Groundwater resource evaluation of urban Bulawayo aquifer

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Abstract

Judicious management of a groundwater system requires an understanding of its hydrogeology and response to various recharge and pumping stresses. However, in developing countries, groundwater resource evaluations are hampered by a lack of adequate data that will allow for its complete characterisation. Under such circumstances it is not uncommon for *ad hoc* groundwater management measures to be embarked upon, especially during drought conditions. These were the conditions that existed during the 1991/92 drought when the CSIR Stellenbosch evaluated the groundwater resource of an urban aquifer in Bulawayo, Zimbabwe. Their recommendations revealed that about 3.5×10^6 m³/a could be safely abstracted from the aquifer. In this work, a more comprehensive hydrogeological investigation was carried out which included pumping tests, estimation of abstraction rates and recharge, and numerical modelling of the aquifer. The investigations indicate that the aquifer is unconfined with hydraulic conductivity and specific yield ranging from 0.1 m/d to 2.09 m/d and 0.02 to 0.11, respectively. Recharge estimates indicate an annual recharge of 105.5 mm with 38.4%, 52.1% and 9.5% accounting respectively for direct recharge, water mains and sewer leakages. Furthermore, a long-term sustainable annual abstraction of 6.1×10^6 m³ or 15% of current city water demand can be obtained from the aquifer.

Keywords: groundwater flow; pumping tests; urban groundwater; numerical modelling; groundwater resource evaluation.

Introduction

Inadequate hydrogeological data continue to present one of the greatest challenges to planning and managing of groundwater resources in many developing economies, particularly under extreme environmental conditions of drought and erratic rainfall patterns. That has been the case with the city of Bulawayo which is located in a water-scarce region of Zimbabwe that is affected by recurrent droughts. The 1991/92 drought prompted *ad hoc* measures to be adopted of which one was a groundwater abstraction programme from the Matsheumhlope well-field that underlies the city to supplement dwindling supplies from surface reservoirs whose levels fell below critical values. In addition a preliminary study of the aquifer was undertaken by the CSIR, and one notable finding was the groundwater potential of the aquifer from which an annual yield of 3.5×10^6 m³ could be obtained. The study is herein expanded to provide a more comprehensive hydrogeological analysis of the aquifer. The outcome of such an analysis provides for the adoption of a more scientifically-based management policy by the Bulawayo City Council (BCC) which is charged with that responsibility. A management policy for the Matsheumhlope well-field, with the primary objective of optimal utilisation of the groundwater resources without engendering undesirable environmental consequences and meeting other technical and non-technical constraints, has been elusive to the BCC. Failing to achieve this, BCC has relied largely on water supply from Mzingwane, Lower Ncema, Upper Ncema, Inyankun, and Msiza Dams that are all located some 45 km south-east of the city. A small fraction of the total water supply to the city is obtained from groundwater that is pumped from the Nyamandlovu aquifer located 60 km north-west of the city (Fig. 1B). In terms of pumping costs, these will certainly be much higher than those incurred from an aquifer that underlies the city, if it can yield a comparable amount and quality of water. Furthermore, the enormous amount of agricultural activities currently taking place at Nyamandlovu puts that aquifer at great risk of over-exploitation and contamination from fertilisers and pesticides. It is therefore expected that the results of this study will provide the BCC with the basis for a management policy on the Matsheumhlope well-field.

To pursue our objective of evaluating the water resources of the Matsheumhlope well-field, hydrogeological investigations were carried out, including estimating recharge and current abstraction by private individuals and corporate bodies. Pumping tests were carried out on 18 boreholes which produced data that were digitally analysed with the software AQUIFER TEST. The results from these tests confirmed the geophysical investigations of Martinelli and Hubert (1985) that the aquifer is predominantly unconfined. Recharge estimates were carried out using the water balance approach. It is acknowledged that our estimates of recharge are preliminary, having not been verified by another independent method. Because the aquifer is an urban one, the estimate for recharge has not only taken into consideration direct recharge from precipitation but also that due to water mains and sewer leakages. Recharge due to over-irrigation of parks, gardens and lawns has not been estimated because of difficulties associated with its quantification. The city and its environs imports all water for domestic, commercial and industrial activities to the tune of 43×10^6 m³ from outside the project area and transports its wastes through a network of sewers to treatment works located outside the project area. Recharge estimates indicate that direct recharge accounts for 38.4% of the total annual recharge of 105.5 mm, while water mains and sewer leakages account for 52.1% and 9.5%, respectively.
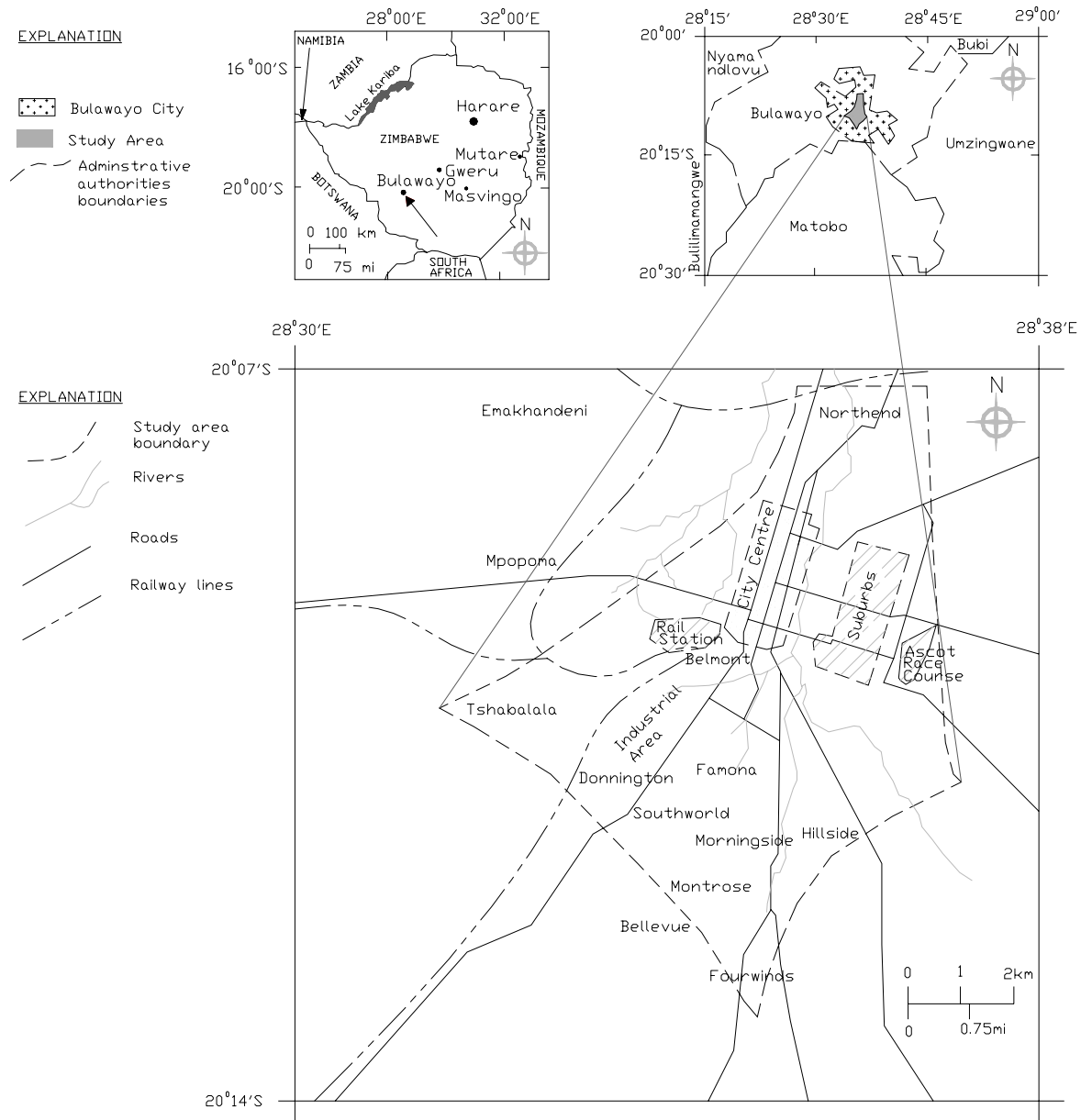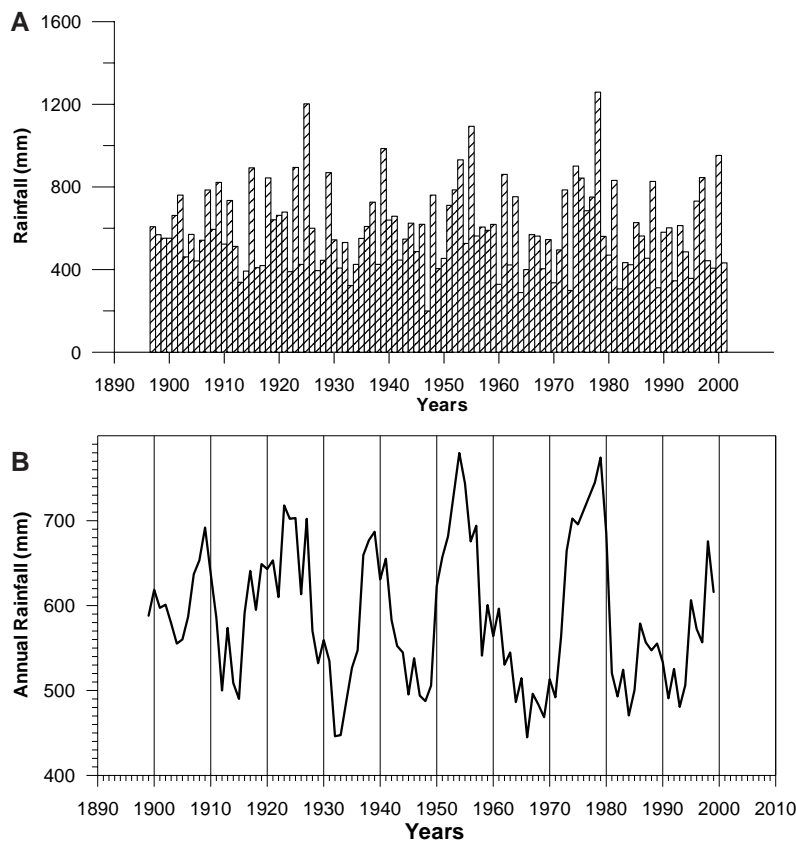
Figure 1
Location Map. A) Map of Zimbabwe. B) Map of Bulawayo. C) Study area, Matsheumhlope well-field and land use map

