Groundwater recharge and flow in a small mountain catchment in northern Ethiopia

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Abstract The hydrodynamic behaviour of a sloped phreatic aquifer in the Tigray Highlands in northern Ethiopia is described. The aquifer is situated in the soils of a plateau on top of a basalt sequence and lies on steep slopes; the latter lead to hydraulic gradients that can cause high discharge fluxes. Distinct wet and dry seasons characterize the climate of the Tigray Highlands and recharge is absent during the dry season. Because of the fertile vertisols that have developed, the plateau is heavily cultivated and thus has great local economic, and hence social, importance. Water for land irrigation is almost exclusively delivered by rainfall, which is largely restricted to the period June–September. During the dry season, the water table drops dramatically and the aquifer drains nearly completely, under the strong gravity-driven, sustained discharges. This study strives to give insights into recharge and discharge mechanisms of the aquifer, in order to improve the effectiveness of the implemented water conservation measures.

Key words groundwater recharge; integrated water balance; water management; runoff; soil moisture balance; MODFLOW; Ethiopia

Recharge et écoulement hydrogéologiques dans un petit bassin versant de montagne en Ethiopie du nord

Résumé L'article décrit le comportement hydrodynamique d'un aquifère phréatique incliné dans les Tigray Highlands en Ethiopie du nord. L'aquifère se situe dans les sols d'un plateau aux pentes raides, au sommet d'une séquence basaltique. L'escarpement cause des gradients hydrauliques conduisant à des écoulements importants. Les saisons humide et sèche bien différenciées caractérisent le climat des Tigray Highlands, et la recharge est nulle pendant la saison sèche. A cause des vertisols fertiles, le plateau est intensément cultivé et présente par conséquent une valeur locale économique et sociale importante. L'eau d'irrigation provient presque exclusivement de la pluie, qui est largement limitée à la période Juin–Septembre. Pendant la saison sèche, la nappe descend énormément, et l'aquifère est presque complètement drainé, en raison des flux gravitaires continus importants. Cette étude continue à la compréhension des mécanismes de recharge et d'écoulement de l'aquifère, dans le but d'améliorer l'efficacité des mesures implémentées de conservation de l'eau.

Mots clefs recharge hydrogéologique; bilan hydrologique intégré; gestion de l'eau; ruissellement; bilan d'humidité du sol; MODFLOW; Ethiopie

INTRODUCTION

The management of groundwater levels can only be realized if the hydrodynamics of the related aquifer systems is well understood. The water balance is a key element in understanding and quantifying the water cycle components. Subsurface water balance components can be estimated from field measurements and observations, or can be obtained from a groundwater flow model. In the latter case, the conceptual model that is used must include the relevant hydrological processes, such as recharge and discharge mechanisms. In this study, to obtain a subsurface groundwater balance, a groundwater flow model is combined with a runoff model and a soil moisture balance model to estimate aquifer recharge. The method is applied on a small-scale catchment in northern

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Ethiopia, a region characterized by a climate with distinctive wet and dry seasons. The results of the three model components are combined to produce an overall water balance, including surface runoff, soil moisture storage, aquifer recharge, storage in the phreatic aquifer, groundwater seepage and spring discharges. The result is a transient water balance for the period 1995–2006, with monthly averages for the different balance components.

Statement of the problem

Rainfall is the most important climatological factor for crop production and forage in Ethiopia (UNESCO, 2004). However, inter-annual rainfall variability is high, with the risk of a substantial and extended deviation of rainfall, which negatively affects crop production and vegetation growth. Drought in Ethiopia is a frequently recurring phenomenon. The spatial distribution and the frequency of its occurrence have increased in recent years. In the past, drought used to hit Ethiopia at least once every 10 years, but, as of the last few years, it recurs every two or three years with a different level of intensity, as in the years 1997/98, 2001/02 and 2002/03 (UNESCO, 2004). During the dry season, the water table in sloped phreatic aquifers drops dramatically, dewatering them almost completely. The aquifer then becomes unsuitable to deliver irrigation water for crop demand until the next rainy season. During dry years, refilling of sloped aquifers will not occur, while groundwater storage is at its minimum. Available groundwater in sloped phreatic aquifers will strongly depend on both seasonal and inter-annual fluctuations in recharge and discharge intensities. The main problem addressed here is the development and implementation of a conceptual model that can explain and quantify the strongly transient hydrodynamic behaviour of sloped phreatic aquifers in relation to the highly variable rainfall patterns.

Objectives of the study

The main objectives of the study are:

- to collect field data that will allow description and quantification of the hydrodynamics of the aquifer;
- to identify the recharge and discharge mechanisms;
- to develop a conceptual model to describe the hydrodynamic functioning of the aquifer; and
- to implement the conceptual model into a numerical groundwater flow model.

DESCRIPTION OF THE STUDY AREA

The choice of location and size of a study area are usually constrained by the spatial scale of the subject of study. As spatial and temporal resolution of observations is often limited in terms of numbers of measurements or installed observation sites (wells), increasing the size of the studied area means that small-scale features or processes may not be detected or recognized in the field data. As one of the main objectives in this study was the identification of groundwater discharge mechanisms on a local scale, only a small part of the Zenako-Argaka basin was studied. However, it is representative of the Trap Basalt Plateau and it can be expected that the general conclusions will be valid for the whole sloped phreatic aquifer present on top of the basalts.

The Zenako-Argaka catchment

The study area is a 2-km^2 sub-basin of the Zenako-Argaka basin near some sources of the May Zegzeg waterway, east of the town of Hagere Selam in Tigray Region, northern Ethiopia. The May Zegzeg flows into the larger Geba River, which drains much of the area and forms part of the Atbara-Tekeze river system that further drains this water into the Nile.

