation is about 1200 mm; however, the mean annual potential evapotranspiration according to Hargreaves and Samani, 1985 is approximately 2800 mm. The landscape of the Ouémé basin is characterized by peneplains with scattered inselbergs and plateaus. The Ouémé River crosses the basin from North to South and flows into Lac Nokoué which empties into the Gulf of Benin. The vegetation is dominated by tree and shrub savannah intersected with a mosaic of cropland and bush fallow. The majority of the soils in the Ouémé basin are characterized by leaching, erosion and iron redistribution processes. The topsoils are predominantly sandy and clay content increases with soil depth. Water storage capacity is usually limited by low clay content and considerable amounts of coarse fragments (nodules, gravel and stones) which can form impermeable layers cemented by iron oxides.

2.2. Hydrogeological situation and groundwater use

In Benin groundwater availability and accessibility are largely determined by a division of the country in two hydrogeologically contrasting parts: The southern coastal sedimentary basin and the crystalline basement in the northern part of the country (Fig. 3).

In the northern part, a precambrian crystalline basement is covered by a tertiary Regolith and a lateritic weathering zone ('Saprolite'). Zones of improved hydraulic properties (i.e. potential aquifers) are limited to the thin (0–20 m) weathered zone and to the intensively fractured zones in the vicinity of major faults. The resulting groundwater bodies usually have a low storage capacity and are not hydraulically interconnected (Fass and Reichert, 2003; El-Fahem, 2008). Nevertheless, in the Northern part of the country, groundwater is an important source of water supply in rural areas. Small yields and quality problems (Heidecke, 2006) make it an unreliable resource, particularly during dry periods. The storage in the small, shallow groundwater bodies located in the weathered zone seems to be mainly controlled by vertical processes influenced by the actual climatic situation (see the discussion of Fig. 9).

The southern coastal basin is dominated by weakly consolidated sand, sandstone, clay and claystones. The sand dominated parts form productive aquifers. The stratification leads to the formation of several separated, confined to leaky aquifer systems. Some of them are connected to the ocean and are therefore particularly at risk of sea water intrusion if extraction is not balanced (Direction des Ressources en Eau, 2004; UNEP-DEWA, 2004).

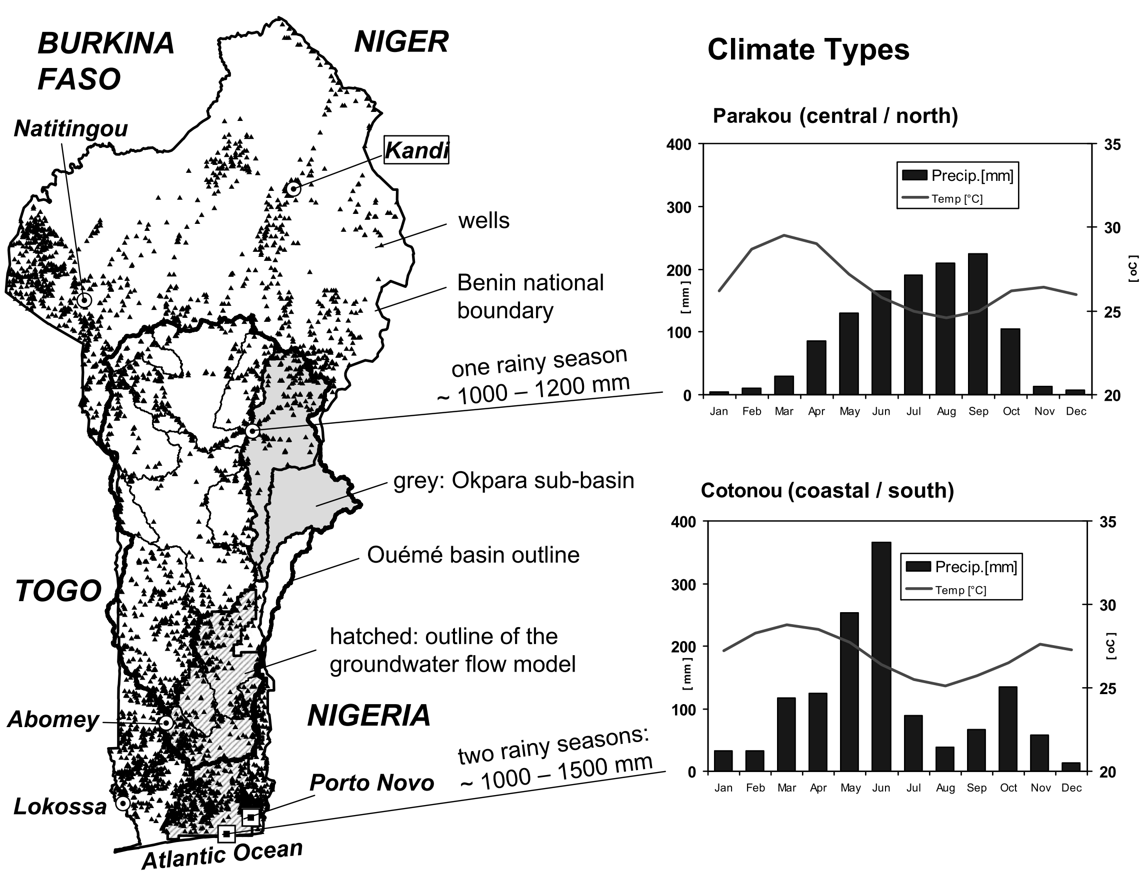

Fig. 2. The country of Benin and neighbouring countries, catchment boundaries and groundwater flow model boundaries, location of wells according to the BDI (Banque des Données Intégrée) right hand side: climatic conditions in the Ouémé basin (after Fass, 2004, modified).

In most rural parts of the country the mode of water use and the availability depend on the actual precipitation which shows a strong seasonal influence (Fig. 2). Highly productive deep wells and surface water reservoirs, which would help to overcome this dependency, are scarce. Irrigation is limited to small operating systems with one exception (sugar cane plantation near Save). Most people living in permanent legal settlements have access to drilled or dug wells (10–200 m; see Fig. 2) and additionally obtain their water from shallow dug wells, rivers and waterholes ("marigots"). However, even the yield of deeper wells is often low, and subject to large seasonal or even diurnal variations. Not all wells are equipped with electrical pumps (BDI data).

In larger cities up to 74% of the population have connections to public water supply systems which tap groundwater in the south (Cotonou, Port Novo) or water from surface reservoirs in the north (e.g. Parakou, see Fig. 2). In general, the natural water quality of drilled wells is good, but can become very poor especially in wells situated within or in the vicinity of settlements (Schopp, 2004; Heidecke, 2006).

Water resources management in the Ouémé River basin has received increasing attention during the last decade through research initiatives with an interdisciplinary, long-term perspective. Amongst others, the IMPETUS project (www.impetus.uni-koeln.de, Bormann et al. 2005; Giertz et al., 2006a) and the German Research Foundation Special Research Programme 308 ("Adapted Farming in West Africa" – DFG SFB 308), which mainly was concerned with soils and agricultural issues, carried out widespread research activities related to water in the basin. However, investigations specifically related to *groundwater* issues are relatively scarce. There are a limited number of studies dealing with *local* hydrogeological issues (e.g. Boukari et al., 1995; Boukari et al., 1996; Fass, 2004; El-Fahem, 2008) as well as maps and reports compiled by the governmental water authorities (e.g. Azonsi and Adjomay, 2005; Le Barbe et al. 1993; Direction des Ressources en Eau, 2004; Direction de l'Hydraulique, 1985a; Direction de l'Hydraulique, 1985b).

Groundwater and hydrological assessment can be based on a relatively high number of existing, yet largely unexplored data which are stored in a countrywide water resources database (Banque des Données Intégrée, BDI, see Section 3.2) and detailed countrywide GIS data (hydrography). In this respect it should be mentioned that detailed digital geological maps were only available for the southern and central regions of the country. The northern region is still under development.

Table 1 summarizes groundwater related problems resulting from the climatic, hydrogeological and socio-economic conditions and indicates the most pressing problems of groundwater management in the Ouémé basin.