One major challenge that was encountered in this study was the estimation of well abstraction rates in a situation where groundwater prospecting is unregulated. The unregulated manner of groundwater prospecting is not as a result of lack of legislation nor attempts by individuals and private corporations to flout the law, but to lack of awareness by the BCC of the water resource potential of the aquifer, and therefore the need to put in place a management program. With only records on applications to the BCC for permits and absence of abstraction rates from individuals with permits, an indirect approach was used to estimate abstraction rates by random survey of users and interviews with drilling contracting firms. Future projections on total groundwater abstraction were made on the basis of known temporal trends in permit applications, which were then correlated with climatic factors and the national economy.

The field measurements of hydrogeological parameters, recharge and abstraction estimates, measured water levels, and geometric boundary data of the aquifer were input into a numerical model GEMFLOW based on the Green element method (GEM).

Numerical modelling of the aquifer was considered the most viable approach to adopt since it allows for a fairly comprehensive conceptualisation of the subsurface flow conditions in comparison with analytical methods or the CSIR's approach that was fraught with assumptions largely based on experiences from similar rock aquifers. The GEM is a relatively new computational method that exploits the accuracy of the singular boundary integral theory and the efficiency of the finite element methodology to achieve a sparse, banded matrix that can be efficiently decomposed. By this approach, the singular boundary integral theory becomes readily amenable to non-linear and heterogeneous problems, like the one addressed in this paper. The method has been widely applied to many groundwater problems (Taigbenu, 1995; 1999; Taigbenu and Onyejekwe, 1995; 2000).

The data on water table distribution and results of numerical simulation show that flow in the aquifer is generally in the northern direction with hydraulic gradients ranging from 1:1000 to 1:54, with an average gradient of 1:250. The northern end of the well-field,
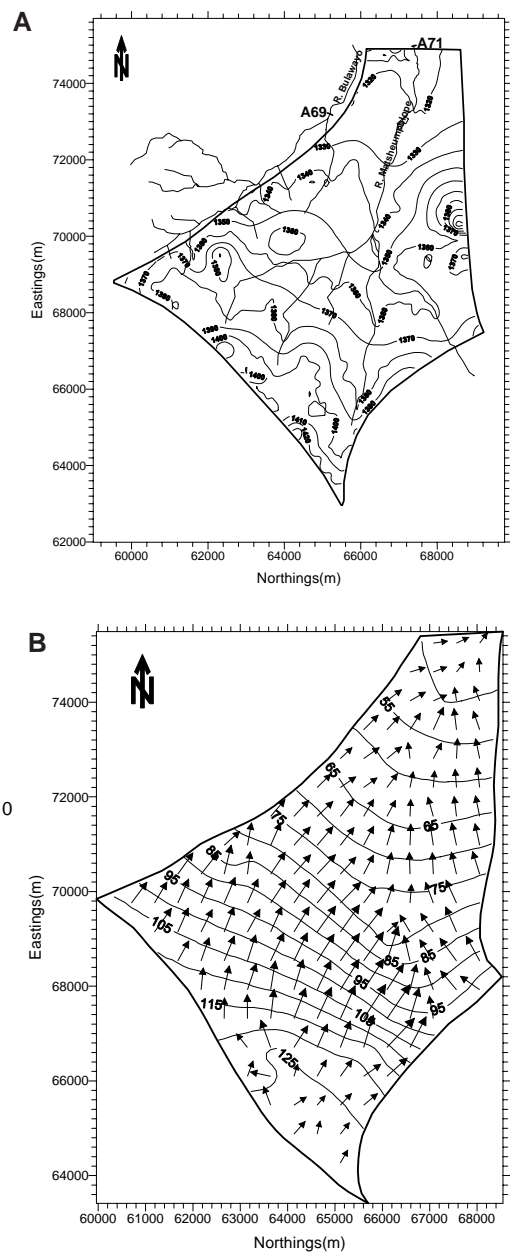
Figure 2
A) Annual rainfall from 1890 to 2000
B) 5-year moving average of annual rainfall

Figure 3
A) Ground surface contour
B) General groundwater flow direction from water table measurements taken on April 2, 2001

which serves as a discharge boundary, allows, on the average, outflow of about 0.13 m³/d per unit length of boundary. An extended simulation of the aquifer indicates that a long-term annual abstraction of 6.1×10⁶ m³ can be sustainably achieved, with average drawdown of about 6.3% of the average flow thickness of the aquifer. The simulation also indicates areas most vulnerable to large drawdown that could trigger contamination of the aquifer from anthropogenic activities (Mangore, 2002).

Study area

The study area is the Matsheumhlope well-field which underlies and runs across the city of Bulawayo, a water-distressed region of Zimbabwe (Fig. 1). The gross command area is approximately 52km² in areal extent. Bulawayo is the second largest city in Zimbabwe with a population of over 1 million persons, and its development, in terms of industrial and commercial activities, has been linked to the availability and reliability of water of suitable quantity and quality. The climate is semi-arid with dry winters and wet summers. The dry months are between April and October, while the wet months cover the period between November and March, with the most reliable rainfall taking place between December and February. Based on the annual rainfall histogram from 1890 and 2000, presented in Fig. 2A, the variability of rainfall from year to year is quite significant, and this is indicative of an erratic and unreliable rainfall pattern. The average annual rainfall is about 600 mm with a range of values from 199.3 mm and 1258.8 mm and a standard deviation of 202.3 mm. Though there are no well-defined periodicities in the rainfall data, a 5-year running average that is shown in Fig. 2B seems to indicate a general trend towards drier

years. The past two decades have witnessed a 10-year recurrent drought (1982, 1992 and 2002); the first two are indicated in the running average plot of Fig. 2B. However, this 10-year cycle of drought is not reflected in the earlier part of the data.

The general geology indicates that the study area is underlain by a greenstone formation that gives characteristic dark reddish soils, which are generally thin and fairly stony. Most of the outcrop is built up so that little original vegetation exists, apart from remnant strands of brachystegia bush. The developments that have taken place for over a century have led to the replacement of the original vegetation with ornamental plants of phreatophytic character.

