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Conceptual modelling of groundwater–surface water interactions in the Lake Sibayi Catchment, Eastern South Africa

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ABSTRACT

Lake Sibayi, a topographically closed fresh water lake in northern KwaZulu-Natal, South Africa, and coastal groundwater aquifers surrounding the lake, are important water resources and are used extensively for domestic water supplies. Both the lake and groundwater support important and ecologically sensitive wetland system in the area. Surface and subsurface geological information, groundwater head, hydrochemical and environmental isotope data were analysed to develop a conceptual model of aquifer–lake interaction, upon which a three dimensional numerical model will be based. Local geologic, groundwater head distribution, lake level, hydrochemical and environmental isotope data confirm direct hydraulic link between groundwater and the lake. In the western section of the catchment, groundwater flows to the lake where groundwater head is above lake stage, whereas along the eastern section, the presence of mixing between lake and groundwater isotopic compositions indicates that the lake recharges the aquifer. Stable isotope signals further revealed the movement of lake water through and below the coastal dune cordon before eventually discharging into the Indian Ocean. Quantification of the 15 year monthly water balance for the lake shows strong seasonal variations of the water balance components and average residence time of water in the lake is about 7.5 years. Recent increase in rate of water abstraction from the lake combined with decreasing precipitation and rapidly increasing pine plantations appears to be responsible for lake level reduction which would have dramatic negative effects on the neighbouring ecosystem and a potential seawater invasion of the coastal aquifer.

1. Introduction

South Africa is a semi-arid country where water is scarce and therefore, water resources need to be managed in a sustainable manner (Davies et al., 1993). The South African National Water Policy recognises that water resources cannot be managed in isolation and that development and use thereof is undertaken in a way that is sensitive to the environment (Kelbe et al., 2001; Kelbe and Germishuyse, 2010). In rural settings, development and effective management of water resources is essential, particularly with respect to rural water supply, which serves as a means of poverty alleviation especially in previously disadvantaged communities (Mkhwanazi, 2010). Water has long been recognised as a fundamental element in the fight against poverty, the cornerstone of prosperity, and its shortage can be a limiting factor to growth (Basson et al., 1997).

Lake Sibayi, the largest inland freshwater lake in South Africa, is a popular tourist destination and is exploited for urban and rural water supply (Allanson, 1979; Meyer et al., 2001). Lake Sibayi forms part of the iSimangaliso Wetland Park which has been given UNESCO World Heritage Site status and is classified as one of the RAMSAR Convention Wetlands of International Importance (RAMSAR Site #528) (Obura et al., 2012). The lake is therefore a vital source of fresh water for the ecology and local community, and is often the only source of water for certain animals during periods of drought. Historically, the inflow and outflow components of the Lake Sibayi system have been in dynamic equilibrium. Surface runoff, groundwater recharge and precipitation on the lake have, on an annual basis, been balanced by evaporation from the lake and groundwater outflow to the sea, resulting in relatively constant lake levels. In recent years, significant development has occurred around the lake, which has been brought about primarily through human settlement and land use change (Bruton et al., 1980; Combrink et al., 2011). These new developments are located within the lake's catchment, which does not fall within the conservation area, making conservation and management of the lake challenging. Catchment activities include commercial forestry, subsistence agriculture, and rural development particularly near the town of Mseleni. Groundwater abstraction from within the lake catchment and water abstraction from the lake for local community water supply have commenced in the last few years. This artificial abstraction from the lake and groundwater system, which recharges the lake, impact on lake levels and could potentially reverse the hydraulic gradient of

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groundwater around the lake, inducing saltwater migration from the sea to the lake's catchment.

Thus, in order to prevent permanent damage to one of South Africa's largest primary aquifers and salinization of the lake, it is vital that all the water balance components of the lake's system be quantified and the interaction of lake–groundwater understood. This study aims to report the current water balance of the lake, lake–aquifer interaction and the impacts of developments within the catchment on the lake.

1.1. Location of the study area

Lake Sibayi, a coastal freshwater lake, is situated on the seaward margin of the Maputaland Coastal Plain along the northern KwaZulu-Natal coastline of South Africa (Fig. 1). The lake falls within the Coastal Lake Zone proposed by Mountain (1990). This area is characterised by a chain of barrier lakes, lagoons and swamps, situated behind high vegetated barrier dunes. The lake is situated approximately 180 km north of Richards Bay and 60 km south from the Mozambique border, falling within the uMkhanyakude District Municipality. The rural towns of Mbazwana and Mseleni are located around the lake's periphery. Recent measurements show that the lake has an average surface area of 58 km^2 and a catchment area of approximately 450 km^2. According to WR90 (Midgley et al., 1994) and WR2005 (Middleton and Bailey, 2009), Lake Sibayi falls within the W70A quaternary catchment and W3E rain zone. The lake falls within DWA's Water Management Area 6, Usuthu to Mhlatuze, and within the Mkuzu Sub-water Management Area. According to the Atlas of Freshwater Ecosystem Priority Areas (FEPA) of South Africa reported by Nel et al. (2011), Lake Sibayi and the rivers feeding the lake and associated sub-quaternary catchment are classified as FEPAs. The lake and rivers are further classified as fish sanctuaries as they are home to critically endangered and endangered species of fish. Lake levels have dropped significantly over the last decade, dropping from approximately 20 m above mean sea level (amsl) to 16 m amsl at present.