In general it can be stated that groundwater is an important resource, yet information on its reliability in terms of quantity and quality is still lacking. Availability and accessibility are distributed unevenly both spatially and temporally. In view of these statements a demand for research in the following fields can be determined:

1. From a hydrogeological and hydrological point of view, it remains unclear whether the current use of groundwater has already reached its limits with respect to availability, sustainability, quality (health) issues and economically feasible solutions, or whether a better understanding of hydrological and hydrogeological processes, better groundwater management and more efficient technical solutions might be able to enhance the situation substantially.
2. Subsequently, from a socio-economic point of view, it remains unclear if it is possible to use groundwater to develop more secure agricultural and economic systems and to which degree better management can support current population development.

In the following sections, an attempt to answer these questions is made based on observed data and models developed within the RIVERTWIN project.

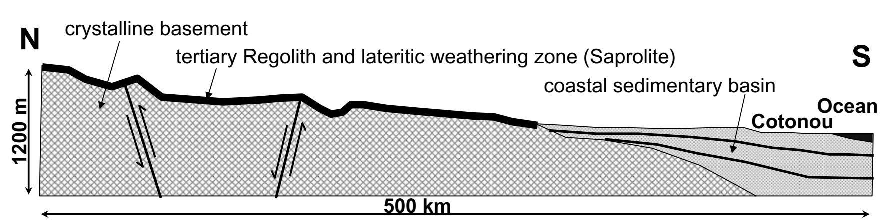

Fig. 3. Schematic general geological situation of the Ouémé basin – cross-section. The sketched faults do not represent the actual location or direction of tectonic displacements.

Table 1
Groundwater management tasks in the Ouémé basin

	Rural areas (north and south)	Urban areas (south only, north = surface water mainly)	Basin wide – general
Groundwater related problems and issues	• Hygienic conditions/water quality • Low yields, scarcity in the dry season (especially towards the end of dry season)	• Groundwater depletion • Sea water intrusion • Hygienic problems, waste-water seepage	• Water scarcity in the dry season • Poor water supply and sanitation infrastructure • Low reliability of water supply
Groundwater related management tasks	• Optimizing well locations and well design to improve accessibility, yield, reliability and hygienic conditions • Find means of storage to overcome seasonal water shortage	• Avoid aquifer over use, develop new resources • Prevent seawater intrusion • Enhance sanitation infrastructure	• Enhance monitoring system • Increase reliability and reduce effect of seasonality on water availability • Enhance infrastructure • Advertise measures of local integrated water management • Assess and predict groundwater availability under changing boundary conditions

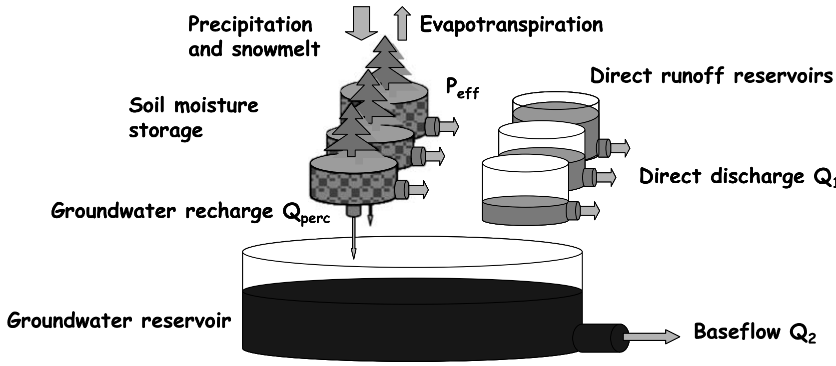

Fig. 4. Structure of the distributed HBV model (Götzinger and Bárdossy, 2007).

3. Groundwater resources analysis: methodology and results

In order to address the research questions stated in the previous section three practical analytical tasks were carried out:

(A) *Hydrological modelling*. Determine the upper bound of extractable groundwater per 3 by 3 km cell → *dynamic* spatial analysis and quantification of groundwater recharge, long-term *availability*, *sustainability* and *reliability* of groundwater resources
(B) *Spatial hydrogeological analysis*. Determine hydrogeological and hydraulic properties per 3 by 3 km cell → *static* spatial analysis of groundwater extraction potential (*extractability, accessibility* and *vulnerability*), and groundwater development options (*feasibility*)
(C) *Health analysis*. Investigate the spatially explicit relation between diarrhea prevalence and groundwater quality and aquifer *suitability* conditioned for prevailing socio-economic characteristics → evaluate the impact of water *accessibility* interventions on the health status of the poor and rich segments of the society.

The objectives of the study on a temporal scale are therefore twofold:

(1) To make a synopsis of groundwater resources characteristics and use for the past and present situation.
(2) Based on (1) try to predict changes under scenario- (climate-, socio-economic-) conditions

3.1. Hydrological modelling

The main purpose of hydrological modelling in the context of this study was to estimate the spatial and temporal distribution of groundwater recharge since the mean long-term recharge can be regarded as the upper limit of a sustainable extraction of groundwater. Here it has to be noted that a conceptual hydrological approach cannot differentiate between the recharge to different aquifers. In RIVERTWIN, a modified version of the semi-distributed conceptual HBV model (Bergström, 1995) was developed (Götzinger, 2007). HBV has conceptual routines for calculating soil moisture and runoff generation, runoff concentration within the sub catchment and flood routing of the discharge in the river network. The main modification of the version used in this study is that the runoff generation and concentration routines are fully distributed on a 3 by 3 km raster. Fig. 4 shows the general model structure of the distributed HBV model.

Additionally, an attempt was made to more specifically represent groundwater storage (which is vertically undifferentiated in HBV, see Fig. 4) using MODFLOW2000 (Harbaugh et al., 2000), a deterministic numerical model concept. The four-layer groundwater model which was developed does not cover the whole catchment (see Fig. 2), since only in the south, in the coastal sedimentary basin, the formations are suitable for the development of a regional groundwater flow model. For a detailed discussion see Barthel et al. (2008). Groundwater modelling did not yield reliable quantitative results and is therefore not discussed further in this paper. However, the groundwater model revealed some very interesting aspects which may be helpful to better understand groundwater related processes in this area (Barthel et al., 2008).

The HBV model was adapted to the Ouémé basin for the calculation of climate and socio-economic scenarios. Under the given data limitations and focus of the study, simulation runs compared with observed data show an acceptable agreement with measured discharges (Nash-Sutcliffe coefficient 0.77, see Fig. 5).

In order to study the potential impacts of climate change on the water balance on spatial and temporal scales, the HBV model has been run with observations and different climate scenarios (for a description of the scenarios see Yang and Bárdossy, 2006). Fig. 6 shows a comparison between simulated groundwater recharge based on observed climate input and recharge based on a moderately dry climate scenario.[2] In the climate scenario a 9% reduction of precipitation and increased temperature lead to an average decrease of groundwater recharge of almost 40% for the whole basin.

Whereas the temporal distribution of groundwater recharge shown in Fig. 6 is very important for the assessment of groundwater resources availability on a temporal scale, it has also to be taken into account that groundwater recharge, due to differences in climate, soil types, geology and land use is highly differentiated on the spatial scale. Fig. 7 shows the spatial distribution as calculated by HBV on a 3 by 3 km grid for an extremely wet and for an extremely dry year. The extreme spatial and inter-annual variability of groundwater recharge are of very importance for the actual availability of (ground-) water, in particular for shallow aquifers with low storage capacities in North Benin. In these regions it was observed that groundwater levels react with a very short delay of 0.5–2 month to the seasonal change of precipitation and groundwater recharge (compare Fig. 2, Fig. 6, Fig. 9). This means that there is no significant capacity to store water in the subsurface over larger periods of time. During the wet season, the shallow Regolith/Saprolite aquifers are filled and lose water from storage quickly in the following dry season, most likely due to horizontal flow

[2] The scenario is the result of downscaling GCM output from ECHAM4 based on the IPCC scenario A2.