The basin is centred around 13°39′N, 39°12′E (Fig. 1). Topographically, the north of the study area is a gently southward sloping plateau, around the level of 2600 m above sea level (m a.s.l.) at the highest point, and dropping to around 2500 m a.s.l. It is bound to the south by steep cliffs, which drop for around 100 m. More southward, the topography keeps dropping, but

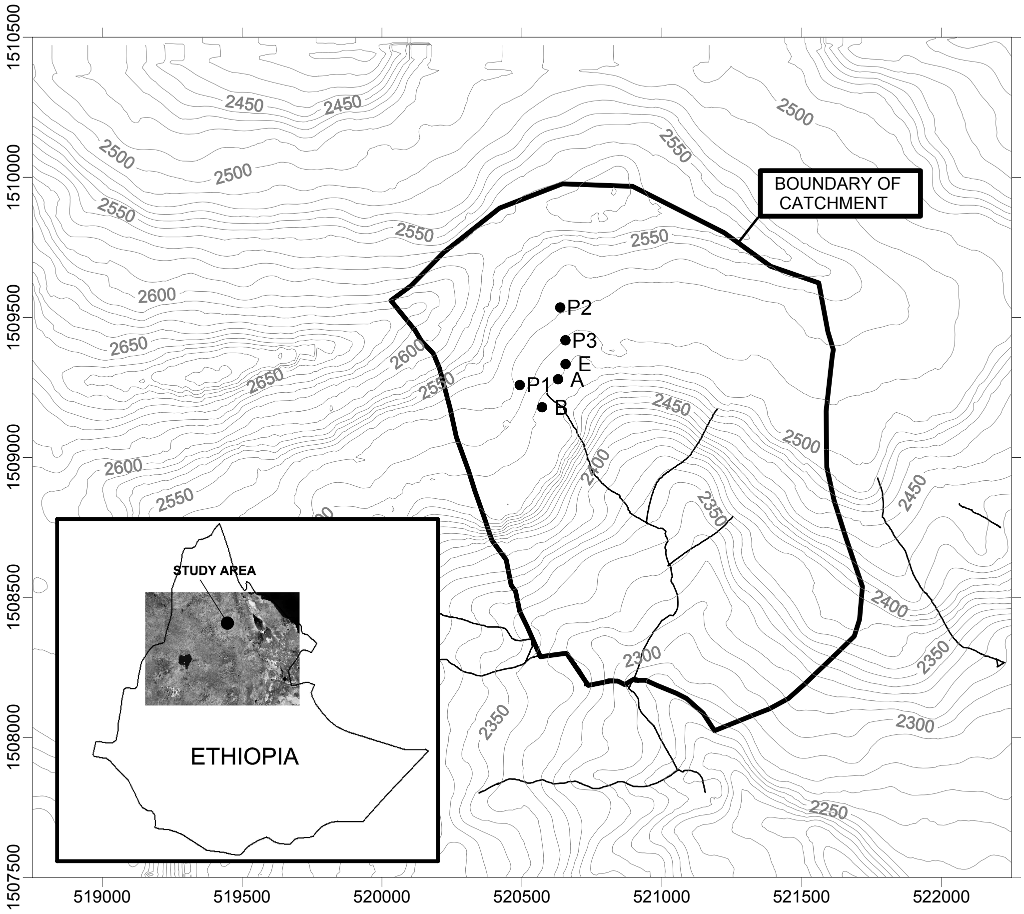

Fig. 1 Topography and hydrography of the May Zegzeg basin with location of the piezometers.

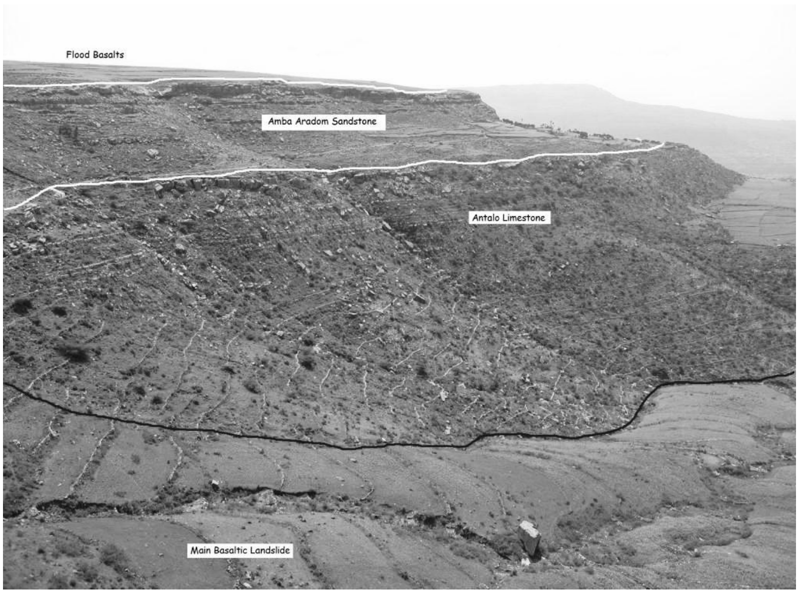

Fig. 2 View over the middle part of the Zenako-Argaka Zegzeg basin with some geomorphological characteristics.

more gently. The topography is strongly determined by the geology (Fig. 2). At present, the semi-natural vegetation is scarce and of savannah type. The original forest has disappeared by increased desertification, as a result of anthropogenic and climatic influences. The relatively level parts of the land are being farmed with increasing intensity, especially the fertile basaltic vertisols on the upper plateau (Vandecasteele, 2007; Nyssen *et al.*, 2008).

Geological set-up

The geological basement is formed by limestones of the Antalo Formation (Upper Jurassic age) (Arkin *et al.*, 1971; Bosellini *et al.*, 1997). These marine deposits are described as parasequences of massive limestone and marl with locally high fossil concentrations. The minimum thickness in the study area is 190 m. The limestones outcrop in the southern and topographically lowest part of the basin. They are overlain by the Amba Aradam Sandstone, assumed to be of Cretaceous age (Mohr, 1962; Nyssen *et al.*, 2006a) and consisting of fluviatile sandstones and shales. The sandstones are around 50 m thick and form steep cliffs in the landscape. On top of them the volcanic Trappean Series Basalts (Oligocene age; Kieffer *et al.*, 2004) are found, consisting of strongly weathered basaltic pillars. These can have a thickness of up to 120 m. The plateau north of the cliffs is developed on the weathered basalt sequence. In the far north of the region, the topographic height coincides with the outcrop of Tertiary silicified lacustrine deposits (Merla, 1938; Mohr, 1962), the thickness of which is limited to some 20 m. This topographic high is taken as the northern boundary of the basin (Vandecasteele, 2007). The relationship between geology and hydrogeology has been described by Chernet & Eshete (1982).

Climatology and meteorology

The climate is characterized by distinct dry and rainy seasons. The main rainy season spans from mid-June to September, whereas small, so-called “Belgh”, rains occur irregularly from March onward. The main rainy season accounted in 2006 for 79% of the total yearly precipitation. On the Eritrean highlands, around 150 km to the north, 80% of daily precipitation occurs between 12:00 and 16:00 h (Krauer, 1988). The convective nature of the rain explains why individual showers have a very local distribution (Nyssen *et al.*, 2005). From October onward, until the arrival of the “Belgh” rains the next year, the dry season sees very little or even no rain at all. Rainfall is of high intensity, falling in periods of short duration, often only a few minutes. Between 1998 and 2006, the average yearly rainfall was 687 mm. Potential evapotranspiration far exceeds rainfall, and is typically between 1800 and 2000 mm (Vandecasteele, 2007).