The topography of the study area is one of rolling hills and valleys that serve as natural drainage courses in the southern part, and fairly flat slopes in the northern part (Fig. 3A). Bulawayo lies on an average elevated height of 1 350 m above mean sea level

(a.m.s.l.). The ground slopes in the northern direction with the highest point around Montrose with an elevation of 1 420 m a.m.s.l., while the lowest points with elevation of about 1 300m lie in the flood plains of flowing watercourses. It is drained by two streams – the Bulawayo and Matsheumhlope streams both of which flow north-ward and join to become one stream outside the project area. The general groundwater flow direction is northerly as indicated by the water table contour and flow direction of Fig. 3B. The average hydraulic gradient is 1:250, and the northern boundary of the study area acts as a discharge boundary for the aquifer.

Groundwater occurrence

Matsheumhlope well-field is underlain by basal volcanic formation of the Umganin and Avalon formations that constitute the Upper Greenstones as shown in Fig. 4 (Garson and Mutswangwa, 1995). It comprises mainly metabasalts, intercalated high-magnesia metabasalts and in some parts mafic and ultramafic sills and dykes. Because of its prevalent mafic character which tends to promote deep weathering, the rock formation supports an aquifer with fairly good water storage capacity and permeability. Hydrogeophysical investigations carried out by Martinelli and Hubert (1985) on the study area revealed that occurrence of groundwater is solely controlled by the development of secondary porosity and permeability within the otherwise impervious rock mass. They attributed the secondary porosity of the formation to chemical weathering in contrast to the proposition of Weaver et al. (1992) that the secondary porosity in the well-field was due to fracturing. The proposition of Weaver et al. (1992) lends itself to widely circulated reports on basement aquifers that their groundwater potential arises from fracturing of the original rock formation. However, because the investigations of Martinelli and Hubert (1985) were *in situ*, their finding that chemical weathering accounts for secondary permeability and porosity is considered more credible.

The geological features of the Bulawayo aquifer system bear semblance to those of basement formations that have earlier been studied and investigated (Wright, 1992). In these formations, groundwater occurs within residual overburden (the regolith) and the fractured bedrock. Rock samples that were obtained from a number of drilling sites give support to the weathering profile described by Wright (1992). The weathering profile comprises the regolith (the collapsed zone and saprolite), and the bedrock (saprock and unweathered bedrock) as shown in Fig. 5. Weathering alters the mineral composition of the original rock by such processes as hydration, oxidisation and hydrolysis, among others, so that the new minerals exhibit different physical characteristics. The result of this complex process is the opening of grain boundaries and alteration of fracture spacings, thereby enhancing the storage and the transmitting capacity of the formation. Martinelli and Hubert (1985) provide strong evidence that the weathering profile of the Bulawayan formation is relatively deep with depths of over 40 m in certain places.

The results of pumping tests carried out in this work support earlier findings that the Bulawayan formation is essentially phreatic in nature with localised semi-confined units scattered randomly throughout the system. As a predominantly unconfined system, direct recharge by precipitation plays a significant role in the long-term sustenance of the aquifer.
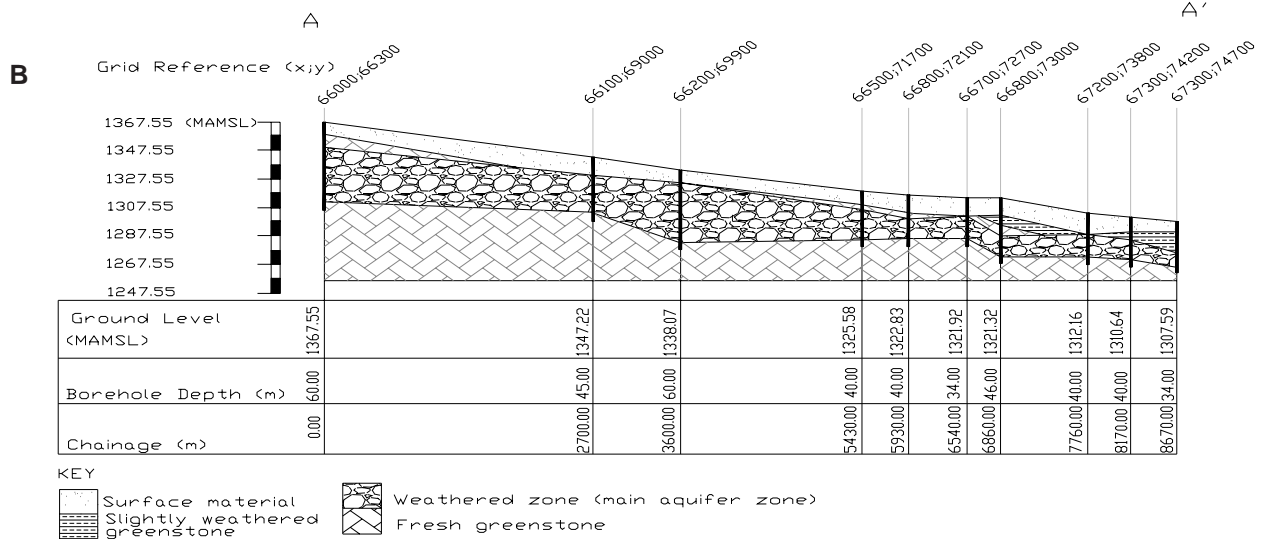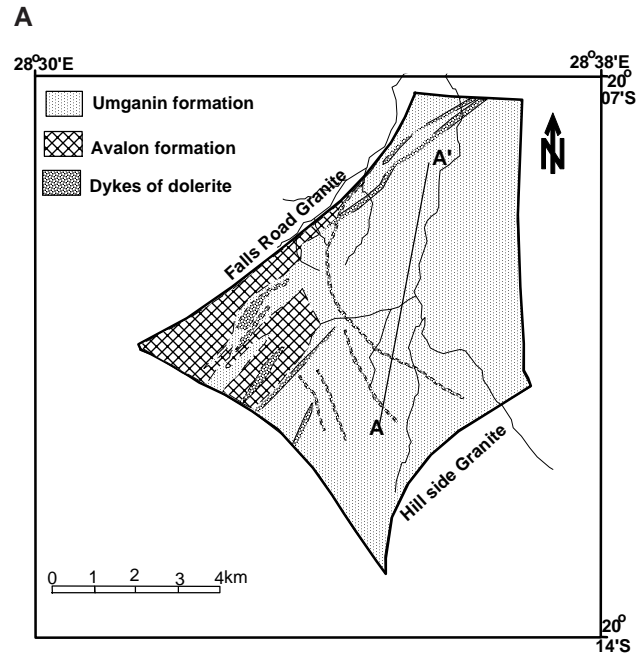
Figure 4
A) Geology of study area. B) Stratigraphic section A-A'

Recharge estimation

Methods for estimating recharge into aquifers have been the subject of numerous research papers, symposia, and workshops (Lerner et al., 1990; Hendrickx et al., 1991; Rushton and Ward, 1979). An entire volume of the *Hydrogeology Journal* was devoted to the subject of groundwater recharge (*J. Hydrogeol*. **Vol. 10** (2002)). Groundwater recharge estimation continues to receive the interest and attention of hydrogeologists not only because of its importance for long-term sustenance of groundwater systems but also because of the difficulties and challenges associated with its estimation. Considerable attention has been devoted to recharge estimation in arid and semi-arid environments because groundwater sources are usually the most reliable water sources available for human uses. In particular, recurrent droughts that have been experienced in the region rule out long-term consumptive use based on surface water sources. In our case, urbanisation introduces additional complexity to the already complex flow of infiltrated water to the regional groundwater flow. Detailed discussions on water budget, tracer, numerical modelling and physical techniques for estimating recharge, and their merits, demerits and appropriateness are well documented in the literature, and as such are not repeated in this paper. No borehole hydrographs are available in the study area, but water level observations at a number of wells indicate a general rise in water levels from January to the early part of the dry month of April, and falling water levels thereafter during the dry months, suggesting active recharge from precipitation to the basement aquifer. Furthermore, hydrogeological investigations from the analysis of pumping tests indicate that the underlying aquifer is largely unconfined and as such capable of receiving direct recharge flux from precipitation. It is generally accepted that reliable estimates require the use of at least two techniques, but limited resources hampered the use of more than one technique. However, the results obtained are compared with estimates in other similar geological systems in Zimbabwe, except for the influence of urbanisation. The water balance technique used in this work estimates recharge by the relationship:

$$R = P + Q - ET_a - \Delta W \tag{1}$$

where:
  R is recharge
  P is precipitation
  Q is net runon (runon minus runoff)
  ET_a is actual evapotranspiration
 ΔW is change in soil moisture storage

