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Sustainable Groundwater Exploitation under Natural Conditions in Southwest Ghana

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Groundwater has been recognised as the most cost-effective option of safe water supply to rural communities in Ghana. The demand for potable water has led to the drilling of a large number of boreholes in many parts of the country. To establish the threshold of groundwater development from storage in a major river catchment (Pra River) in South-West Ghana, studies on recharge to the weathered aquifer and statistical evaluations of specific capacity and potential yield have been carried out. The SAC-SMA conceptual hydrological modelling system was used for the recharge estimate. With recharge rate of 50 mm/yr, the natural groundwater resources in the basin was estimated to support a maximum withdrawal of 12 l/s for a 10 hour per day pumping. The groundwater resources potential of 1.6 l/s/km^2 could be considered the threshold of groundwater exploitation in similar river basins in South-West Ghana. A study into the relation between permeability and recharge under different conditions and scenarios is required to define their limiting role in groundwater resources development.

Key words: *Groundwater storage, recharge, aquifer, specific capacity, base flow, hydrologic budget*

1 INTRODUCTION

Groundwater remains the most dependable source of water supply for the numerous scattered rural communities in Ghana. It can be developed at a small capital and the time required for development is comparatively very little. About 33% of the population is supplied by groundwater. Hard consolidated rocks however, underlie the greater part (about 80%) of the country making it difficult to develop large concentrated supplies of groundwater. Even so, the demand for potable water has led to the drilling of a large number of boreholes in many parts of the country. There is therefore the need to determine the potential of groundwater as a resource and to find out if the increasing withdrawal is sustainable. The results could provide useful information for policy formulation and regulated development of groundwater as a natural resource.

To ascertain the threshold of groundwater abstraction, and verify the methodological approach of assessing natural groundwater resources (including groundwater recharge capacities) of hard rocks, studies on well productivity and direct natural recharge to the shallow aquifers in the Pra River Basin in South-West Ghana have been carried out.The Pra River Basin lies between latitude 5^0 00'N and 7^0 10' N, and longitude 0^0 25'W and 2^0 14'W (**Fig. 1**). With its two main tributaries, the Birim and Offin Rivers, the basin covers an area of about 22,836 km^2. The Pra River traverses several towns and serves as the main source of water supply for many communities and industries. The basin is warm and moist throughout most of the year, and the vegetation is of moist semi-deciduous forest type. There are two rainfall regimes with different intensities. The main rainy season begins from April/May and ends in July, with the maximum rainfall occurring in June when the maritime instability causes a surge of the moist south-westerly air stream resulting in the intensification of the monsoon rain. The minor rainy season occurs between September and November, when several disturbance lines sweep across various parts of the area with local thunder activities. The annual rainfall varies between 1170 - 1500 mm. The average maximum and minimum temperatures are 32 ºC and 21 ºC for cooler periods of June to September/October respectively. The mean annual runoff ranges from 51 to 93m^3/s, representing only about 6 - 9 % of rainfall. The seasonal trend and response of channel inflow to precipitation are shown in **Fig 2**.

Precambrian Birimian rocks (slate, phyllite, schist and tuff) and the associated granitoid intrusives, as well as the Tarkwaian rocks (quartzite, sandstone, shale and conglomerate) underlie the basin.

