



How does water-reliant industry affect groundwater systems in coastal Kenya?



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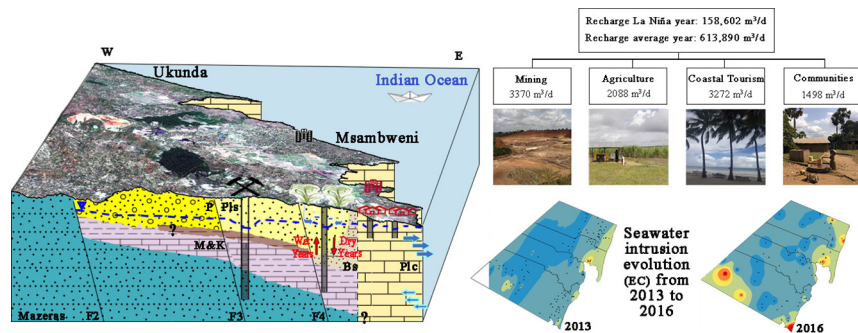
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HIGHLIGHTS

- New water-reliant industries are becoming established on the East African coast.
- New methodology used to estimate abstraction in areas with uncertain or no abstraction data.
- Even after severe droughts, recharge recovers from current abstraction rates.
- The shallow aquifer that local communities rely on is less resilient to drought than the deep aquifer.
- Aquifer storage recovers the year after drought but groundwater quality does not.

GRAPHICAL ABSTRACT



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ABSTRACT

The industrialization process taking place in Africa has led to an overall increase in groundwater abstraction in most countries in the continent. However, the lack of hydrogeological data, as in many developing countries, makes it difficult to properly manage groundwater systems. This study presents a real case study in which a combination of different hydrogeological tools together with different sources of information allow the assessment of how increased competition for water may be affecting groundwater systems by analysing the sustainability of new abstraction regimes under different real climatic condition (before, during and after La Niña 2016). The area where this approach has been applied is Kwale County (in Coastal Kenya) in a hydrogeological context representative of an important part of the east coast of the continent, where new mining and agriculture activities co-exist with tourism and local communities. The results show that the lack of aquifer systems data can be overcome, at least partly, by integrating different sources of information. Most of the time, water-reliant users collect specific hydrogeological information that can contribute to defining the overall hydrogeological system, since their own main purpose is to exploit the aquifer with the maximum productivity. Therefore, local community water usage, together with different stakeholder's knowledge and good corporate water management act as a catalyst for providing critical data, and allows the generation of credible models for future groundwater management and resource allocation. Furthermore, complementary but simple information sources such as in situ interviews, Google Earth, Trip Advisor and easy-to use analytical methods that can be applied in the African context as

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in many developing countries, and enables groundwater abstraction to be estimated and the sustainability of the aquifer system to be defined, allowing potential future risks to be assessed.

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1. Introduction

The exploitation of groundwater generates different types of negative externalities (Giannoccaro et al., 2017): (i) reduced availability of the resource for other current or future uses; (ii) increase in extraction costs; (iii) possible risk of water quality degradation; and (iv) damage to groundwater dependent ecosystems. If the exploitation of groundwater occurs close to the coastline, other negative externalities and costs are generated: (i) reduced groundwater supply due to enhanced corrosion and well failure; (ii) health problems, (iii) negative effects on agriculture, since crop, land quality and cropping area potentially decline (SASMIE, 2017).

Anticipated increases in abstraction must be considered together with the expected increase in droughts in dry periods and precipitation in wet periods (Solomon and Qin, 2013; Stocker et al., 2013). Climate change will affect hydrogeological system dynamics and their water resources quality (Mas-Pla and Menció, 2018). For example, aquifer recharge reduction caused by climate change is an important factor in aquifer salinization (Oiro and Comte, 2019). The increased abstraction is poorly compatible with the sustainable use of coastal aquifers where there is a high population density and where tourism is concentrated (Dhar and Datta, 2009; Mantoglou, 2003; Okello et al., 2015), since the use of coastal groundwater is compromised by salinization (Michael et al., 2017). Many coastal aquifers in the world are currently experiencing intensive saltwater intrusion (SWI) caused by both natural and man-induced processes (Custodio, 2010; De Filippis et al., 2016a, 2016b; SASMIE, 2017; Werner et al., 2013).

In the last couple of decades many African countries have seen unprecedented economic growth rates, and this has drawn the region into the global limelight (World Bank, 2013). This growth has led to an increase in groundwater abstraction in most African countries (Adelana and MacDonald, 2008). The drilling of new deep boreholes with higher abstraction rates than traditional dug wells or shallow borehole handpumps has increased in many areas to meet the water demands of these new economic activities (Comte et al., 2016).

The high socio-economic and ecological importance of groundwater and the fact that groundwater is an important strategic resource are recognised throughout developing countries. A study by Pavelic et al. (2012) emphasizes that data on groundwater systems throughout Sub-Saharan Africa SSA are sparse, so the current state of knowledge creates a barrier to sustainable groundwater development. In order to define realistic local management policy it is essential to understand groundwater use and users. One of the major challenges to proper governance is lack of scientific and general (social, economic, environmental among others) knowledge about aquifers. Without an adequate general understanding of aquifers, actors may not properly identify the source of aquifer pollution or depletion and may be prone to blaming each other for mismanagement (IGRAC, 2019). Thus, in the absence of coordinated efforts to manage aquifers, it is unlikely that any advanced understanding will be achieved. This paradox is the crux of the groundwater governance challenge and perhaps explains why effective groundwater governance regimes are still elusive today.

Therefore, key aquifers need urgent characterization to change the current situation, in which development proceeds with insufficient aquifer knowledge (Olago, 2018). One of the main challenges when studying these aspects in developing countries is the lack of information, especially with respect to abstraction data and the location of abstraction well fields, in order to determine the possible future impacts at the local and/or regional scale on groundwater systems. To the

knowledge of authors, there are no studies that determine the effects of new abstractions in relation to current economic growth in Africa.

Hence the aim of this study is to present a real case study in which a combination of different hydrogeological tools together with different sources of information allow the assessment of how increased competition for water may be affecting groundwater systems by analysing the sustainability of new abstraction regimes under different real climatic conditions. The coastal area of Kwale (Kenya coast) has been selected as a unique case due to: 1) local communities co-exist with tourist activity in the coast and new water-reliant industries established since 2012, representative of what is happening in many areas of the continent; and 2) this area presents a hydrogeological context representative of an important part of the East coast of the continent. Furthermore, aquifer sustainability has been assessed during a drought period caused by the 2016 La Niña event and during the following recovery period after the significant rains of 2017.

The approach presented looks to avoid repeating the errors made in many areas worldwide, such as in the Mediterranean basin, where some coastal aquifers were salinized decades ago by tourism, industrial and agricultural groundwater abstraction and where local economies suffered the consequences, costs and expense of developing the new water sources that were required (SASMIE, 2017). In this regard, some final remarks are made considering the socio-economical and institutional situation in many parts of the Africa continent.

2. Methods

2.1. Application area

The 660 km² study site is located in Kwale County, on Kenya's southern coast, around 50 km south of Mombasa; it had a 2013 population of around 730,000 (Commission on Revenue Allocation, 2013). The majority (82%) of Kwale's inhabitants live in rural areas in small and scattered communities. The coastal areas host urban communities, including Ukunda, Msambweni and Diani. Most of the local economy is based on small-scale agriculture.

Protected wells and boreholes are accessed by more than a fifth of the county's populace and 43% of households use an improved drinking water source (Foster and Hope, 2016). There are around 300 handpumps providing drinking water to local communities, schools and healthcare centres scattered across the study area. These handpumps are used daily by the population to fill buckets for different purposes, such as drinking and domestic water uses. The coastal strip has a long established coastal tourism industry at Diani. Most of the hotels are located in the coastal area in the north of the study area. Furthermore, the Ukunda area has many private homes that have their own shallow well or borehole. In the last two decades, the acquisition of small parcels of land has increased in this area to build bungalows/maisonettes for which the source of water for construction and supply is often groundwater.

Since 2012, two new, major economic activities have been established in Kwale County, increasing the pace of environmental, economic and social change in the area. One is the country's largest mining operation: the Kwale Mineral Sands Project, operated by Base Titanium Ltd. (Base). The other is irrigated sugarcane by the Kwale International Sugarcane Company Limited (KISCOL). Water demand for both companies is met by a combination of surface and groundwater.

The Special Mining Lease operated by Base Titanium cover 1661 ha. The Project resource comprises two dunes that contain economically

viable concentrations of heavy minerals. These two areas are separated by the Mkurumudzi River (Fig. 1). Mine construction was completed at the end of 2013 and the first bulk shipment of mineral departed from Mombasa in February 2014. Projected 2019 production is up to 450,000 t of ilmenite; 93,000 t of rutile (14% of the world's rutile output); and 37,000 t of zircon. The total mineral resource on 30th June 2018 was estimated to be 134 million t.

Currently KISCOL's sugarcane fields occupy a total area of 5500 ha, of which 4100 ha has been put to cultivation of sugarcane since 2008; 800 ha are currently under sub-surface drip irrigation (www.kwale-group.com). The fields are located in the Kinondo, Milalani/Shirazi and Nikaphu areas, the last one being located south of the study area (Fig. 1). The factory has the capacity to crush 3000 t of cane per day and it is projected to produce 3500 t/day of sugar at full capacity, self-generating 18 MW of electricity in a bagasse-fired power plant, and producing around 50,000 L/day of ethanol (<http://www.kwale-group.com>). The planned area for irrigated (not rain-fed) sugar at KISCOL is 3000 ha, to be achieved when all dams and the bulk water system (BWS) is completed in the coming years.

