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An approach to sustainable rural water supply in semi-arid Africa with a case study from Namibia

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Abstract Sustainable-yield estimation in semi-arid conditions is always challenging, especially for fractured rock aquifers. An approach to assess sustainability is discussed using a case study from rural semi-arid Namibia. The fractured-rock aquifers in the study area have complex configuration. Geology maps, hydrocensus data, geophysical surveys, and drilling and hydraulic testing data were used to produce a conceptual model. Aquifer parameters were estimated based on the hydraulic test data and numerical modelling. Due to lack of data, as is often the case in rural Namibia, the simulation results had to be verified against geological and hydrogeological constraints. It is concluded that the aquifer system is sustained by episodic recharge and the long-term gain in storage (about 3,285 m^3/a) represents the maximum extractable volume. It is recommended that the continuous monitoring system for groundwater level, river flow and rainfall should be part of a long-term scheme. The magnitude and frequency of the recharge events and extraction should be monitored in order to sustainably manage the resource. Although the illustrated approach is based on limited data, it provides a basis for management of individual groundwater schemes in semi-arid conditions in sub-Saharan Africa.

Keywords Arid regions · Namibia · Fractured rocks · Groundwater management · Numerical modelling

Introduction

In arid and semi-arid sub-Saharan Africa, rural communities are dependent on groundwater, a large part of which is located in hardrock aquifers. The management of these low-potential but widely occurring groundwater sources is vitally important to maintain the dispersed communities in drought prone areas (Braune and Xu 2010; Calow et al. 2009) and appropriate management of the resource depends on conceptual understanding of the aquifer systems (Robins et al. 2006; MacDonald et al. 2008). The principal issues in fractured aquifer management are knowledge of aquifer boundaries and recharge (Wright 1992). Groundwater supply sources in rural areas are often established under emergency drought relief programs that address the immediate water shortage issues. The large number of boreholes drilled in recent years by governments and under several poverty reduction, water supply and sanitation programs does not necessarily alleviate the water supply problem when sustainability of the resource is not ensured (Calow et al. 2009).

In this context, an approach adopted for sustainable yield evaluation from a fractured aquifer in semi-arid Namibia is discussed where common hydrogeological tools were utilised but by taking into consideration several key data sets collected at the scale of the rural water-supply scheme. About 52 % of Namibia by surface area is underlain by hardrock aquifers (Christellis and Struckmeier 2001) and sustainability from these sources has been an issue due to structural complexity of the aquifers, irregular recharge, and often limited resources to carry out detailed investigations. A resource evaluation procedure using numerical flow modelling illustrates the importance of incorporating the structural complexity of the aquifer and understanding of episodic recharge in assessing sustainable yield, an approach not available with conventional projection using analytical methods.

Several approaches have been suggested for evaluation of sustainable yield (van Tonder et al. 2000; Carlsson and Ntsatsi 2000; van Tonder et al. 2002). Generally, sustainable yield of small-scale abstraction schemes is estimated on the basis of analytical solutions applied to constant-rate test data and forward modelling with the estimated transmissivity and storativity. The modelled abstraction rate is adjusted to limit the drawdown to a predefined level (usually the uppermost water strike) at the end of a designed production period. Difficulties arise in applying analytical solutions where the simplifying assumptions are not supported by field data (Walton 2008; Cook 2003),

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complex field conditions cannot be explicitly represented, or where conceptual understanding is incomplete. van Tonder et al. (2002) gave a methodology based on drawdown derivative analyses for determination of the conceptual model and analytical solutions for estimation of aquifer parameters and abstraction rates but cited limitations of the methods and recommend numerical models for cases where aquifer parameters (particularly storage coefficient) cannot be uniquely determined under complicated boundary conditions.

Evaluation of fractured rock aquifers for long-term abstraction, therefore, requires estimation of aquifer properties from hydraulic test data based on a sound conceptual model that incorporates key hydrogeological constraints together with estimates of the recharge rate to the aquifer. The limited number of boreholes drilled into fracture zones in rural water supply schemes rarely provides enough data for a detailed conceptual model or an understanding of the recharge mechanism and requires use of other available datasets (Fig. 1). The purpose of this study was to formulate and test a hydrogeological model compiled using data collected during field exploration and development of the resource that included geological and structural information, hydraulic testing, and water-level-monitoring information. The model is tested with a simple finite difference numerical model at the scale of the supply scheme and used to gain insight into the recharge mechanism.

Geological setting

Geological information at the scale of the study area was derived from aerial photo and satellite imagery interpretation, field mapping, geophysical profiling and drilling (Fig. 1). A steeply dipping (70° southeast) marble band has weathered quartz-biotite schist in the hanging wall side and granitic gneiss to the footwall side. The marble and schist units belong to the Blaukranz Formation, Hakos Group, of the Damara Supergroup. These rocks were tectonised, being part of the southern margin zone of the Damara Orogenic Belt, and were affected by multiple phases of thrust faulting (Miller 2008). The direction of movement is north to northeast against the pre-Damara Supergroup basement rocks, the Hohewarte Metamorphic Complex. Locally, the marble and quartz-biotite schist units have a northeast strike and the faulted contact between the units dips southeast at a high angle (70°). The marble is karstified to variable degrees and average borehole blowout yield (960 m^3/day) is high (data sourced from Department of Water Affairs and Forestry, Namibia). Boreholes drilled during this study were located in the down-dip side of the contact, penetrating the weathered hanging-wall-quartz-biotite-schist-fractured contact zone, followed by marble. The core of the marble band is less fractured, and includes interbedded talc schist, sericite-quartz schist and dolomite. The footwall contact with basement rock is, however, fractured and karstified. Its extent along the strike is terminated by faults at approximately 1,200 m southwest (Fig. 1) and 2,400 m to the northeast of the Usip River, which is the main surface drainage and flows southwards across the northeast-striking lithological units. River alluvial sediment forms a cover up to 500 m wide along the channel but widens towards the south over the weathered schist (Fig 1).

Materials and methods

Hydraulic test

Constant rate tests (test 1) carried out in a borehole penetrating the fractured contact zone are seen to be influenced by barrier boundary effects at intermediate to late time. Test 1 consisted of a 2-day constant-rate test at 379 m^3/day followed by water-level-recovery monitoring for 3 days. The tested borehole (PBH1) penetrated the fractured contact zone between 27 and 49 m below ground level followed by the marble unit below. One observation borehole is located in the fracture zone (OB1) at right angles to the fracture direction at a distance of 25.6 m from PBH1. A second observation borehole lies in the competent marble (OB2) at a distance of 190 m from PBH1 (Fig 1). Unfortunately, observation boreholes were not drilled in the quartz-biotite schist in the southern direction due to financial constraints.

Interpretation of the constant-rate test with Theis type curve fits (Kruseman and DeRidder 1994; Duffield 2007) is given in Fig. 2. The semi-log time drawdown plot (Fig. 2a) shows a constant positive slope with stabilisation of the drawdown derivative in intermediate to late time (after 10–600 min), indicating conditions equivalent to infinite-acting radial flow. Theis curve fit is possible under these conditions (van Tonder et al. 2002) and gives a transmissivity value of 75 m^2/day and storativity of 0.0018. The drawdown data up to the first 10 min were affected by discharge fluctuations.

