FLUID FLOW INTERACTIONS IN OGUN RIVER, NIGERIA

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ABSTRACT

Surface and groundwater interaction is an important aspect of the hydrologic cycle that borders on the watershed assessment, protection and restoration. In groundwater/surface water interactions, the groundwater component is much greater than the surface water but is much less visible and attracts less public interest. The mixing between surface and groundwater enables them to import their characteristics upon one another thereby counting a change in their parameters. Groundwater interacts with surface water in nearly all landscapes, ranging from small streams to major river valleys. Many scientists have studied the physical aspects of groundwater/surface water interactions, but it is in recent times that these interactions have been looked upon in relation to their ecological implications. With the coming of a more holistic approach to environmental flows and environmental protection, surface water/groundwater (SW/GW) interactions should receive heightened attention at multidisciplinary scale and more so, by policy makers and watershed managers. It is generally understood in conceptual form that surface water therefore has the ability to enhance or detract from groundwater quality and vice versa, yet little is known about the processes by which these two entities interact (Gardener, 1988). In the past, emphasis has been placed on studying the physical and chemical effects that groundwater has on surface water but it is also important to look at the ecological role surface water and groundwater interactions can play in maintenance of environmental flows in a river basin. In area where surface water and groundwater directly interacts, the important issue commonly raised in recent times are not only concern with water quality but related with ecology and biodiversity. Therefore, there is a need for thorough understanding of the surface water and groundwater interactions within catchments so as to enhance the sustainable development and management of water resources system. The analytical technique discussed in this paper is an aid to assess the relationship of surface and subsurface hydrology to enlighten a broad audience on the importance of this relationship to environmental flow regulations. The target goals of this paper includes making a case for environmental flows in planning for water allocation and to gain the attention and create awareness that will support future research in environmental flow assessments.

INTRODUCTION

The Ogun river basin in located in southern Nigeria, bordered geographically by latitudes 6^o 26' N and 9^o 10'N and longitudes 2^o 28'E and 4^o 8 'E. About 2% of the basin area falls outside Nigeria in the Benin Republic. The land area is about 23,000km^2. The relief is generally low, with the gradient in the North-South direction. Ogun river took its source from Igaran Hills at on elevation of about 530m above the mean sea level and flows directly southwards over a distance of about 480km before it discharges into the Lagos Lagoon. The major tributaries of Ogun river are the Ofiki and Opeki rivers (Figure 1).

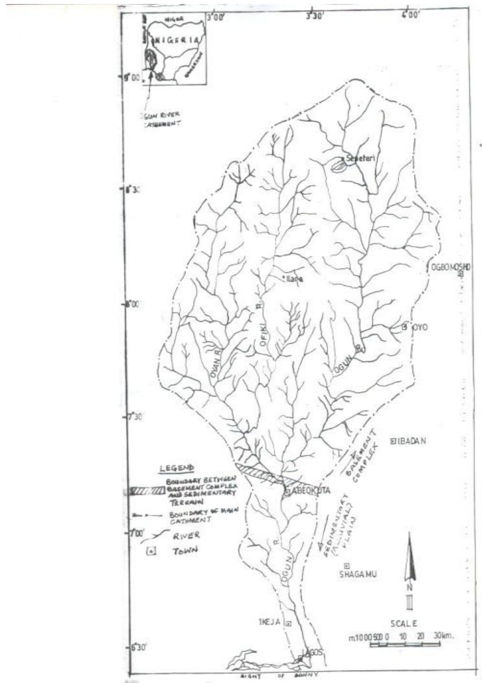


Figure 1: Ogun River Basin

Two seasons are distinguishable in Ogun river basin, a dry season from November to March and a wet season between April and October. Mean annual rainfall ranges from 900mm in the north to 2000mm towards the south. The estimates of total annual potential evapotranspiration have been put between 1600 and 1900mm.

The two major vegetation zones that can be identified on the watershed are the high forest vegetation in the north and central part and the swamp/mangrove forests that cover the southern coastal and flood plains, next to the lagoon.

The geology of the study area can be described as a rock sequence that starts with the Precambrian Basement (Jones and Hockey, 1964); which consists of quartzites and biotite schist, hornblende-biotite, granite and gneisses. The foliation and joints on these rocks control the course of the rivers, making them to form a trellis drainage pattern, particularly to the north of the study area. The sedimentary rock sequences are from Cretaceous to Recent; the oldest of them, the Abeokuta formation, consists of grey sand intercalated with brown to dark-grey clay. It is overlain by Ewekoro formation, which typically contains thick limestone layers at its base. About 9km upstream of Abeokuta town, there is a sharp change in land gradient thereby changing the river morphology from fast flowing to slow moving thereby leading to the formation of alluvial deposits overlying the sedimentary formation of Ewekoro, Ilaro and Coastal plain sands in sequence towards the Lagos Lagoon.