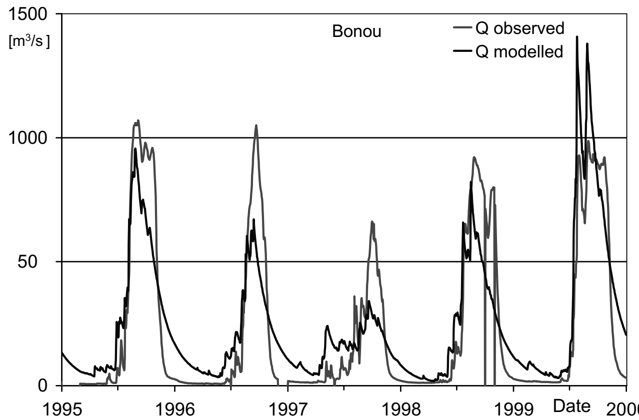

Fig. 5. Observed and modelled discharge by regionalisation at the Bonou gauging station (outlet) from 1995 to 2000 (validation period).

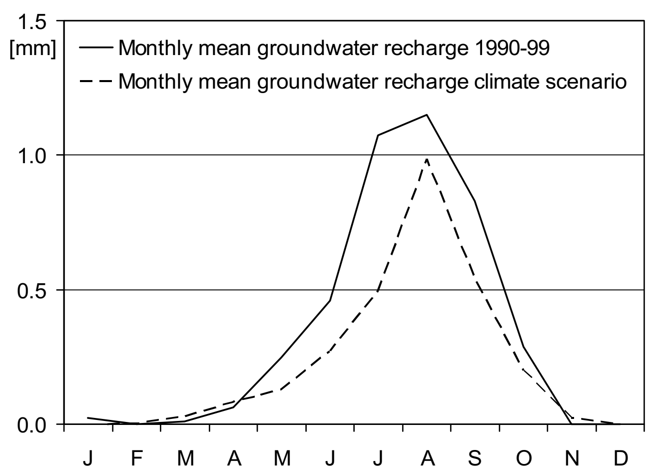

Fig. 6. Monthly mean groundwater recharge in the Okpara sub-basin (see Fig. 2) in the reference period and the climate scenario.

towards rivers and depressions and to direct evaporation. This is only valid for the shallow aquifer (Fass 2004). Subsequently, the water supply in dry periods can not draw on storage from previous years (see Section 3.2 also). It should be mentioned however, that according to Fass (2004) the high mineralisation of groundwater due to intensive groundwater-rock interaction points to longer residence times of groundwater as a result of the low permeability of the Saprolite.

3.2. Hydrogeological analysis

The analysis of the physical aspects of the groundwater resources in Benin was mainly based on the evaluation of a water database[3], including data on wells drilled during the last 25 years. This database, the so-called BDI (Banque de Données Intégrée) was partly made available to the RIVERTWIN research cooperation by the Direction Générale de l'Hydraulique (DGH – now Direction Générale de l'Eau, DGE) It contains data on about 5000–6000[4] drilled wells built from 1983 to 2004[4] in more than 100 programs sponsored by different national, international, governmental and non-governmental organisations from different countries, mainly from the 1980s until the present. There are data on geology, hydrochemistry, well design (depth, diameter, filtered sections, etc.) and important characteristics such as hydraulic conductivity, aquifer type, yield and details on the pumps installed. The aim was to regionalize the main data on hydrogeological, hydraulic and hydrochemical properties on a 3 by 3 km grid covering the whole country. Initially it was planned to perform a full geostatistical analysis of the data set for that purpose. However, at first attempts to systematically explore the data it became clear that most of the data in its present form[5] was too heterogeneous, unreliable and inconsistent to be meaningfully analysed in a quantitative way. One main reason is that the exact coordinates of the wells are often not known or found to be incorrect upon closer consideration the other that it is often doubtful whether values of the same database field have the same physical meaning (more detailed discussion below). In general, the spatial distribution of the wells is highly irregular, making it difficult to interpolate or regionalize the data (see Fig. 2).

The first step accordingly was an analysis of the *spatial* structures (the database does not contain any transient data, see below) and the quality and reliability of the data. This proved to be a time-consuming and difficult task since a closer look at the seemingly well organized data revealed many inconsistencies. The main problems encountered were:

1. Up to 12 wells can have the same coordinate pairs[6] with differences in groundwater head of up to 50 m. It is very likely that in such cases (or maybe even more often) the well coordinates contained in the database are actually indicating some central point in a village or even district. For the regional assessment this might be acceptable as long as the elevation of the well top, which in most cases is not available, is not needed.
2. The spatial distribution of wells is rather erratic and follows rather roads and main rivers than hydrogeological structures. This is quite common for hydrogeological data, yet difficult to deal with in the attempt to regionalize the data.
3. It remains partially unclear what the individual database fields mean (see discussions for "yields" below).
4. There is an obvious, yet not quantifiable, amount of subjectivity and subsequently inconsistency in the data which probably results from the fact that the data were initially collected by different people during three decades. The data collectors (as quite common in the well drilling business) had probably no scientific evaluation of the data in mind but rather a short documentation of what was done and what was observed.

As a result of the quality and reliability assessment of the data it was decided not to use any advanced approaches to spatially analyse and regionalize the data. There is quite a number of interesting approaches from the geostatistical family of techniques, yet they would have required an inappropriately high level of effort. In addition, secondary data required for many approaches was not available countrywide in digital formats. The individual contents of the database would require a very thorough and detailed discussion in order to point out the practical problems of creating consistent, reliable and meaningful data sets. It is however not within the scope of this article to describe and discuss all the related issues in detail.

[3] Put together as a joint effort by Danish DANIDA and DGH (see IDA/DANIDA, 1998; DANIDA, 2000; DANIDA, 2004) three main chapters: surface water, groundwater and water quality.

[4] For the Ouémé basin a data base sub-set with more and more recent data was provided to the RIVERTWIN research consortium but not all tables and database fields were available and filled.

[5] The BDI database is currently being updated and reorganized (DANIDA, 2004 and personal communication Tobias El Fahem, Felix Azonsi, DGH/DGE). At the time this study was completed, the different database subsets containing inconsistent data were available to the authors.

[6] An uncounted number of wells with identical *X* OR *Y* also exists.

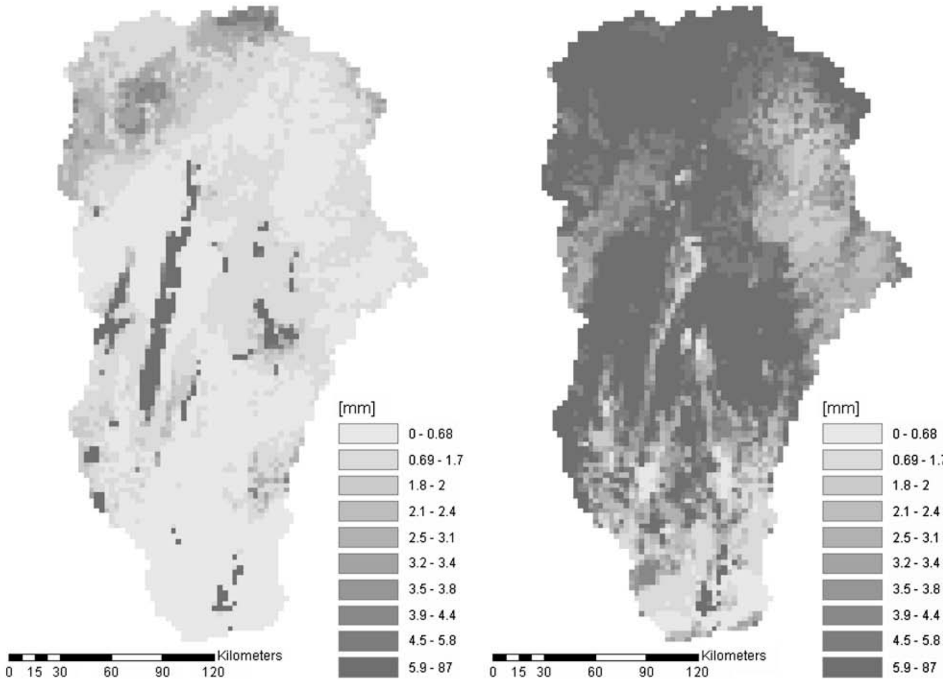

Fig. 7. Spatial distribution of annual groundwater recharge in 1983 (very dry) and 1999 (very wet) in the Ouémé basin.