At late time, the slope of the drawdown curve in the semi-log plot quadruples (from 0.75 to 3 in OB1 and from 1 to 4 in PBH) and suggests that the aquifer is affected by perpendicular barriers (van Tonder et al. 2002). According to the site geology, barrier boundaries could be expected on three sides of the aquifer—the impervious basement to the north, fault truncated contact to the west and contact with quartz-biotite schist to the south. The best fit to the drawdown data is, however, achieved with barrier boundaries at right angles to the north and west at distances of 180 and 100 m, respectively. Trial with an additional barrier to the south results in poor fit, particularly to the recovery data. The weathered nature of the quartz-mica schist suggests that the contact with the schist cannot be considered a barrier.

To verify the heterogeneity of the aquifer, the data and interpreted curves are shown in a composite plot

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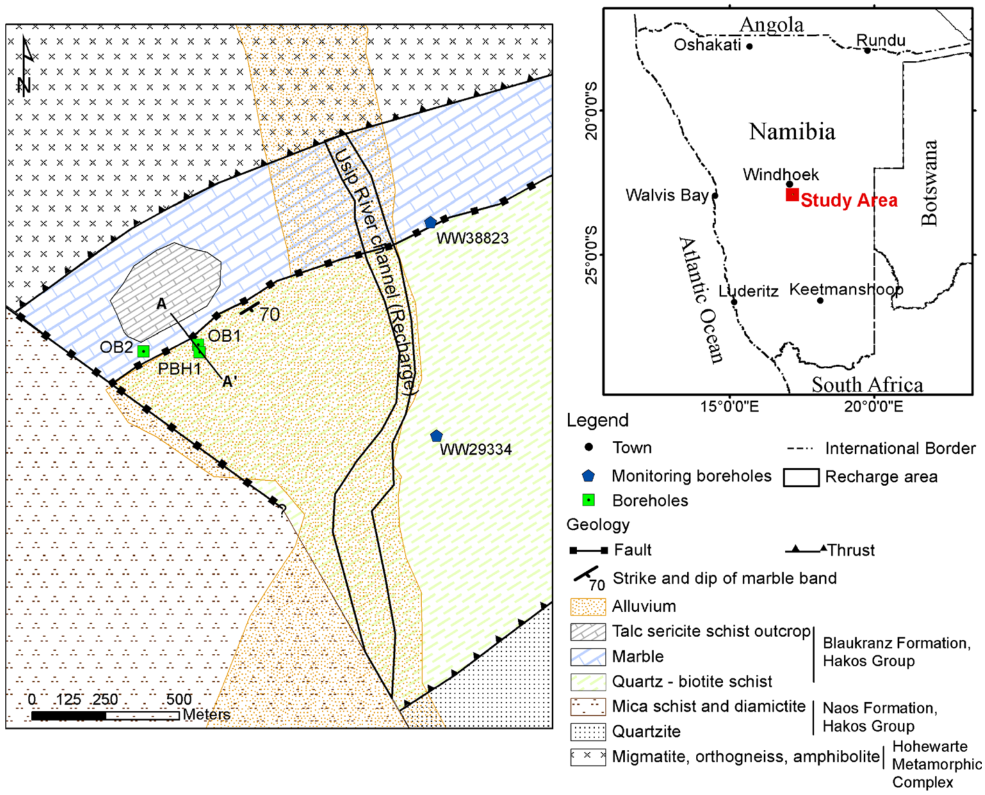

Fig. 1 Borehole positions and simplified outcrop geology of the study area in Groot Aub, Namibia (pumping borehole *PBH1*; observation borehole 1: *OB1*; observation borehole 2: *OB2*)

(Fig. 2b). In the composite plot, drawdown is plotted against time data divided by the square of the radial distance to the observation borehole as described in Kruseman and DeRidder (1994) and Duffield (2007). In a homogeneous aquifer, drawdown data from fully penetrating observation boreholes will fit a single type curve, provided that the Theis model is applicable. Drawdown data from complex aquifers with multiple borehole observation data can be plotted in a composite plot to gain insight into the effect of heterogeneities such as barrier boundaries and skin effect. In the composite plot (Fig. 2b), the effect of barrier boundaries and skin on the Theis curve fit for a confined homogeneous aquifer is illustrated (red dotted line). The departure of the fitted curve from the Theis fit in OB1 and OB2 is due to the barrier boundaries, while the pumping borehole is probably affected by both negative borehole skin and barrier boundary effects. The geological information supports the presence of barrier boundaries at right angles. Recovery of water levels in pumping and observation boreholes following the constant rate test was incomplete in a period of monitoring equivalent to the pumping period. This is interpreted to be due to the bounded nature of the aquifer. Additionally, test 1 was carried out during a long period of hydrograph recession after a recharge event. The residual drawdown at the end of the test indicates that replenishment of the bounded aquifer through river-bed leakage is not significant and likely to occur only during times of flow in the ephemeral stream. Analytical methods (e.g. Theis) have limitations in estimating storage coefficient values in a heterogeneous system (van Tonder et al. 2002). Estimation of sustainable yield required that the storage coefficient of the aquifer units and no-flow boundaries be verified.

Conceptual understanding

The conceptual understanding based on the geology and hydraulic test interpretation that forms the basis of the numerical model setup, and in turn being tested, includes the following:

1. The fractured contact zone between marble and quartz-mica schist forms a transmissive unit. The marble unit in the northern contact is variably fractured and heterogeneous. For the purposes of the study, the marble unit and the fracture zone (Table 1) are considered separate aquifer units (zone 1 and zone 2 respectively). Zone 3 is the quartz-mica schist unit.
2. The constant-rate test data show that the aquifer is bounded by no-flow boundaries at right angles with impervious basement rocks to the north and termination of the marble unit by faulting to the southwest.
3. At the time of the hydraulic test, the groundwater levels had declined for 330 days following a recharge event. The groundwater system, as evident from hydrographs, does not attain steady state within the design time scale of a groundwater supply scheme (typically 20–

