Vegetation Driven Groundwater Recharge Below the Okavango Delta (Botswana) as a Solute Sink Mechanism – An Indicative Model

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Abstract

The mean inflow, both surface flow and rain, into the Okavango Delta (Botswana) is about 16 billion m^3yr^{-1}. Approximately 96% of this returns to the atmosphere by evapotranspiration, only 2% leaving the Delta by surface outflow through the Thamalakane and Boteti Rivers. The remaining 2% is thought to infiltrate into the groundwater below the Delta. The solute content of the surface outflow, however, is lower than expected from water mass balances. The Delta therefore acts as a solute trap under present climatic conditions.

Several studies outline the role of transpiration from island vegetation in this respect. Due to transpiration solutes accumulate on or near the surface of the islands, initially destroying the vegetation at the centre, but finally poisoning the entire marginal fringe.

This paper describes the results of conceptual groundwater flow models and computer simulations of solute transport. These models suggest that groundwater density flow below the island centres may be one of the contributing factors to the solute sink mechanisms operating in the Delta. The models indicate a possible route of solutes to the deeper groundwater and suggest an unusual recharge mechanism.

1. Introduction

The confluence of the Angolan rivers Cubango and Cuito at the Namibian–Angolan boundary west of the Caprivi Strip (Fig. 1) marks the beginning of the Okavango River which enters Botswana at Mohembo. After flowing through a narrow swamp, the Panhandle, confined on both sides by high shoulders of Kalahari sand, the river spreads out into a delta-shaped system of swamps and distributary channels covering an area of 6000 to 13 000km^2, depending on prevailing floods and precipitation. The Okavango

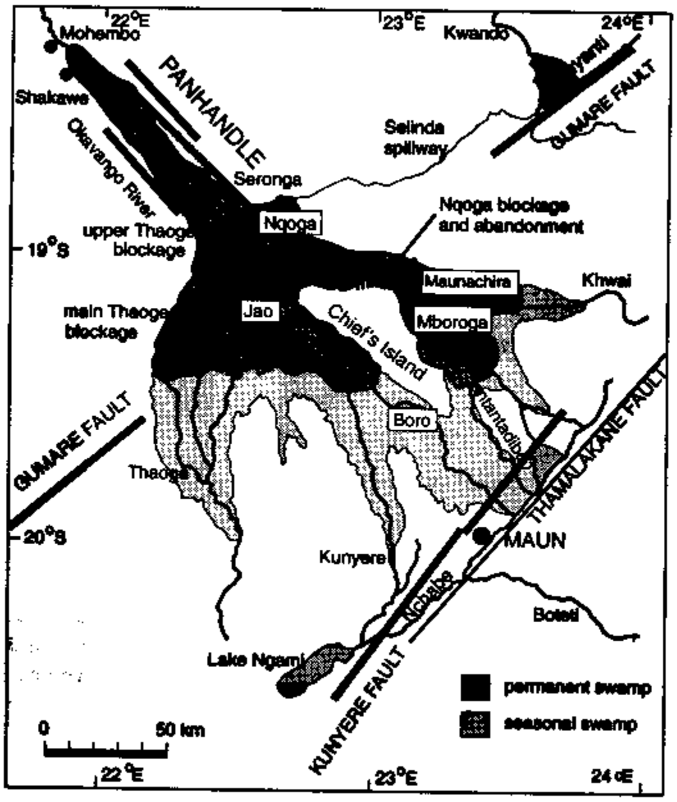
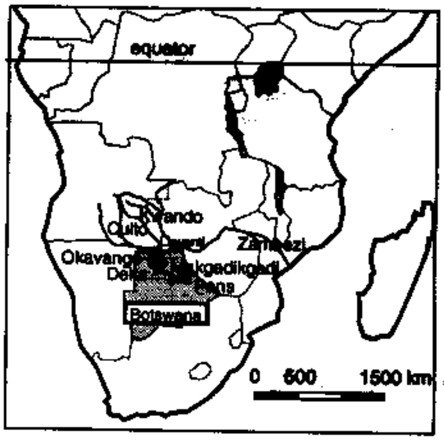


Fig. 1 The Okavango Delta in Botswana (after UNDP/FAO, 1977 and Hutchins et al., 1976)

Delta is drained at its distal end by the Thamalakane and Boteti Rivers through which the remaining water is carried towards the Makgadikgadi Pan, the lowest point of the Kalahari Basin.