The study area is divided into 4 zones (Fig.1) that represent the areas where each economic activity takes place. Zone 1 covers the area where the sugar fields irrigated with groundwater from in-situ boreholes are located; Zone 2 includes the mine and its well field; Zone 3 is the area where the sugar fields are irrigated with surface water from the Mtawa River but not from boreholes; and Zone 4 includes the area where most of the hotels are located.

2.1.1. Climate

The area experiences a bimodal rainfall pattern: 1) "long rains" generally fall from April to June (AMJ), and "short rains" occur between October and December (OND) (CWSB, 2013). The driest months on the

coast are those from January to March (JFM). The precipitation range is between 900 and 1500 mm/year and the average temperature is about 26.5 °C (County Government of Kwale, 2013). In recent years, from 2012 to 2017, the average rainfall was 1145 mm/year. Rainfall in 2013 (1286 mm) and 2017 (1265 mm) were close to the average whilst 2014 (1604 mm) and 2015 (1345 mm) were well above, and 2012 (711 mm) and 2016 (636 mm) were both well below the average. From May 2016 to early 2017, the study area experienced unusually dry conditions. Local weather data (Kwale Agricultural Department Station KMD 9439001 in Kwale) suggest that this period represents one of the most extreme droughts since 1974 in this area (Ferrer et al., 2019).

2.1.2. Hydrogeology

The region is physiographically divided into three units, from inland to the coast: the Coast Range (Shimba Hills) in the west, with elevations ranging from 366 to 454 m a.s.l (above mean sea level); the Foot Plateau from 60 to 137 m a.s.l, and the Coastal Plain, generally below 50 m a.s.l (Fig. 2).

The conceptual model of the groundwater system has been defined in detail in Ferrer et al. (2019). This aquifer system comprises two hydrogeological systems: a shallow aquifer composed of young geological materials, including silicate sands (Pliocene Fm.) and carbonates, corals and sands (Pleistocene Fm.), and a deep aquifer composed of older materials, mainly sandstones (Jurassic and Triassic) which crop out in the western part of the area in the Shimba Hills range. The shallow aquifer thickness is 25 m thick and the deep aquifer is around 350 m thick (ISGEAG, 2019). The hydrochemical facies and the water isotopic composition indicate that there is hydraulic connectivity across the materials that comprise the shallow aquifer. The same data show that the Mazeras sandstones in the Shimba Hills are hydraulically connected with the deep aquifer.

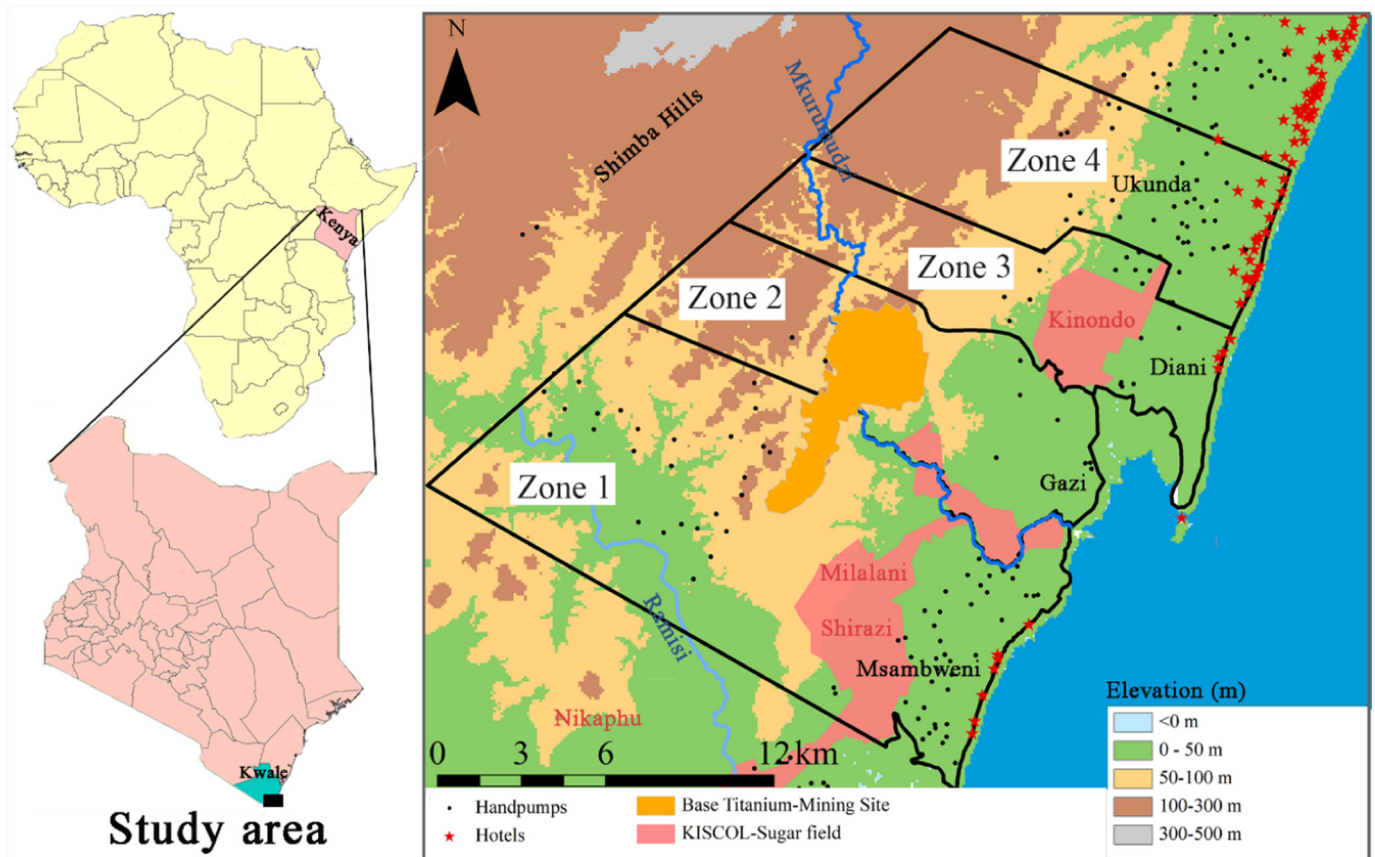


Fig. 1. Location of the study area, which is divided into four zones according to the different economic activities present: 1) includes the larger part of KISCOL's Milalani fields and a part of the mine; 2) includes Base Titanium mining facilities; 3) includes KISCOL's Kinondo fields; and 4) includes the major proportion of hotels and private plots.

The Kilindini sands and coral limestone form the major part of the shallow aquifer in the study area. The deep aquifer acts as a confined unit due to the presence of a very low permeability aquitard emplaced between the young and old materials. This confined aquifer is disrupted across the area by two in-filled palaeochannels perpendicular to the coast (in Zones 1 and 3) that enhance the connectivity between the shallow and deep aquifer in each of these zones. These palaeochannels are filled with sedimentary and re-worked fluvio-deltaic materials.

The shallow aquifer is directly recharged by local rain through the ground surface and the deep aquifer is recharged laterally from the Shimba Hills where it outcrops. The discharge of both aquifer systems is at the littoral zone of the Indian Ocean (Fig. 2). Equipotential lines of the shallow aquifer show that the groundwater flow direction is from the Shimba Hills to the Indian Ocean (Fig. 2). The potentiometric map and the hydrochemistry indicate that the Ramisi (Zone 1) and Mkurumudzi (Zone 2) Rivers are gaining streams, receiving water from the aquifer, at least in their upper parts (Ferrer et al., 2019).

2.2. Estimation of the water budget with lack of data

2.2.1. Recharge estimation

In order to assess the sustainability of the aquifer system during the 2016 La Niña drought and the recovery period in 2017, the total recharge to the aquifers of the study area needs to be known, as it is the main input to the system (Ferrer et al., 2019). The recharge was calculated following the methodology presented in Ferrer et al. (2019), based on the soil water balance for the period 2010–2017. As the resolution of the geological map is not the optimal to obtain proper recharge estimation, the soil and terrain database for Kenya (KENSOTER) was used as the principal data source to define the soil properties for the study area. The information of the soil map has been correlated with the geological map and validated with several field samples in different locations across the study area.

In that study, groundwater recharge was calculated for each land cover type and each soil type, following the process presented in the supplementary material. Rainfall data and meteorological parameters were obtained from three different stations for the period 2010–2015. At the end of 2015, 11 manual rain gauge stations were established across the study area. These new data improved the accuracy of recharge estimation. During 2016–2017, temperature data were obtained from the Trans-African HydroMeteorological Observatory (TAHMO) stations (www.tahmo.org) (Fig. 3).

2.2.2. Current and future abstraction estimation

One of the main challenges when studying this type of area is the lack of information, especially abstraction data and the location of production boreholes. Depending on the abstraction data available in a specified area, different methodologies can be applied. The abstraction data accuracy will depend on the information source used.