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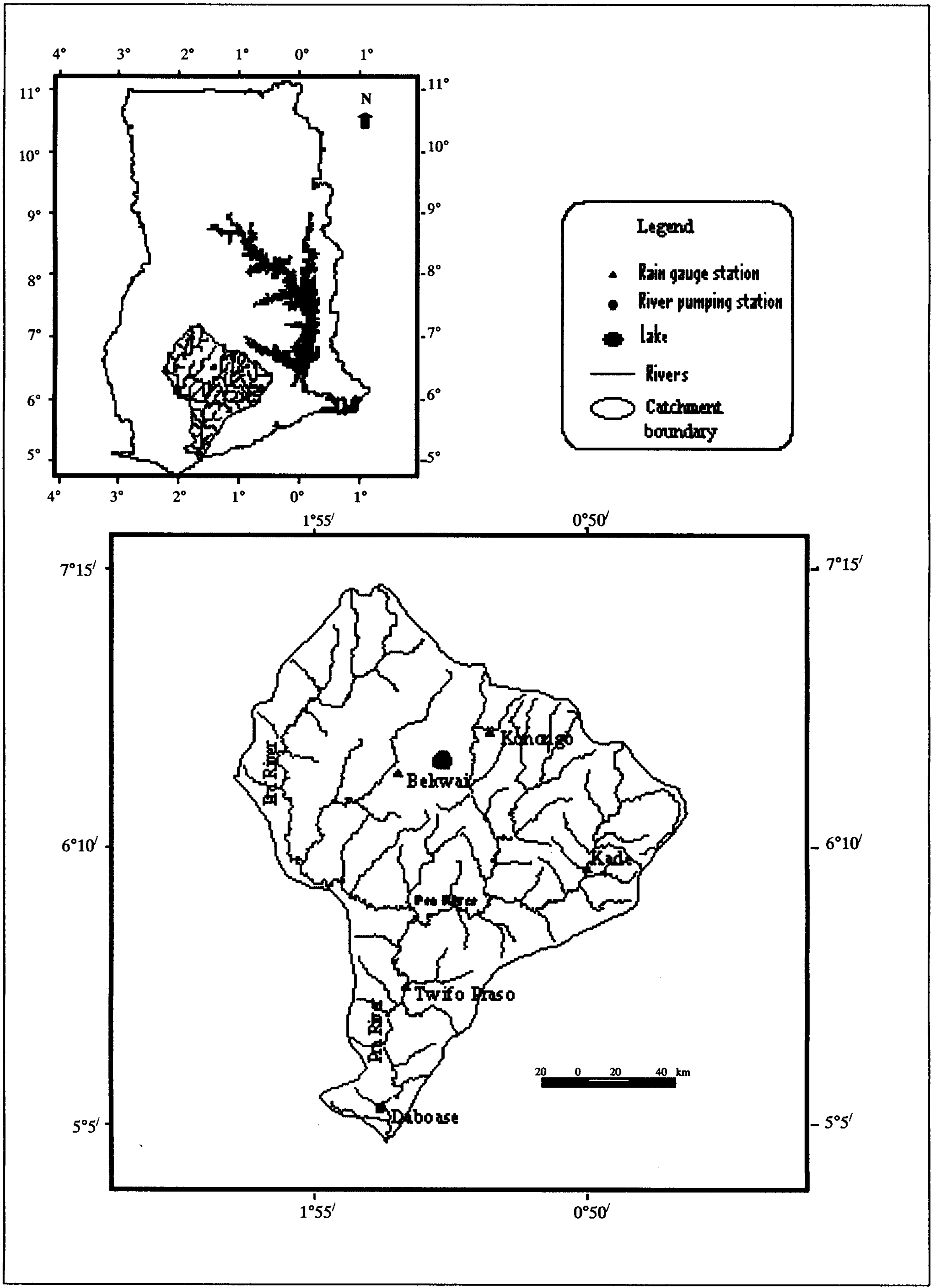
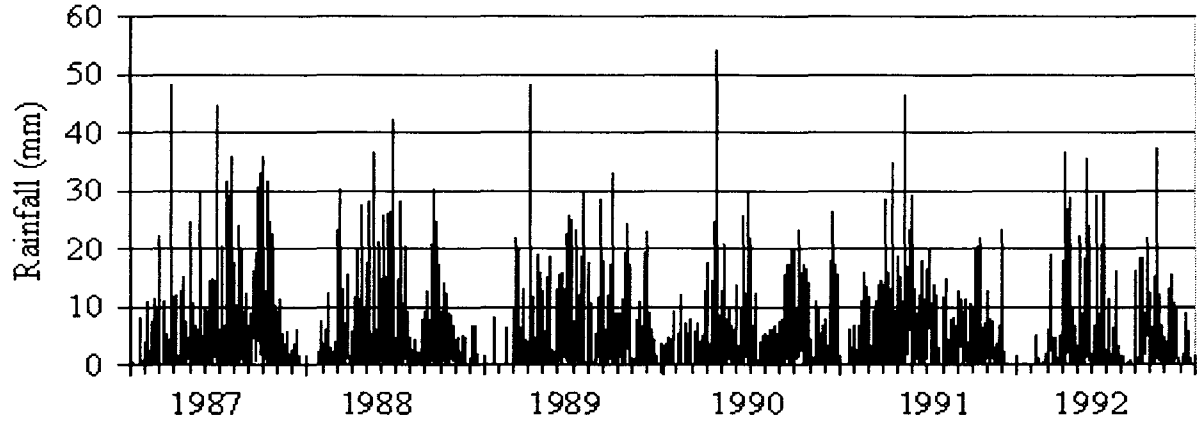
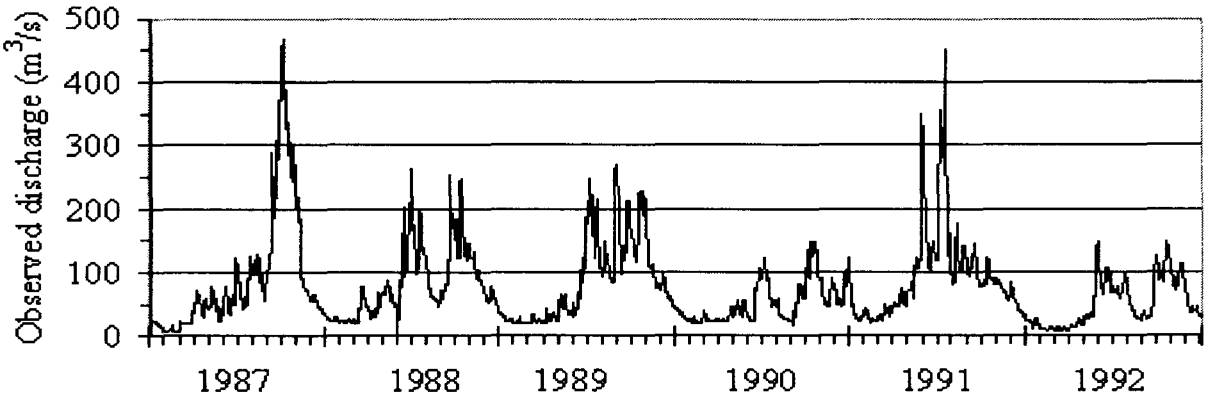