Despite the extremely flat relief, the distribution of water in the Delta is controlled by a northeast trending fault system, the Gumare, Kunyere and Thamalakane Faults. The concentration of seismic activity along these faults (Hutchins et al., 1976) indicates that rifting in an extension of the East African Rift continues. The system has been described by McCarthy (1992) as a half-graben dominated by Okavango sedimentary deposits. Older alluvial deposits also occur in areas adjacent to the present Delta (Thomas and Shaw, 1991) and geomorphological evidence indicates that the Okavango Delta was once part of Lake Palaeo-Makgadikgadi which reached an area of over 120 000km^2 at its Quaternary maximum.



In the Panhandle, water is carried through a meandering but fairly stable river system. Below the Gumare Fault, however, the Okavango river water is distributed through the swamps by a complex network of ever-changing channels and floodplains, usually subdivided into perennial and seasonal swamps (McCarthy, 1992). The Botswana Department of Water Affairs has recorded river flow at Mohembo since 1933, and the outflow at Maun since 1969. Moreover, a network of water level gauges was installed in the Delta in various channel systems. Average annual inflow at Mohembo is 11 billion m^3 while the average outflow at Maun is in the order of 300 million m^3. Since inflow by precipitation is about 5 billion m^3, the Maun outflow corresponds to about 2% of the input. Based on a surface water balance study in a small catchment in the seasonal swamps (UNDP/

FAO, 1977) it was estimated that about 2% leaves the Delta by groundwater flow and total evapotranspiration is therefore thought to be close to 96%. Flood peaks in Mohembo generally occur in April but may vary according to rainfall patterns in the upper Angolan catchment. River stage levels at Maun usually peak in August, five months later than at Mohembo. Detailed studies of the swamp's hydrology were made by SMEC (1987), Porter and Muzila (1989) and a recent analysis of the available material was made by the IUCN (1992) while the results of the Witwatersrand University research group were reviewed by McCarthy (1992). Recently a new outflow model was proposed by Gieske (1996, 1997)

Sedimentation can be considered in terms of solute, flotation, suspended and bedload components (Thomas and Shaw, 1991). Although the last three of these undoubtedly play a crucial role in channel evolution and Delta geomorphology, the role of solutes is receiving increased attention, as salt concentrations in the outflow are rather low given the total evapotranspiration. It was estimated by SMEC (1987) and McCarthy and Metcalfe (1990) that about 400 000 tonnes of chemical sediments accumulate in the Delta annually. Studies by McCarthy et al. (1991) have indicated that concentration and precipitation of salts such as calcite, trona and thermonatrite in groundwater below islands and on island surfaces may be one of the reasons for low main channel solute loads. As more data on major ion chemistry of the Delta's surface water system are being obtained (Cronberg et al., 1995), better quantitative modelling of these solute transport processes will become possible. This paper concentrates on some modelling aspects of surface-shallow groundwater interactions, especially in relation to the islands in the Delta.