In the study area, it proved very helpful to integrate information from the Water Resources Authority (WRA) and from groundwater users in the area (particularly the mining and sugar companies). The abstraction permits for each economic activity were obtained from the Water Resources Authority (WRA). The WRA data comprised the permitted daily well/borehole abstraction volumes for individual consumers and companies, such as Base, KISCOL, the hotels in the South Coast, and community boreholes. However, not all the abstraction data from the different water users have the same accuracy.

Base Titanium provided daily abstraction data from the end of 2013 to 2017. These actual abstraction estimates are very accurate.

Unlike Base Titanium, KISCOL's actual abstraction rates were not available. However, the company report that they control drip irrigation by means of soil humidity sensors to conserve water. Therefore, KISCOL's estimated monthly abstraction is based on soil evaporation deficit (ETD). The ETD is the difference between potential evapotranspiration and actual evapotranspiration under natural conditions, which gives the minimum amount of irrigation water required to maintain

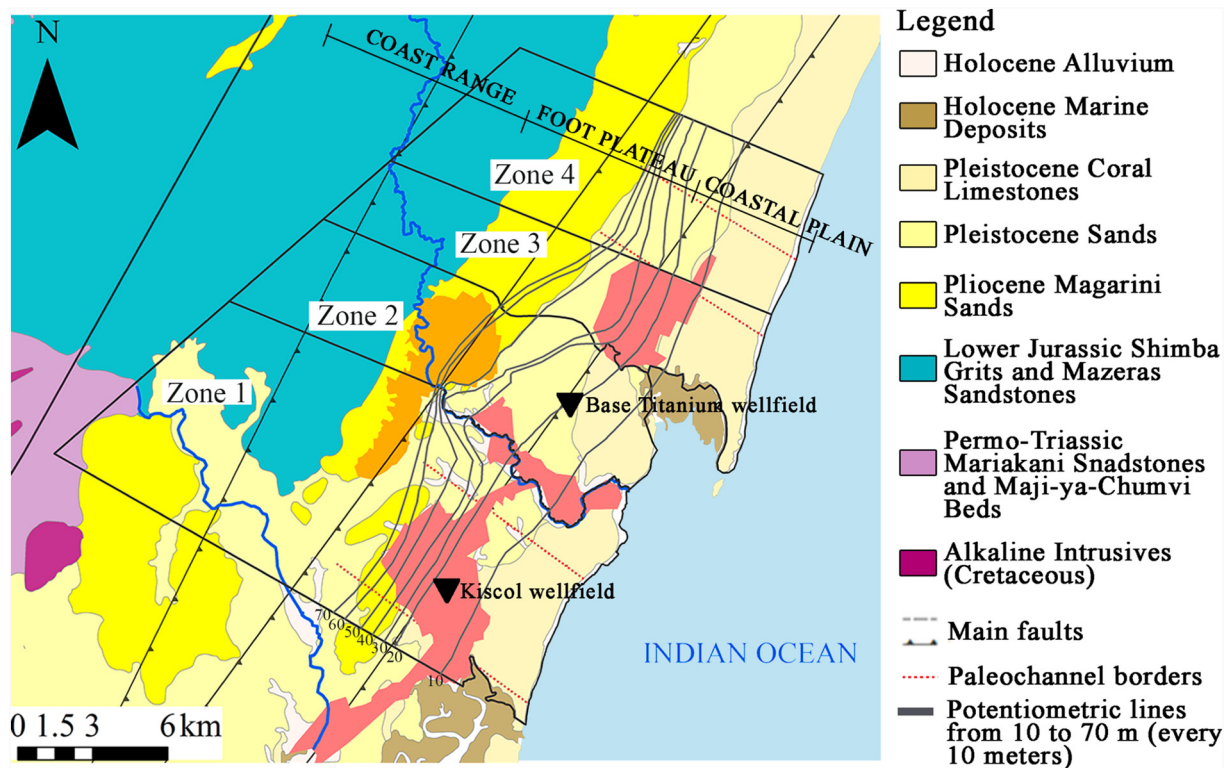


Fig. 2. Geological map with the main faults and the two palaeochannels (red dotted lines) shown. Potentiometric contours measured in the March 2016 field survey. The triangles indicate the locations of the wellfields developed by Base Titanium and KISCOL (Milalani area). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

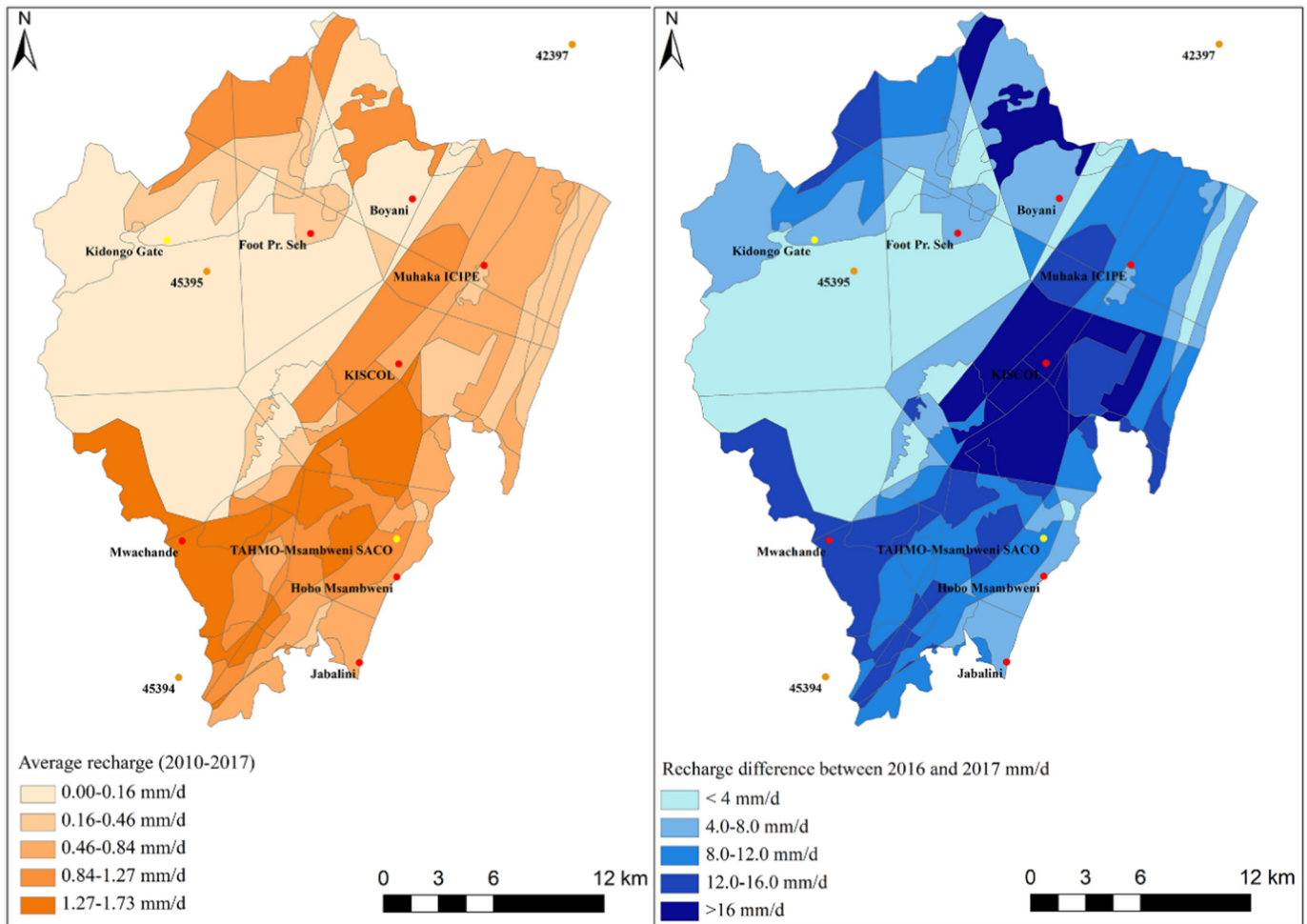


Fig. 3. (Left) Average recharge from 2010 to 2017 in mm/d. (Right) Recharge difference between La Niña (2016) and a normal climatic year (2017). The coloured dots are the meteorological stations used to calculate the net recharge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the soil moisture that allows the crop to get the water it needs. Multiplying the ETD by the KISCOL irrigation area, the minimum crop water requirement (MCWR) is obtained.

Observed groundwater abstraction was available for only one hotel located at the coast in Zone 4. Therefore, a complementary estimate of hotel abstractions using other data sources was made. Hotel locations, both those with and without WRA permit data, were obtained from Google Earth. The number of rooms for each hotel and the hotels' class were collected from the TripAdvisor webpage. Total groundwater volume consumed by hotels was estimated using the consumptions specified in the Practice Manual for Water Supply Services in Kenya (2005) for each type of hotel, assuming a water use of 600 L/day per bed for high class hotels and 300 L/day per bed for medium class. For 35% of the hotels identified from Google Earth, interviews with hotel managers validated consumption data. The Kenya National Bureau of Statistics (KNBS) provided bed occupancy data for the South Coast 2015 to 2017. Despite hotel abstraction data not having the same degree of accuracy as Base Titanium data, using this methodology it is possible to estimate the order of magnitude of hotel abstraction.

The average abstraction of the community handpumps was obtained from Water point Data Transmitters (WDTs), which provide reliable real-time data on handpump usage (Thomson et al., 2012). Using a low cost integrated circuit (IC) based accelerometer, the WDT automatically monitors the number of strokes made in operating a handpump and then transmits this information to a computer over the GSM network. Volumetric abstraction was calculated from the accelerometer

data for the period 2014–2015. These data provide information on hourly pump use.