METHODOLOGY

Measurement of piezometric levels

Six piezometers are located on the Trap Basalt Plateau in the north of the basin and were regularly measured during the rainy season of 2006 (Fig. 3). Well A has the longest record as it has been measured since its installation in 2001 (Fig. 4). Unfortunately, not all the piezometers were measured at all times, so the piezometric time series are not uniform. All piezometers are only a few metres deep, within the vertisol and colluvium on the basalts. The recorded water levels represent water table elevations in the soil horizon. To calculate hydraulic heads from measured water depth, the relative elevation of each piezometer head was measured using a laser theodolite total station. The relative heights were translated into absolute elevations by referencing to the elevation of one of the wells obtained by GPS. No piezometric measurements are available in other hydrostratigraphic units, such as the unweathered basalts, sandstones or underlying limestone.

Quantification of groundwater recharge

The groundwater recharge in the basin was quantified using a combination of a runoff estimation model, based on the US Soil Conservation Service (SCS, 1972) method, and a soil moisture balance model, based on the methodology described by Thornthwaite & Mather (1955). For the latter, the WATBUG code was used (Willmott, 1977). The models are based on a continuous

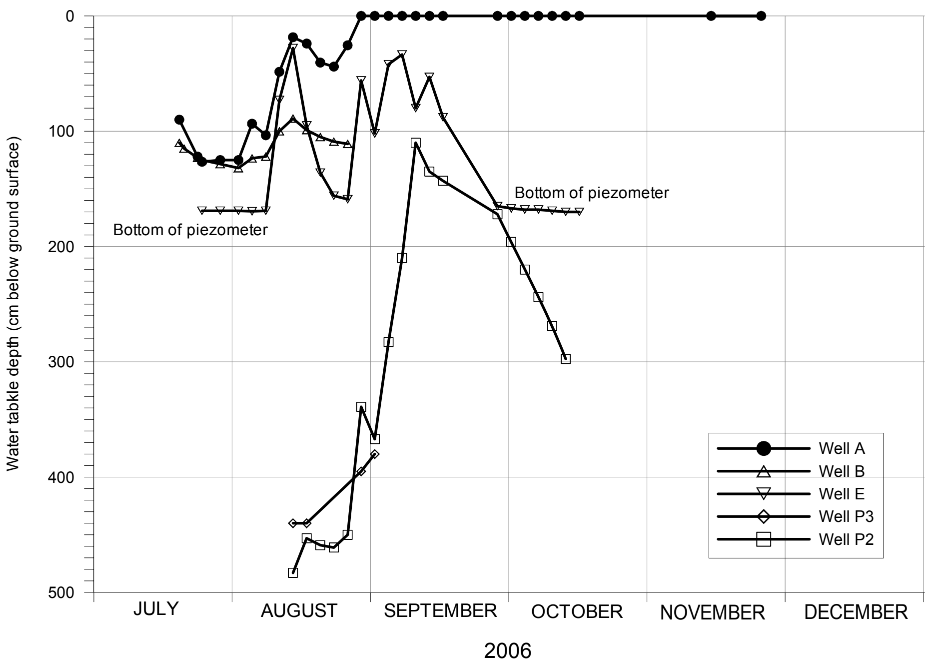

Fig. 3 Measured water table depths in the observation wells along the profile in 2006.

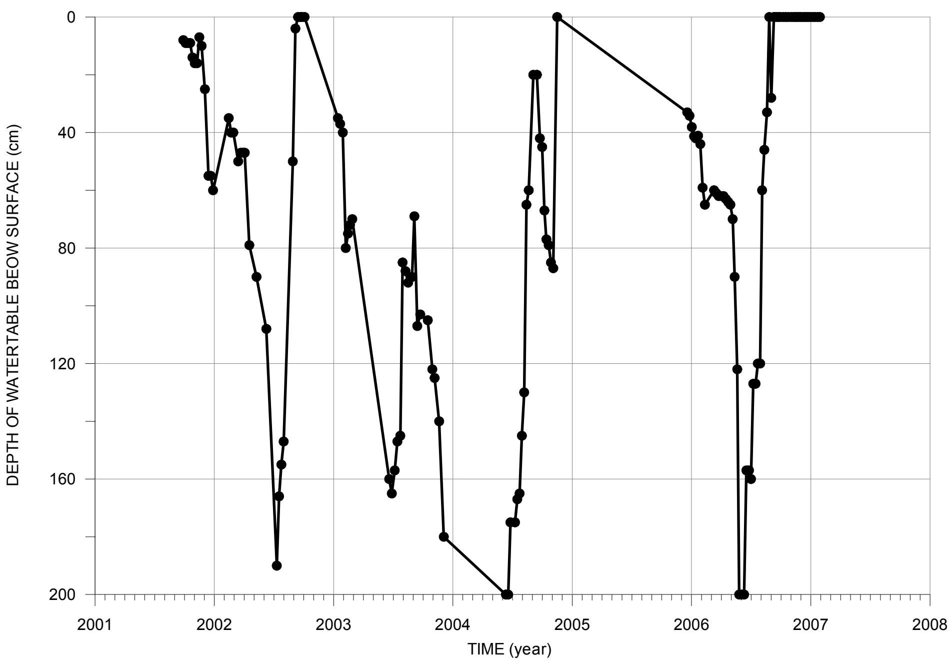

Fig. 4 Measured water table depth in observation Well A (2001–2007).

series of recent meteorological data (precipitation, temperature), obtained for the period 1995–2006 for the Hagere Selam station, 2 km west of the study area (MU–IUC, 2007).

The runoff model The SCS curve number (SCS-CN) method was proposed (SCS, 1972) as a way to estimate runoff from precipitation data. In this study, the curve number value was derived by calibration to obtain an average runoff coefficient of 0.16 at the plot scale on farmland, which was reported for this area (Nyssen *et al.*, 2006b). The required value obtained for potential maximum retention of the soil was 35 mm.