2. Islands

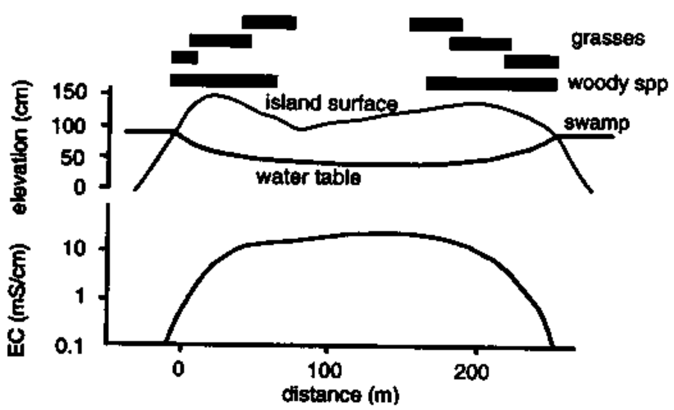


Fig. 2 Water table and electrical conductivity below islands in the Delta after McCarthy et al. (1994).

The Delta islands range in size from several metres to over 50km. They may be round, linear, sinuous or irregular. Some small islands are almost certainly abandoned termite mounds (McCarthy, 1992) whereas long sinuous islands are probably former channel beds or point bar deposits. Other islands, especially in the lower Delta, may have originated as sand dunes. However, irrespective of shape, islands (Fig. 2) are usually fringed by a zone of broad-leafed evergreen trees, giving way to deciduous trees and palms and eventually to sparse grassland, or even to bare soil in the island interior (McCarthy and Ellery, 1994). This zonation results from shallow groundwater chemistry below the islands, as electrical conductivity (EC) usually increases from less than $100\mu Scm^{-1}$ in surface water to more than $10\ 000\mu Scm^{-1}$ in groundwater below the islands. These salinity gradients are believed to be caused by transpiration. Although water level fluctuations are higher in seasonal than perennial swamps, these salinity gradients with resulting vegetation zonation have also been found in seasonal swamps (McCarthy et al., 1994). The water table below the islands in the perennial swamps is about 50cm below the water level of the surrounding Delta. The same holds for the islands in seasonal swamps when flooded.

Transport of solutes towards the centre of islands is complex and its mechanism remains unclear. Surface waters are dominated by silica and bicarbonates of Ca, Mg, Na and K. As concentrations increase, calcite and silica precipitate first, causing the edges of the islands to rise, leaving a depressed interior below which the groundwater contains the more soluble components. Occasionally highly saline pools form in the centre. A surface crust of trona is quite common (McCarthy et al., 1991).

3. Hydrogeological Models Without Solute Transport

Assuming a homogeneous unconfined aquifer of constant depth H below a one-dimensional island with infinite length, the simplest steady state model can be described as a depressed water table due to constant evapotranspiration (Fig. 3). Diffuse recharge by rain is here under the prevailing climatic conditions much less than the evapotranspiration E and can be neglected. The salinity gradients are ignored here (see later). Assuming Dupuit conditions, flow is governed by the continuity principle and Darcy's Law leading to:

$$q = -Ex \ (E \text{ is taken as positive})$$

$$q = -kh\frac{dh}{dx} \tag{1}$$

where k is the hydraulic conductivity and L the length from the centre of the island to the edge. Solving this set of equations leads to:

$$h^2 = H^2 + \frac{E}{k}(x^2 - L^2) \tag{2}$$

which, if the saturated thickness H is much larger than Δh (the depression of the water table), can be further simplified to:

$$\Delta h = \frac{E}{2T}(x^2 - L^2) \tag{3}$$

where T is the aquifer transmissivity (T=kH).

Similar formulae may be found for radial symmetry, i.e. the case of a circular island:

$$h^2 = H^2 + \frac{E}{2k}(r^2 - R^2) \tag{4}$$

where R is the radius of the island. Simplifying Eqn (4) as in Eqn (3) leads to:

$$\Delta h = \frac{E}{4T}(r^2 - R^2) \tag{5}$$

Other cases may also be solved in this way. For example, the case where evapotranspiration occurs only between r=R and r=R leads to a lowering of the water table in the centre given by:

$$\Delta h = \frac{ER^2}{T}\left[\frac{\ln 2}{8} - \frac{3}{16}\right] = \frac{ER^2}{10T} \tag{6}$$

Although it would be possible to solve more complicated cases analytically using general flow equations, numerical schemes would in that case generally be more convenient to handle.