To create raster maps covering the whole country, the data was interpolated on a 3 by 3 km grid using the inverse distance weighting approach with a low power value (1.5) to eliminate local effects. The search was carried out within a 30 km radius (i.e. 10 cells) split in four quadrants using the condition that at least two sectors contain data. This allows for the creation of interpolated raster maps over the entirety of the county. Here it is important to note that there are some interpolated values with very low data support. A cross-validation analysis was carried out to prove the quality of the interpolation results. As expected, the local uncertainty is high in locations with either low data support or high variability. Some data were log-transformed (transmissivity), and outliers were removed. In the case of nominal data, (aquifer type) integer values were assigned before interpolation was performed. Wells having identical coordinates were treated differently according to the nature of the variable in question and the respective numerical values. The overall goal for all variables was to keep as much data (well locations) as possible and at the same time exclude data of low reliability which proved to be a difficult task.

In the following paragraphs key intermediate and final results are explained in detail. Fig. 10 shows the most important final results and some of the intermediate results.

3.2.1. Aquifer type

The rock formation that is used to extract groundwater (i.e. the aquifer) is often situated at a considerable depth (here 10–200 m) and can in such cases be significantly different from the formation at the land surface. This makes any regionalisation of aquifer types based on point data and secondary information (geological maps) difficult, because detailed structural information (3D) does not exist[7]. From the various attempts to classify and summarize the aquifer type information into a reasonable number of types, only the simplest approach is presented here. Four major groups were defined and assigned integer values: unconsolidated sedimentary – (1), consolidated sedimentary (2), igneous (3) and metamorphic rock (4). The numerical values were interpolated using the nearest neighbour method and reclassified. The results were used to determine the → *aquifer suitability* (see below) but are not visualized here.

[7] In addition, a consistent countrywide digital geological map was not available.

3.2.2. Transmissivity, hydraulic conductivity and storativity/specific yield

For 1599 wells transmissivity calculated from pumping tests analysis was given in the DBI. Unfortunately the reliability and comparability of this data is low, since most of the data were not calculated on the basis of pumping tests having long durations, but instead using relatively short (some hours to one day) time periods, with the aim of roughly determining how much water might be extracted from a well. In particular for crystalline regions this can lead to a significant misinterpretation, in most cases leading to a significant overestimation of the transmissivity (El-Fahem, personal communication). The hydraulic conductivity K (m/s) was calculated using the saturated aquifer thickness b (m) (see below) and the transmissivity T (m^2/s) where $T = K*b$. This calculation is based on weak data, not only because of the low reliability of the transmissivity data stored in the BDI (see above) but also because of the uncertain information that is available to estimate the saturated thickness (see below). Hydraulic conductivity however is a property unbiased by aquifer thickness and therefore better suited for spatial analysis and comparison than transmissivity.

There was very little information on storativity or specific yield contained in the BDI (values for 53 wells only) which was quite surprising since pumping test were carried out and analysed. It is well known that grids of the hydraulic conductivities interpolated from heterogeneously distributed points in fractured aquifers are not at all meaningful – only a very general trend can be expected (Fig. 10a).

3.2.3. Yields per well and per grid cell

After the transmissivity and the hydraulic conductivity values, yield information at each well can be considered to be the most relevant data type for the aims of the present study. However, the reliability of the yield data in the database tended to be low. Yield data is contained in the various database fields[8] which are in turn parts of different database tables. It remained unclear what exactly the different fields stood for, even after a discussion of this matter with local experts. Most terms often made sense in a specific context, however it seems that the data were not entered in a consistent, context specific way. Since the yield data is absolutely essential for a groundwater resources assessment within the scope of this study, it was decided to use any yield data regardless in which field they were stored using an ‘‘educated guess" approach to transform all values in what is assumed to be an ‘‘average yield", deemed to be close to the ‘‘maximum yield". It is important to point out that the various yield values in the database refer to one date only (in most cases from the date the well was drilled or the pumping test was carried out). As we know, that yields of small rural wells in Benin can vary significantly seasonally or even daily, this limits the relevance of this data drastically. A spatial interpolation of the data cannot be representative since data from different years and seasons are compared. On the other hand, this is the only data set that exists and it can be assumed that at least on a very rough scale the yield values can be related to the average yield or average potential yield of a typical well in a region.

Finally, roughly 4000 well locations were available for the regionalisation. The data were interpolated (a) using the yield of each individual wells, (b) using the sum of all wells within a 3 by 3 km cell. The results of (a) might be close to the ‘‘typical yield" of a well in the specific grid cell (Fig. 10b), whereas the results of (b) might be closer to the potential groundwater extraction rate in a grid cell. Both conclusions, but (b) in particular, are based on very weak assumptions.

The attempt to correlate the sum of yields per cell with the groundwater recharge in the corresponding cell yielded no unambiguous results. In the southern sedimentary basin, wells tapped deeper confined aquifers that receive recharge by means of horizontal flow or contain older groundwater (see conclusions). In the crystalline region of the north, the current mode of groundwater use was not suitable to capture large amounts of the actual recharge. In all parts of the country (apart from the Cotonou area) total yields are constrained by the demand, the number of wells and the individual characteristics of individual wells rather than by the regional groundwater availability. All this indicates that there is a high likelihood that a larger amount of groundwater could be used; however a more detailed assessment would be required to quantify this statement.

3.2.4. Normalized yields

Since the depth of wells varies considerably (Fig. 10d) and it can be understood that the goal of building wells was to meet both demand and to minimize well construction costs, the absolute yield of a well might not be suitable to characterize an aquifer at a specific location. Therefore the absolute yield per well (see discussion above) is normalized with the aquifer thickness used (i.e. the filter length or the difference between uppermost water entering depth and total well depth, see below). The values obtained are considered to show unbiased aquifer suitability (Fig. 10c). In Fig. 8 the normalized yield values were plotted against the transmissivities of the respective wells. As can be expected normalized yields and transmissivity are weakly correlated, i.e. the higher the transmissivity the higher the normalized yield. The range of transmissivity values for wells with the same yield is however large. An interesting detail is the relatively large cloud (~200) of high transmissivity

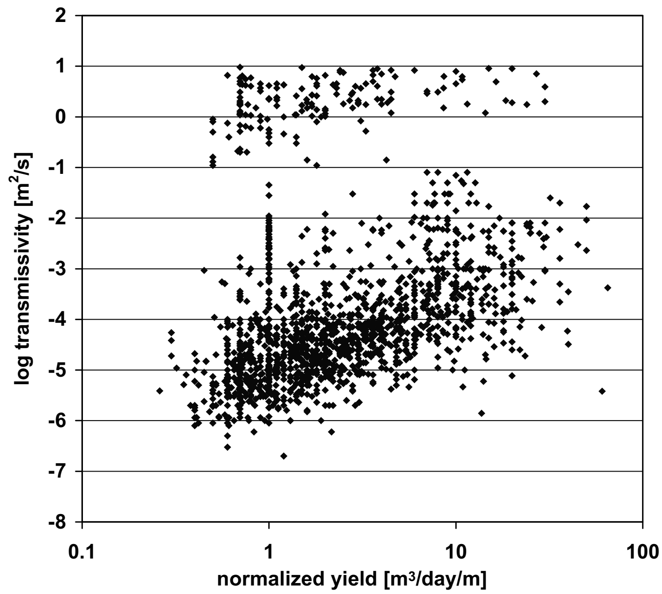

Fig. 8. Scatter plot of normalized yields and transmissivity values.

values which plots about 5 orders of magnitude above the majority of wells. Here we assume that these high transmissivity values are the result of an overestimation due to inappropriate pumping test length or analysis methods (see above)

In addition, the yields were also related to the total depth of the well. The resulting values are considered to be a rough proxy to determine how deep a well needs to be at a certain location in order to extract a certain volume per day. Here the thickness of rock formations above the aquifer at a certain location is also included such that the results can be considered a characteristic of a location, rather than a characteristic of an aquifer.