The soil moisture balance (SMB) model Recharge from precipitation forms the main input in the aquifer system, and is therefore an important quantity that controls overall hydrodynamics. However, direct measurement of the aquifer recharge is not simple and, therefore, it is usually estimated using approximate methods. Alene (2006) used remote sensing to estimate evapotranspiration rates for the Geba River basin and to compute a regional water balance. A frequently-used methodology is based on a water balance of the soil layer, and this was applied here. Potential evapotranspiration is often estimated using the well-known FAO Penman-Monteith equation. Apart from the site location, the FAO Penman-Monteith equation requires air temperature, humidity, radiation and wind speed data for daily, weekly, ten-daily or monthly calculations (Allen *et al.*, 1998). For the study area, only precipitation and temperature data were available. The FAO Penman-Monteith method can be used with limited climatic data, as it includes procedures and standard values for cases where some of the climatic variables are not measured (Allen *et al.*, 1998). However, because there is limited experience in using the FAO method with minimal data, here the empirical approach of Thornthwaite (1948) was used, as modified by Thornthwaite & Mather (1955, 1957) to make it more applicable over a wide range of soils and vegetation. Thornthwaite proposed an expression for evapotranspiration requiring only information on temperature and day length (Shelton, 2009). The major advantage of empirical approaches is that they can be applied in areas where only standard climatic data are available, and they are often applied successfully to areal estimates (Shelton, 2009). The WATBUG program by Willmott (1977) was used for this purpose. It calculates the potential evapotranspiration (PET) values from temperature data and can be run on a monthly or daily basis. Daily data for precipitation and temperature (MU–IUC, 2007) were assembled into a time series for 1995–2006 for processing with the runoff and soil moisture balance programs. The field capacity for the May Zegzeg basin was derived from the data set of Dunne & Willmott (1996) and set at 160 mm.

The SMB and MODFLOW models are coupled through the MODFLOW recharge module (McDonald & Harbaugh, 1988). Aquifer recharge fluxes calculated with the SMB model can be used as input in the recharge module. In this study, the SMB and MODFLOW models were run with different time discretizations, on a daily and a monthly basis, respectively, and daily recharge fluxes were integrated and averaged over the longer MODFLOW stress periods. Although it is technically possible to run the SMB model for every MODFLOW grid cell separately to produce a heterogeneous recharge field taking into account spatially variable parameters, recharge is treated here as a uniform boundary condition and should be considered as a spatially averaged value for the small basin.

Description of groundwater flow model

The MODFLOW simulator (McDonald & Harbaugh, 1988) was used to implement a groundwater flow model of the catchment. A groundwater flow model on a regional scale of the Geba basin has been implemented by Bedane (2006). The shallow water table aquifer in the basaltic colluvium is modelled here with the MODFLOW simulator (Fig. 5). The fact that springs are located at the interface between the basalts and the underlying sandstones indicates that the hydraulic permeability of the sandstones must be lower than that of the basalts. It is considered that leakage through the underlying rocks (sandstones) is small compared to the horizontal flow fluxes in the vertisol and other basaltic colluvium. Because no piezometric measurements were available in the deeper hydrostratigraphic units, no meaningful value for the leakage flux could be derived.

The model uses a spatial discretization of 20 m based on a square grid and a transitory flow regime with stress periods of one month, covering the period 1995–2006. Aquifer recharge is defined as monthly totals in the recharge module and was obtained from the results of the soil moisture balance computations. Three distinct discharge mechanisms were built in using the MODFLOW DRAIN module. In the DRAIN module, water can leave the model domain if the calculated piezometric value in a model cell is above a defined threshold, called the drainage level. The exchange flux is then calculated from the head difference between both and a conductance factor (expressed in m^2/d).

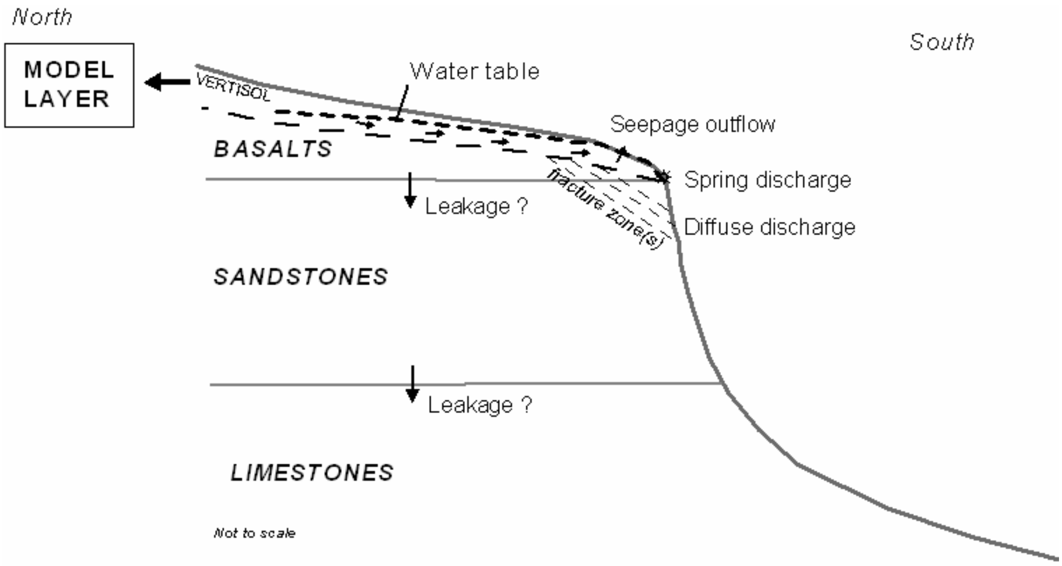

Fig. 5 Schematic hydrostratigraphic cross-section and hydrodynamic conceptual model.

Groundwater seepage can occur in a variably sized area dependent on the water table level. If it exceeds land surface elevation, outflow of groundwater occurs. In the model, recharge is always combined with a drainage level, which should be derived from topographic data, and is a heterogeneous field. The model calculates both intensity and the extension of the seepage surface. A drawback of this approach is that the DEM used to derive ground elevations must be quite accurate. The available DEM apparently did not have the required accuracy, thus leading to unacceptable deviation between calculated and observed seepage. An updated, higher-accuracy version of the DEM is under construction (Frankl *et al.*, 2009), based on newer field data, but it was not available when the modelling was done. For this reason, as a stopgap measure, ground levels were replaced by a level field, which was derived from the calculated transient piezometric field itself.

The drainage level of the two springs was estimated from the topographic height of their location. The conductance was adapted during model calibration by comparing calculated spring discharge rates with the measured flows of summer 2006.

The third discharge mechanism causes further outflow from the aquifer during the dry season, when water levels are below the drainage seepage level. Drainage cells along the southern border of the aquifer are defined at 2475 m a.s.l. and as having a small conductance factor. Because of the small conductance, discharge through this boundary will be small.