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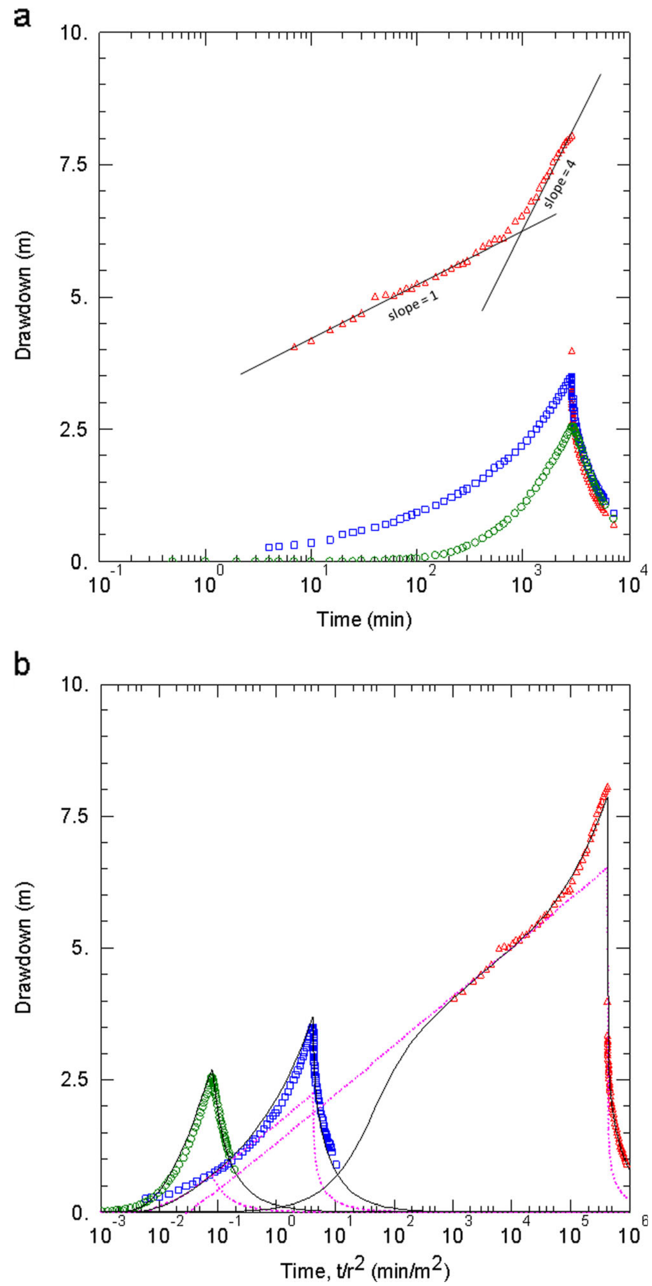

Fig. 2 **a** Semi-log plot of constant-rate test data. **b** Constant-rate test data with fitted curve using Theis Method in a composite plot (PBH1 *circles*; OB1 *squares*; OB2 *triangles*). The early time data are influenced by discharge fluctuations. Barrier boundaries are located at right angles at 180 and 100 m from the pumping borehole. The *red dotted line* shows the fitted curve without the influence of well bore storage in the pumping borehole and barrier boundaries

50 years). However, for the purpose of the study, water level data collected prior to the test are used as initial conditions.

4. The Usip River alluvium and weathered bedrock at surface jointly form a continuous unit of limited thickness along the river (Fig. 1). Recharge occurs during times of flow in the river and inflow from the eastern extent of the marble unit takes place under pumping stress. Higher recharge flux to the marble and fractured contact zone is expected relative to quartz-mica schist.
5. The pumping borehole drilled into the fracture zone is affected by the negative borehole skin.

Simulation of the hydraulic test

The physical system described in the previous provides a framework for setting up and calibrating a transient numerical groundwater flow model of the hydraulic test using the pumping and recovery-water-level data as observations. Initial head distribution in the model domain was calculated by calibrating a steady-state model under the same boundary conditions using water level observations measured prior to the hydraulic test.

Model construction

The finite difference code MODFLOW-2000 (McDonald and Harbaugh 1988; Harbaugh et al. 2000) was used to construct the models. The finite-difference code numerically solves the three-dimensional (3D) groundwater-flow equation under steady or transient flow conditions in a heterogeneous and anisotropic medium (Harbaugh et al. 2000). The layer property flow package and the Observation Process, Sensitivity Process and Parameter-Estimation Process in MODFLOW-2000 were used for inverse modelling calculations (Hill et al. 2000; Hill and Tiedeman 2007).

Input of hydraulic properties was obtained using parameters and zone arrays (Harbaugh et al. 2000), which include horizontal hydraulic conductivity, vertical hydraulic conductivity (as a ratio of the horizontal hydraulic conductivity), specific storage and recharge (Table 1). The parameters were assigned to all layers, except recharge, which applies to the top-most layer only. The model incorporates the fractured contact and the marble to the north and weathered quartz-mica schist to the south (Figs. 3 and 4) as separate zone arrays. The fractured contact is modelled simply as a narrow zone extending along strike bounded by a zone each to the north and south, representing the marble and schist units (Fig. 3). The model extends to the fault-terminated end of the marble band to the southwest and immediately northeast of the Usip River.

The grid is oriented northeast at 58° to north so that the principal hydraulic components align to the orientation of the lithological units (Fig. 3). The southwest and northwest sides of the grid define no-flow boundaries as conceptualised in the preceding. The extent of the southeast side is at the limit of the mapped quartz-mica schist at a considerable distance from the pumping borehole. The northeast extent of the grid is east of the Usip River channel. Inflow from the eastern extent of the marble unit and from leakage from the Usip River alluvium is combined by using the recharge package. The recharge zone array was assigned along the active

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Table 1 Model input and estimated parameters. Location of *zones 1–3* is shown in Fig 3. Parameter value estimates are given for a high and low specific storage of zone 3. Higher and lower 95 % linear confidence intervals are given *in parentheses*

Parameter (units)	Value 1	Value 2	Description
Zone 1 Hk (m/day)	2.82[a] (3.15/2.52)	2.87[a] (3.22/2.56)	Hydraulic conductivity (Hk) of fractured marble. Initial value from hydraulic test is 1.5 m/day
Zone 2 Hk (m/day)	1.050	1.050	Hydraulic conductivity of contact zone. Starting value from hydraulic test is 1.25 m/day; manually adjusted
Zone 3 Hk (m/day)	0.035	0.035	Hydraulic conductivity of quartz-biotite schist; manually adjusted
Zone 1 S_s (m^{-1})	1.34e-6[a] (2.06e-6/8.67e-7)	1.77e-6[a] (2.46e-6/1.28e-6)	Specific storage (S_s) of fractured marble
Zone 2 S_s (m^{-1})	5.70e-5	6.04e-5	Specific storage of contact zone. Starting value from hydraulic test is 6e-5 m^{-1}; manually adjusted
Zone 3 S_s (m^{-1})	6.98e-6 (high)	3.28e-6 (low)	The model was run in two scenarios using a low and a high specific storage value of the quartz-mica schist unit
DRN_Par1 (m/day)	0.50	0.50	Drain (DRN) conductivity. Estimated from steady state model
RCH_Par1 (m/day)	0.0026[a]	0.0026[a]	Recharge (RCH) flux. Estimated from steady-state model
VANI_1	1	1	Ratio of horizontal to vertical hydraulic conductivity (VANI) of zone 1
VANI_2	1	1	Ratio of horizontal to vertical hydraulic conductivity of zone 2
VANI_3	10	10	Ratio of horizontal to vertical hydraulic conductivity of zone 3

[a] Estimated through inverse modelling (MODFLOW 2000)

channel of the Usip River overlying the marble and schist units (Fig. 3). Outflow from the model is to the southwest boundary using the drain (DRN) package (Fig. 3).

The top and bottom surfaces were derived from a 30-m grid digital terrain model (sourced from Department of Surveys and Mapping, Namibia) and depth to water strikes recorded in nine boreholes. Most water strike depths ranged from 24 to 50 m from surface with one deep water strike reported at a depth of 81 m. The layer of enhanced hydraulic properties conditioning the aquifer is estimated to extend to 60 m depth from this information. The depth at which groundwater is encountered compares well with estimates in other dipping carbonate aquifers reported (Seimons 1989).