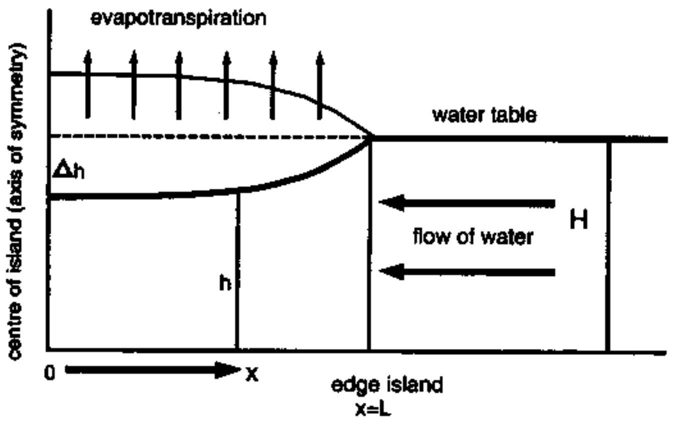


Fig. 3 Conceptual hydrogeological model with horizontal flow according to Dupuit assumptions, without solute transport.

The importance of these simple solutions is that they show the direct proportionality between evapotranspiration E and transmissivity T, given a particular water table and island configuration. T values obtained through traditional well testing, may thus lead to better quantification of the elusive E values. Determination of transmissivity and conductivity values of aquifers below islands is therefore an important aspect in assessing their water balance and long-term role in trapping solutes.

A typical calculation can be made with the following parameters. Suppose the average E is $2000 mmyr^{-1}$ (or $0.0055 mday^{-1}$) which is the characteristic PET value for the climatic conditions around Maun. Suppose further that $\Delta h = 0.5m$ (for $r=0$) and that $R=100m$. It then follows, using (5), that $T=27 m^2day^{-1}$ which can be verified by well test analysis.

4. Solute Transport Modelling

The SUTRA package (Voss, 1984) was used to obtain an idea of solute transport and the effect of salinity gradients. This computer programme is primarily intended for finite-element two-dimensional simulations of groundwater flow, energy or solute transport in both saturated and unsaturated zones. Although it only allows the simulation of a single ionic species, it has been applied successfully to seawater intrusion problems. Sources, sinks of solutes and density changes due to changing concentrations which affect flow patterns, may also be taken into account. This last characteristic is of particular interest to the problem of groundwater flow below islands in the Delta. Although the main simplifying assumption is the restriction to transport of a single species, other assumptions are also required (listed in Table 1 together with the main model parameters).

A circular island with a radius of 130m in the seasonal swamps (McCarthy and Ellery, 1994), was adopted as an example to illustrate the influence of density changes on groundwater flow patterns. It was assumed that transpiration of $2 myr^{-1}$ (the PET value in the region) occurs in a margin from 80 to 130m. The aquifer thickness was arbitrarily taken as 30m and hydraulic conductivity as $1 mday^{-1}$, resulting in a T value of about $30 m^2day^{-1}$. With Eqn (6) this leads to a steady state depression of about 30cm in the centre of the island, roughly in accordance with the observations by McCarthy and Ellery (1994).

Porosity, fluid and matrix compressibilities were estimated; precise values are not crucial in the steady state groundwater flow problem described here. Longitudinal and latitudinal dispersivities are more important but no field data are available. The values adopted are the author's best guess at present! Density change as a function of solute concentration has been derived from McCarthy et al. (1991) and is in the order of $1000 kgm^{-3}$