The abstraction of the water-reliant industries will increase in the near future; Base Titanium planned to drill more boreholes within the same wellfield, thus increasing the total groundwater abstracted. In the absence of any better estimates, we arbitrarily assumed a 20% increase in groundwater abstraction for irrigated sugar. The Draft Kwale Water Master Plan has assumed a 1% growth per year in water demand for the tourism sector over the next 20 years. In order to supply more water to the population, the Water Supply Master Plan (2018) for Mombasa and other towns within the Coast Province (CWSB, 2016) has proposed developing the Msambweni wellfield to meet future demand for the middle and south coast zones. This is the considered future scenario for groundwater abstraction.

2.2.3. Groundwater levels and quality data

Groundwater levels and quality data, such as field physicochemical parameters (pH, temperature, electrical conductivity ...), are easy and cheap to obtain in countries with lack of data. Therefore, it is relevant to create a monitoring network managed by local people with low cost in order to obtain hydrogeological data for a specified period to evaluate changes under different climatic conditions.

In order to assess the possible effects of the water-reliant industries on the groundwater system, hydrochemical field data obtained during the La Niña event in 2016 from Ferrer et al. (2019) were used.

In order to study the aquifer recovery after the La Niña event in the study area, the groundwater level and electrical conductivity (EC) of 23 points were measured in Magarini sands, Kilindini sands and the Pleistocene corals every two weeks, with a groundwater level range from 4 m bgl to 27 m bgl (below ground level) after the La Niña event (April 2017), until December 2017. These points are part of a monitoring network in which groundwater levels and physicochemical parameters were measured every two weeks. Fortnightly groundwater levels of 35 piezometers measured by Base Titanium in its monitoring network (2012–2017) have also been used to study the aquifer response as well as the potential interaction between the shallow and the deep aquifer during the study period.

To represent EC evolution in the study area, this information was mapped for each of the seven field surveys using ArcGis 10.0 software, and the hydrogeochemical analysis tool QUIMET (Velasco et al., 2014). To represent the spatial distribution of the variables, the Inverse Distance Weighting (IDW) method was used, which is a deterministic method that allows multivariate interpolation from a set of known scattered points. The EC data were obtained from different wells measured during the field surveys carried out in the study area in September 2013, March 2014, June 2014, March–May 2015, and September 2015. The physicochemical parameters measured in situ were temperature, pH and EC₂₅ (electric conductivity at 25 °C) by means of a Hanna Instruments meter.

In order to understand the geochemical processes occurring in the area affected by seawater intrusion (SWI), a geochemical modelling exercise was carried out to understand the long-term evolution in this geological context and the potential impacts of SWI dynamics. Given the composition of the Pleistocene corals, different geochemical models considering several conceptual hydrogeological models were generated to understand which reactions are taking place, to what extent, under which conditions, and how water quality and aquifer mineralogy could change due to SWI.

PHREEQC software was used to simulate the mixing between fresh groundwater located inland in the Pleistocene formation with EC < 1000 µS/cm and one sample from the saline water upwelling on the beach (Diani), which is 83% seawater according to chloride concentration (Table 1. Supplementary material). A total of 20 mixed waters were simulated.

3. Results

This section presents all the results analysed in order to determine the sustainability of the groundwater system. First of all, the recharge from 2010 to 2017 and its change is assessed, since it is the main water input of the system and key to understanding the water budget. Secondly, abstraction for each groundwater use is estimated and used as outputs from the groundwater system. In the third component, the

Table 1
Rainfall and temperature data from different meteorological stations used to calculate groundwater recharge. The location of each station is shown in Fig. 3.

Rainfall & temperature 2010–2015	Rainfall from manual rain gauge station 2016–2017	Temperature 2016–2017
SWAT N° 45395	Boyani station Footprints Kidongo gate KISCOL Muhaka ICIPE Mwachande	TAHMO Kidongo gate
SWAT N° 45394	KISCOL Muhaka	TAHMO Msambweni SACO
SWAT N° 42397	Hobo Msambweni Jabalini KISCOL Mwachande	TAHMO Msambweni SACO

groundwater level evolution is analysed as the main indicator of storage changes in the system, showing the relationship between system inputs and outputs. To evaluate the system in the coastal zone, where groundwater quality plays an important role in the sustainability of the system, the evolution of electrical conductivity (as a proxy for salinity) is analysed. Finally, the results of the geochemical models, which are needed to understand the geochemical processes occurring in the area affected by seawater intrusion, are also presented.

3.1. Recharge

Total recharge volume was calculated for an area of 660 km². This area is bigger than the four study Zones (Fig. 1), covering the recharge area of the shallow and deep aquifers from the sea to the Shimba Hills (Ferrer et al., 2019). While the shallow aquifer is recharged directly from the surface, the underlying deep aquifer is recharged from the Shimba Hills. To estimate recharge across the study area, 123 soil water balances were calculated (Fig. 3).

The spatial distribution of recharge follows the rainfall spatial pattern. Higher recharge occurs near the coast and decreases inland, west of Shimba Hills. However, in the eastern Shimba Hills (around 450 m a.s.l., see Fig. 1) recharge is higher. The highest average recharge volume for the period 2010–2017 occurred in areas underlain by ferralic arenosols, which have low usable soil water reserves (UR). Some areas overlying the shallow aquifer in the Kilindini and Magarini sands also have this type of soil. On the contrary, lower average recharge occurs in areas with high UR ferric Acrisols. These soils are mainly located on the Mazeras sandstone, in the Shimba Hills.

The total recharge during La Niña in 2016 was 58 · 10⁶ m³/year, 74% less compared to 2017 (224 · 10⁶ m³/year). A comparison of recharge during La Niña with previous years (Table 2) shows that there is minimal correlation between total annual rainfall and total annual recharge. This is because the rainfall intensity and distribution through the year influences net recharge, rather than the total annual volume of rainfall. High rainfall peaks produced by intense but short storms are more effective in driving recharge than lower, more continuous rainfall. An intense rainfall event (>100 mm) on a saturated catchment leads to intense and significant recharge. This is consistent with other studies on the phenomenon (Taylor et al., 2012; Taylor and Jasechko, 2015). The recharge volume represents 7% of the annual rainfall in the driest years, but up to 23% in 2017.

3.2. Groundwater use by water-reliant industry

In this sub-section we present a detailed description of each water-reliant user in the area and its abstraction rate estimate.

3.2.1. Base Titanium Ltd

The mining company constructed and commissioned an 8.4 10⁶ m³ water supply dam on the Mkurumudzi River to meet most of its water requirements for mining. This supply is backed up by a wellfield comprising four, 95–105 m deep boreholes. At the end of 2013, both surface and groundwater were abstracted to start the mine. The average

Table 2
Annual precipitation in mm/year obtained from the different meteorological stations located in the study area (Table 1) and the annual recharge volume in 10⁶ m³/year.

Year	Precipitation (mm/year)	Recharge (10 ⁶ m ³ /year)
2010	1022	71
2011	1406	160
2012	987	50
2013	1154	86
2014	1715	156
2015	1757	169
2016	867	58
2017	1442	224

groundwater abstraction for a “normal climate year” such as 2014 and 2015 was 1449 and 1806 m³/day, respectively. However, during the 2016 La Niña event, this abstraction increased by around 66% to 4272 m³/day on average (Table 3). After the La Niña event, the daily average abstraction fell by around 26% (3370 m³/d) in 2017, compared to 2016 (Fig. 4). It should be pointed out that Base Titanium recycles a considerable proportion of process water: in 2016, it recycled >70% of the total daily water use. It improved in 2017, recycling around 78%.

The mine site is located on the Pliocene formation but the Base wellfield is on the Kilindini sands (Pleistocene) east of the mine (Fig. 2). These production wells are screened in the deep aquifer, to ensure that groundwater is pumped only from the Jurassic and Triassic formations. This was a deliberate design philosophy to reduce as much as possible adverse effects to the shallow aquifer that local communities use for water supply.

Adjacent to each operational borehole a shallow and deep monitoring piezometer measures the groundwater level fluctuations under baseline conditions and due to subsequent abstraction. Under natural conditions before abstraction started in 2013, the deep groundwater levels were higher than the shallow groundwater levels as the piezometric control area of the confined deep aquifer is at a higher elevation, in the Shimba Hills. Once abstraction started at the end of 2013, the shallow piezometric trend shows a limited effect from pumping from the deep aquifer, maintaining the hydraulic relationship between the shallow and deep aquifer, except sporadically due to occasionally higher abstraction rates, as in April 2014 (Fig. 4). However, during the dry year of 2016 (the La Niña event), some deep boreholes had a piezometric level below the shallow aquifer groundwater level.

Since 2013, Base Titanium has also monitored the groundwater quality in its production boreholes and some shallow and deep community wells spread around the mine. The hydrochemical composition of the pumped water from 2013 to the present (data not shown, Base Titanium monitoring network) indicates that there is no significant change in groundwater quality in the groundwater pumped from the deep aquifer, even during the La Niña event. The EC values measured in the inland deep community wells monitored by Base Titanium have been <1500 µS/cm from 2012 until the present.