Fig.1 Pra River Basin in Ghana (Darko, 2002)



(a) Rainfall



(b) Observed discharge

Fig. 2 Response of channel inflow to rainfall – Pra River (Darko, 2002)

2 METHODOLOGY

The Sacramento Soil Moisture-Accounting (SAC-SMA) hydrological modelling system was used to simulate groundwater storages and recharge within the Pra River Basin. Though the distribution of rainfall and gauging stations in the catchment is quite dense, continuous, uninterrupted daily records covering a maximum period of six years (1987-1992) could be obtained from one main discharge gauging station (Daboasi), and four rainfall stations (Twifo-Praso, Konongo, Kade and Bekwai). The available hydro-meteorological data was used for the analysis and simulation.

Statistical analysis on specific capacity data was carried out to estimate the potential for groundwater abstraction. Because it accounts for the loss in head that is associated with pumping, specific capacity is preferred to yield as a measure of well productivity (Knopman 1990). It also provides initial approximations to water abstraction possibilities in the hydrogeologic environment (Krasny 1993). From the model output, the amount of groundwater obtainable from storage was estimated.

The modelling procedure involved the determination of the proportions of major components of the hydrologic budget by the simulation of rainfall–runoff processes. If the measured discharge of groundwater across the boundary of the study area is equal to the net recharge inside the area, then the average groundwater discharge (base flow) over the aquifer boundary provides an estimate of net recharge.

Burnash et al. (1973) describe in detail the principal features of the SAC-SMA model. The model embodies complex moisture-accounting algorithms to derive volumes of several runoff components, while using an empirical method to convert the inputs to the outflow hydrograph. The algorithm computes runoff in six main runoff components, which are listed as follows:

(a) direct runoff from permanent impervious areas (IMP);
(b)direct runoff from temporary impervious areas-parts of the basin which become impervious after saturation (DIR);
(c)surface runoff due to precipitation occurring at a rate faster than percolation and interflow can accommodate when both upper zone storages are full (SUR);
(d)interflow resulting from the lateral drainage of

temporary free water storage (INT);

(e) supplementary base flow-essentially the seasonal component of outflow from groundwater storages (SUP) and

(f) primary base flow-long term component of base flow (PRM).