Table 1. SUTRA Model Parameters and Assumptions

radius island	130m (island from McCarthy et al., 1994)
vegetation	80–130m (about 60% of islands covered with vegetation)
evapotranspiration	$5 mmday^{-1}$ (corresponds to about 2 m per year)
aquifer thickness *H*	30m (estimate, no data)
permeability *k*	1×10-12 m^2 (corresponds to about 1 $mday^{-1}$)
transmissivity *T*	$T = kH = 30\ m^2day^{-1}$
porosity/specific yield	0.2 (estimate based on grain size distribution)
fluid compressibility β	4.47×10^{-10}
matrix compressibility α	estimated to arrive at storativity $S = \rho g(\alpha + \xi\beta) = 0.2$
effective diffusivity *De*	$\approx 1 \times 10^{-9}\ m^2s^{-1}$
longitudinal dispersivity	10m (depends on aquifer heterogeneity, no data)
transversal dispersivity	1m (commonly used ratio, no data)
density ρ_0	$1000 kgm^{-3}$
density change with TDS	1000 after McCarthy et al. (1991), for sea water commonly 700
viscosity μ	$10^{-3}\ kgm^{-1}s^{-1}$
production/decay of solutes	precipitation of trona, calcite, etc near surface ignored
reaction/adsorption processes	ignored