3.2.2. KISCOL sugar fields

KISCOL uses different water sources to meet sugarcane water demand. Its water demand depends on the crop water requirements of the sugar plant. As expected, the minimum crop water requirement (MCWR) is higher during the driest months, with an average of 40,784 m³/day from January to March and 28,349 m³/day for the wet period (April to June).

Groundwater is obtained from up to 17 boreholes, 60–100 m deep, drilled in and spread across the sugar fields. According to WRA, KISCOL has been allocated a total of 10,535 m³/day from 12 production boreholes. However, information available indicates that only eight boreholes are currently operational, so actual groundwater abstraction is probably lower than the WRA allocation. These eight boreholes are operational (since mid-2015), and are located in the Milalani fields (Zone 1, Fig. 1). The Kinondo fields are irrigated by surface water (Zone 3, Fig. 1) as the borehole pumps are not connected to power lines and electrical generators have been vandalized. Pumped

Table 4

Hotel groundwater abstraction (m³/d) based on different information sources.

Source	Kind of data	Number of points with available data	Abstraction (m ³ /day)
WRA	WRA allocation permits	29	2760
Hotels	Answer direct from the Hotels	38	1809
Estimate	Google Earth + Trip Advisor + Manual for Water Supply Services	91	3272

groundwater is stored in one-day storage lagoons, together with water coming from the dams, which is the other water source for sugar irrigation. Groundwater acts as a strategic water reserve; volumes used are small compared with water from dams. According to current WRA rules, the maximum volume that may be pumped is 60% of the well test discharge rate over a ten-hour pumping day. It means that the mean estimated abstraction rate for the eight KISCOL boreholes is 2088 m³/day (Table 3). This value is in accordance with the KISCOL test yields for these eight boreholes and it is in the same range as other unpublished data from KISCOL.

KISCOL wells are multi-screened, taking water from multiple water-bearing zones in the shallow and deep aquifer units. This well design increases the yield but produces a mix of groundwater from aquifer levels, as shown by the isotopic and hydrochemical composition (Ferrer et al., 2019). Therefore, this screen configuration may facilitate the entrance of contaminated water from the shallow aquifer towards the deep one, contrary to the Base Titanium boreholes which are only screened in the deep aquifer.

Water quality was measured within KISCOL's Milalani plantation in a monitored borehole at different depths in the June 2016 field survey (Ferrer et al., 2019). The most significant result was the measured nitrate concentration in this borehole: 48 mg/L at 21 m bgl and 31 mg/L at 65 m bgl, as NO₃. Furthermore, a well located at Nikaphu, south of the study area, had 1.2 mg/L of ammonia, as NH₄, during the March 2016 field campaign. Taking into account that groundwater has an Eh of +239.4 mV and dissolved oxygen of 1.42 mg/L, the relatively high ammonia content indicates that the sample is not in chemical equilibrium. This shows a relatively fast recirculation of shallow groundwater around the pumping well. Currently, there are no nitrate polluted shallow wells around the KISCOL Milalani fields. Conversely, in the Kinondo fields (Zone 3), where sugar is irrigated only with surface water, there is only one point at the outflow from the end of the fields that is polluted by nitrates, at 73 mg/L NO₃ in June 2016.

3.2.3. Tourism

From the data obtained from Google Earth, 85% of the hotels located on the coast are located in Zones 3 and 4 on the Diani coast, with only a few situated on the Msambweni coast in Zones 1 and 2 (Fig. 1).

The highest tourism season is from October to March and the lowest from April to July. Hotel water use is closely associated with the number of tourists, so both intra- and inter-annual abstraction varies considerably (Fig. 5). Most hotels use water from private boreholes, from which large volumes of water are withdrawn using electrical and/or

Table 3

The allocated and the actual or estimated groundwater abstraction for each water user. Hotel groundwater use marked with (*) is based on Table 4.

Period	Recharge (m ³ /d)	Groundwater abstraction (m ³ /d)				
		Base titanium	KISCOL	Hotels	Handpumps	Community boreholes
Dry year: La Niña 2016	158,602	Current: 4272 Allocated: 5280	Current: 2088 Allocated: 2528	3272*	450	991
Recovery/average year: 2017	613,890	Current: 3370 Allocated: 5280				
Future abstraction		8800	9504	3926	540	11,500

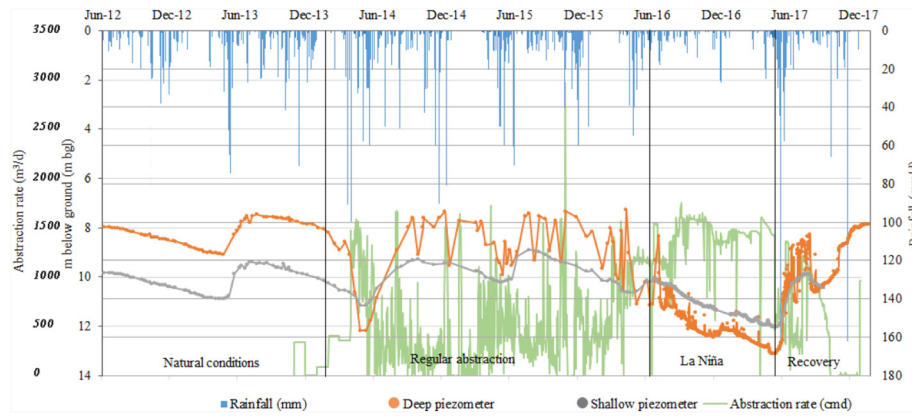


Fig. 4. Comparison between shallow and deep groundwater levels of piezometers located near a production borehole recorded by Base Titanium. Black vertical lines indicate the hydraulic relationship between the shallow and the deep aquifer under different conditions: 1) “Natural conditions” refers to groundwater levels when the wellfield was not intensively pumped before October 2013; 2) “regular abstraction” shows the shallow and deep groundwater levels once the deep aquifer exploitation started; 3) “La Niña” shows the groundwater levels during the drought period caused by the La Niña event in 2016/2017 and 4) “Recovery” refers to the recovery of the aquifer hydraulic relationship after the rains of April 2017. Rainfall volume data is from Kwale Agricultural Department station (Kenya Meteorological Department) (mm/d). The green line shows Base Titanium groundwater abstraction as m³/d. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

diesel driven pumps. The groundwater abstraction points that support this economic activity are located near the coast, mainly exploiting the shallow aquifer located in the Pleistocene corals formation (Fig. 1). Using both Google Earth and Trip Advisor it was possible to identify 109 hotels and obtain the number of rooms for 91 hotels. Personal interviews with hotel managers improved the understanding of water use and water source for each hotel. Around 40% of the hotels were unwilling to answer the questions and the remaining 60% of hotels at least revealed the water source. Of the 60% of the hotels that answered, 72% are only supplied by private boreholes while the remaining 28% supplement groundwater with municipal piped water from the Tiwi aquifer, located 6–12 km north of Ukunda and covering an area of approximately 30 km².

We estimated hotel groundwater abstraction according to the different type of data source (WRA allocations and hotel interviews). We also estimated hotel groundwater abstraction using the number of rooms and the hotel class type.

The total number of beds available on the south coast has decreased around 40% from 2015 to 2017, since some hotels closed during this period. However, the percentage of beds occupied has increased, maintaining an occupancy rate of around a million bed-nights/year for the period 2015–2017. The Draft Kwale Water Master Plan assumed a 1%/year growth in water demand for the tourism sector over the next 20 years.

Hotel groundwater use varies through an order of magnitude across the months of the year, based on bed occupancy (Fig. 5). Water consumption is lower during the wet season, since it coincides with the

months with lowest tourism activity. However, the water consumption in the rest of the year is significant. It is worth emphasizing that the highest bed occupancy rate and thus the highest water consumption occur from October to December, just before the dry season.

3.2.4. Community abstraction

Groundwater abstraction from commercial activities takes place alongside the traditional dispersed 300 functional handpump-equipped shallow wells and boreholes, and 22 community boreholes (some with solar pumps installed by Base Titanium), that provide drinking water to communities and institutions. The WRA allocation for 22 community boreholes within the study area is 991 m³/day (Table 3). There are also some open wells operated with buckets within the study area for which no abstraction data exist; however, anticipated abstraction rates are much lower than in handpump-equipped boreholes.

Weekly data obtained from the transmitters (WDT) from the 300 handpumps during 2014 and 2015 gave a mean daily abstraction of approximately 1.5 m³/day per pump. Water pumped from community handpumps also depends on rainfall (Thomson et al., 2019). Abstraction varied from 0.71 m³/day per pump in the wet season to 2.05 m³/day per pump in the dry season, with monthly variation shown in Fig. 6. They operate under different dynamics, according to the economic activities in the area. The monthly average volume pumped is lower than the annual average abstractions from May to December. This shows that communities use other water sources during wet periods, such as rainwater collection (Thomson et al., 2019).

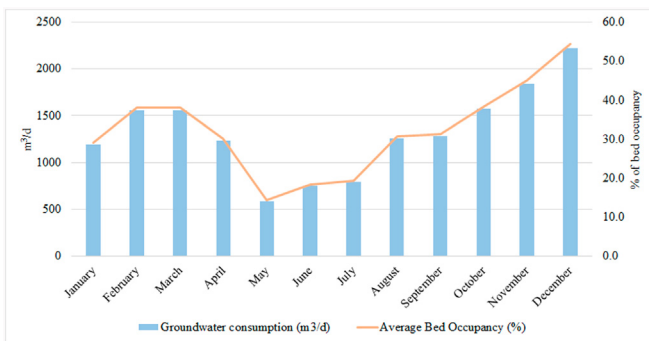


Fig. 5. Groundwater consumed in (m³/d) each month based on the average bed occupancy from 2015 to 2017 obtained from the Kenya National Bureau of Statistics (KNBS).