Grid discretisation

The steady-state model grid of the approximately 1,500 m by 2,000 m model domain is spatially discretised into 20 m by 20 m cells. A single geologic unit was vertically discretised into five layers of 12 m thickness each. The grid consists of 107 columns and 95 rows. For the transient model, a finer grid of 10 m cell size was refined with the minimum cell size of 1 m centred on the pumping borehole PBH. The final grid consists of 264 columns and 243 rows maintaining a spatial aspect ratio of 1:10. The vertical component of flow in the dipping marble unit is considered important and the single geologic unit is vertically discretised to 15 layers of equal thickness of 4 m. Trials using larger number of layers, up to 30, showed that a higher degree than 15 layers did not change parameter estimates significantly but required significantly larger computation time.

A limitation of using a numerical model based on rectilinear finite difference grids is in simulating axi-symmetric flow to boreholes, as head gradients are underestimated in the vicinity of the pumping borehole (Barrash and Dougherty 1997). This is mainly due to the difference between volume of the cell containing the borehole and the actual volume of the borehole, and between hydraulic properties of the borehole and the aquifer material surrounding the borehole. This problem is resolved by derivation of several schemes to modify the grid design, particularly in the case of MODFLOW 2000 (Reilly and Harbaugh 1993; Samani et al. 2004; Langevin 2008). A finer rectilinear discretisation scheme from the borehole outward was successfully used to simulate drawdown in a pumping borehole where well losses are not significant (Barrash and Dougherty 1997). In this study, the pumping borehole PBH1 shows negative borehole skin.

Borehole skin

The drawdown in the pumping borehole PBH1 is affected by borehole skin. The borehole skin is a region immediately around the borehole of very low storage capacity where the hydraulic conductivity differs to that of the formation (Kruseman and DeRidder 1994). A skin zone with higher conductivity, as through interception of the fracture zone, results in a negative borehole skin factor. The drawdown during the pumping phase measured in the borehole with negative skin is less compared to that in the formation immediately outside the skin zone. For a homogeneous infinite aquifer, constant discharge from a fully penetrating borehole with negligible well bore storage will result in a curve parallel to one without skin. In a heterogeneous aquifer, barrier boundary conditions affect the value of skin as shown in van Tonder et al. (2002). The water-level-recovery data from the pumping borehole is not affected by borehole skin (Kruseman and DeRidder 1994) and is, therefore, used as observations together with the drawdown and recovery of the observation boreholes in calibrating the constant rate test.

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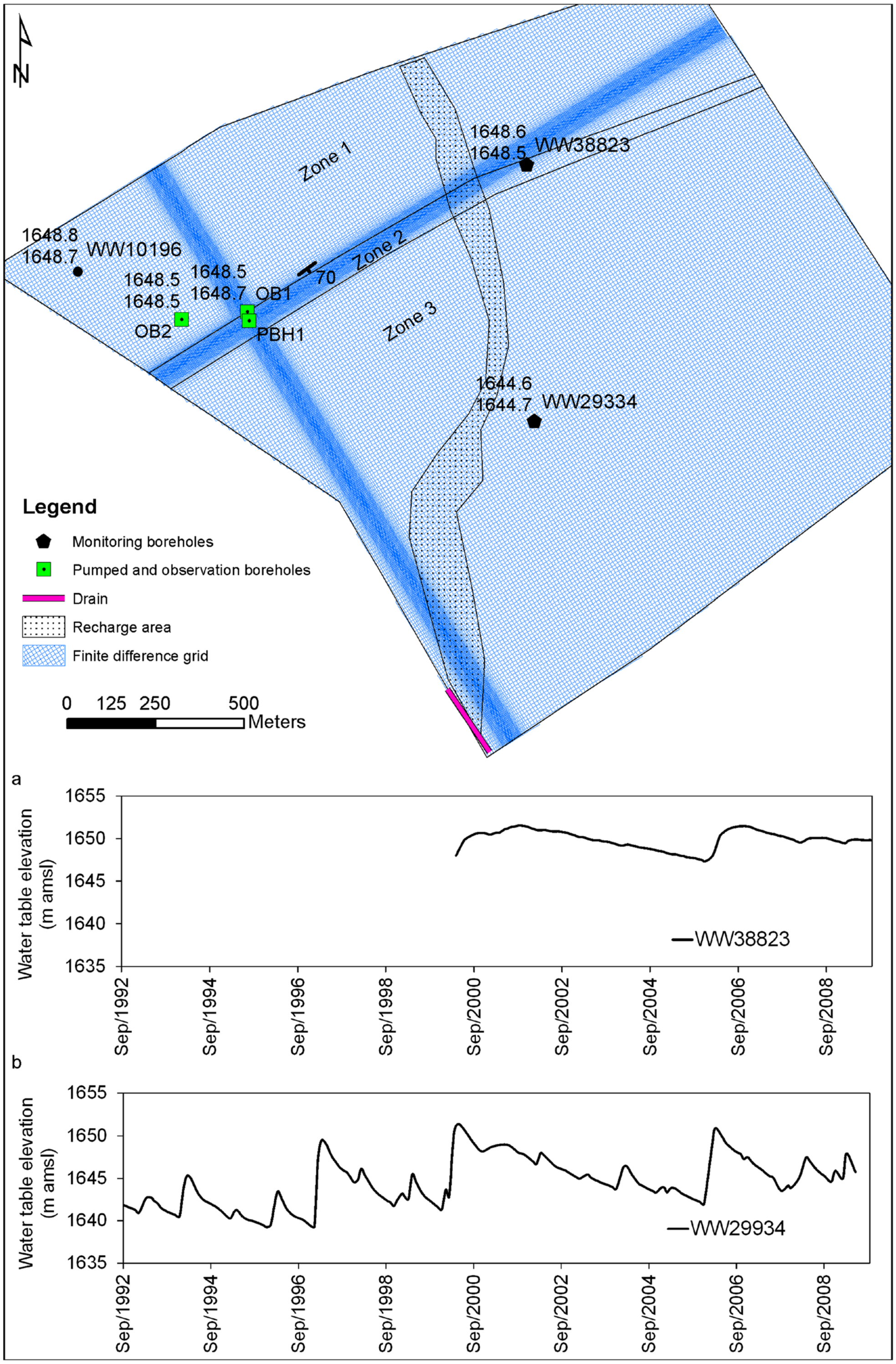

Fig. 3 Model grid cell and boundaries, and zones. Steady-state observed (*upper value*) and simulated (*lower value*) heads are shown next to boreholes—meters above mean sea level (m amsl). **a** Hydrograph of monitoring borehole WW38823; **b** Hydrograph of monitoring borehole WW29334

Steady-state calibration

Groundwater head decline from north to south in the model domain and five water level measurements (Fig. 1) taken preceding the hydraulic tests were available. The data were collected after a prolonged decline of water levels, representing conditions when no significant recharge occurred. Inflow from the extension of the fracture zone and the marble unit to the east is accounted through the recharge package.