MATERIALS AND METHODS

Ogun river basin can be divided into two parts; a high slope (average 15%) terrain marks the upper zone (section I) while the lower zone (section II) is of extremely low slope (< 1%) characterized by flooding with marshes and swamps. This study covers the lower part of Ogun river where the morphology of the river has entered the mature state. The study was carried out on the site of Ajambata Floodplain irrigation project. The depths of rising floods were monitored throughout the year and the maximum depth (stage) was recorded. After recession, the depth of water in the river channel was monitored with the static depth of water in the tube-wells that were drilled on the site. Data on the tube-wells (including hydraulic conductivity, aquifer thickness and the tube-well lithology) were obtained from the project engineers.

HYDRAULICS OF SURFACE WATER /GROUNDWATER INTERACTION

High land slope encourage fast movement of rivers and so, the channels are narrow but deeply incised into the geologic formation. Ogun River flows over the solid rocks of the basement complex and has maintained a stable geomorphology since base rocks naturally armour the riverbeds. In the lower reaches after the geologic divide, the river flows slowly through a flatter terrain over alluvial plain.

Flow net model is used to determine the hydrologic interaction in the river-aquifer system along the river. Flow line is an imaginary line that traces the path that a particle of groundwater would follow as it flows though an aquifer (Fetter, 1994). The flow nets were constructed based on water table and river level measurements. Two sites were chosen for these measurements, one was located in the upper section of Ogun River while two was located at the lower section.

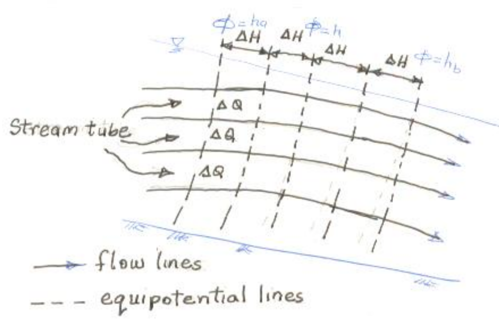


Figure 2: Flownet diagram

The following assumptions were made in the construction of the flow nets:

- The Soil structure is homogeneous
- The Soil and aquifer are fully saturated.
- The independent strata are isotropic.
- There is a steady state condition (no change in potential field with time).
- The Soil and water are incompressible
- The boundary conditions are known (depth of water in the river and the water table in the soil).

The upper section of the river continues to receive effluents from ground water thereby lowering the water levels in the vicinity, resulting in a loss of storage. This condition is maintained throughout the year, even during the dry season when there is no precipitation, the river discharge will be supported by discharges from the adjoining aquifer. The armoured riverbed is part of the impermeable layer as shown in figure (2).
A survey was carried out on the river channel to locate, measure, and sample the pools that were formed during the dry season. This was done to assess and account for areas that can be classified as ecotone (habitats) and the hyporheic (river and groundwater ecosystems) zones.
In the lower section where Ogun river channel flows through an alluvial plain that is the water table aquifer (Fig 3.). This case is treated as a one-dimensional and transient groundwater flow problem (Polubarinova–Kochuna 1962), since the shape of the water table is a function of time. Darcy's equation of groundwater flow is applied with the earlier assumptions so as to take account of the water volumes moving into or discharged from the aquifers.

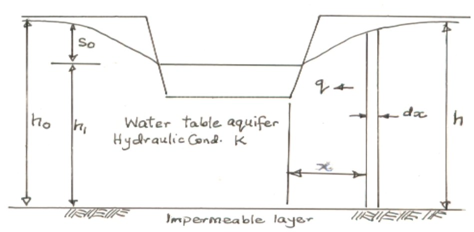


Figure 3: Schematic Diagram of Water Table Aquifer intercepted by Ogun river channel.

The flow q through the depth h for a unit length of river channel from one side, according to Darcy's law, is:

$$q = KiA = Kh\frac{\partial h}{\partial x} \quad \text{………………………………….(1)}$$

Where

q = flow rate intercepted by the river channel per unit length from one side.
K = hydraulic conductivity of water table aquifer
i = hydraulic gradient
A = cross sectional area of the porous medium normal to the direction of flow.
h = saturated depth above an impermeable lower boundary
x = distance measured from the river channel.