The transmissivity of the aquifer was determined at 1.75 m^2/d during model calibration, by comparing calculated with measured groundwater levels in August 2006. The specific yield of the water table was taken as 0.10, but was not adjusted during calibration. It should be noted that transmissivity will depend on the water table elevation, as saturated thickness changes; but as the real bottom of the aquifer is not known, the assumption of a constant transmissivity was retained.

RESULTS AND DISCUSSION

Field observations: piezometric levels and groundwater flow

As can be expected for a phreatic aquifer, the water table follows the general topography, with the highest levels in the north, at Well P2, dropping in the southward direction to Well B. At mid-August 2006, the level difference between P2 and B was about 45.8 m over a distance of around 360 m. The water table gradient was almost 1/8, which is large.

The groundwater depths monitored in the piezometers during the 2006 field campaign are shown in Fig. 3. They increase to the north, as topography rises. In the south section of the profile, the water table depths in piezometers A and B, at the start of the rainy season, are between 1 and 1.5 m below ground level (b.g.l.). In early August, levels rose after a heavy rainfall event of 48 mm on 9 August. The rise in Piezometer A was 85 cm, but smaller in Piezometer B. From the end of August onward, the water table in Piezometer A reached the ground surface. Because of its location in a local depression, accumulation of water had caused ponding. The complete time series since 2001 of Piezometer A (Fig. 4) shows that in most rainy seasons the water table rises to the land surface. Runoff during these periods can significantly increase as no rainwater can infiltrate into the soil. Piezometer B had become blocked by the end of August. At that time, the water table was still more than a metre b.g.l. Piezometer E, located halfway down the profile, was too shallow to indicate water table depth at the start of the monitoring in July, since the water table was deeper than the piezometer depth of 1.7 m. After the rain of 9 August a water column of 1.40 m was found in the piezometer on 14 August. Three days later it had already dropped by 68 cm and about 1.3 m after nine days. By the end of August, levels rose again after some rainy days. The highest levels were reached in early September, after which they started to decline as the rains ceased. By the end of September the well had become dry again. In Piezometer P3, the water table was initially at a depth of around 4.5 m b.g.l. Later the tube became obstructed and monitoring was discontinued. The northernmost Piezometer P2 has a depth of 4.95 m and was dry before the rains of 9 August arrived. In early September, water had risen to around 1 m b.g.l., which represents a total rise of almost 4 m, but possibly much more. From the middle of September onward, the water table dropped and the quasi-linear decrease after the end of September may indicate a near-constant discharge of groundwater out of the aquifer, in the absence of rainfall as the rainy season was finished. However, it is unlikely that the same declining trend would continue for the whole dry season.

Hydrodynamical system analysis and conceptual model of groundwater flow

The hydrodynamical system analysis gives an identification and synthetic description of the mechanisms that control groundwater flow cycles and piezometric water levels and thereby define the dynamic, transient behaviour and responses of the aquifer system to changing boundary conditions. In this study the system analysis was mainly derived from analysis of the piezometric time series, in relation to precipitation data and the responses of the water table to recharge and discharge conditions.

A schematic visualization of groundwater flow in relation to the hydrostratigraphy is given in Fig. 5. The phreatic aquifer on the Trap Basalt Plateau is located in the vertisol that has developed on top of the basalts. Its thickness is estimated as between 5 and 10 m. Although located on a topographic plateau, the shallow phreatic aquifer shows a large gradient of around 45 m over 350 m distance and can therefore be considered as a sloping aquifer system, as the thickness of the aquifer itself is small compared to the height difference along the plateau slope. Water levels indicate that groundwater flow follows the topography and is southbound towards the sandstone cliffs. The differences in water level fluctuations during the rainy season (in 2006) are large along the profile and increase upstream. This suggests that, in the southern part of the plateau, during the rainy season, the water table rises fast to ground level (as in Piezometer A), and this likely indicates seepage flow out of the aquifer. Groundwater is discharged into local smaller and/or intermittent waterways and this process can be rather diffuse through a lot of differently-sized pools and marshes. A similar situation was recently described in a hill-slope aquifer in South Africa (Wenninger *et al.*, 2008). After the rainy season, when aquifer recharge has ceased (from mid-September onward), groundwater stored inside the aquifer is drained through seepage and spring outflow, and levels in the northern, upstream part decline fast. In this northern part, the aquifer probably becomes completely dewatered during the dry season.

The behaviour of the aquifer is strongly transient and dynamic, as it gets completely filled during the rainy season and nearly runs empty in the dry season. The whole aquifer acts as a closed system, which is filled up to the upstream part by recharge events during the rainy season and slowly empties during the dry season, probably by three different outflow mechanisms: seepage in the downhill part of the plateau into local waterways, small spring discharges, and maybe another discharge pathway that causes the further decline in the water table below the seepage face in the dry season (as in Piezometer A). The measured spring discharge rates are too small to explain this. Fracture zones in the basalts could constitute such a pathway, allowing drainage at a level beneath the outcrop of the shallow aquifer. During the rainy season, the aquifer is filled with rainwater and, depending on the intensity and length of the rains, this can elevate the water table to ground level in a variably sized seepage region. At least around Piezometer A, this happens nearly every year, as the long time series (2001–2007) indicates (Fig. 4). Farther upstream, the water table usually stays below ground level (as in piezometers P2 and E). After the rains, groundwater seeps out of the shallow aquifer, discharging through seepage, springs and probably other pathways, such as fracture zones, in the underlying basaltic rocks. As storage decreases, the upper part of the aquifer becomes dry, as the fast dropping of water levels in the upstream piezometers (e.g. P2) indicates. Slowly the extension of the downstream seepage surface decreases and groundwater outflow becomes less pronounced. The fact that in the dry season the water table drops below ground surface approximately downstream of Piezometer A, indicates that still another discharge mechanism must be active besides seepage. Spring discharges are no more than a few m^3/d and too small to explain the further water table decline by the springs alone.