Sensitivity analyses carried out prior to steady-state model calibration showed that the recharge flux parameter and hydraulic conductivity parameter of

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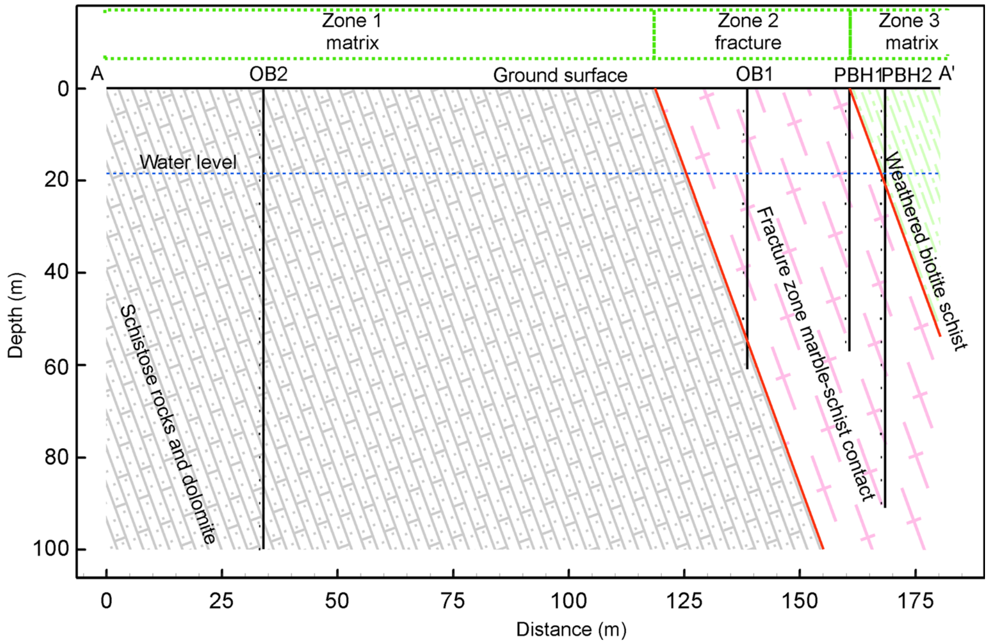

Fig. 4 North–south cross-section across the marble and quartz-biotite schist contact and modelled zones

zone 1 are most sensitive with the highest composite-scaled sensitivity (CSS) value of 11, while other parameters are insensitive. As the recharge and hydraulic conductivity are correlated parameters, all hydraulic conductivities and the drain conductivity were manually set. Inverse modelling was carried out to obtain the recharge parameter, RCH_Par1 (Table 1).

Transient model calibration

The observations consisted of 39 constant-rate test and recovery water level measurements for each observation borehole. Only recovery data were used, as observations of the pumping data are affected by borehole skin. No observations from the unit to the south of the fracture zone are available. The preconditioned-conjugate gradient solver (PCG2) and the calibration process were run in two stress periods for pumping and recovery stages in 25 steps each.

The transient model was calibrated using a combination of manual and inverse methods. Composite-scaled sensitivities (CSS) were calculated for the transient model parameters by using the sensitivity process in MODFLOW-2000 for all the hydraulic-conductivity, recharge, drain and vertical hydraulic conductivity parameters (Fig. 5) following Hill and Tiedeman (2007). The larger CSS values have greater importance in the estimation of the model-simulated water levels. The overall sensitivity of the parameters were low, the maximum value being 3.6. The most sensitive parameters were the hydraulic conductivity of zone 1 followed by specific storage of zone 2. The next sensitive parameter is the recharge flux followed by specific storage of zone 1 and hydraulic conductivity of zone 2. The model is least sensitive to hydraulic conductivity and specific storage of zone 3, drain conductivity, and the ratio of horizontal to vertical hydraulic conductivity (VANI) of all three zones. The zone 2 hydraulic conductivity and specific storage values (1.251 m/day and 6e-5 m^{-1}) were based on early time OB1 drawdown data and adjusted to match the pumping borehole recovery observations (Table 1). Zone 1 to the north representing the main marble unit includes the observation borehole OB2 and hydraulic conductivity and specific storage values were determined by inverse modelling (Table 1). Vertical hydraulic conductivity is assigned using the interlayer vertical anisotropy parameter (VANI), defined as a ratio of the horizontal to vertical hydraulic conductivity. Within the steeply dipping fracture zone, the vertical component of flow is important and a ratio of 1 was used in the absence of any data.

The largest uncertainty lies in the value of specific storage of zone 3. In the absence of field data, the specific storage was calculated using Jacob's equation (Eq. 1) as given in Domenico and Swchwartz (1998).

$$S_s = \rho\ g(\beta_p + n\beta_w) \quad (1)$$

where S_s = specific storage, ρ = mass density of water (kg/m^3), g = acceleration due to gravity (m/s^2), β_p = matrix or skeletal compressibility (Pa^{-1}), n = porosity (dimensionless ratio) and β_w = compressibility of water (Pa^{-1}).

With measured values of vertical compressibility and porosity, specific storage can be calculated with known compressibility of water. A range of vertical compressibility values for fissured rock, from 3.3e-10

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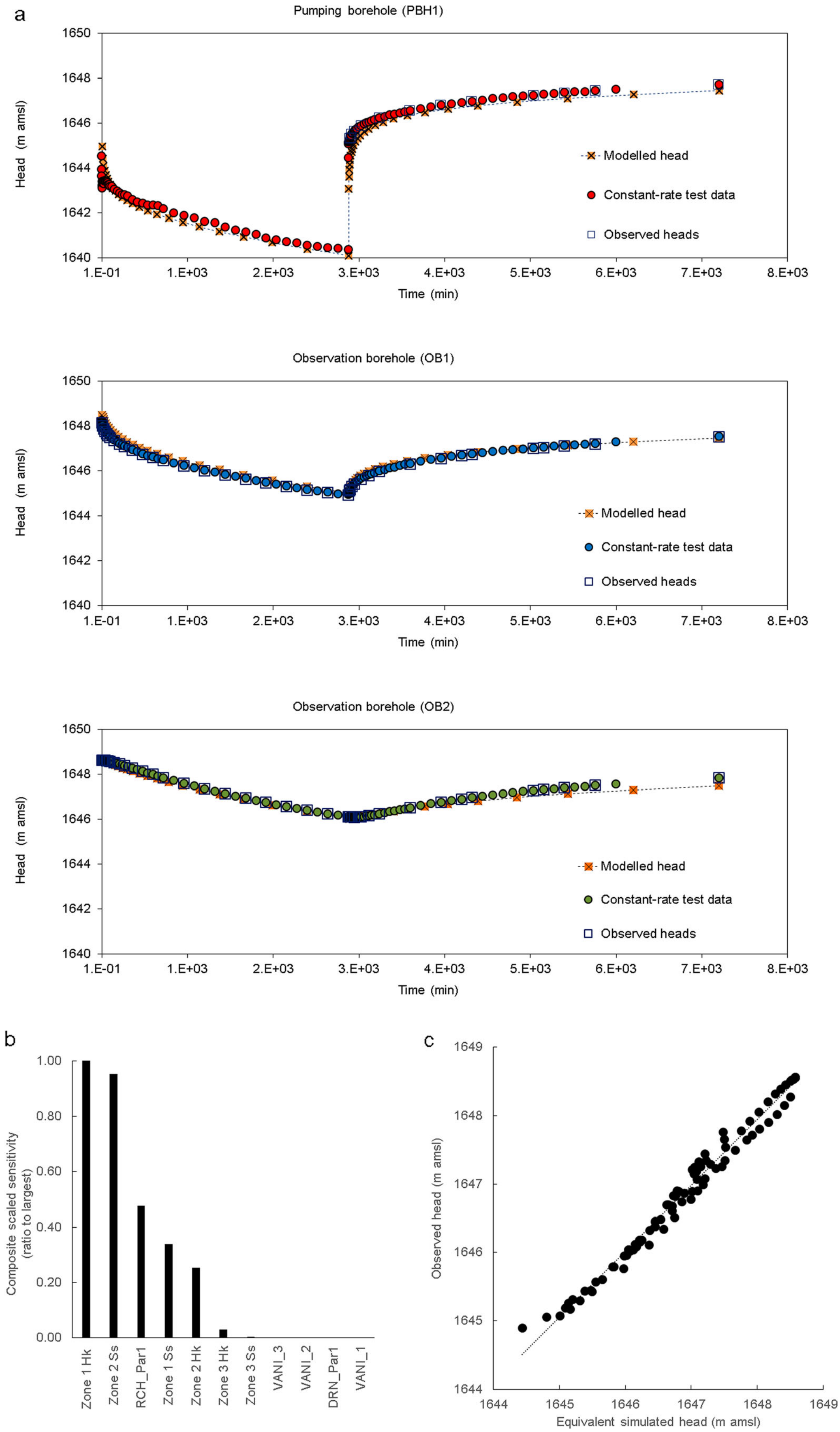