3.2.5. Aquifer thickness used

There are two different fields in the database which can be used to determine which parts of the borehole are actually used to extract the groundwater. This is (a) ‘‘water entering depth" or (b) the specification of filtered sections. The first type of information is better related to the aim of the analysis but is available for a fewer number of wells. Since the information is required to calculate important characteristics such as specific yields and hydraulic conductivity, it was decided to use whatever information is available regardless of detail and reliability. It is absolutely clear that the ‘‘aquifer thickness" values derived through this approach are for most cases not the real aquifer thickness as the length of the filter section and total depth of the well will usually be results of economic considerations rather than showing the hydrogeological conditions. However, this is the closest one can get as this is the only directly related information contained in the BDI. An analysis of the lithology fields of the BDI might give further insights in some cases but the effort this requires would be in no reasonable relation to the gain of information. We assume that the results of this thickness estimation will at least reflect the order of magnitude of the real aquifer thickness.

3.2.6. Groundwater Levels, piezometric heads below surface

For any groundwater related study contour maps of the groundwater level (potentiometric surface or water table) are an essential prerequisite to answer many groundwater related questions. In the BDI, groundwater level data is given as drawdown, i.e. meters below surface. For only about 200 of the wells is the elevation of the well top given. In order to create a common basis for the interpo-

[8] Débit exploitable, débit équipé, débit maximum, débit spécifique, débit critique, débit développement, débit fin foration.

lation of a potentiometric surface, the elevation $H(X,Y)$ for each borehole location was derived from a 90 m SRTM mission digital elevation model (DEM). Looking at the spatial resolution of the DEM it is obvious that significant errors may arise from this, in particular in areas having a steep relief. An additional problem arises from the fact that the coordinates of the boreholes are not reliable, since there are a considerable number of wells having identical coordinates (see above). This is a problem that affects the interpolation of all variables, but in the case of the groundwater levels it is most relevant. It has to be pointed out that the problems described here limit the practical use of the BDI data for groundwater modelling drastically (see Barthel et al., 2008). For an estimation of the groundwater depth below surface, the problems mentioned above are less relevant. In cases where two or more wells had the same coordinates, the arithmetic mean was used, if the difference between the individual drawdown values was less than 10 m, in case the difference was larger, the data from this location was not used at all (Fig. 10g).

3.2.7. Minimum required drilling depth and typical borehole depth

The minimum depth required to reach groundwater is an important factor in the cost analysis as it is a value which can be considered to be independent from demand or technological and economic constraints. The minimum drilling depth was calculated as a combination of the values ''uppermost groundwater entering depth' per well, and the 'top of filter section' information. Only for unconfined aquifers it is identical to the depth to the groundwater (Fig. 10e). The total depth of each well is available for almost all wells and considered to be comparably reliable information. The interpolated grid of total depth is considered the ''typical'' borehole depth for each grid cell (Fig. 10d).

3.2.8. Confined – unconfined/aquifer state

For all kinds of groundwater analyses it is important to distinguish between confined and unconfined aquifers. In the present case, it is especially relevant for groundwater vulnerability, sustainability and reliability. Confined aquifers are less prone to contamination and decoupled from the actual climatic situation. In general, confined aquifers are better suited for reliable water supplies independent from seasonal changes. There are several ways to determine the aquifer state from the data contained in the DBI: (a) compare groundwater heads and uppermost water entering depth, (b) compare groundwater heads and filter information (Fig. 10g).

3.2.9. Drilling properties

The drilling properties are an important factor in the analysis of well construction and water provision costs, in particular in a country where the optimum technical equipment can not be made available at all times and all locations. In this context it should be mentioned that in the sedimentary rocks dug wells of up to 70 m depth and 1.8 m diameter exist. Since a countrywide digital geological map of enough detail did not exist and the efforts to analyse the whole lithology information contained in the database would have been inappropriately high, the drilling properties were assigned according to the main aquifer of each well, ignoring the fact that in some parts of the country up to 150 m of overlying rocks need to be drilled through until the aquifer is reached. Properties were assigned according to the four main aquifer types (see above) leading to a very rough and general classification.

3.2.10. Aquifer suitability

The aquifer suitability calculated here is related to the static properties of the aquifers available at each grid cell. Dynamic information related to the actual available amount of water is not included. The suitability ranking refers firstly to the main aquifer, where sedimentary unconsolidated rocks are assigned a value of 1 (best), consolidated sedimentary rocks = 2, igneous = 3 and metamorphic = 4 (worst) and secondly to the hydraulic conductivity which was classified in 4 classes (10^0–10^{-2} = 1,...,10^{-7}–10^{-8} = 4). The values were multiplied and the results reclassified to four suitability classes: very high, high, low, very low (Fig. 10f). The shallow Regolith/Saprolite aquifer is not included in the suitability ranking as a distinct category since less than 1% of the wells contained in the BDI database that are less deep than 30 m deep and only for about 0.2% of the wells in the BDI Regolith/Saprolite can be clearly identified as the main aquifer.

3.2.11. Failure risk

The ''yields'' database fields (see above) contain the entry ''dry'' for 502 wells. Even if it remains unclear if all failed drilling attempts are included in the database, the existence of such ''dry'' wells gives an indication whether drilling a well in a region carries a risk of failure. It was attempted to quantify that risk by dividing the number of dry wells in the vicinity of each cell by the total number of wells in a 10 km radius. It is interesting to note that even in areas with potentially high yields a risk of failure risk exists. The uncertainty of this failure risk probability is of course enormous as the raw data cannot be considered to be representative.

3.2.12. Groundwater quality

Groundwater quality always has two aspects: (a) the natural quality of groundwater which is a result of the minerals the groundwater was in contact with in the saturated and unsaturated zone, the hydrochemical and biochemical conditions (pH, Eh, T, p, presence of bacteria, etc.) and temporal aspects (flow/infiltration velocity, residence time), and (b) the anthropogenic groundwater quality influenced by human activities that add components to the groundwater or change natural equilibriums. In Benin, it is obvious that anthropogenic influences, in particular contamination with pathogens (see below) play a very important role. It is however not meaningful to regionalize such local effects or relate them to natural aquifer (location) characteristics. In terms of *natural groundwater* quality, the most outstanding problem in Benin seems to be salinity. The parameter in the database that can be related to this problem and is available for most wells is the electrical conductivity. It was therefore interpolated to the grid and classified (Fig. 10h). Local effects of sea water intrusion due to overpumping close to the city of Cotonou are not captured by this large scale analysis.

It should be noted that hydro-geochemical analysis was not of focus of this study. More detailed results on the spatial distribution of groundwater quality parameters are presented by Silliman et al. (2006)

3.2.13. Dynamic groundwater analysis

The variables evaluated and regionalized in the previous section can mainly be related to the static aquifer properties. A study aimed at evaluating availability, reliability and sustainability of groundwater resources must however include dynamic aspects, i.e. the temporal variability and trends of groundwater recharge, river discharge and above all groundwater levels. Only an analysis of groundwater level changes reveals how aquifers react to climatic changes (on all scales from daily to decades) and to groundwater withdrawal. At this point the present study faces a severe problem since transient data on groundwater levels is not readily available in Benin. The official monitoring network of Benin currently consists of only 61 observations whereby more than 50% are clustered in the coastal area (Azonsi and Adjomay, 2005). In addition, a larger number of piezometers were installed by the IMPETUS project in the Upper Ouémé Catchment (Fass, 2004).