It is well known that the reliability of the recharge estimate on the basis of Eq. (1) depends on how accurately the individual components are estimated. Hendrickx et al. (1991) used a simplified relationship of Eq. (1) that was applied to semi-arid Mali of West Africa. According to the postulation of Hendrickx et al. (1991), the net runon Q and soil moisture storage change ΔW are neglected, and the actual evapotranspiration ΔW replaced with the potential evapotranspiration ΔW , so that Eq. (1) now becomes:

$$R = P - ET_p \tag{2}$$

We have retained the form of Eq. (1) and assumed that the soil moisture change ΔW is negligible. Over a time scale of one year, soil moisture conditions tend to remain the same, although they do vary over shorter time intervals. With this assumption, Eq. (1) now becomes:

$$R = P - Q - ET_a \tag{3}$$

As with most recharge estimation methods, the water balance method estimates the potential recharge or recharge that can be
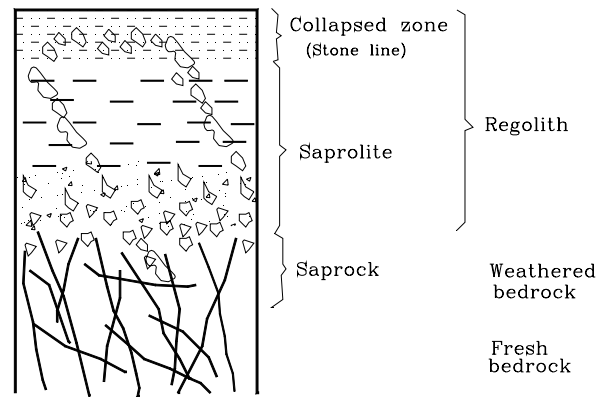
Figure 5
Generalised weathered profile above crystalline basement rocks
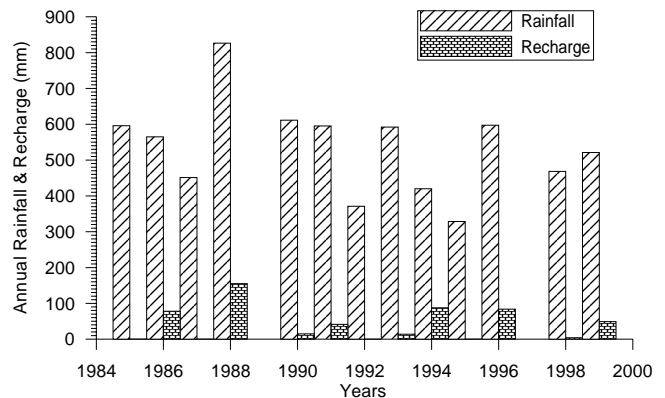
Figure 6
Histogram of annual rainfall and direct recharge

attained, rather than actual recharge that reaches the water table. The time interval that is used in the water balance method has considerable influence on the recharge estimation. In arid and semi-arid regions, long time intervals, say a year, usually indicate that there is no natural recharge to the aquifer, while short time intervals, say a day, tend to overestimate the recharge. Using Eq. (2), Hendrickx et al. (1991) recommended a time interval within a range of 1 to 10d for the calculation of recharge. By evaluating the daily rainfall, evaporation and runoff data that were collected for the project area, we found that summing recharge within 1 to 10 d interval by the water balance equation gave average annual recharge values that were much higher than estimates from similar parts in the region. We then opted for a 30 d time interval with the results presented in Fig. 6.

At the Goetz Observatory Station located within the study area, daily precipitation data were available for the period from 1952 to 1999. In estimating evapotranspiration, no comprehensive meteorological data could be obtained that would allow the use of energy balance methods, and for that reason daily pan evaporation data from 1963 to 1999 were used for the calculations. The measurements were taken with a Class A US Weather Bureau land pan. They were converted to potential evapotranspiration using a pan coefficient of 0.84. There is as yet no simple functional relationship between actual and potential evapotranspiration arising from moisture deficit (Linsley et al., 1975). The actual evapotranspiration depends on vegetation cover, soil moisture conditions, land-use and climatic factors. For simplicity, we have used the potential

evapotranspiration in Eq. (3) instead of the actual by assuming that the calculations would indicate positive recharge values when large storms occur that produce conditions that approximate potential evapotranspiration. Daily surface runoff values from 1985 to 1999 were obtained at two stations shown in Fig. 3A. These two stations are the Bulawayo Spruit (Station No. A69) with a drainage area of 23.84 km² and the Matsheumhlope Stream (Station No.A71) with a drainage area of 63.55 km². The data from Station No. A71 were, however, discarded in the calculations because they did not reflect the storm intensities indicated by the rainfall data. The data at Station A69 were scaled up to account for the larger ground surface area overlying the aquifer by assuming that the drainage area of the stream at Station A69 is hydrologically similar to that of the study area. The computed natural recharge ranges between 0 and 155.1 mm/a with an average of 40.5 mm/a or approximately 6.8% of the average annual rainfall of 600 mm.

A study carried out by Houston (1990) gives recharge estimates of between 2% and 5% of the annual rainfall for an area around Masvingo (Fig. 1A) with an average annual rainfall of 728 mm. A preliminary estimate of recharge carried out by Larsen et al. (2001) in a Karoo sandstone aquifer in the Nyamandlovu area, 60km north-west of Bulawayo, gave a range of between 2% and 24% of the average annual rainfall of 550 mm. Their average recharge estimate of 25 mm/a amounts to 4.5% of the average annual rainfall of 550 mm. Other studies carried out in the same aquifer give recharge estimates of 125 mm/a or 22.7% of the average annual rainfall by the water balance method (Beasley, 1983), and a range from 9 mm/a to 23 mm/a (1.6% to 4.2% of average annual rainfall) using C14 groundwater ages (Martinelli and Hubert, 1996). Though our current recharge estimate of 6.8% of the average annual rainfall is within the single digit estimates of other places in Zimbabwe, the need for validation by another independent method is acknowledged. For the present, our estimate of direct recharge is regarded as preliminary.

Because a considerable portion of the Matsheumhlope well-field underlies an urban environment, other components of recharge apart from those due to precipitation have to be considered. The other components of recharge are those from leaking water mains, sewer lines, and return flow from over-irrigation of gardens, lawns and parks. The effect of urbanisation on recharge remains a subject of considerable interest in the groundwater literature (Lerner et al., 1990: 201-213; Yang et al., 1999; Lerner, 2002). Using groundwater and solute transport models, Yang et al. (1999) indicated that mains and sewer leakages accounted for about 70% of the total recharge to the Nottingham urban aquifer. Lerner et al. (1990) cited factors that should be taken into account in considering the effect of urbanisation on recharge. These include the amount of water imported into the city for domestic, commercial and industrial uses, area of aquifer under urban influence, condition of sewer and water mains and land use, among others. They provided simple rules of thumb for estimating urban recharge in different environments, but these seem more useful for preliminary design than in a research work of this nature. Virtually the entire Matsheumhlope well-field is under urban influence with the level of urbanisation diminishing from the city centre to the outskirts in the residential and industrial areas (Fig. 1C). All the water that is used by the city is imported from dams that are outside the well-field, while most of the city is sewered and its waste treated outside the project area. From records as at 2001 provided by the Bulawayo City Council, a total of about 43×10⁶ m³ of water is imported from surface water dams and Nyamandlovu aquifer that are all outside the project area. Prior to 1998, a considerable amount of treated water to the tune of 40% was lost due to leakages at weak joints, faulty meter connections and along

worn-out pipes, but a water conservation and leak detection programme embarked upon by the Council has considerably reduced leakages to between 20% and 25% of the total water pumped to the city. Using the lower figure of 20%, about 8.6 ×10⁶ m³ accounts for leaks in the entire distribution system of which approximately one-third occurs within the project area. The amount of 2.87×10⁶ m³ of water mains leakage translates to approximately 2.87×10³ / 52 or 55 mm of potential recharge of the aquifer annually. The sewerage system is largely centralised, but some sewer lines have collapsed at a number of locations due to the age of the pipes. It is not uncommon to find burst sewers with their contents being emptied into natural drainage courses. In another study, Mangore (2002) sampled the quality of groundwater from 30 sites within the project area and found that 27% of the samples showed positive results with respect to total coliforms and 8% to faecal coliforms. She attributed the source of coliforms to sewer leakages of domestic waste, and this confirms active recharge of the aquifer from sewage. The central district of the project area, constituting about 5% of the total area, has a high percentage of impermeable surfaces in the form of concrete walkways, asphalt-paved roads and car parks. The level of impermeabilisation and land use decreases away from the central district with attendant increase in lawns, trees and shrubs and domestic gardens. To estimate the sewer leakage, it is assumed that 85% of the annual water consumption is the sewage flow or 0.85 x (43 - 8.6) = 29.24 × 10⁶ m³ ×10⁶ m³. Data obtained from the City Council indicate that the amount of sewage that is treated at the eight treatment works in 2001 is about 28.19×10⁶ m³, implying that sewer leakage is 1.05×10⁶ m³. The area that is sewered is about twice the area of the aquifer, and as such the average recharge to the aquifer from the sewer lines is 0.53 × 10³ / 52 ≈ 10 mm/a.