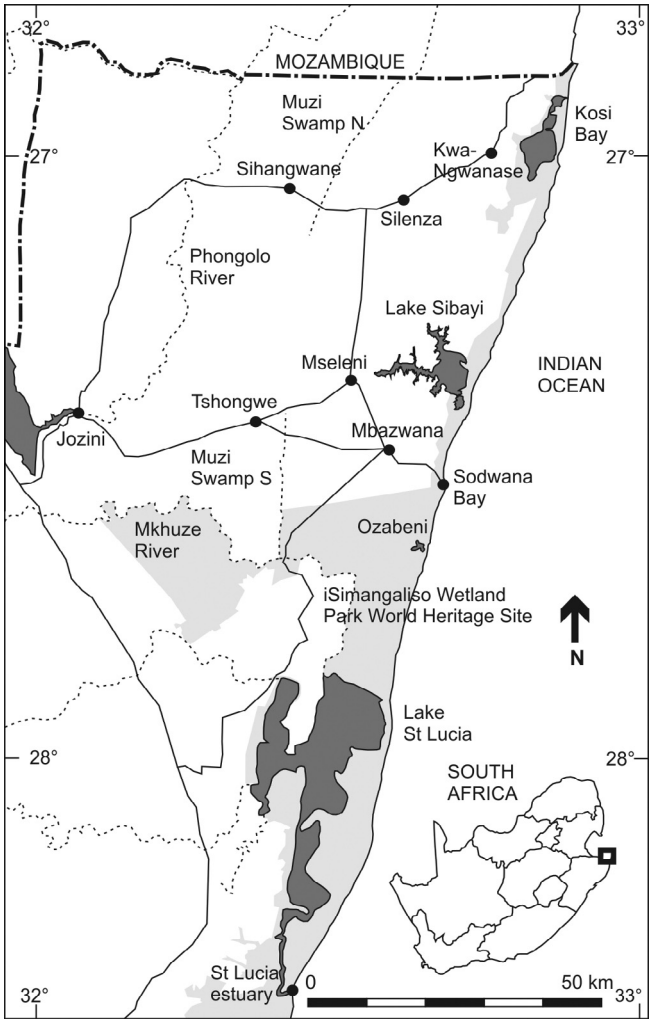

Fig. 1. Locality map showing Lake Sibayi with names of the main sites within the region. Major roads are shown as solid lines and major rivers as dashed lines. Note that the light grey shaded area indicates the iSimangaliso Wetland Park World Heritage Site.

1.2. Climate, drainage and hydrometeorological data

The region is characterised by a humid, subtropical climate with warm summer temperatures, dominated by the southern subtropical high-pressure belt (Hunter, 1988; Boucher, 1975). Rainfall in the area is derived from both tropical and middle latitude weather systems. The tropical influence results in easterly waves which advect warm moist air from the Indian Ocean in association with equatorial troughs and the Inter-Tropical Convergence Zone (ITCZ). Low-level convergence in the presence of unstable atmosphere produces frequent cumulus convective rainfall during the summer months (Kelbe et al., 2001). The vegetation of the area consist of a mosaic of coastal thicket, licuati sand forest, woodlands, woody edaphic grassland and patches of hygrophilous grassland, reed swamps and swamp forests (Matthews et al., 2001).

There are no major surface water drainage features present; the only inflow is the Mseleni River feeding the western arm and the non-perennial Kumzingwane and Velindlovu streams feeding into the northern arm of the lake. This coupled with a relatively flat topography and shallow groundwater levels result in an intimate relationship between surface waters of the lake and the groundwater, as the lake forms a surface expression of the groundwater (Meyer et al., 2001). The lake is cut off from the sea by a series of high north–south trending forested sand dunes, thereby having no direct connection to the sea.

The WR2005 data (Middleton and Bailey, 2009) was used to establish a rainfall pattern for the lake and its catchment. Precipitation was found to increase from 600–700 mm in the western part of the catchment to 800–1000 mm over the central part of the lake before decreasing again to 700–800 mm between the lake and coastal dune cordon. The Mbazwana Meteorological Station (established in 1997) provided monthly data on precipitation, temperature, humidity and wind speed. Average monthly meteorological data from this station is presented in Table 1 and Fig. 2 (SAWS, 2013). Evaporation for the catchment was calculated using the modified Penman method.

A strong season precipitation pattern is observed in the region with most of rainfall occurring during the summer months (with over 40% falling in the 3-month period from January to March). According to WR2005, pan evaporation data for the Lake Sibayi area ranged from 1400–1500 and 1800–2000 per annum for the S and A class pans respectively (Middleton and Bailey, 2009). The mean wind speed measured at the station was 2.22 m s^{-1} while maximum gust speeds of up to 23.7 m s^{-1} were measured at the Mabibi School, adjacent to Lake Sibayi. Dominant wind directions are NE and SW (Diab and Sokolic, 1996).

1.3. Geological setting and evolution of Lake Sibayi

Lake Sibayi is underlain by unconsolidated to semi-consolidated fine sands that blanket most of the Maputaland coastal plain (Fig. 3). These sediments, which are mainly Cretaceous to

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