The first four components (direct, surface and interflow) are summed and transferred by the unit hydrograph. The unit hydrograph was calibrated to less than 10% of the estimated sub-catchment areas by using 35 ordinates defined at 24-hour intervals. This matched the computational time interval of 24 hours for mean discharges. The remaining two components (primary and supplementary base flows) were added directly to the outflow hydrograph. The primary base flow characteristics were estimated from the daily discharges when the flow rates remained almost constant for an extended period. Percolation, the transfer of water from the upper potion of the soil to the lower soil, supplies moisture to three lower zone storages. These are the lower zone tension water storage (LZTWC), free water primary storage (LZFPC) and free water supplementary storage (LZFSC). Base flow in the catchment is generally defined as discharges from the lower free zone storages.

The simulation was carried out over the calendar year, instead of the hydrologic year (March-February). Four time series were weighted, taking into consideration the area coverage of the sub-watersheds represented by the rainfall stations, topography and landform, distance of the rainfall stations from the discharge gauging point and possible anthropogenic effects (land-use).

During the simulation, the difference between the long-term annual rainfall and runoff was used as first estimate of evapotranspiration demand. The average evapotranspiration demand was set at the middle of each month. By taking into account the annual cycle of air temperatures, rainfall and/or evaporation, the evapotranspiration demand was distributed into individual months. These starting values were then corrected in subsequent iterations, by closely following the observed and simulated monthly runoffs and the simulation statistics. From these values, the model then computed the daily actual evapotranspiration separately from the individual zones. More emphasis was laid on low-flows, as they are more important for the evaluation of groundwater storage.

3 MODEL OUTPUT AND GROUNDWATER STORAGE

The potential base flows (PRM and SUP) constituted about 90% of total runoff, with the long-term component (PRM) representing an average of about 50%. **Table 1** presents the proportions of the various runoff components. The PRM values ranged between 48% and 55%, indicating moderate fluctuations and generally depending on the seasonal and annual distribution of rainfall **(Fig. 2)**.

The three storage components, especially the LZTWC, closely mirrored the seasonal trend of precipitation, with a drag or delay period of about two months. This implied that the base flow response to meteorological inputs was not directly synchronous. The annual cycles of the storages and outflows are typical of shallow groundwater, with probable provision of water from the LZFPC to supplement evapotranspiration during the dry seasons when there are large deficits in tension water.

Groundwater recharge was estimated by considering the measured discharge of groundwater across the boundary of the basin to be equal to the net recharge inside the catchment. Over periods of equivalent storage, recharge to groundwater is thus given by the long-term component of base flow from the hydrograph. For the period of investigation, the recharge rate amounted to an annual average of 50 mm. This gives natural groundwater resources potential of 1.6 l/s/km^2. **Table 2** shows the recharge variations for the respective years. On temporal basis, recharge tended to be correlated with rainfall (correlation coefficient equals 0.83).

Table 1 The proportions of runoff components - Pra River Basin (after Darko, 2002)

Year	Discharge		Simulated runoff components (%)					
	Observed (Q_{obs})	Simulated (Q_{sim})	PRM	SUP	IMP	DIR	SUR	INT
1987	129.4	124.2	49.49	38.21	7.78	4.48	-	0.02
1988	116.5	109.0	53.15	36.47	6.70	3.62	-	0.04
1989	122.5	106.5	50.62	37.72	7.52	4.14	-	0.01
1990	74.8	71.0	52.52	33.63	8.66	2.19	-	0.01
1991	131.6	101.8	48.44	39.24	8.25	4.09	-	-
1992	72.3	80.4	54.83	35.45	7.41	2.25	-	0.01
Mean	-	-	51.51	36.79	7.72	3.46	-	0.02

Table 2 Results of recharge-runoff simulation - Pra River Basin (after Darko, 2002)

Year	Rainfall (mm)	Recharge (mm)	Regional groundwater resources (l/s/km^2)
1987	1492.6	61.5	1.9
1988	1288.5	57.9	1.8
1989	1374.1	53.9	1.7
1990	1165.7	39.4	1.2
1991	1378.5	49.3	1.6
1992	1179.9	44.0	1.4
Mean	1313.2	51.0	1.6

4 ESTIMATION OF THRESHOLD FOR GROUNDWATER ABSTRACTION

The statistical evaluations of specific capacity of the rocks that underlie the basin gave an estimated mean sustainable yield of 0.8 l/s, assuming an available drawdown of 5 m (Darko & Krasny, 2000). For this yield, the average output will be 10,500 m^3/yr, over a 10 hour per day pumping, 365 days per year.