Over 90% of the estimated current abstractions from the aquifer is used for gardening and watering of lawns, and the resultant over-irrigation, which is a common feature in Bulawayo, causes underlying drainage that eventually recharges the aquifer. This is particularly pronounced in the high-income residential areas where untrained labourers, who carry out irrigation of the lawns and gardens, regard excellent service as synonymous with green, splash and well-watered lawns. To achieve this, irrigation water flows along roadsides and adjoining areas. Because wide variation exists in water-application practices, it is virtually impossible to quantify the amount of return flow that contributes to recharge. It is for this reason that this component of recharge is not estimated.

It should be recognised that estimates of mains and sewer recharge are potential values, in the same way as the estimate for direct recharge from precipitation. Some amount of the leakage from the water mains and sewers may not reach the water table of the aquifer. Part of the leakage could serve to enhance soil moisture in the unsaturated zone, while some portion could contribute to interflow along preferential flow paths in the upper layers of the soil, depending on the depth of the mains and sewers from the ground surface. Because the water table is below the sewer lines, infiltration flow from groundwater into the sewers is not considered.

Groundwater abstraction estimation

Groundwater prospecting of the Matsheumhlope well-field has been carried out in an unregulated manner. As earlier indicated, this has been largely due to the fact that the BCC gives attention to groundwater use when a drought looms and the surface water dams that supply water to the city are at critically low levels. In essence, therefore, there has been minimal management of the aquifer by the BCC, resulting in a lack of data on groundwater abstraction rates. However, an estimate of the groundwater abstraction has been

Figure 7
Trend in groundwater prospecting in Bulawayo
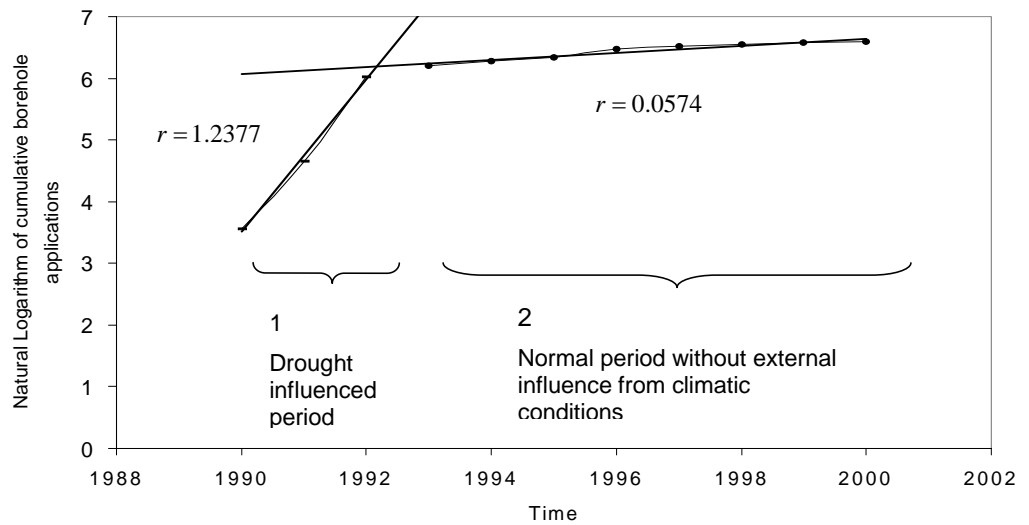
carried out in an indirect manner by making use of information from applications for permits to drill boreholes, and those provided by borehole drilling companies operating in the area. The total abstraction rate Q is provided by the simple relationship:

$$Q = q.TB_t \tag{4}$$

where:

q is the average quantity of water abstracted from a borehole
TB_t is the estimated number of stands or landed property with boreholes.

In Bulawayo, a green lawn on a property during the dry months is an insignia of an active borehole. This knowledge was used in the sampling of representative households from which information on average abstraction rate per stand was obtained. This information was gathered through questionnaires and by informal interviews. The average total abstraction at each property with a borehole was estimated as 972 m³/a (Rusinga, 2002) and this amount of water is utilised over a period of between six and nine months of the year. To establish the trend in borehole drilling activities, information were gathered from borehole drilling contractors and the BCC. The information provided by drilling contractors was limited primarily because, in our opinion, they were more interested in protecting the privacy of their clients, while the BCC provided information on application for borehole drilling permits. It should be noted that an application for a permit to drill a borehole did not necessarily mean that one was drilled or that a drilled borehole was still operational. It was, however, gathered that there was a high probability that an application resulted in an operational borehole. Using the applications made by individuals and corporate bodies for permits to drill boreholes on their property for the period from 1990 to 2000, a trend in groundwater abstraction was deduced. A plot of cumulative number of applications against time indicates an exponential growth in borehole drilling activities (Rusinga, 2002). The trend was fit with the relationship:

$$TB_t = TB_0 e^{r(t-t_0)} \tag{5}$$

where:

TB_t is the total number of boreholes at time t
TB_0 is the total number of borehole at some initial time t_0
r is the rate of increase in borehole drilling activities that is a function of climatic and prevailing economic conditions.

Using 1985 as our initial time when the Bulawayo City Council last updated the map indicating boreholes in the Matsheumhlope well-

field (that is $TB_0 = TB_{1985}$), the rate of increase in borehole drilling was obtained by plotting the cumulative values of applications for drilling against time as shown in Fig. 7. Two distinct segments of the plot emerged. The first segment or region covers the period between 1990 and 1992, while the second segment covers the period beyond 1992 to 2000. The first region coincides with the drought period when surface water levels in supply reservoirs were critically low, necessitating the introduction of severe water rationing and punitive tariff measures, and diversification of supply that included groundwater from Nyamandlovu and Matsheumhlope well-field. This accounts for the large number of applications for permits to drill boreholes, hence, the large value of r. In the second segment or region of the plot, normal climatic conditions prevailed and the City Council relaxed measures on water usage. That accounts for the low r value. A closer look at the plot in Region 2 shows that the curve becomes flatter after 1997. In Zimbabwe, 1997 represents the beginning of the decline of the economy, characterised by capital flight, depreciation of the local currency, decline in foreign currency reserves and sky-rocketing inflation that had a negative impact on borehole drilling activities because of their huge foreign currency dependence. That decline has continued to date, indicative of a lower value of r. These observations show that the value of r largely depends on both prevailing climatic and economic conditions. For simplicity, it is suggested that an r value of 5.74×10^{-2} be used for normal climatic periods, and an adjusted value as high as three times that for normal climatic periods when extreme drought conditions are experienced.
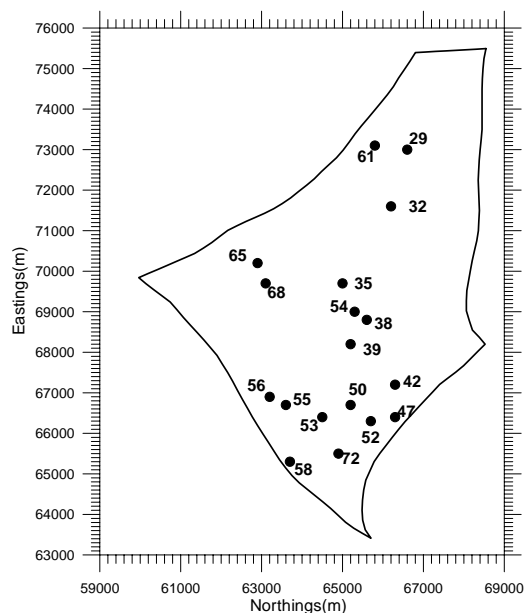
The variation of borehole densities across different land-use areas was obtained from the borehole distribution map of 1985 provided by the BCC. It is assumed that new boreholes followed the same pattern after 1985 that allowed the deduction of indicative spatial distribution of groundwater abstraction shown in Fig. 8.