The accumulation of flow in the element dx during the time dt is:

$$\frac{\partial q}{\partial t}(dx)(dt) = K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right)(dx)(dt) \quad \text{……...……………….......................… (2)}$$

The continuity requirement that the flow intercepted by the canal must be consistent with the rate of fall of the water table, is:

$$\frac{\partial q}{\partial t}(dx)(dt) = n\frac{\partial h}{\partial t}(dt)(dt) \quad \text{………..……………………………………… (3)}$$

Where

n = effective porosity of water table aquifer

Equating equations (2) and (3), a non-linear partial differential equation for the flow of water intersected by the river is formulated as:

$$K\frac{\partial}{\partial x}\left(h\frac{\partial h}{\partial x}\right) = n\frac{\partial h}{\partial t} \quad \text{……………………………..…………………………………. (4)}$$

Subject to the following initial and boundary conditions:

$h = h$o, for $x > 0$ when $t = 0$ …………………….……………. (5)
$h = h$i, for $x = 0$ when t > 0 …………………….………… (6)

To avoid difficulties imposed by the non-linearly, the basic differential equation, equation (4) is linearised by letting

$$h = h_1 + s \quad \text{…………………..…………………………………………(7)}$$

Where

s = the depression of water table measured from the bottom of the river channel, and;
h_1 = depth of saturated thickness at the vicinity of the river.

By assuming that *s* small compared to hi equation (4) can be simplified to;

$$Kh_1\frac{\partial}{\partial x}\left(\frac{\partial s}{\partial x}\right) = n\,\frac{\partial s}{\partial x} \qquad \text{(8)}$$

Or

$$\alpha\frac{\partial^2}{\partial x^2} = \frac{\partial s}{\partial t}$$

Where

$\alpha = K\frac{h_1}{n}$ = the aquifer constant which can be determined by field tests

The boundary conditions required to satisfy the field test are:

$s = s_o$, for $x > 0$ when $t = 0$ …………………… (10)
$s = 0$, for $x = 0$ when $t > 0$ …………………… (11)

Wang and Overman (1978) introduced an analytical solution, which can be expressed in the form of error function;

$$s = s_0\frac{2}{\sqrt{\pi}}\int_0^u e^{-u^2}\,du \qquad \text{(12)}$$

Where

$$u = \frac{X}{\sqrt{4\alpha t}} \qquad \text{(13)}$$

The validity of the expression, s, which satisfies both the differential equation and boundary conditions, is given elsewhere (Wang and Overman, 1978).

The flow rate q of groundwater at $X = 0$ is computed approximately as:

$$q = Kh_1\frac{\partial s}{\partial x}\Big|_{x=0} \qquad \text{(14)}$$

Differentiating equation (12) and substituting into equation (14), we obtain:

$$q = Kh_1\frac{s_0}{\sqrt{\pi t}} \qquad \text{(15)}$$

The flow *f* intercepted by the river channel (per unit length along the channel) from one side, between 0 and t is:

$$f = \int_0^t q\,dt = 2Kh_1 s_0\sqrt{\frac{t}{\pi\alpha}} \qquad \text{(16)}$$

Then, the total flow *F* intercepted by river channel from both sides, per unit length along it is:

$$F = 2f = 2s_0 n\sqrt{4\alpha t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

For the purpose of this analysis, it can be viewed that as the flood recedes and flow in confirmed to the river channel, the river channel assume the role of a drainage canal as soon as water level starts to drop in it. The alluvial soil becomes a surface aquifer that will start to lose groundwater into the river. From the field investigation that was carried out in Ajambata, on the eastern side of Ogun river it was observed that the average depths of the tube-wells were 15m. The data collected on the field that was used in the analysis included the following:

h_0 = depth of the semi – permeable (sandy clay) layer below the aquifer
K = permeable of aquifer
n = effective porosity of the aquifer
s_0 = water table drawdown at the river channel
α = aquifer constant = $K(h_0 - s_0)/n$
t = time step (one month) at which drawn down is monitored

The expression $I = \frac{2}{\sqrt{\pi}}\int_0^u e^{-t^2}\,dt$ is termed the probability integral which can be read from the available statistics (Glover, 1974).

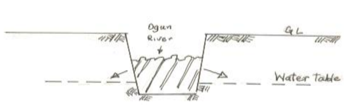
Therefore, equation (12) becomes:

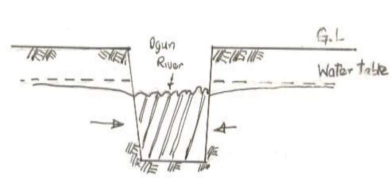
$$s = s_0 I$$

There are seven wash bores (or tube wells) used to determine the water level gradient between Ogun river and the farm plots (Fig 5). The data collected from the field and those given by projects engineers were used to compute the quantity of discharge into the river and the water table drawn-down in the aquifer.