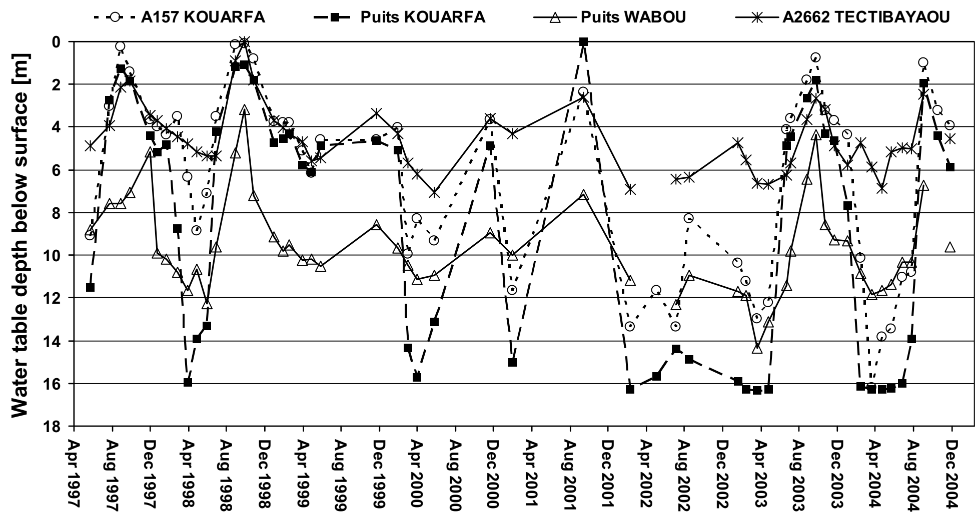

Fig. 9. Groundwater level fluctuations in the crystalline part at the northern boundary of the Ouémé catchment in shallow saprolitic aquifers (modified after Azonsi and Adjomay, 2005).

Most available records however are short (Fig. 9) and therefore not suitable for a long-term analysis. The few available piezometers in the North however reveal interesting facts about the groundwater resources of the crystalline regions. Examples are shown in Fig. 9 and conclusions are presented in Section 3.1. It seems that the situation in the shallow unconfined aquifers in the weathered zones is largely controlled by seasonal fluctuations. The present study has not analysed these transient aspects further since time series data on a regional scale does not exist.

Here we would also like to point out that maps displaying similar properties as the ones shown in Fig. 10 have been published some 23 years ago by Direction de l'Hydraulique (1985b). The approach used by Direction de l'Hydraulique, 1985b was however, quite different and based on the assignment of properties to geological formations. Since there was far less data available at the time the map was created, it is therefore very difficult to compare the results.

3.3. Socio-economic analysis: prevalence of diarrhea and improved water access

This section illustrates the importance of the groundwater inventory in the design of policy interventions which secure access to reliable water sources and prevent the occurrence of water borne diseases in the Ouémé basin. The results are part of a larger study (Keyzer et al., 2007) where diarrhea prevalence and its associated geographic and socio-economic dimensions were evaluated by relating information on georeferenced household surveys to the inventory of groundwater resources. The section is organised as follows. We start with a brief description of the data sets that were used in the health analysis. Next, we analyze the influence of water accessibility on diarrhea prevalence and evaluate the costs of water accessibility by an assessment of drilling costs for wells that is based on groundwater characteristics. Finally, we combine the information on the cost of drilling wells with a diarrhea prevalence model to evaluate the impact of pro-poor policy interventions.

The Demographic and Health Survey for 2001 (DHS, 2001) constitutes the basic data set for household information in this study. It relies on a multi-stage sampling design, stratified by region and urban/rural status, with sampling probability proportional to the population of selected enumeration areas (or clusters). DHS clusters are usually census enumeration areas, sometimes villages in rural areas or city blocks in urban areas. The coordinates of a cluster refer to the centre of the corresponding settlement areas (Montana and Spencer, 2004). A total of 6219 women aged 15-49 years, sampled from 247 clusters were asked various question about health including those pertaining to children below the age of 5 within their households. The question used to determine prevalence of diarrhea was whether a given child "Had diarrhea recently?" in the last 24 hours, last week, etc. A total of 5796 households were covered by the survey. The DHS also comprises questions related to household specific characteristics, including the geographic cluster to which the household belongs, as well as topics such as source of drinking water, existence of toilets, places of washing hands, disposal of rubbish, and condition of house. These were used to create indicators of household characteristics and socio-economic indicators.

The spatial data set that is used for the health study include maps of aquifer suitability, ground water quality, settlement population, mean annual rainfall, and county level diarrhea occurrence. The first two spatial data sets are obtained from the sources mentioned in Section 3.2. They are created by spatial interpolation and classification of various groundwater attributes available in Benin-wide well data set. Population data is obtained for all documented and geo-referenced settlements in Benin (Keyzer et al., 2007). Both these data sets are then used to create population by settlement maps as well as municipality-level population density maps. Mean annual rainfall data set is obtained from FAO/IIASA (2000). County data on diarrhea occurrence was obtained from National Health Management Information System of Benin (MSP, 2003). The co-ordinates of the centre of the geographic cluster are used to assign the relevant spatial data to a particular household.

To analyze the influence of groundwater accessibility on diarrhea prevalence we develop a stress indicator that relates aquifer suitability to population pressure (Vorosmarty et al., 2005). We create this stress indicator by ranking the aquifer suitability index (see Section 3.2, Aquifer type) according to the prevailing population densities, such that the most suitable aquifer under lowest population density refers to the most favourable geographic condition while the least suitable aquifer under highest population density is the least favourable. Next the total number of combinations was subdivided in five classes of equal size (see Keyzer et al. 2007). The trend line in Fig. 11 connecting median diarrhea prevalence at cluster level[9] with this stress indicator, clustered into five classes of

[9] Clusters refer usually to census enumeration areas, sometimes villages in rural areas or city blocks.

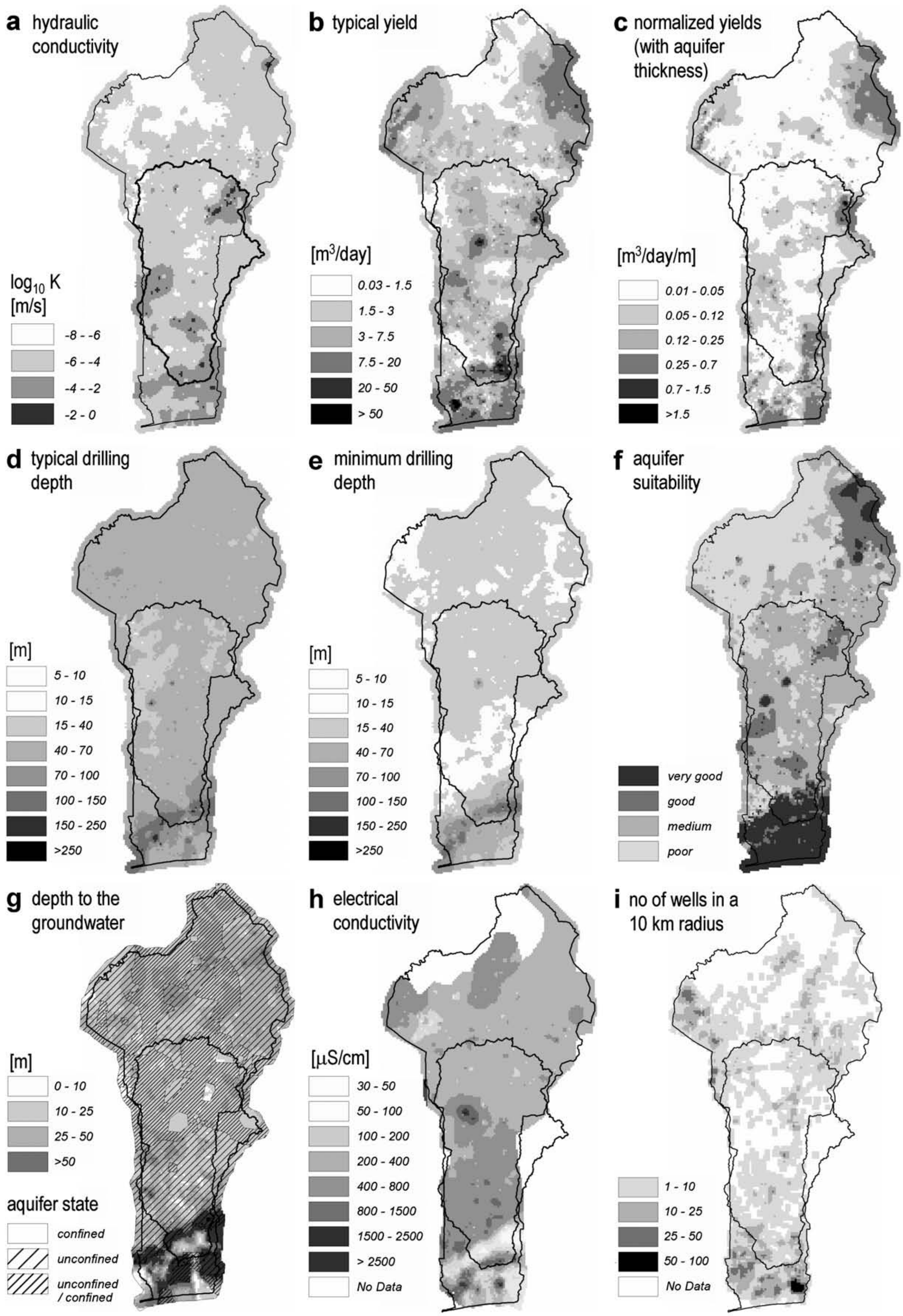

Fig. 10. Hydraulic and well properties interpolated to a 3 by 3 km grid for further explanation please refer to the corresponding paragraphs above.