If it is assumed that the yield is totally dependent on precipitation recharge, then an area of 0.2 km^2 will be required for its sustenance at the recharge rate of 50 mm/yr. This is equivalent to a recharge radius of only about 260 m around the borehole. Based on equivalent conditions and average aquifer characteristics for basement rocks, the cone of depression due to pumping could extend to at least 1000 m around the borehole (Houston 1988). Taking this minimum extent of the depression cone as the required zone around the borehole for recharge, the natural groundwater resources in the basin was estimated to support a maximum withdrawal of about 12 l/s for a 10 hour per day pumping. This is equivalent to 5 l/s for continuous pumping.

Except in special conditions, such as in zones of higher permeability where the rock permits the abstraction of larger quantities of groundwater, recharge is not likely to be a limiting factor for groundwater resources development from storage in the Pra River Basin. For regional groundwater resources assessment, the results obtained for the Pra Basin could be applied to other river basins in the South-West part of the country, which have similar climatic and hydrogeologic conditions. The relationships between permeability and aquifer replenishment should be taken into consideration in assessing the groundwater resources potential.

5 DISCUSSION

The quantification of groundwater recharge in crystalline formations is often fraught with problems of varying magnitude and hence substantial uncertainties. The balances between runoff to joints, hydraulic properties of materials in joints and evaporative losses coupled with topography and landforms, vegetation and land-use, as well as precipitation trends, pose considerable challenges for recharge estimates from hydrological analysis. Although the dangers of generalisations are obvious, in areas of shallow aquifers where the weathered zone forms the main groundwater reservoir, climatic factors could mask the different geological properties.

For a moist tropical environment with rainfall averaging 1400 mm per annum, the estimated recharge rate of 50 mm/yr appears to be rather low. It is noted however, that the Pra River Basin is one of the most urbanised basins in the country where substantial volumes of water are abstracted from the river for water supply to a number of communities and various industries. This impacted on the simulation where the side flow parameter (i.e. fraction of observed base flow that leaves the basin by non-channel subsurface routes) was set at 50% in order to attain model stability. The recharge rate should therefore be considered as the minimum.

It is obvious that longer data length will be required in any comprehensive assessment of recharge. Since the necessary data for such evaluations are rarely available, it becomes important to apply a variety of techniques for cross checks and references. In addition, because rainfall is more frequently documented, detailed investigations into rainfall as input into the hydrologic cycle could lead to a greater insight into potential recharge patterns. As more data and improved techniques become available, groundwater resources assessment as an iterative process would be much enhanced.

Recharge estimated by different methods from other areas of identical basement rocks also gave similar results. Muralidharan et al. (1988) reported a mean recharge value of 42.5 mm or 5 % of average rainfall for the Vedavati basin in India, which is underlain by granites, gneisses and schists, using the leaky aquifer concept. The same results had also been obtained from tritium injection studies. Houston (1988) carried out investigations on basement rocks in Zimbabwe, which included river base flow analysis, chemical analysis of groundwater and simulation modelling. All the three methods produced consistent results suggesting that recharge to the weathered aquifers amounted to 2 - 5 % of annual rainfall. Using a lumped parameter hydrologic model, Thiery (1988) also obtained an average recharge of 3.3 - 6.5 % of annual rainfall into the fractured granites of Burkina Faso.

6. CONCLUSIONS

The water balance and recharge components of the Pra River basin in Ghana have been discussed in the paper and the main conclusions are:

(a) The potential base flow components constituted approximately 90 % of total runoff;
(b) The long-term base flow (primary base flow) represented an average of 50 %;
(c) The mean annual recharge rate was 50 mm;
(d) The natural groundwater resources in the basin was estimated to support a maximum withdrawal of 12 l/s for a 10 hour per day pumping;
(e) The natural groundwater resources potential was 1.6 l/s/km^2; and
(f) The groundwater resources potential would be sufficient to sustain a threshold yield of 5 l/s.

The above conclusions will be the case for most rocks in South-West Ghana, where permeability and aquifer replenishment could be the limiting factors on groundwater development. For regional groundwater resources assessment, the results could be extended to other river basins in South-West Ghana.

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