Runoff, soil moisture balance and aquifer recharge model

We calculated the runoff with the SCS model for daily rainfall amounts, which we integrated to monthly sums and yearly totals and compared with rainfall data (Fig. 6). Calculated year-averaged runoff coefficients varied between around 10 and 25%. Apparently, the precipitation, runoff and runoff coefficient were larger before 2000. The years 2002–2004 were drier, with precipitation totals of less than 600 mm/year and with less runoff and a smaller runoff fraction. The year 2005 was wetter, with 725 mm of rainfall. All calculations of runoff coefficients were made under the

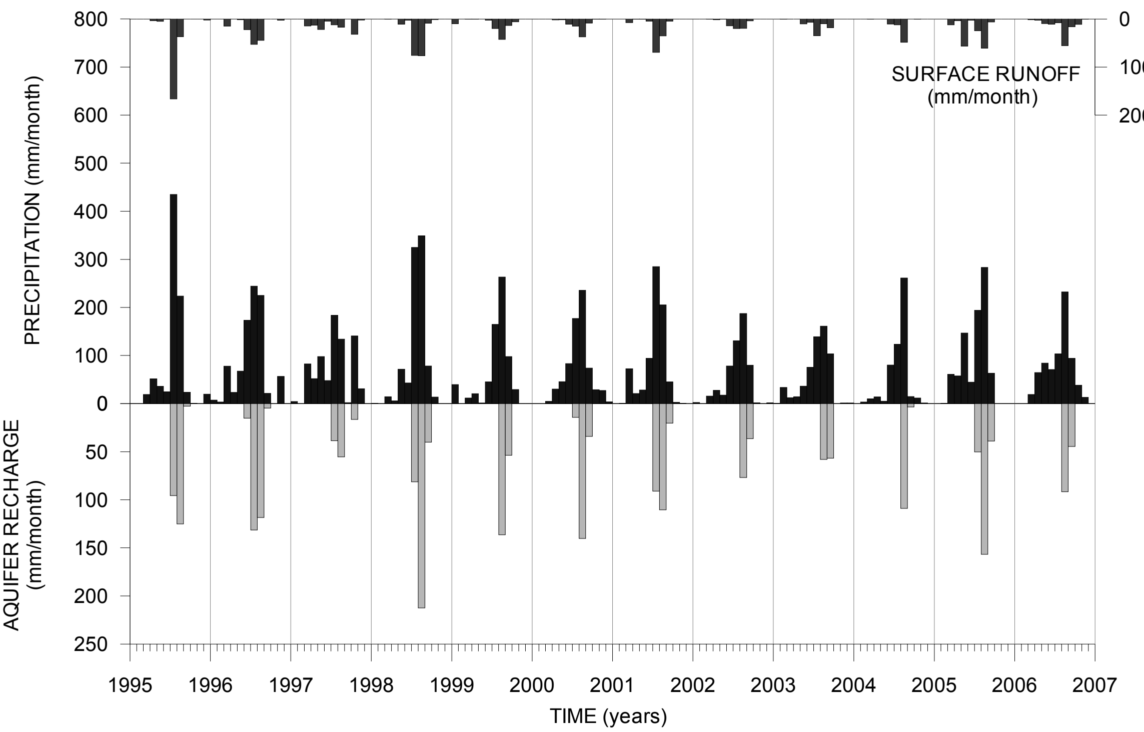

Fig. 6 Precipitation, calculated runoff and aquifer recharge, 1995–2006.

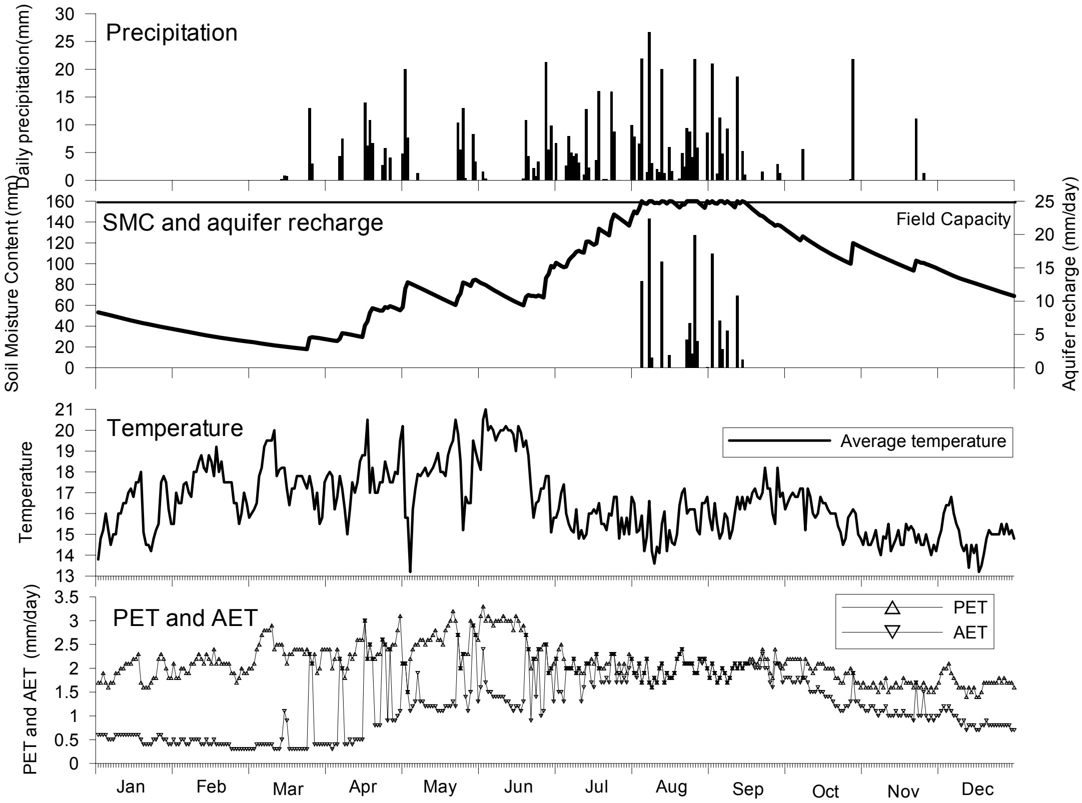

Fig. 7 Soil moisture balance and aquifer recharge in 2006.

assumption that land cover and land management did not vary during 1995–2006. Overall land use in the small study area remained the same. The main changes in land use are related to the implementation of soil conservation measures to prevent and/or limit soil erosion. These measures typically involve construction of small dams around individual land parcels. Nyssen *et al.* (2009) report on the effects of catchment management on the hydrology of the studied catchment.

The results of the aquifer recharge calculations from the WATBUG program for the year 2006 are graphically presented (Fig. 7); input precipitation is plotted in the upper graph of Fig. 7. The second graph visualizes the soil moisture content (SMC), where the upper limit is the field capacity; aquifer recharge occurs when SMC equals the field capacity. The calculated daily values of aquifer recharge are plotted with bars and can be compared with the precipitation bars in the uppermost graph to see which precipitation events actually cause aquifer recharge. The lower graphs show the calculated values of potential (PET) and actual evapotranspiration (AET), and the temperature data from which they were derived. The calculated data for 2006 given in Fig. 7 show the evolution of the soil moisture balance in a typical hydrological year. Graphs for each year from 1995 till 2006 were constructed.