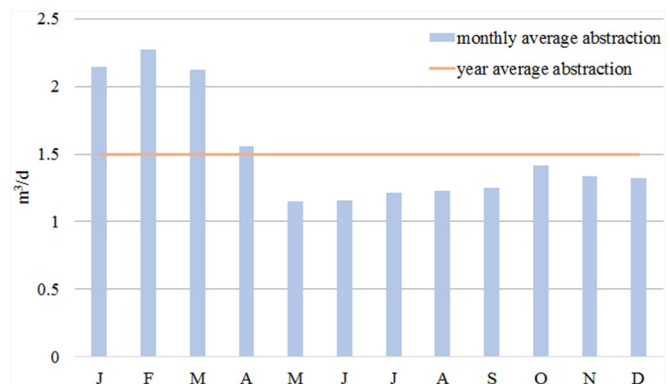


Fig. 6. Monthly average abstraction variation for handpumps during 2014 and 2015

3.3. Groundwater level evolution

In order to determine the sustainability of the groundwater system under different abstraction regimes, it is important not only to consider how abstraction could affect aquifers during a drought, but also how the systems recover after such climatic events. Therefore, the present study goes beyond that of Ferrer et al. (2019), as it focuses on the recovery of groundwater levels during 2017 after La Niña event and especially on shallow aquifer recovery. The shallow aquifer is the source of water for most communities in the study area.

During the La Niña event, there was a groundwater level decline in 86% of the measured shallow wells. In the remaining shallow wells, the groundwater levels were nearly constant. However, levels in 95% of the shallow wells affected by La Niña drawdown recovered after the first rainy season (AMJ) in 2017 (Table 2S Supplementary material). In this regard, the first rainy season (AMJ) is more effective in the recovery of the groundwater system than the short rains (OND).

Regarding groundwater level recovery after the La Niña event in the deep aquifer, there are only data from Zone 2 (from the Base Titanium monitoring network). Fig. 4 shows the effects of recharge and abstraction on deep piezometer water levels; this shows that groundwater levels recovered after the first rainfall event in April 2017, to values close to those observed in previous wet years.

3.4. Groundwater quality on the coastal strip

Sea water intrusion (SWI) in aquifers occurs naturally in coastal areas around the world (Custodio, 2010; SASMIE, 2017). The position of the seawater/fresh water-mixing zone is influenced by groundwater discharge into the sea and aquifer thickness, as well as aquifer hydraulic conductivity. The natural discharge rate could be affected by groundwater abstraction, reducing diffuse discharge into the sea. In order to study short-term salinity changes, we carried out a spatial analysis of groundwater EC (electrical conductivity) between 2013 between 2016.

The evolution of EC since 2013 (Fig. 7) shows that salinity increased, mainly in 2016. This illustrates the relationship between EC increase and decreasing rainfall, since the total rainfall during 2016 (when the La Niña event occurred), was 49% less compared to the 2014 total (Table 2). The highest EC values in June 2016 correspond to the wells located in Zones 3 and 4 (except for a point in Zone 1), with an EC mean value of 2814 $\mu\text{S}/\text{cm}$ and a maximum of 3793 $\mu\text{S}/\text{cm}$ (Table 3, Supplementary material). Looking at the EC variation across 2016–2017 for the wells located near the coast, around 88% of the sampled sites show an EC increase across the period. The wells that do not show any EC increase are mainly located inland in Zone 4, and in some wells in the Magarini sands in Zone 1 (Table 2, Supplementary material).

We compared hydrogeochemical modelling results with the samples from wells/boreholes affected by SWI in the shallow aquifer to understand the importance of the SWI change. Field samples contain between 0% and 30% of seawater (Fig. 8a), except for the sample taken from a beach upwelling, which had 83% seawater. The conceptual model that gives results closest to the observed field samples is the mixing of fresh and saline water, both in equilibrium with calcite (i.e. Fig. 8a).

Looking at the delta ion evolution for calcite (total quantity of precipitated/dissolved calcite mineral) in this conceptual model, during mixing between fresh groundwater and saline water (Fig. 8b) the increase in salinity tends to dissolve calcite, with 30–40% maximum dissolution in a water mixture containing 50% of seawater.

4. Discussion

4.1. Current situation

The total groundwater abstraction represented 6% of the recharge during La Niña and 1.3% of recharge during a normal climatic year,

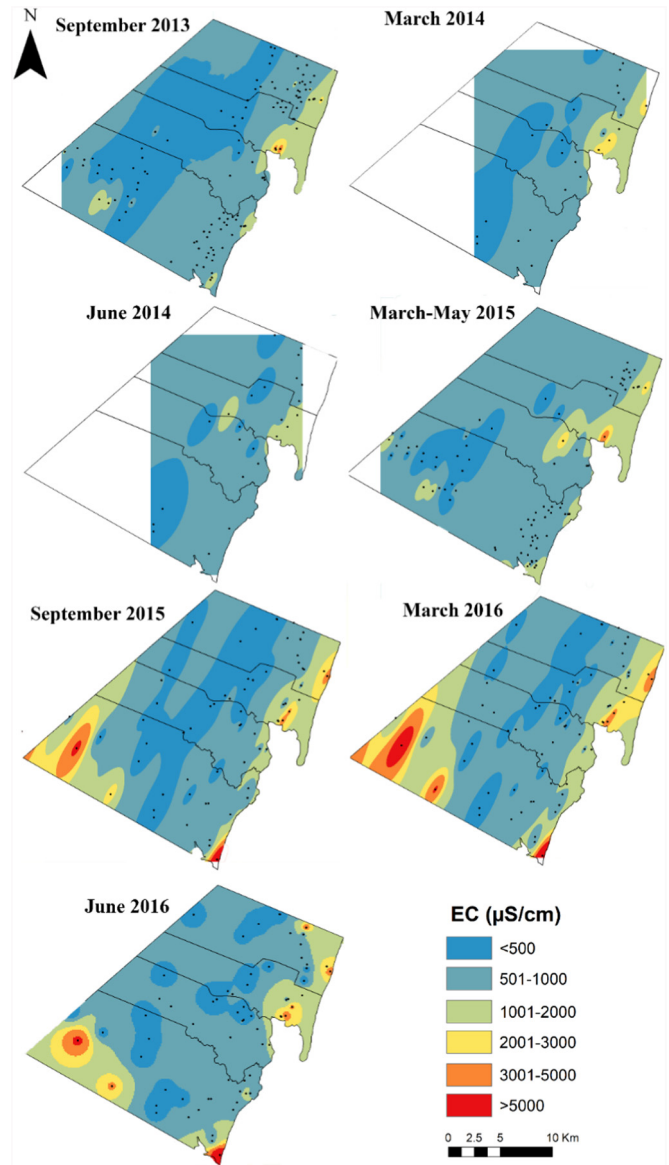


Fig. 7. EC spatial distribution along time after the different field surveys from 2013 to 2016. The inland white areas mean that no data is available. The high EC values located inland in from September 2015 to June 2016 correspond to a saline geological formation, the Maji ya Chumvi beds (Caswell, 1953).

such as 2017. The recharge volume is an important component of the aquifer system dynamics, responsible for groundwater level variation in both the shallow and deep aquifers.

Not all water users exploit the same aquifers layers. The community wells, handpumps and hotels mainly abstract groundwater from the shallow aquifer. The recharge areas of this aquifer unit are those exhibiting more volume variation between drought and a normal climatic year (i.e. 2017) (Fig. 3). The shallow aquifer unit is less resilient to climate variation than the deep one. This explains why some wells located in the Kilindini and Magarini sands became dry during the La Niña drought. The aquifer system exhibited swift recovery after the first normal rainy season in 2017. This allowed the system to return to the average groundwater budget and to face the next drought period.