Fig. 5 Model of constant-rate test calibration results. **a** Modelled and actual drawdown data, and pumping and recovery periods of the constant-rate test. **b** Composite-scaled sensitivity of parameters (see Table 1). **c** plot of observed and simulated heads

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Table 2 Modelled recharge values derived from simulation of hydrograph of borehole WW29334 using the upper estimate of zone 3 specific storage together with identified recharge events from rainfall data

Hydrological year	No. of months when rainfall exceeded 40 mm/month	Rainfall in period (mm)	Total rainfall in year (mm)	Gain in storage (Storage OUT) during recharge event (m^3)	Modelled recharge as % of total rainfall in year
1997–1998	2	178.8	230.4	39	0.01 %
1998–1999	2	149.6	269.8	2,885	0.62 %
1999–2000	4	545.6	623.7	9,632	0.56 %
2000–2001	4	408.4	459.4	6,412	0.50 %
2001–2002	3	345.0	376.4	2,224	0.21 %
2002–2003	3	210.7	281.7	2,089	0.32 %
2003–2004	4	422.2	475.8	2,172	0.16 %
2004–2005	7	467.6	467.6	643	0.04 %
2005–2006	6	689.6	715.7	11,163	0.52 %
2006–2007	1	56.0	189.9	0	0.00 %
2007–2008	3	342.2	387.6	5,524	0.52 %
2008–2009	5	581.1	637.2	3,030	0.17 %

to 6.9e-10 Pa^{-1}, is given in Domenico and Schwartz (1998). A measurement in schist reported in du Preez et al. (2007) gives a value of 5.68e-10 Pa^{-1}. Specific storage values of 3.28e-6 to 6.98e-6 m^{-1} (5.61e-6 to 5.79e-6 m^{-1} in schist) were calculated using the range given in Domenico and Schwartz (1998) using porosity values of 1–5 %. The porosity values were based on range of estimates for fractured aquifers reported in Adams et al. (2004) for similar rock types in arid northwestern South Africa. The model converges with the lower and higher value of specific storage (3.28e-6 to 6.98e-6 m^{-1}) with minor adjustments in other parameters (Table 1).

The overall simulated heads agree well with the observed values (Fig. 5) and the standard error of regression value is 0.175. The water level recovery data show slightly larger simulated values for PBH1 and OB2.

Simulation of groundwater hydrograph

Two monitoring boreholes maintained by the Namibian Department of Water Affairs and Forestry (DWAF) are located approximately 900 m east and southeast of the pumping borehole, on the left bank of the Usip River (Fig. 1). Monitoring borehole WW38823 is located on the marble and schist contact zone, while WW29334 is located in quartz-biotite schist. The data show three significant recharge events in 2001, 2006 and 2010 with relatively minor events in 2008 and 2009 (Fig. 3). The Windhoek rainfall record (Namibia Meteorological Station, unpublished data, 2012) is shown in the groundwater hydrograph as no river gauging records are available. To test the recharge process, the period from 1997 to 2009 of a hydrograph record (WW29334) was simulated using the calibrated models with two sets of parameters values given in Table 1 and assigning recharge parameters to each event (stress period). Inverse modelling with the hydrographs records as observed heads was carried out using MODFLOW 2000. Instantaneous response to rainfall event (and flow in the river) is seen in WW29334, while a much smoother hydrograph record is seen in borehole WW38823. WW29334 was modelled, as the hydrograph of WW38823 is complex with a lag in response of 4 months probably due to intermediate storage in the alluvium, which is not been considered in the model.

The duration of recharge events were derived from rainfall records as no river gauging data were available. Runoff in the ephemeral rivers in rocky terrain is a direct result of rain in the catchment, usually with little delay. Visually, no influence is seen in the hydrograph for events of less than the long-term monthly average of 40 mm. Events larger than 40 mm/month occurred within the wet summer months from November to May. These periods were selected and, to be used as recharge periods.

Results and discussion

The observed heads of the constant rate test are reproduced by a simple transient numerical model (Fig. 5) representing dipping aquifer units bounded by no-flow boundaries in two sides. The initial hydraulic conductivity and specific storage estimates from curve fitting are comparable to the values obtained (Table 1) for the fracture zone (zone 2). Hydraulic conductivity estimated for the main marble unit (zone 1) is higher but is reasonable considering the fractured nature of the unit.

The partial recovery of water levels in all observed boreholes after a period equivalent to the duration of pumping (Fig. 5) was reproduced, with the model water balance showing water is sourced from storage during pumping within the limited extent of the model domain. The low inflow rate, modelled using the recharge package at a rate calibrated in the steady-state model, leaves a residual drawdown in a time period equivalent to the pumping period and recovery of water levels to pre-pumping levels would take more than 2 times the pumping period. Thus, under 'normal' conditions, net outflow rates (including extraction) could exceed the rate of inflow and groundwater levels would decline. Abstraction would effectively be from the stored volume within the bounded aquifer. Episodic recharge events replenish the aquifer after long intervals, when rainfall exceeds a