Hydrogeological parameter estimation

Estimates on the hydraulic conductivity and specific yield of the unconfined system of the Matsheumhlope well-field were obtained from the analysis of pumping tests that were carried out on about 30 boreholes, with successful tests on only 18 boreholes that are shown in Fig. 9 (Kruiseman and De Ridder, 1991). The testing equipment comprised a test rig that was fabricated to suit prevailing local conditions, electronic water depth meter, and flow measuring device. The test rig consisted of a mono pump, diesel Lister engine, and 50 mm galvanised pipes which were coupled so that one end terminated with one end coupled to the pump in the well . Two
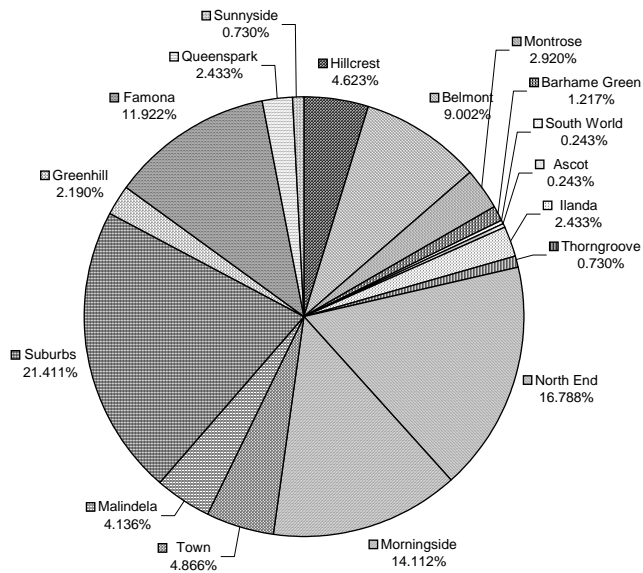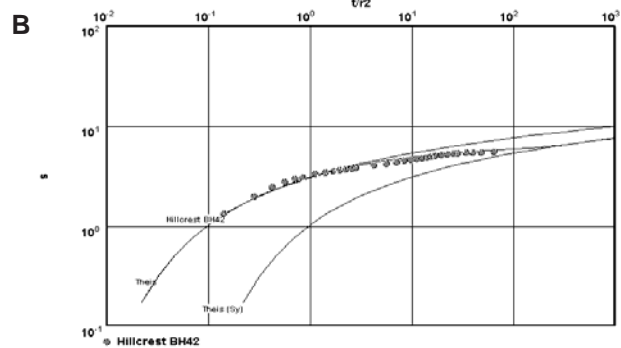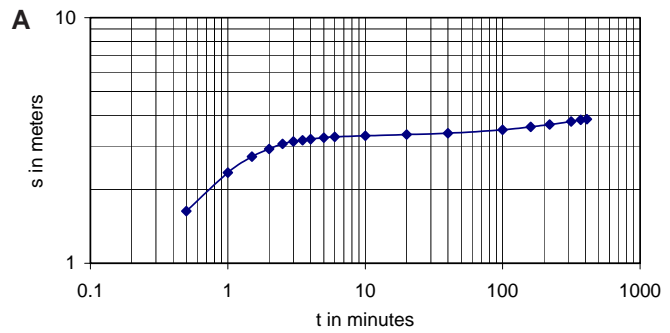
Figure 8
Distribution of abstraction from aquifer

Figure 9
Location of boreholes at which pumping tests were done

Figure 10
*A)Typical field curve from pumping test.
B) Matching of field curve with Moench curves with
AQUIFER TEST*

(Theis, 1935). Thereafter, gravity drainage begins to play a more prominent role in the release of water from storage, culminating in the attainment of the specific yield of the aquifer S_y. The drawdown curve at the later times follows Theis' but with a storativity value that is equivalent to the specific yield S_y. The field data were analysed by means of the Moench theoretical curves (Moench, 1993) that have been programmed in the software AQUIFER TEST (Waterloo Hydrogeologic, 2001). The Moench solution, which is an extension of the Neuman solution for unconfined aquifers (Neuman, 1972), can be applied to homogeneous, anisotropic, confined or unconfined aquifers. We found that all the drawdown curves obtained from 18 boreholes could be adequately matched with the Moench curves in the AQUIFER TEST software. A typical case of matching the field data with the AQUIFER TEST is presented in Fig. 10B. The results are presented in Table 1.

Groundwater flow simulation

A generalised hydrogeological section of the aquifer is schematically presented in Fig. 11 as an essentially heterogeneous unconfined aquifer with variable saturated flow thickness to which Dupuit-Forchheimer assumptions apply. For such a system, the flow is governed by (Bear, 1972):

$$\nabla \bullet \left[K(h-\eta)\nabla h \right] \quad = \quad S_y \frac{\partial h}{\partial t} - f_d + f_p \qquad (6)$$

where:

$\nabla = \mathbf{i}\partial / \partial x + \mathbf{j}\partial / \partial y$ is the 2-D gradient operator

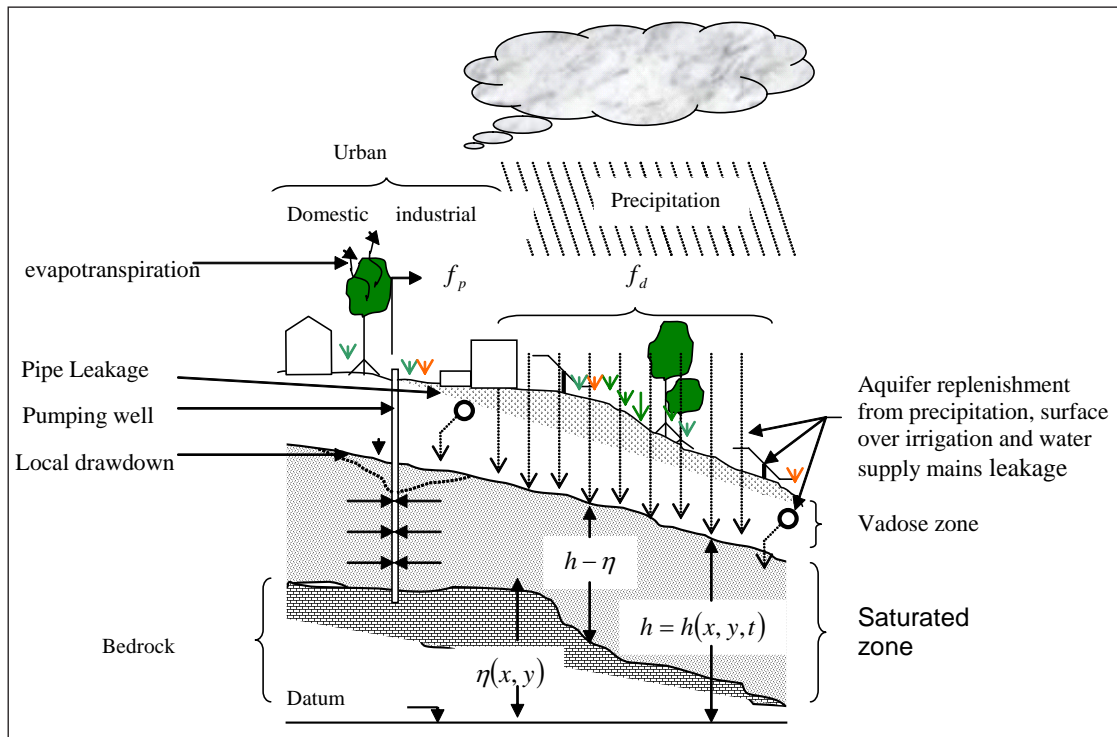h(x, y, t) and η(x, y) respectively denote the water table and bedrock elevations above a datum

S_y is specific yield (or effective porosity) of the aquifer
f_p is the groundwater abstraction and
f_d is the aquifer replenishment.