One consequence of wells becoming dry is the increase in walking distance to collect water. As reported during fieldwork in June 2016, during the La Niña event, some communities stated that they had to walk longer distances to collect water because the nearest borehole or well was dry. Among other impacts, Demie et al. (2016) found that spending more time searching for water had a negative impact on

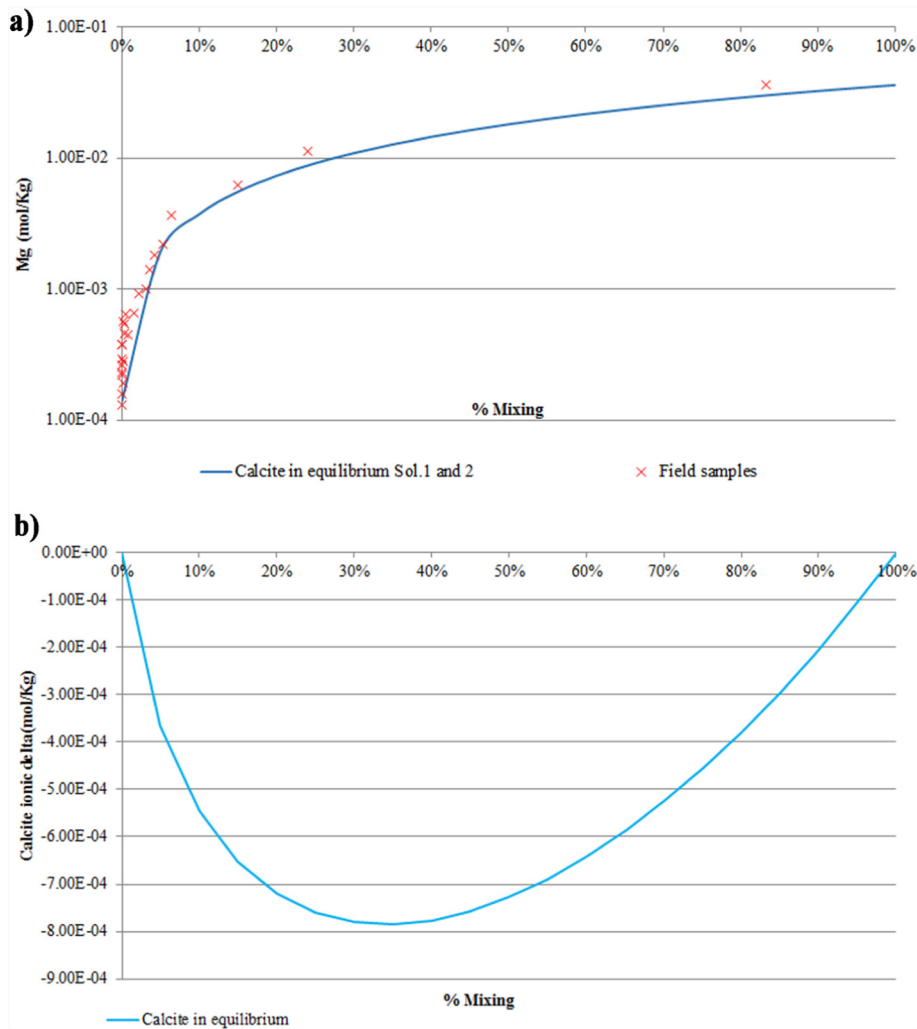


Fig. 8. a) Mg vs. percentage of mixing. The red crosses represent sampled waters near the coast. The X-axis shows the percentage of mixing from 0% to 100% of fresh water in the coast samples and the upwelling. The light blue line represents the best-fitting conceptual model (water solutions in equilibrium with calcite). b) Calcite ion delta (change) vs. percentage of mixing of the model in equilibrium with calcite. The Y-axis represents the calcite saturation index and the X-axis shows percent mixing. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

girls and women, since this forces them to stop investing time in their education and other important activities. Furthermore, the reduction in groundwater availability leads to an increase in the price of the water sold to local residents. The Gro for Good research team found that during the drought event of 2016/2017, some areas having very limited access to drinking water suffered a peak in the price of vended water, with charges ranging from 20 to 50 Ksh per 20 L reported west of the Shimba Hills. Such costs are an order of magnitude higher than the usual price for vended water, which is 2 to 3 Ksh per 20 L. This price increase has a huge impact on families in an area where the average household income is about 330 Ksh/day, about the cost of 2.5 kg of rice. This price increase will either result in households having reduced funds for other needs because of the drought, or reducing their water use, or a combination of both. This may cause adverse health impacts from compromised hygiene behaviour.

Unlike communities and hotels, Base exploits the deep aquifer and KISCOL both aquifer units. The fact that the recharge variation is less in the Shimba Hills than in the lowland means that the deep aquifer is more resilient to drought events. This favours groundwater abstraction by these users, since they can continue to exploit the deep aquifer during periods of drought without impacting the shallow aquifer exploited by the communities and hotels lasting at least as long as the last La Niña event.

Focusing on mining, the abstraction rate depends on rainfall patterns, increasing during the dry period in 2016, and reducing during wet years, such as in 2017. The influence of abstraction on the shallow aquifer is insignificant up to the present, according to observation piezometer water level data in the shallow and deep aquifer in the Base watershed. This is due to the presence of an aquitard between the two aquifers. Groundwater abstraction only significantly affected the piezometric level of the deep aquifer system during the 2016 drought. This groundwater level decline could be due to the combination of abstraction from the deep aquifer and the reduced recharge during the drought in the Shimba Hills (Fig. 4). Unlike in other areas, like Italy, Tunisia, Mediterranean Spain and the Canary Islands (La Vigna et al., 2013; Maliki et al., 2000; SASMIE, 2017), where intensive exploitation permanently affects the relationships between aquifer units, after La Niña event the hydraulic relationship between the shallow and deep aquifer recovered following the rains in April 2017, showing that the impact on the deep aquifer in 2016 was attributed to reduced recharge.

Like Base, KISCOL water use changes over time, as their principal use is for irrigation: less water is consumed during the wet season and more during the dry season and droughts. At present, current KISCOL abstraction has a dual effect on groundwater quality, as the potential pollutants related to fertilizers used in the sugarcane fields are present in the deep pumping wells but do not spread beyond the sugar fields due to the

recharge of irrigation return flow (Fig. 9). The presence of NO₃ concentration (31 mg/L) at 65 m depth in a KISCOL control piezometer located in Milalani (in the southern fields), demonstrates the aquifer unit's connection through the well due to the long screened sections. The northern fields (Kinondo), which are irrigated with surface water, shows how the pollutants may move following groundwater flow, as a well located down flow of the fields is one of the few in the area with elevated nitrate (Ferrer et al., 2019).

The relationship between the shallow and deep aquifer at the coast itself is unknown. Furthermore, as there are no data for the deep aquifer in the area between the coast on the one hand and the sugar fields and the mine on the other, it is not possible to determine the effects of sugarcane irrigation and mining abstraction on saline intrusion in the deep aquifer. However, none of the deep boreholes sampled during this study (up to 100 m depth, from the Base Titanium monitoring network) shows SWI influence. Moreover, it is unknown how water abstraction from boreholes located within or near the palaeochannel could increase the SWI, mainly around the Msambweni area, in Zone 1 (Fig.1).

In the coastal areas with major tourism concentrations, recent years' data seem to show a local salinization effect in the shallow aquifer due to the higher abstraction induced by tourism and associated activities. However, a longer period of observation is needed to determine the saline water intrusion dynamics in order to consider rainfall fluctuations and to differentiate between seasonal effects (still unclear but possible) and long-term trends. As the zone with most of the hotels is also the area with the highest population density, it is not possible to differentiate between saline intrusion caused by the hotel sector itself and that caused by wells and boreholes serving private dwellings or used by local communities.

EC in most measured shallow wells remained high after the drought period, even after the important rains of early 2017, indicating that groundwater quality in the coastal zone did not fully recover (Table 2, supplementary material). This behaviour is in agreement with many other well-studied areas (Custodio, 2002; SASMIE, 2017), which show that salinity takes much longer than groundwater level to change and to recover once the aquifer is salinized.

4.2. Future situation

Total groundwater abstraction is expected to increase by a factor of four over the current rate (see Table 3). This level of abstraction would represent 22% of the total recharge occurring during the La

Niña event. Currently, the existing water-reliant industries are exploiting the aquifer without significantly affecting groundwater levels. However, the possible local effect of pumping wells on the aquifer system and the consequences of future increased groundwater abstraction during long drought periods should be evaluated. The number of dry shallow wells could increase in the future due to more frequent and longer droughts, but also due to augmented abstraction.

Considering the groundwater level difference between aquifer units during La Niña in the 14 m-thick aquitard (the minimum aquitard thickness reported by Base) and the estimated vertical hydraulic conductivity, Darcy's Law shows that the vertical water downward displacement through the aquitard is of the order of 2 m/year, penetrating much less than the aquitard thickness in one year. Consequently, pollution from the upper aquifer level cannot reach the deep aquifer except due to poor well construction. However, in a future scenario with a four-fold increase in groundwater abstraction rate and/or longer droughts, a longer and possibly permanent shift in the difference in piezometric levels between the aquifer units may occur, produced by induced larger vertical gradients across the aquitard, increasing the risk of contamination from vertical drainage through the aquitard.

A future increase in groundwater abstraction by the sugar company during a drought period may affect both the shallow and the deep aquifer, as those wells are screened in both aquifers (for maximum borehole yield). A potential reduction in groundwater level in the shallow aquifer in Zone 1 may affect the Ramisi River-aquifer relationship in that area. A fall in the shallow aquifer level would decrease aquifer discharge to the river and at some point could induce river water infiltration into the aquifer. The infiltration of naturally saline water from the Ramisi River could affect the groundwater quality in shallow wells adjacent to the river by increasing its salinity, thus limiting their use. The maximum EC upstream in the Ramisi River was 5594 µS/cm (Ferrer et al., 2019). In extreme cases, the EC could limit the use of groundwater from the shallow aquifer. This does not only apply to domestic uses but also to sugar irrigation, as the threshold EC for sugarcane is 1700 µS/cm (FAO, 2018), if some of abstraction wells were located close to the river. In order to prevent this occurring, KISCOL might consider irrigating the south sugar fields with surface water from dams located in the Mkurumudzi catchment. Furthermore, it is expected that in periods when the groundwater level in the deep aquifer stays lower than in the shallow aquifer, pollution of the deep aquifer can be induced in the wells, as has occurred in other areas (Menció et al., 2011) and is a common occurrence in coastal areas.