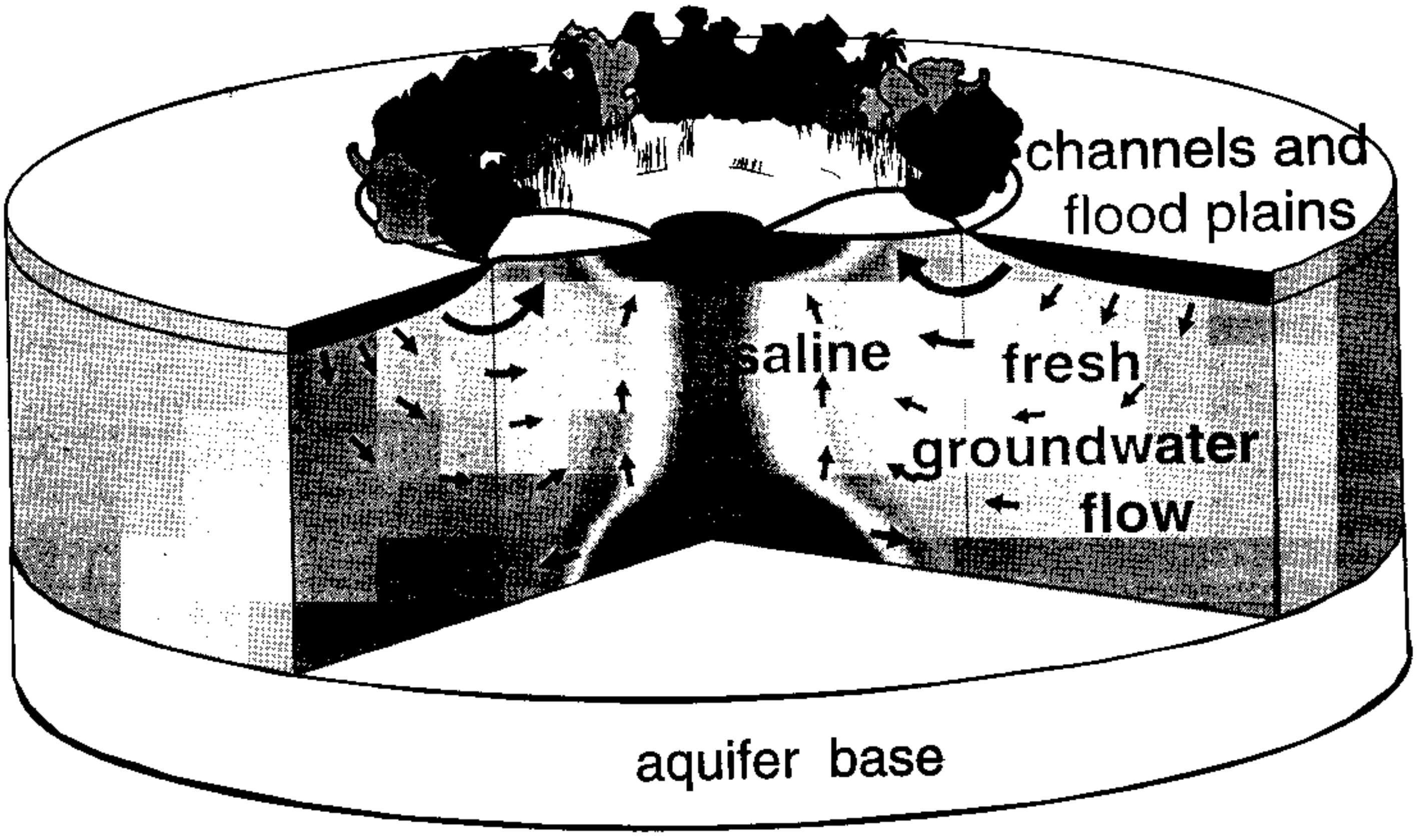


Fig. 4 Modelling of density-dependent saline groundwater flow with SUTRA, showing downward flow of saline water in the centre of a conceptual circular island. Further from the centre upward flow occurs with mixing of saline and fresh groundwater. A saline pool is shown in the centre. Pools of this type only occur occasionally.

per unit increase in mass fraction (for seawater $700 kgm^{-3}$ is normally used). Precipitation and reaction/adsorption processes have been ignored. Finally, it was assumed that the groundwater initially contains 100ppm of solutes and that swamp surface water always has a constant solute concentration of 100ppm.

Fig. 4 illustrates the flow pattern emerging after 18 years of simulation with time steps of 12 days. The inflow of swamp water leads to downward flow of saline water in the centre with concentrations in the order of 25 000ppm. Downward velocity in the centre was found to be in the order of $3\ myr^{-1}$. Surprisingly, a little distance away an upward flow component was found with a velocity of $0.3 myr^{-1}$. The strong flow due to transpiration at the island margin seems to whip up a saline groundwater flow vortex in the centre. It was also found that solutes at the bottom of the aquifer spread from the centre outwards, slowly increasing the salinity at depth. Although one should be extremely careful in assessing these preliminary results in view of the lack of reliable aquifer information, results seem to indicate a long-term solute trapping process as already suggested by McCarthy and co-workers. Modelling also shows that, when the floods recede, the denser column of saline water in the centre continues to subside, to be replaced by fresher water near the surface.

5. Discussion

These simple flow models have shown the relation between evapotranspiration E and transmissivity T. Hydrogeological investigations of aquifers below the Delta islands would thus contribute to a better understanding of water balance components. To improve such models it is also necessary to determine both horizontal and vertical conductivities in order to take aquifer anisotropy into account. It is important to continue with a programme of systematic groundwater level measurements below the islands. Response of groundwater levels to advancing and receding floods may make transient flow modelling possible which will give better insight into aquifer properties.

Solute transport modelling tentatively confirms downward density flow below the centres of islands, providing a stable mechanism for solute transport from the surface to the deeper groundwater. This transport process may be viewed as a recharge mechanism. Unfortunately such groundwater recharge would be very small. If groundwater with solute concentrations of over 20 000ppm has ultimately evolved from surface water of 100ppm then the concentration factor would be over 200. This leads to recharge percentages of less 0.5% as opposed to the 2% estimated by UNDP/FAO (1977). This latter figure was arrived at through a surface water balance study at only one location in the Delta. The crucial hydrogeological problem is where this groundwater recharge component would be going to, because hydraulic gradients and aquifer transmissivities in the region are far too small to explain outflow in the order of $3.2x10^8 m^3yr^{-1}$ (2% of the total inflow) over large distances.

With respect to solute transport modelling, it is clear that more data are needed on aquifer characteristics before valid quantitative conclusions can be drawn with respect to overall water balances, flow velocities, island evolution and stability. Determination of all parameter values listed in Table 1 for only a few islands would constitute a valuable and long-term hydrogeological and hydrogeochemical research programme.

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