independent methods were used to measure discharge. One was with a discharge meter installed on the delivery main from the borehole, while the other used a stop-watch to measure the time to fill a 25 ℓ container. Due to limited resources, additional observation wells could not be drilled at suitable distances from the discharging wells so that? and therefore measurements of water depths were taken at the discharging wells. A typical drawdown curve that was obtained is shown on a log-log plot in Fig. 10A. The curve exhibits three distinct segments that are associated with unconfined aquifers. The first segment refers to early times after pumping has commenced, and the aquifer behaves as a confined one with the elastic property of water and the aquifer matrix playing the most significant role in the release of water from storage. This segment, referred to as the early-drawdown curve, essentially follows the Theis' curve

Figure 11
Schematic representation of the aquifer flow section

		TABLE 1		
Hydrogeological parameters of the Bulawayo aquifer obtained from pumping tests				
BH No.	Coordinates		S_y	K (m/d)
29	66 600	73 000	0.03	0.48
65	62 900	70 200	0.09	0.31
68	63 100	69 700	0.04	0.45
35	65 000	69 700	0.06	0.17
54	65 300	69 000	0.06	0.10
38	65 600	68 800	0.02	0.57
39	65 200	68 200	0.04	1.40
42	66 300	67 200	0.05	0.59
32	66 200	71 600	0.06	0.39
47	66 300	66 400	0.08	0.49
52	65 700	66 300	0.06	0.35
50	65 200	66 700	0.05	0.22
72	64 900	65 500	0.03	0.15
53	64 500	66 400	0.07	0.16
58	63 700	65 300	0.11	1.11
61	65 800	73 100	0.09	0.77
55	63 600	66 700	0.02	0.14
56	63 200	66 900	0.02	2.09
		Average	0.05	0.55

The flow equation with appropriate boundary and initial conditions is solved by the Green element method (GEM). The method is only briefly described here, and readers are directed to the references indicated for a more in-depth treatment of the method (Taigbenu, 1995; 1999; 2001a; 2001b; Taigbenu and Onyejekwe, 1995; 2000). The general philosophy of GEM lies in achieving a discretised system of equations via the boundary element theory that is efficiently solved because of its structured form. By rewriting the flow equation in the form:

$$\nabla^2 h \;=\; \Psi[S_y \frac{\partial h}{\partial t} - f_d + f_p] - \nabla\Theta \bullet \nabla h \tag{7}$$

where:

$$\Theta = \ln K(h - \eta)$$
$$\Psi = 1/K(h - \eta)$$

Using the fundamental solution to complementary equation $\nabla^2 G = \delta(r - r_i)$, that is $G = \ln(r - r_i)$, Green's second identity can then be applied to Eq. (7) and the complimentary equation to give the integral equation is the following:

$$-\lambda h(r_i, t) + \int_\Gamma \left(h\frac{\partial G}{\partial n} - G\frac{\partial h}{\partial n} \right) ds + \iint_\Lambda G\left[\Psi\left(S_y \frac{\partial h}{\partial t} - f_d + f_p \right) - \nabla\Theta \bullet \nabla h \right] dA = 0 \tag{8}$$

where:

λ is the nodal angle at source node $r_i = (x_i, y_i)$

Γ and Λ are the boundary and domain of the flow region.

A discretised system of the integral equation is obtained by discretising the flow domain into suitable polygonal elements and approximating flow variables by appropriate interpolation functions. The temporal derivative is further simplified by finite differencing in time. The aggregation over all the elements of the implemented integrations in each element gives a matrix equation of the form:
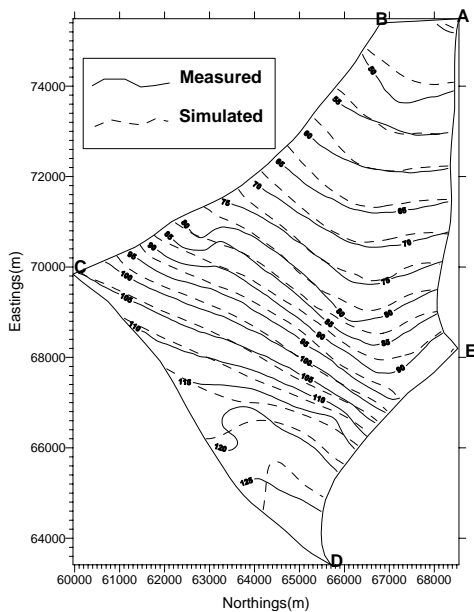
$$A_{ij} u_j \;=\; R_i \tag{9}$$

where:

$u_j = \left\{ h_j, q_j \right\}^T$ is a mixed vector of the water table elevation h at every node and normal flux q at the external nodes

A_{ij} is the global coefficient matrix which, because of the nonlinear nature of the flow, depends on the water table elevation
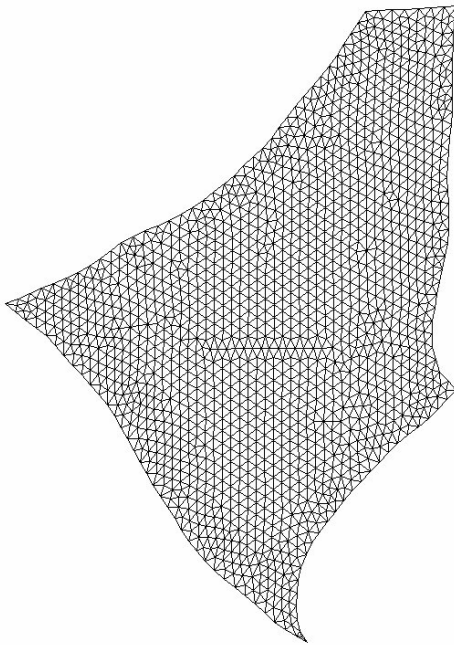
Figure 12
GEMFLOW discretisation of Bulawayo aquifer

Figure 13
Measured and Green element simulated water tables levels
on May 7, 2002

R_i is a known vector that accounts for the boundary and initial conditions, and recharge and pumping stresses.

The non-linear matrix equation has been linearised by the Picard algorithm which incorporates estimates of the water table elevation into the matrix A_{ij} and refines those estimates with the solution of Eq. (9). Convergence at any simulation step is achieved when the mean absolute deviation between solution iterates fall below a predetermined tolerance value. One feature of this formulation is the ease with which it treats the contribution from wells. That is because the singular contribution of wells is embodied in the singular

Green's function G of the formulation, so that only its values at nodes neighbouring each well are calculated and supplied to the known vector R_i. It is this feature of the formulation that eliminates the need for very fine refinement of the grid of elements around wells.

A computer code based on the above formulation, referred to as GEMFLOW, is used to simulate the flow in the Matsheumhlope well-field. The code has been widely tested and validated on various examples with exact solutions and solutions from other numerical techniques.

The Matsheumhlope well-field is modelled as a heterogeneous unconfined flow system with bedrock depth that varied from 10 to 105 m. The aquifer is discretised into 2 892 triangular elements with 1 513 nodes that are optimally numbered so that the half-bandwidth of the coefficient matrix is 52 (Fig. 12). The first simulation uses the water table elevation measurements taken on April 2, 2001 as the initial data to calibrate the model with measurements of water table elevations were taken on May 7, 2002. The boundary conditions, which represent the interaction of the aquifer flow with its environment, were obtained from both the geology of the area and earlier work carried out by Weaver et al. (1992). The western boundary (BC) and south-eastern boundary (DE) are treated as no-flux boundaries because on most of these boundaries the greenstone formation is in contact with granite formation (Fig. 13). The eastern boundary is also treated as a no-flux boundary as measured water table elevations approximate a water divide along which flow is predominantly northerly. The northern (AB) and south-western (CD) boundaries are treated as head boundary with the former serving as a discharge outflow boundary and the latter as an influx one. Measured water table levels are imposed at these boundaries. In the first simulation that covered another drought period when annual rainfall was 432.8 mm, there was a constant decline of the water table so that the average decline over the period was about 1.6m. This was as a result of increased use of groundwater and as well as the elevated water table levels caused by Cyclone Elene-induced floods of the previous season. During years with normal rainfall, groundwater use is restricted to no more than six months of the year between April and September, but in drought years, as in 2001, groundwater usage takes place all year round. The simulation is done with zero recharge and with a time step of 0.1yr. Trial runs were carried out with well distribution being adjusted till the best match between measured and simulated water table elevations in May 2002 was achieved. The contour plot of the water table elevations is given in Fig. 13. The total annual abstraction rate that is used in the simulation is $2.27 \times 10^6\,m^3$ which is about 86% higher than the abstraction rate using the estimate provided by Eq. (5). That should not come as a surprise because, as indicated earlier, drought years are characterised by increased groundwater use for gardening and irrigation of lawns and parks.