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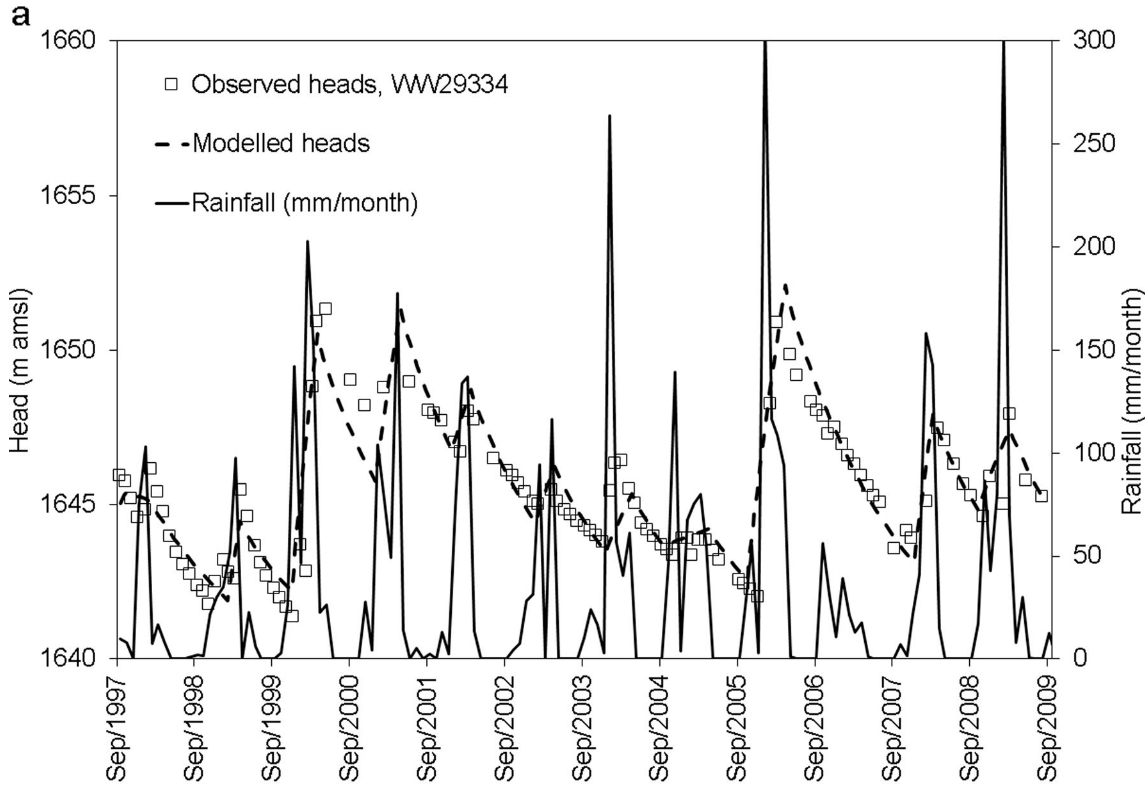

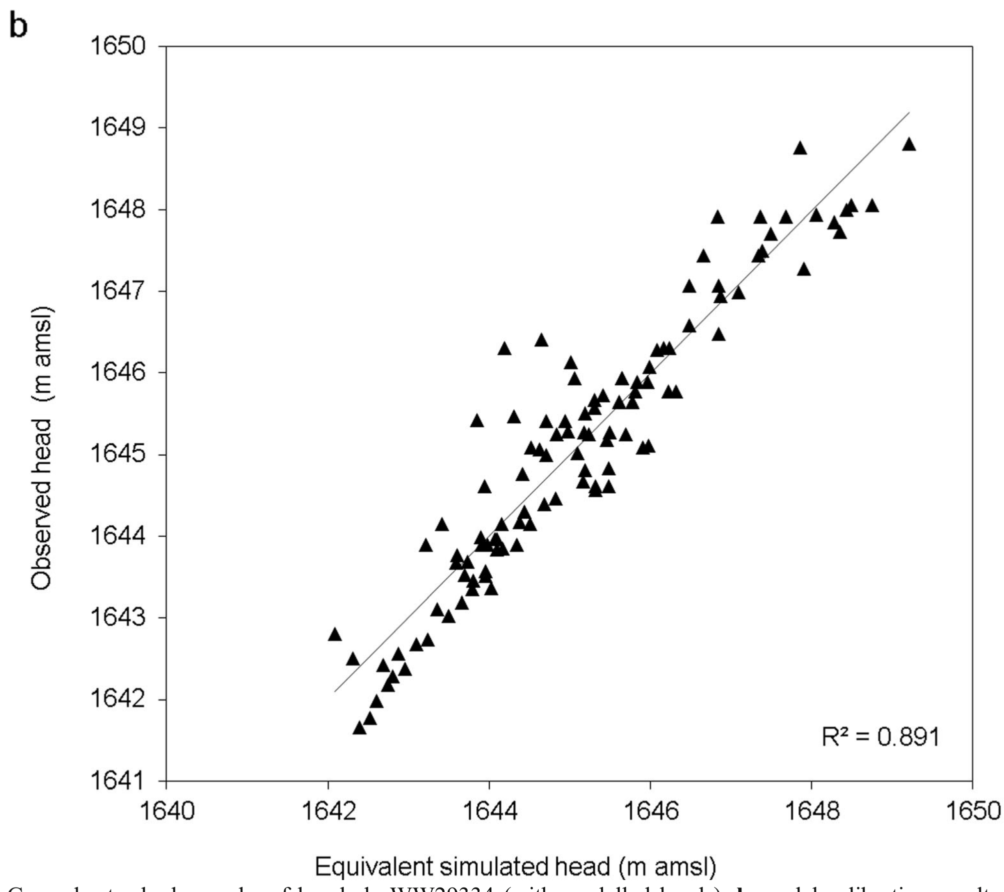

Fig. 6 **a** Groundwater hydrographs of borehole WW29334 (with modelled heads). **b** model calibration results – plot of observed and simulated heads

certain threshold value (van Tonder and Bean 2003) and cause substantial flow in the ephemeral river. This is consistent with the general model put forward for episodic recharge in semi-arid areas including Namibia by Xu and Braune (2010).

Episodic recharge is further examined by simulation of the hydrograph of WW29334. The water balance in each stress period, when rainfall exceeds a threshold value, involves recharge, discharge through the Drain package, and volumes in and out of storage in the aquifer (Eq. 2).

$$\text{Recharge IN} + \text{Storage IN} = \text{Drain OUT} + \text{Storage OUT} \quad (2)$$

Except during the recharge events, recharge (Recharge IN) and storage gained by the aquifer (Storage OUT) are zero and Storage IN balances Drain OUT, i.e., the aquifer storage is drained and the hydrograph shows a decline. During recharge events, when recharge exceeds aquifer losses, the Storage OUT value is positive representing actual gain of storage to the aquifer. The Storage OUT values are part of the output from the water balance data of the model and are used to calculate storage gained over the model domain for each event (Table 2).

The modelled hydrographs using the two sets of parameters in Table 1 gave similar water budgets with estimates of yearly storage gained in the range of 3,054–3,711 m^3. The results (Table 2) show that episodic events can account for all recharge with very limited inflow during the remaining period. Long-term recharge over the approximately 12-year modelled period is 0.3 % of annual rainfall. Recharge events vary from 0.04 to 0.6 % (Table 2) of annual rainfall. Significant recharge events are related to higher intensity rainfall events that are separated by periods of up to 5 years, e.g., 1999–2000 to 2005–2006 (Fig. 6), similar to the estimate of the one in 5–9 years years for such events in semi-arid South Africa (van Wyk et al. 2012). In addition, rainfall events that follow on a major recharge event does not produce a similar water level response (Fig. 6). Based on the sum of the aquifer storage gained in the long-term (12 years), it is seen that a limited volume (3,054–3,711 m^3/a or 8–10 m^3/day) is taken into storage. At a WHO recommended basic water requirement of 25 L/capita/day (WHO 2003), the scheme can support a population of about 360 taking the average value of 9 m^3/day. This value is an estimate of the maximum long-term available resource taking into account all existing outflow from the model domain and presuming that the current climate conditions persist. Uncertainty of the estimate primarily arises from the localised distribution and small number of observation points around the pumping borehole and the absence of observation boreholes in the quartz-mica schist unit. The quartz-mica schist is the largest unit in the domain and uncertainty in its specific storage estimate has large influence on the total calculated resource. The lack of local rainfall and ephemeral river flow monitoring data adds to the uncertainty of the sustainable yield estimate.