In early springtime, following the dry season, which lasts several months (till March 2006), SMC is at its lowest. In 2006 SMC dropped to around 20 mm, or one eighth of the field capacity. Also, the ratio of AET to PET is at its lowest as little water is available for evapotranspiration: the PET values lie between 2 and 3 mm/d, while the AET is usually lower than 1 mm/d. Then, in springtime (March–May), occasional rain showers occur, but rain events are separated by dry periods of maybe up to one week. Precipitation intensity can reach 15–20 mm/d. Following these rain events, AET increases rapidly and the remaining water is used to increase the SMC, which is still far below field capacity. No aquifer recharge occurs during springtime. When the main rainy season finally arrives, sometime in June (mid-June in 2006), both the intensity and frequency of rain events increase and a systematic increase in SMC occurs. During this period both PET and AET are nearly the same at around 2 mm/d. The rains freshen the air, lowering its temperature and increasing its relative humidity, and decrease PET values from 3 to around 2 mm/d. As sufficient water is now available, actual evapotranspiration can increase to around PET. However, it takes until August (early August in 2006) before SMC reaches field capacity and the underlying aquifer is recharged. From now on till the end of the rainy season, sometime in September, most of the precipitation water percolates through the soil to the water table. Finally, after the rains end, ongoing evaporation and evapotranspiration lower the SMC below field capacity. The post-rainy season is characterized by lower temperatures and, consequently, also by decreasing PET values (from 2 to 1.5 mm/d by end December). As the SMC declines to half the field capacity near the year end, the AET/PET ratio also drops significantly. This ratio keeps dropping till the spring rain showers arrive, around March the following year.

Calculated values for total yearly aquifer recharge ranged between 110 mm (in 1997) and 334 mm (in 1998), or a ratio of 3:1 for the highest compared to the lowest value. The wettest year between 1995 and 2006 was 1998, with 900 mm of rainfall; the driest year was 2004, with 525 mm, or a ratio of around 1.7:1. The inter-annual variation in aquifer recharge seems higher than inter-annual variation in precipitation.

No extensive sensitivity analysis has been done, as this was not the subject of this study. The curve number in the runoff model was found by calibration with field data. The SMB model is based on measured meteorological data close to the study area. Probably the main error in the SMB model is contributed by the PET values calculated in the WATBUG program, which are based on the equations from Thornthwaite & Mather (1955), and which may be too low. Better estimates can probably be obtained by other methods. Other authors have already investigated the sensitivity of estimated groundwater recharge to land surface parameters (Finch, 1998), parameter values in the Penman equation (Howard & Lloyd, 1979) and rainfall distribution (Mileham *et al.*, 2008). Calculated recharge fluxes with soil moisture balance models are supported by the results of flow modelling and stable isotope tracers (Taylor & Howard, 1995).

Groundwater flow model

The conceptual groundwater flow model is implemented in a numerical flow model. This model produces piezometric distributions, internal flow fluxes and boundary condition exchange fluxes at the end of each monthly stress period. From these, piezometric maps and piezometric time series can be generated. Calibration of the model was based on data from four of the six existing observation wells (B, A, E and P2). These lie more or less on a north–south oriented profile and can be used to derive the hydraulic gradient on the basalt plateau. The remaining piezometers, P1 and P3, were used for model validation. As five of the six wells were measured only in a single rainy season during 2006, measured piezometric levels in August 2006 were selected for model calibration. Longer multi-year time series would be required to apply the split-sample technique during calibration. The calculated piezometric map for August 2006 is given in Fig. 8. Deviations between calculated and measured levels for this month lead to an average absolute error of 5.32 m and a RMSE of 6.94 m. In August 2006, the measured piezometric difference along the profile was 30.4 m, while the model produced 39.7 m. The deviations may be caused partly by aquifer heterogeneity and the schematic way seepage is included into the model. More field data would be needed to reduce these uncertainties. The actual knowledge of model input parameters and their spatial behaviour are not sufficient to expect a far better model fit.

Time graphs of the piezometric level are plotted in Fig. 9 for piezometers B, A, E and P2. Clearly visible are the seasonal and also the interannual variations. The impact of the defined drainage level can be recognized in the graphs of wells B and A, both located in the lower part of the profile: the water table rises every rainy season to ground level; from then on, seepage starts and the maximum peak levels are roughly the same every year (surface level). In the upstream part of the aquifer, as can be seen in the graphs of wells E and P2, level fluctuations are larger and only during wet years does the water table reach ground level, meaning the aquifer is completely filled with water in these wet seasons.

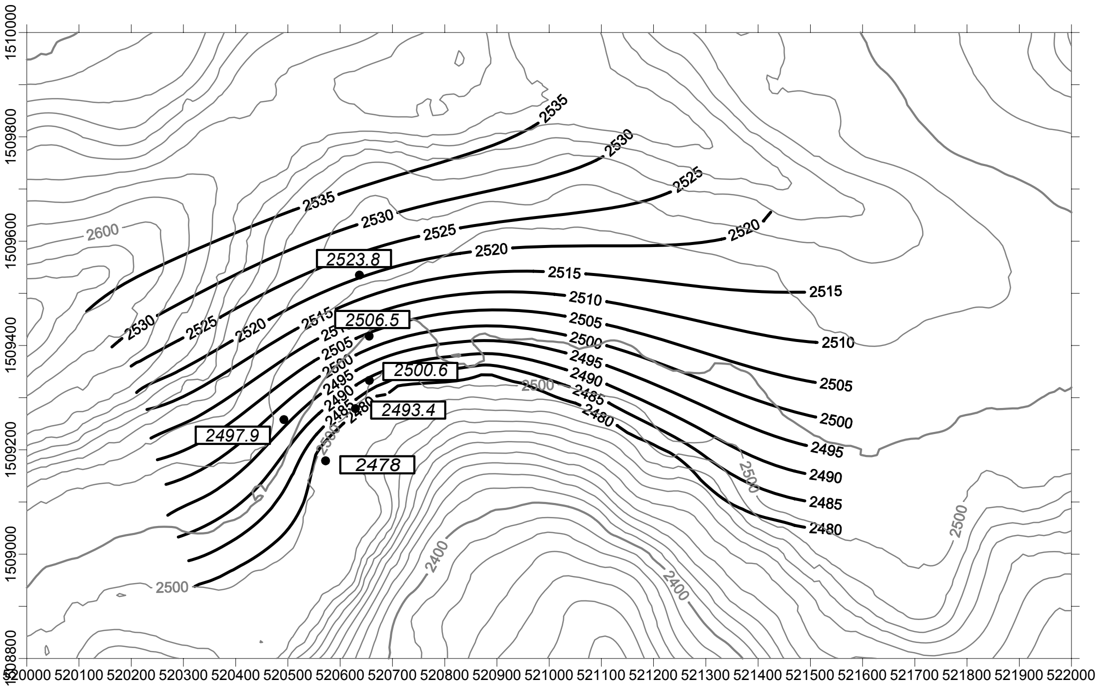

Fig. 8 Calculated (isolines) and measured (rectangles) piezometric levels in the shallow Trap Basalt Plateau aquifer in August 2006. DTM after Frankl *et al.* (2009)