increasing magnitude, shows a rising trend in diarrhea prevalence under increasing stress on the aquifer for classes 1, 2 and 5, where, admittedly, the slightly decreasing trend between classes 3 and 4 somewhat blurs the relationship. Yet, classes 3 and 4 have higher

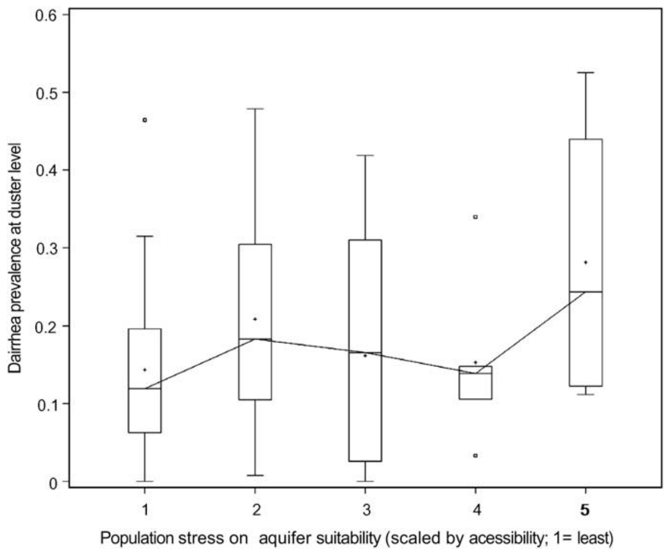

Fig. 11. Diarrhea prevalence variability with increasing aquifer suitability stress.

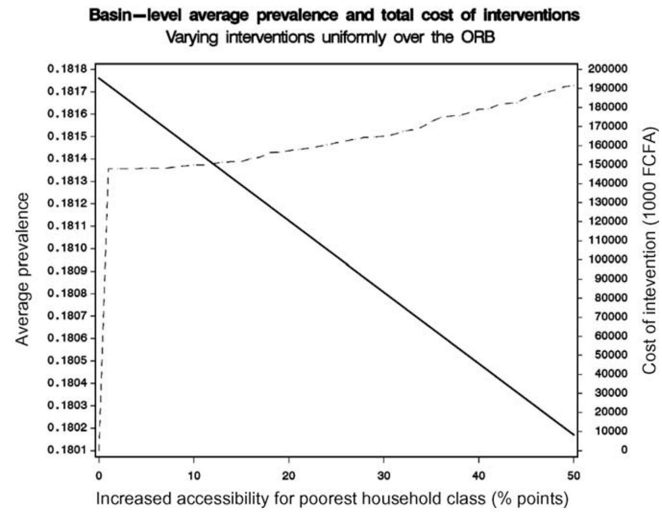

Fig. 12. Changes in average prevalence over the basin with policy intervention of increasing accessibility to the lowest household class (solid) and total cost of these interventions (dashed).

median values compared to class 1 and we conclude that, in general, there is a rising trend in diarrhea prevalence under less favourable aquifer conditions. Furthermore, a significant (at 95% confidence level) positive effect of a combined geographic stress indicator on diarrhea prevalence was found when diarrhea prevalence was quantitatively modelled via logit regression (see Keyzer et al., 2007).

In effect, we imply that higher stress is induced in clusters that have higher percentage of households with poorer access. It also can be noted that median diarrhea prevalence almost doubles from the lowest stress class to the highest. Hence, while the exact detrimental effect of resource stress on health cannot be established the evidence of trend of diarrhea prevalence with increasing stress conditions suggests a pattern that is clearly not random.

The inventory of ground water characteristics also allows for a spatially explicit assessment of drilling costs for wells at each grid. Applying an average cost of drilling per meter depth as 5000 FCFA (personal communication with experts from DH, Thornton, 1998 and Ball, 2004) the total cost of drilling a well is calculated by multiplying this average rate to a maximum of interpolated depth to the water table and total drilling depth for each grid. Finally, some heterogeneity about this average total drilling cost is introduced by considering a multiplicative factor that mimics aquifer suitability condition for each grid. Thus the total cost of drilling a single well, C_s, at any grid location, s, can be formulated as,

$$C_s = 5000\eta_s(q_s) \cdot \max(d_s, w_s),$$

where for each grid s, d_s: total drilling depth, w_s: depth to the water table, $\eta_s(q_s)$: aquifer suitability multiplicative factor and q_s: aquifer suitability.

Finally, we combine this spatially explicit cost assessment with the results of a diarrhea prevalence model to evaluate the costs and impact of specific pro-poor interventions. The diarrhea prevalence model is based on a logit-estimation, accommodating the compiled information on stress indicators on aquifer suitability and ground water quality with other non-redundant (e.g. socio-economic) variables. To illustrate the effect of an intervention in this sphere, we raise the frequency of access from 0% to 50% for the lowest income households, keeping access frequencies of the middle-income and richer household classes constant.

Fig. 12 shows the prevalence of diarrhea for the lowest household class for the entire basin, plotted versus the cost of drilling wells if this increased accessibility is realized through addition of wells. Each such well serves at most 250 people in each of the settlements in the basin. One remarkable outcome is the reduction of 0.17% only achieved at maximal intervention, from the average diarrhea prevalence in the ORB of 0.9%. This leads us to conclude that drilling of wells can in principle provide access to good water which is important for the poor but far from sufficient to tackle the problem.

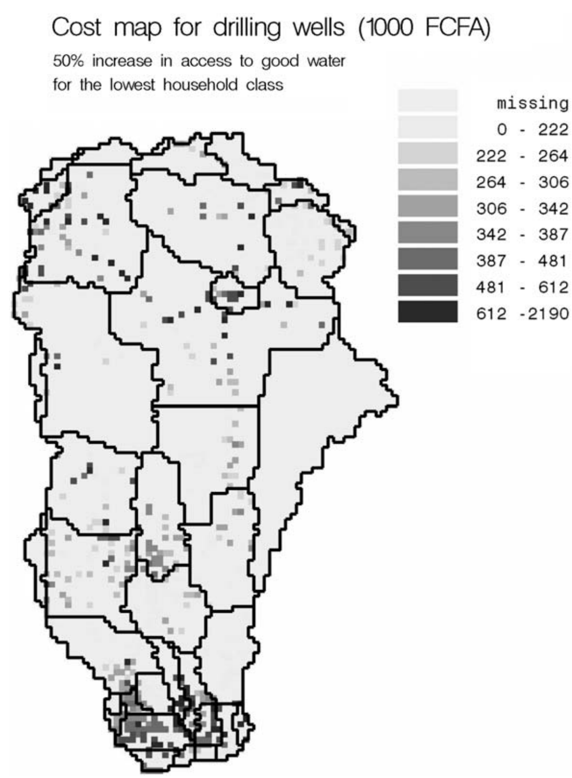

Fig. 13. Spatial distribution in the ORB for the cost of increasing accessibility of the lowest household class by 50%.

Fig. 13 uses the previously mentioned cost assessment for the drilling of wells to show its associated spatial distribution. Note that these costs are not costs of drilling a single well in each location but of a number that satisfies the need of the intervention.

Thus, the map shows mixed effect of requirements to reach the target, which depend on the number of people covered by the intervention, and location-specific information on aquifer properties. Fig. 13 shows that costs are highest in the south and some places in the mid-north as well as north-west. For the majority of the remaining basin, the costs of the intervention remain low. In other words, given the low overall cost, projects in this direction seem viable.