The use of a numerical model however allows incorporation of the complexity of the aquifer interpreted through the geological and hydraulic test data to be represented and continued evaluation of the scheme during production period against observed water level, abstraction and rainfall and river flow monitoring data. The initial solution obtained may not be unique but serves as a starting point to be tested against observations.

Conclusions

Fractured rock aquifers in semi-arid regions are sustained by recharge from exceptional rainfall events. Inflow rates into aquifers are generally low and extraction of groundwater is from storage in the aquifer, which is replenished through episodic recharge events. The aquifer extent and boundary conditions derived from direct field observations were represented in the numerical model. The conceptual aquifer model, including the recharge mechanism, was tested and serves to show the limited resource available and dependence on the episodic recharge events. The lack of data makes similar evaluations difficult in common rural water supply schemes. A policy to include data collection and continued assessment of isolated rural schemes would increase security of supply. This report demonstrates a useful approach to arrive at sustainable yield for a rural area under arid-semi and arid conditions.

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References

Adams S, Titus R, Xu Y (2004) Groundwater recharge assessment of the basement aquifers of central Namaqualand. South African Water Research Commission report 1093/01/04, SA Water Research Commission, Pretoria, SA, 234 pp

Barrash W, Dougherty ME (1997) Modelling axially symmetric and nonsymmetric flow to a well with MODFLOW, and application to Goddard2 well test, Boise, Idaho. Ground Water 35:602–611

Braune E, Xu Y (2010) The role of groundwater in sub-Saharan Africa. Ground Water 48:229–238

Calow RC, MacDonald AM, Nicol AL, Robins NS (2009) Ground water security and drought in Africa: linking availability, access and demand. Ground Water 48:246–256

Carlsson L, Ntsatsi J (2000) Village water supply in Botswana: assessment of recommended yield for production boreholes in a semi-arid environment. J Afr Earth Sci 30:475–487

Christellis G, Struckmeier W (2001) (eds) Groundwater in Namibia an explanation to the hydrogeological map. Department of Water Affairs (Division Geohydrology), Pretoria, SA, 128 pp

Cook PG (2003) A guide to regional groundwater flow in fractured rock aquifers. CSIRO Land and Water, Glen Osmond, SA, Australia, 108 pp

 DOI 10.1007/s10040-014-1178-1

Domenico PA, Schwartz FW (1998) Physical and chemical hydrogeology. John Wiley and Sons, New York, p 506
du Preez M, Dennis R, Van Tonder G (2007) Experimental measurement of specific storativity by the determination of rock elastic parameters. South African Water Research Commission Report KV 184/07, SA Water Research Commission, Pretoria, 42 pp
Duffield GM (2007) AQTESOLV for Windows version 4.5 user's guide. HydroSOLVE, Reston, VA
Harbaugh AW, Banta ER, Hill MC, McDonald MG (2000) MODFLOW-2000, the U.S. Geological Survey modular ground-water model: user guide to modularization concepts and the ground-water flow process. US Geol Surv Open-File Rep 00–92, 121 pp
Hill MC, Tiedeman CR (2007) Effective groundwater model calibration: with analysis of data, sensitivities, predictions and uncertainty. Wiley, Hoboken, NJ, 455 pp
Hill MC, Banta ER, Harbaugh AW, Anderman ER (2000) MODFLOW-2000, the U.S. Geological Survey Modular Ground-Water Model: user guide to the observation, sensitivity, and parameter-estimation processes and three post-processing programs. US Geol Surv Open-File Rep 00–184, 210 pp
Kruseman GP, DeRidder NA (1994) Analysis and evaluation of pumping test data (2nd edn.), Publication 47, Intern. Inst. for Land Reclamation and Improvement, Wageningen, The Netherlands, 370 pp
Langevin CD (2008) Modeling axisymmetric flow and transport. Ground Water 46:579–590
McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference groundwater flow model. United States Geological Survey, Denver, Colorado, p 586
MacDonald A, Davies J, Callow RC (2008) African hydrogeology and rural water supply. In: Adelana S, MacDonald A (Eds) Applied groundwater studies in Africa. CRC, Boca Raton, FL, pp 127–148
Miller R Mc G (2008) The geology of Namibia: Neoproterozoic to Lower Palaeozoic, vol 2. Geological Survey of Namibia, Windhoek, Nambia
Reilly TE, Harbaugh AW (1993) Simulation of cylindrical flow to a well using the US Geological Survey modular finite-difference groundwater flow model. Ground Water 31(3):489–494
Robins NS, Davies J, Farr JL, Calow RC (2006) The challenging role of hydrogeology in semi-arid Southern and Eastern Africa. Hydrogeol J 14:1483–1492
Samani N, Kompani-Zare M, Barry DA (2004) MODFLOW equipped with a new method for the accurate simulation of axisymmetric flow. Advances in Water Resources 27:31–45
Seimons WS (1989) Omarassa–Otjiwarongo regional state water scheme: report on the geohydrological investigation and evaluation of the marble aquifer to supplement the water supply to Otjiwarongo Town. Report no. 12/7/G8, Department of Water Affairs Namibia, Windhoek, Nambia
van Tonder GJ, Bean J (2003) Challenges in estimating groundwater recharge In: Xu Y, Beekman H (eds) Groundwater recharge estimation in Southern Africa, UNESCO IHP Series no. 64, UNESCO, Paris
van Tonder GJ, Kunstmann H, Xu Y, Fourie F (2000) Estimation of the sustainable yield of a borehole including boundary information, drawdown derivatives and uncertainty propagation. In: Calibration and reliability in groundwater modelling. IAHS Publ. no. 265, IAHS, Wallingford, UK
van Tonder G, Bardenhagen I, Riemann K, van Bosch J, Dzanga P, Xu Y (2002) Manual on pumping test analysis in fractured rock aquifers. Report no. 1116/1/02, Water Research Commission, Pretoria, South Africa
van Wyk E, van Tonder GJ, Vermeulen D (2012) Characteristics of local groundwater recharge cycles in South African semi-arid hard rock terrain: rainfall–groundwater interaction. Water SA 38:747–754
Walton WC (2008) Upgrading aquifer test analyses. Ground Water 46:660–662
WHO (2003) Domestic water quantity, service, level and health. World Health Organization, Rome
Wright EP (1992) The hydrogeology of crystalline basement aquifers in Africa. In: Wright EP, Burgess WG (Eds) The hydrogeology of crystalline basement aquifers. In: Africa Geological Society Spec. Publ. no. 66, The Geological Society London, London
Xu Y, Braune E (eds) (2010) Sustainable groundwater resources in Africa: water supply and sanitation environment. Balkema, Leiden, The Netherlands

 DOI 10.1007/s10040-014-1178-1