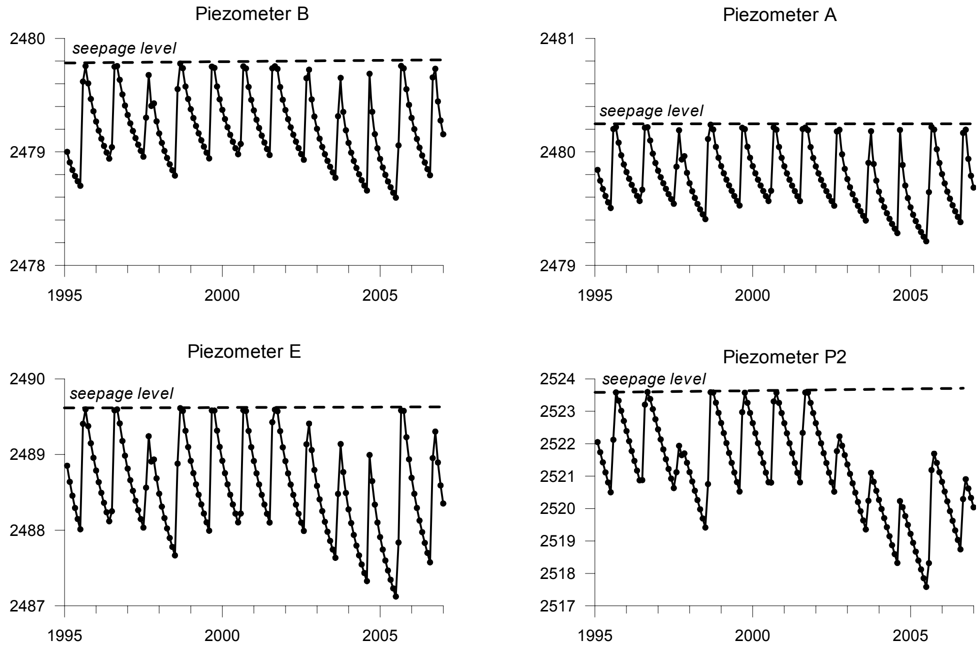

Fig. 9 Time graphs of the calculated piezometric level on the location of selected piezometers along the north–south profile (from downstream to upstream).

Calculated discharge for Spring S3 is very low; field measurements for S4 give a few m^3/d. Compared to the total discharge of the aquifer, the spring rates are very small and constitute only a small component of the water balance of the aquifer system. Discharge from the aquifer occurs mainly by the other two discharge mechanisms: diffuse outflow where the water table reaches the surface, and drainage along fracture zones.

CONCLUSIONS

The Trap Basalt Plateau in the northern Ethiopian Tigray Highlands forms a fertile and, therefore, intensively cultivated area with an important function for supporting the local population. A thin phreatic aquifer has developed in the vertisols on top of the basalts and is crucial for water availability and sustainability of agriculture. As the climate has distinct wet and dry seasons, potential groundwater recharge is limited to the main rainy period in the summer. Continued groundwater discharge in the dry season through seepage, springs and along fractures in the underlying basalts, causes the phreatic aquifer to dewater largely. This makes it very sensitive to droughts during years with less than normal rainfall, which occur every few years.

The water balance has been investigated in a small (2-km^2) basin for the period 1995–2006. Based on field measurements of piezometric levels, a conceptual model of the groundwater flow was derived and the main discharge mechanisms were identified. Recharge rates in the period 1995–2006 were estimated by combination of a surface runoff estimation model, based on the SCS method, and a soil moisture balance model. The climate is characterized by distinct rainy and dry seasons. The main rainy season runs from June to sometime in September, but rainy days occur also in springtime (“Belgh rains”), though these are less frequent and less intense. Because of erosion problems during the rainy season, runoff phenomena had already been investigated and it was known that the runoff coefficient at the field scale was on average 16% of precipitation. Using daily rainfall data, the SCS model was calibrated to obtain this average value, and fluctuation of the runoff coefficient over the period 1995–2006 ranges between 10 and 25%. Precipitation was corrected for runoff and used as input to calculate the soil moisture balance using daily time steps. The results were presented graphically. The SMB showed that no aquifer recharge occurs during the spring “Belgh rains”, as the infiltrating water is used to increase soil moisture. Even in the main rainy season, it takes about a month before water inflow into the aquifer takes place, usually in August. From mid-September on, the discharge period sets in and lasts until the rainy season in the following year.

The recharge–discharge cycle was recognized in piezometric time series in five piezometers that were placed on the basalt plateau and measured regularly in the summer of 2006. The series show that, in the lower part of the plateau, the water table rises to ground level in the rainy season and seepage occurs. In the upper part of the plateau, water levels rise fast in the rainy season, but drop dramatically once the rainy season ends. In the dry season, the water table drops to below ground level in the lower part of the plateau. This indicates that another discharge pathway must be present besides two small springs, the discharge rates of which are too low to explain this further decline. Hydrodynamically, the aquifer system acts as an inclined box that is filled with water in the rainy season and empties after the summer rains have ended. This emptying occurs rapidly at first, as groundwater seepage is the main discharge mechanism causing the water levels in the upper part to fall very fast and probably dewater the whole aquifer in the upstream section; later outflow is slower, as seepage becomes less significant and discharge proceeds through another deeper pathway. The two springs may be beneficial from a social viewpoint for local water supply, but their flow rates are too low to represent an important water balance component. The major part of discharge takes place in a diffuse way.

The hydrodynamic system was simulated with a MODFLOW model that included the vertisol layer on top of the Trap Basalts as the phreatic aquifer. As the flow situation is highly transient, the model uses a transient flow regime with monthly stress periods defining time varying recharge rates. Each monthly value is the time integration of daily output from the soil moisture balance model. Aquifer discharge is built in with three different boundary conditions using the MODFLOW DRAIN module. The model reproduces the observed hydrodynamic cycle quite well, but needs longer observation series (piezometric levels), more piezometers, as well as hydraulic head data from the deeper layers, in order to be refined.

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