The second simulation is an extended or steady state simulation. It attempts to provide BCC with a management plan on how groundwater use should be managed so that excessive drawdowns are avoided and areas most vulnerable to such large drawdowns are identified. The results of this simulation could be interpreted as providing an estimate of the aquifer safe or sustainable yield – a concept that remains quite contentious in the groundwater literature (Heath and Spruill, 2003; Bear, 1979; Fetter, 1988). Using the distribution of the hydrogeological parameters obtained from the pumping tests, and a uniform recharge of 105.5 mm/yr (direct, mains and sewer recharge), pumping stresses were generated in such a way that the average drawdown at steady conditions does not exceed 6.3% of the average aquifer flow thickness of 40m using the April 2001 water levels as a reference. After a number of trial runs, 467 wells with abstraction rates ranging from 3 m^3/d to 255 m^3/d were

used in the simulation. These wells accounted for a total pumping stress of $6.1 \times 10^6 \, m^3$, distributed according to Fig. 14, and produced the steady-state water table distribution in Fig. 15.

Discussion

Although there is good agreement between the measured and simulated water levels in May 2002 (Fig. 13), the lack of accurate data on groundwater abstraction from the aquifer will continue to hamper its accurate modelling. The results of the extended simulation present some interesting issues. The Matsheumhlope well-field is a marginally good aquifer that cannot support high production wells that would cause unacceptably large drawdowns, thereby making the aquifer more vulnerable to contamination from urban landuse activities that are discussed by Mangore (2002). Our simulations indicate that wells should have maximum production rate of $255 m^3/d$. This value agrees with the information which drilling contractors have from blow yield tests that are occasionally done. Secondly, the simulation indicates areas where borehole failures are most likely to occur. From the abstraction distribution of Fig. 14, a simplified yield distribution plot is constructed and presented in Fig. 16. These poor yield areas are shaded with dots (Fig. 16). They include the suburbs of Ilanda, Hill Side East, Barham Green, Montrose and Morning Side. These areas should be considered as the flash spots in the management of the groundwater system, and would require close monitoring of groundwater prospecting by BCC. Borehole failures have been widely reported but they are not documented. In certain cases, failures occur because of the interaction of a number of neighbouring wells operating at about the same time. In certain instances, the wells are revived when some neighbouring wells cease operation. Thirdly, with a well co-ordinated monitoring programme in which groundwater prospecting is carried out on the basis of the distribution given in Fig. 14, a long-term sustainable yield of $6.1 \times 10^6 \, m^3$ can be derived from this aquifer. This value represents approximately 15% of the current water consumption of the city.

Conclusion

The hydrogeological study of the urban Bulawayo aquifer, commonly referred to as the Matsheumhlope well-field, has been carried out with a view to providing a tool by which the Bulawayo City Council can manage the aquifer. The aquifer is a heterogeneous unconfined system of marginally good aquifer characteristics and holds great promise for the future development of the city whose growth has been considerably hampered by water insecurity. The aquifer is a regolith formation that has achieved its aquifer status by chemical weathering of the original basement rock. Field investigations with pumping tests on 18 boreholes give average hydraulic conductivity of 0.55 m/d and specific yield 0.05. The flow in the aquifer is predominantly in the northerly direction with average hydraulic gradients of 1:250, and annual discharge from the northern end of the aquifer of the order of $0.13 m^3/d$. The potential recharge from precipitation, water mains and sewage leakage amounts to about 105.5 mm annually with the three components contributing 38.4%, 52.1%, and 9.5%, respectively, to this amount. The use of the mass balance method in estimating direct recharge is known to be fraught with errors from summing large numbers, and for that reason the estimate of 40.5 mm/a for direct recharge is considered preliminary and would need to be confirmed by another independent recharge estimation method. It is of interest to note that water mains leakage accounts for highest recharge to the aquifer, and this agrees with the findings of Yang et al. (1999) in their study of the
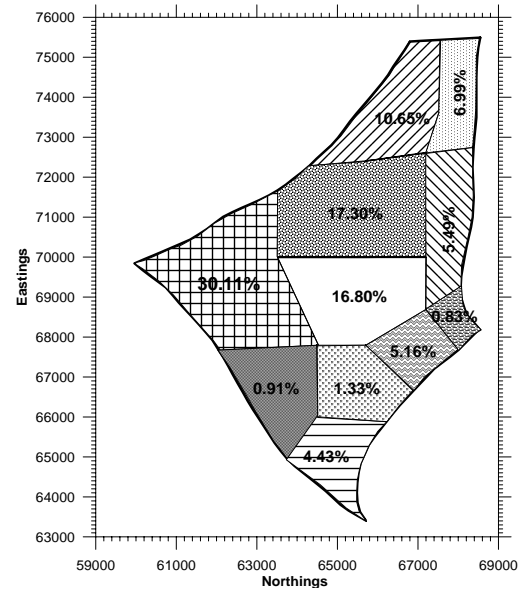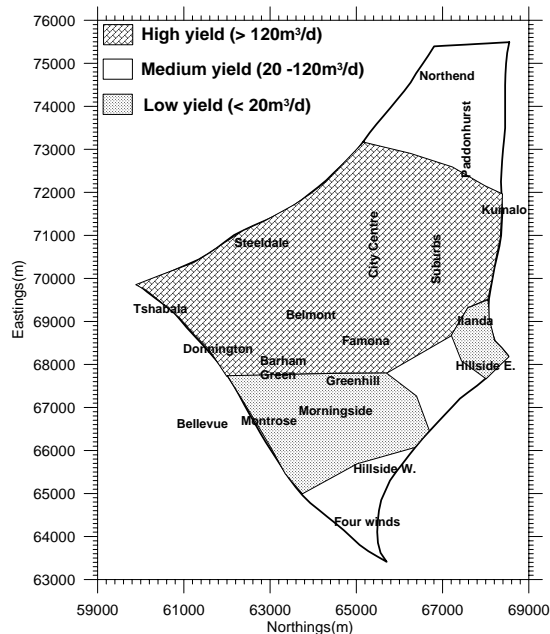

Figure 14
Abstraction distribution for extended simulation
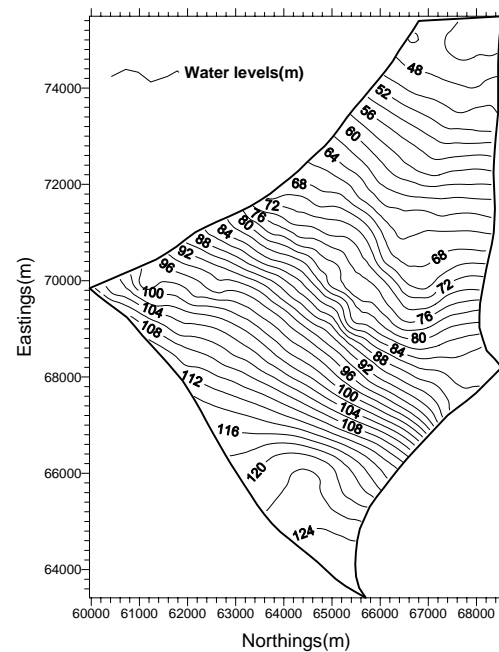
Figure 15
Steady water table contours from extended Green element simulation

Nottingham aquifer. With increased water use due to population growth and demand, the contribution due to water mains leakage to recharge will continue to grow, except if more efforts and resources are put into the water conservation and leak detection programme that the BCC is currently carrying out.

Numerical simulations of the flow in the aquifer using GEMFLOW indicate that, in the long term, as much as $6.1 \times 10^6 \, m^3$ can be safely withdrawn from the aquifer annually. That is an upward revision of the estimated yield of $3.5 \times 10^6 \, m^3$ for the aquifer given by Weaver et al. (1992). The simulation provides a guide on abstraction distribution that should be adopted in order to realise this long-term yield. This guide is provided in Fig. 14. Whereas the

Figure 16
Simplified demarcation of aquifer yield, indicating areas most vulnerable to excessive drawdown

aquifer cannot sustain high production wells because of the excessive drawdowns that will be experienced, there is now a basis for the Bulawayo City Council to start compiling an inventory of operating boreholes and their discharging capacities in order to properly manage the system so that borehole failures and their attendant economic losses can be avoided.

Acknowledgement

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