4. Conclusions

4.1. Summary and critical evaluation of the results

The overall goal of this study was to analyse the availability and reliability of groundwater resources in Benin mainly with respect to future social and agricultural development options. Groundwater is a major source of water in the country, yet currently only 2% of the available recharge is actually used. For any future development plans, it is therefore important to evaluate whether this low percentage is a results of physical constraints or if it can be increased by better technical solutions and management. For that purpose a hydrological model was applied to determine groundwater recharge and a countrywide well database was evaluated to derive well and aquifer characteristics. The information of the groundwater inventory was used to evaluate the impact of increasing water accessibility on the prevalence of diarrhea in the Ouémé basin. The study was embedded in the much larger framework of the RIVERTWIN project which was dedicated to evaluate future management options for water and land use.

One major achievement of the present study in this context was the first comprehensive evaluation of the BDI database of wells in Benin which contains an enormous amount of detailed and valuable information. For roughly 4000 wells, information on yields, aquifer properties, well design, groundwater chemistry were analysed in order to create spatially distributed raster maps of the most relevant variables. These maps subsequently contributed to policy interventions that were designed to reduce the diarrhea prevalence in the country.

In general it must be stated that the overall goal of determining the groundwater development potential could only partly be reached, first and foremost because of the lack of transient data on groundwater levels and groundwater utilisation. Secondly, it revealed that the countrywide data on wells used by this study was very heterogeneous. The database was put together from a large variety of sources, i.e. institutions that carried out well drilling programs during three decades. The data were initially reported for documentation purposes rather than for a scientific analysis. There seems to be a high degree of subjectivity which makes a regionalisation very difficult. The overall reliability and consistency of the data is low.

The results of the different analysis approaches are summarized below:

4.1.1. Recharge and water balance

The spatial distribution of groundwater recharge varies enormously, mainly due to soil characteristics and geological conditions close to the surface. However, only in the northern crystalline part, where shallow, unconfined aquifers dominate, are groundwater recharge and groundwater availability both spatially and temporally correlated. In the south, groundwater resources are decoupled from the regional climate. This can be concluded from the depth and the confined state of the aquifers used (see Fig. 10d, e and g) and from the fact that withdrawal in the area is higher than the recharge (compare Fig. 7 and Fig. 10b and c). In the case of confined aquifers in more than 60 m depth this observation alone does not necessarily mean that the withdrawal is not sustainable. Groundwater age analysis and long-term monitoring are required to better specify this. Additionally a fully coupled groundwater-surface water model and a more in depth hydrogeological analysis would be required to show where the recharge of the aquifers in the sedimentary basin actually stems from and what the dominating hydrological-hydrogeological processes in this area are.

In the north, it was found that the shallow aquifers have no capacity to store groundwater from one season to the next. Most of the groundwater is lost from storage due to lateral flow and subsequent evaporation from depressions and wetlands and discharges into the surface drainage system. The availability of groundwater is therefore strongly related to the amount of precipitation in the wet season. This means that: (a) long-term storage capacities do not exist and (b) groundwater recharge is only partially captured by wells.

It should be mentioned that the groundwater recharge and other water balance components calculated by HBV could not be validated by observations in the study area. Comparison with other studies (Giertz et al., 2005, 2006b) showed nevertheless that the order of magnitude and variability can be reproduced. Therefore, the temporal development of the spatial distribution of soil moisture and groundwater recharge provides valuable information as basis for the planning of water resources management.

4.1.2. Spatial analysis of the hydrogeological conditions and aquifer suitability

The raster maps resulting from the interpolation of data contained in the BDI database show in a very rough and generalized way the spatial distribution of important groundwater related variables in Benin. The enormous amount of data proved to be partly unreliable and very inconsistent. The results of this study show regional spatial trends rather than accurate values on a local scale. They can therefore not be used for local planning and management. They should be seen as a first guideline to sustain the development of monitoring systems, improved data collection and countrywide management planning.

Generally it can be stated that if groundwater recharge decreases as indicated by the results of the hydrological model, increasing problems with groundwater availability can be expected immediately in the northern parts of the country. This will occur where the aquifers are located in shallow depth and the hydrogeological conditions are unfavourable such that water scarcity is an issue even today. In the north, the only way to increase the groundwater extraction would be to drill more wells. But, due to the hydrological conditions of the crystalline rocks, the yields of individual wells will continue to remain low. A higher number of wells however, could capture larger portions of the groundwater recharge. It is a question of the cost as to whether drilling more wells is a feasible option. Even a higher number of wells would not help to alleviate water supply problems in extremely dry years.

The south in contrast, has well yields which will most likely not be affected by a dryer climate in the near future, since aquifer properties are generally better, groundwater bearing formations have relatively large volumes and are often located at a greater depth. It is however important to guarantee that using groundwater from these aquifers is sustainable, i.e. to make sure that the resource is not depleted. Currently it does not seem possible to make suggestions on where the limits of sustainable use of the deeper aquifers in south might be, due to the lack of sufficiently long time series data and missing information on groundwater age. Hence, it is currently not clear if and how the deeper aquifers of the south are recharged (see above) and the possibility of fossile groundwater can not be excluded. Some experts argue that the recharge in the south stems from regions farther away in the north transported through fractures along fault systems (personal communication, DGE) but currently there is no data to prove or quantify this assertion. At the coast, groundwater use that exceeds the natural recharge will most probably invoke seawater intrusion and lead to a permanent damage of the fresh water aquifers.

It is obvious that the spatial analysis of the hydrogeological properties could have been carried out in a much more sophisticated manner throughout all of the required steps. Tasks to be improved or added could have been:

1. The analysis of the raw data contained in the database (removal of outliers, consistency and including plausibility checks, consideration of dependencies and correlations, etc.)
2. The interpolation and regionalisation methods used (geostatistical analysis, including secondary data, etc.)
3. The calculation of ranks and the classification of data (class assignment according to distributions, fuzzy rules, etc.)

Yet, looking at the reliability and consistency of the raw data it was concluded that such efforts are not justified. It is therefore important to note that the regionalisation of the data on grids should not be regarded as a quantitative result.

Socio economic analysis: Finally, the results of the groundwater inventory were used to analyze the relation between aquifer stress conditions and diarrhea prevalence as well as in a cost estimation of increasing water accessibility through well construction. The data confrontation shows a tendency wherein higher diarrhea prevalence correlates with increasing aquifer stress conditions. Applying a formalized relationship between diarrhea prevalence and both socio-economic and groundwater stress conditions in combination with the cost assessment of well construction in the ORB showed that "stand-alone" interventions of increasing access only marginally improve overall health and equity in diarrhea prevalence. The results show that "stand-alone" interventions of increasing access only marginally improve overall health and equity in diarrhea prevalence. However, its costs are low and, thus these interventions still hold promise for the basin given that improved access to water is important for future human development.

4.2. Recommendations

The BDI database is a very helpful and valuable data set. Yet its use with respect to groundwater is limited due to a number of inconsistencies. The data should be homogenized and then analyzed in full detail in an integrated context. Especially important is the temporal scale of the database by adding contemporary observation data to the existing data sets which usually stem from the well construction period only. It would be highly beneficial to document the actual state of the existing wells and to (at least qualitatively) describe the well performance in the recent years (draw down, water level, effects of dry periods, etc.). It is very important to enforce hydrological analysis in Benin to be able to assess the state of the groundwater resources and to predict future changes under scenario conditions. An integrated hydrological study with the aim to fully understand the hydrological and hydrogeological situation of northern and southern Benin is still missing. Such a study would have to be based on a thorough data collection. The groundwater monitoring network should be expanded, and more piezometers are required. The precise calculation of spatially and temporally distributed groundwater recharge values using hydrochemical, isotope and other natural tracer data to determine the source, the age and the fate of waters is highly recommended. Remote sensing can help to get spatially distributed information on hydrological changes. It would additionally be helpful to develop a well-conceptualized groundwater flow model for the whole Ouémé catchment and to combine such a model with a hydrological model to obtain a consistent description of the dominating hydrological processes.

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