SWI is an important issue in coastal aquifers, and has already been observed in Kwale County (Oiro and Comte, 2019). A reduction in groundwater flow would lead to a penetration of the saltwater wedge inland, increasing the percentage of saline water in shallow wells already affected by SWI and affecting new areas. The significance of SWI is that only 2 to 3% of seawater mixed with fresh water is enough to make the resulting water useless for most purposes.

The calculation of the freshwater-saltwater mixing zone is a complex task, but an approximation can be obtained assuming a sharp freshwater-saline water interface and comparing the results with the final equilibrium state. The steady state penetration of the sea water wedge in the case of an homogeneous aquifer can be easily calculated from aquifer thickness and hydraulic conductivity for a given groundwater flow discharging at the coast (see Section 13, (Custodio and Bruggeman, 1986; Custodio and Llamas, 1976). We calculated seawater wedge growth from the coastline for the shallow aquifer, under the future increased abstraction scenario with the same net recharge as during the La Niña event (data in Supplementary material). Increasing groundwater abstraction from 9535 m³/d to 34,270 m³/d will move the steady state saline water wedge from 232 m inland up to 280 m in the final equilibrium state. This advance of the saline wedge could affect hotel groundwater supply and community handpumps located near the coast.

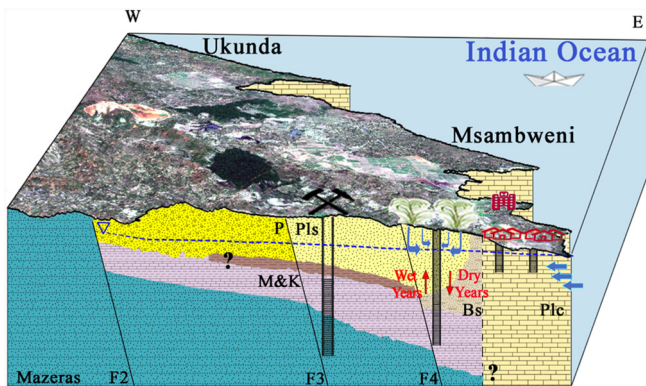


Fig. 9. Schematic hydrogeological conceptual model (not to scale) of the aquifer system with the main economic activities in the area and the location in the geology of the abstraction boreholes for each activity. The question marks indicate the unknown extension of the clay layer (in brown) acting as an intercalated aquitard that reduces the connectivity between the Mazeras Fm and Pleistocene corals and sands, and the discharge of the deep aquifer. Mazeras (Mazeras Fm), M&K (Mtomkuu and Kambe Fm), P (Magarini sands), Pls (Kilindini sands), Bs (Bioclastic sands with clay lenses), Plc (Pleistocene corals). F2 to F4 indicate the main faults in the study area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

We also calculated the saline wedge depth for different distances from the coast and for the different geologies near the coast, i.e. the Pleistocene corals and Kilindini sands (data in Supplementary material). The results show that even during the future abstraction scenario during a drought year like the 2016 La Niña, the saline wedge will not affect the Kilindini sands. Under the future scenario, the saline wedge in the Kilindini sands (around six kilometres inland from the coast) would be around 400 m deep, so the shallow aquifer would not be affected. Only the coral limestone formation is affected by SWI in the present and future scenarios. The saline wedge depth in the coral formation ranges from two meters deep at one meter inland from the coastline, to 100 m deep at the geological contact between the corals and the Kilindini sands, located around four kilometres inland.

The future consequences of borehole salinization would be an increasingly salty taste and at some point unsuitability of the water for human consumption and agriculture. This would increase costs, due to corrosion of domestic appliances, hotel facilities, pipes, and pumps, besides the cost of providing drinking water by other means, and the early abandonment of wells and associated facilities. Furthermore, as shown by Foster et al. (2018), handpump failure risks are higher and lifespans are shorter when groundwater is more saline and the static water level is deeper.

The increase in salinity, as observed in 2016, and the dynamics of the SWI will tend to increase calcite dissolution (Fig. 8b). The related increase in karstification would have a number of potential long-term effects: 1) induced hydraulic conductivity rise will hasten further aquifer salinization and 2) would increase the creation of sinkholes already observed in parts of the coral limestone during fieldwork. New sinkholes may be caused when caverns or channels in the coral limestone collapse due to groundwater overexploitation (Alfarrah et al., 2017; Jakemann et al., 2016; Khanlari et al., 2012). Occurrences of land subsidence in limestone have been globally reported, such as in Spain (Molina et al., 2009), India (Sahu and Sikdar, 2011), Mexico (Ortiz-Zamora and Ortega-Guerrero, 2010) and the United States (Holzer and Galloway, 2005). This has implications for the stability of buildings and other structures constructed on the limestone.

Despite the uncertainty of the impacts caused by the future abstraction scenario and longer forecast drought periods (Stocker et al., 2013), aquifer management decisions regarding the potential impacts on the aquifer system and the linked communities and economic activities are needed. Private sector and public participation in water resources management should be enhanced through decentralised management approaches. In this way, stakeholders, including the Water Resources Authority, private water users and communities in the study area, should carry out decision-making. Water infrastructure and technologies should be fit-for-purpose in application and scale, and the pro-poor focus should be underpinned by appropriately focused management regimes (Olago, 2018).

This decision-making must focus on managing the aquifer system in a sustainable way in order to protect the communities. These are the most vulnerable stakeholders, since they rely on the less resilient aquifer for water supply. Therefore, alternative, secure water resources must be developed to supply vulnerable communities before community wells become dry or salinize. One potential solution could be to supply the communities from deep boreholes, since this aquifer unit is more resilient in the face of adverse climate events. Base Titanium is already working together with Kwale County government to install community water sources into the deep aquifer to provide water security to communities, with a number of Base-drilled boreholes originally with handpumps installed planned to be converted to solar or mains-powered pumps. Other possible actions to ensure community well sustainability would comprise taking measures to protect the main recharge areas as is being done by the Kenya Wildlife Service supported by Base Titanium together with conservation organisations in the Shimba Hills National Reserve – the Water Tower for the Mkurumudzi catchment; managing land use to ensure high infiltration rates;

promoting managed artificial recharge; and conjunctive water use. A common conjunctive management strategy is the recharge and storage of surface water in aquifers when it is available in excess of demand, for withdrawal later when surface supplies are reduced, as during drought (Foster and van Steenberg, 2011). Furthermore, private companies should strive to manage their groundwater resources sustainably, minimising the impact on community well water quality and availability. For example, Base Titanium adopts recycling and conjunctive use, combining surface and groundwater during drought periods as a management strategy.

This study uses easy-to-apply calculations to illustrate the possible future risks of increased abstraction under climate stress to an aquifer system in Kwale County. At present, under 'normal' climatic conditions, we have observed no adverse consequences in the aquifer system since major abstraction started in 2012. However, the study underlines the importance of evaluating all risks to any aquifer system prior to major groundwater abstraction.

5. Conclusions and final remarks

Water-reliant growth in Africa needs to manage multiple risks for sustainable management of strategic groundwater resources. Securing new investors in rural areas where poverty is high and environmental regulation is weak may focus on the former at the cost of the latter. Lack of historical data such as water level, abstraction and quality data is typically the norm and challenge objective decision-making in the face of urgent development priorities. Government and enterprises may find environmental sustainability of secondary importance to advancing economic production, creating local jobs and new sources of taxation. This may translate into unknown risks to local, vulnerable populations and future generations who rely on shallow groundwater for water supply. Droughts compound this risk, with multiple and competing bulk water users abstracting from the same aquifer system without any shared understanding of impacts, including short and long-term damage from saline intrusion in coastal aquifers. As in most aquifers, water quality does not recover in all wells after wet season recharge, and significant amounts of data are needed to evaluate future aquifer response. Furthermore, in areas of the continent with lower precipitation and consequently lower recharge, a lower level of abstraction could be harmful to aquifers. Future risk should therefore be predicted under different abstraction future scenarios, before major abstraction takes place.

While gambling with groundwater may be common in Africa and globally, this study shows that groundwater resources can be significant and resilient to unpredictable but recurrent drought events. Given over half a billion dollars in capital investment in the two water-reliant industries in Kwale, in addition to tourism and related investment, understanding investor risk and liability from groundwater sustainability would seem prudent, if not a legal obligation, before major abstraction starts. Government leadership is essential to manage the aquifer as a system for all, including environmental services, rather than for the powerful few. Without technical, material and political support, water resource management agencies face stark choices in Africa, as limited staff and capacity are unable to ensure that adequate monitoring systems exist to guide regulations that manage water resources in the public interest. Governance failure can promote market failure, by mismanaging groundwater, by design or by accident. Furthermore, the expected impact of climate change across the continent, with variable consequences for water resources availability, could even worsen the situation.

However, this is not inevitable and this study shows how one of the main problems, the lack of aquifer systems data, can be overcome at least partially by integrating different sources of information. Most of the time, water-reliant users present specific hydrogeological information that can contribute to define the overall hydrogeological system, since their own main purpose is exploiting the aquifer with the maximum productivity. Therefore, local community water usage, together

with different stakeholders knowledge and good corporate water management as a catalyst for providing critical data use, allows us to develop credible models for future groundwater management and resource allocation. Furthermore, complementary but simple information sources such as in-situ interviews, Google Earth, Trip Advisor, easy-to-apply analytical methods, etc., that can be achieved in the African context as in many developing countries, enables groundwater abstraction to be estimated and the sustainability of the aquifer system to be defined, allowing potential future risks to be assessed as has been shown by this study.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2019.133634>.

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