RESULTS

The flownets analysis for upper and lower sections of Ogun river showed that there is considerable amount of groundwater flow. This study revealed an intricate groundwater flow pattern that is controlled by lithological and structural factors that creates zone of surface and ground water interaction. These zones are often referred to as ecotone zones within the hypoheic ecosystems. Hence, the relations of aquifers in each zone along the river channel were identified based on pore space, fracture media and sediment materials deposited. Section I is characterized by groundwater discharge to the river from the adjoining aquifers while Section II is characterized by both the recharge into the aquifers and discharge from the aquifers at different period. The head in the aquifers relative to the elevation of the river surface determines whether the section of the river is gaining or losing water to groundwater at a particular time. The head of the water table in the aquifers must be higher than the elevation of the river surface for groundwater to contribute to surface water. For surface water to enter into groundwater through the aquifers, the reverse must be the case. The effluent stream (gaining) condition is when the river receives groundwater discharge and the influent stream (losing) condition when the water table is lower that the river surface elevation. Isolated pools occur on the river beds during the dry season (December to April) and the ones located close to the river bank were observed to contain large quantities of aquatic flora and fauna. At this stage, Ogun river is in effluent condition so the flow is maintained by groundwater discharge. At a stage the influent condition is reached at the peak of the dry season when the pools even lose water into the ground. These pools have an average surface area of 52m^2 and there are 11.3 pools per kilometre length of the river channel. Results from calculation revealed that about 11.5m^3 of water is discharged per meter length from the aquifer into Ogun river channel.





(a) Influent condition (b) Effluent condition

Fig. 4: Schematic Diagram of Ogun River Channel under different conditions.

DISCUSSIONS

The river channel in the upper section cut through the basement rocks on areas where the shallow aquifer is the within 5m of land surface. Therefore, there is a direct hydraulic connection between the river system and the upper portion of the shallow aquifers. This has encouraged fast depletion of groundwater due to rapid loss through the bottom of the channel. As cessation of rainfall starts (that is, time between rainfall events start to increase) in the month of November, the river discharges starts to decrease but can only be sustained by groundwater discharge. The low flow condition in the river (by December) makes the water level in Ogun River to drop to a level that the rocky bottom is exposed. At the lower section of Ogun River, there is continuous interaction between the aquifer and the river channel. This confirms that there is a hydrodynamic interaction of surface and groundwater in the river sections. It is evident that surface water bodies are integral parts of groundwater flow systems. Generally, it is assumed that groundwater is recharged from areas of high elevation and discharged at lower areas; this may be true primarily for regional flow systems. Complex interactions between surface water and groundwater exist as a result of the surface water bodies being associated with the entire local flow systems. Seasonally high flows with dynamic groundwater flow fields associated with surface water, evaporation and transpiration of groundwater from the immediate environment of surface water bodies are the causes of the complexity. Some researchers have suggested that surface water - groundwater interactions may potentially occur up to 2 kilometres from a river channel (Stanford et al, 1994, Gibert *et al* 1997). The problems brought about as a result of interconnection of surface water and groundwater heavily burdens the ecotone that exists in the hyporheic zone. When surface water recharges groundwater, there is opportunity for organic pollutants and detritus to become trapped in the sediment. But Gibert *et al* (1997) found that, while the organic pollutants and detritus remain trapped, sediment bacteria may catalyse reactions that could change the chemicals into a less toxic form or could transform the chemicals into available nutrients. Therefore, many bacterial micro-organisms residing in groundwater aquifers and sediment interstices can carry out some de-nitrification and degradation. The nutrients produced from these organic processes usually boost the pools that are formed on the riverbed during low flows when the groundwater is discharged into the river. To alleviate problems of low flows, the water allocation plan for the watershed should incorporate environmental flow considerations. This would improve the condition of Ogun river during the dry season so that ponding will be eliminated from the river channel while the ecology of the area will be sustained.

CONCLUSIONS

Surface water - groundwater interaction can be investigated by using flow-nets and hydrodynamic methods. Research that will cover the ecological aspects can only be carried out through methods of the measurement that are extremely complex, resources intensive and also require extensive technical knowledge. Present efforts presented in this paper have clearly elucidated the importance of hydrodynamic studies of surface water and groundwater interaction. The approach used in this study can be used as a base water resource management model especially, for conjunctive use of surface water and groundwater in Ogun river basin. Geographical information systems (GIS) software can be found useful in cataloguing data and provide spatial and temporal analysis that can yield results that would be displayed as maps, table and reports. Future planning for water resources management should utilize extensive data and GIS software and incorporate environmental flow regulations.

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