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Challenges in groundwater resource management in coastal aquifers of East Africa: Investigations and lessons learnt in the Comoros Islands, Kenya and Tanzania

Jean-Christophe Comte[a,c,*], Rachel Cassidy[b,c], Joy Obando[d], Nicholas Robins[c,e], Kassim Ibrahim[f], Simon Melchioly[g], Ibrahimu Mjemah[h], Halimu Shauri[i], Anli Bourhane[j,k], Ibrahim Mohamed[f], Christine Noe[g], Beatrice Mwega[d], Mary Makokha[d], Jean-Lambert Join[j], Olivier Banton[l], Jeffrey Davies[e,m]

[a] University of Aberdeen, School of Geosciences, Aberdeen, UK
[b] Agri-Food and Biosciences Institute, Belfast, UK
[c] Previously at Queen's University Belfast, Groundwater Research Group, Belfast, UK
[d] Kenyatta University, Department of Geography, Nairobi, Kenya
[e] Previously at British Geological Survey, Wallingford, UK
[f] University of Comoros, Faculty of Sciences, Moroni, Comoros
[g] University of Dar Es Salaam, Department of Geology, Dar Es Salaam, Tanzania
[h] Sokoine University of Agriculture, Department of Physical Sciences, Morogoro, Tanzania
[i] Pwani University, Department of Social Sciences, Kilifi, Kenya
[j] University of Reunion Island, Laboratory Geosciences Reunion, Saint-Denis, France
[k] Water Office Reunion, Saint-Denis, France
[l] University of Avignon, Laboratory of Hydrogeology, Avignon, France
[m] University College London, London, UK

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ABSTRACT

Study region: Coastal areas of Kenya (Kilifi County), Tanzania (Kilwa district) and Comoros (Ngazidja island), East Africa.
Study focus: Research aimed to understand the physical and societal drivers of groundwater accessibility and identify critical aspects of groundwater access and knowledge gaps that require further monitoring and research. Interdisciplinary societal, environmental and hydrogeological investigations were consistently undertaken in the three areas considered as exemplars of the diversity of the coastal fringes of the wider region. This paper focuses on the hydrogeological outcomes of the research, framed within the principal socio-environmental issues identified.
New hydrological insights: Results confirm the fundamental importance of coastal groundwater resources for the development of the region and the urgent need to match groundwater development with demographic and economic growth. Hydrogeological knowledge is fragmented, groundwater lacks a long-term monitoring infrastructure and information transfer from stakeholders to users is limited. Current trends in demography, climate, sea-level and land-use are further threatening freshwater availability. Despite possessing high-productivity aquifers, water quality from wells and boreholes is generally impacted by saltwater intrusion. Shallow large-diameter wells, following the traditional model of these areas, consistently prove to be less saline and more durable than deeper small-diameter boreholes. However, promoting the use of large numbers of shallow

* Corresponding author at: University of Aberdeen, School of Geosciences, Elphinstone Road, Aberdeen AB24 3UF, Scotland, UK.
E-mail addresses: jc.comte@abdn.ac.uk, jccomte@gmail.com (J.-C. Comte).

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wells poses a significant challenge for governance, requiring coherent management of the resource at local and national scales and the engagement of local communities.
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1. Groundwater in coastal regions of East Africa

Africa is the continent with the fastest growing populations (United Nations, 2011) with coastal regions projected to experience the highest rates of population growth in coming decades (Vafeidis et al., 2011). At the continental level, East Africa has the second highest rate of population growth, after the Central African region (Ashton and Turton, 2009), while having the lowest renewable freshwater resource of Sub-Saharan Africa (Braun and Xu, 2010). In the Mozambique Channel region, the populations of the Comoros Islands, Kenya and Tanzania have quadrupled in the last 50 years (World Bank, 2014a), twice the global average and growing. Most of the population increase is in urban areas, which are already densely populated and where water resources, particularly groundwater which is often the only source of water of acceptable quality, are already under intense pressure (Steyl and Dennis, 2010; MacDonald et al., 2012; Walraevens et al., 2015). Recent papers have shown the importance of groundwater resources that are under growing pressure in developing regions elsewhere, but crucial for economic development (e.g., Mukherjee et al., 2015; Watto and Mugera, 2015). Adequate provision of water is central to human health and economic development in these regions where water scarcity is a serious impediment to growth and poses a threat to political stability.

In a demographic context within Sub-Saharan Africa, groundwater resources are heavily relied upon and the focus of strategic development (Ashton and Turton, 2009) because of both the relative resilience of aquifers to anticipated climate change and the widespread contamination of surface water resources. However, as exemplified by findings from previous inter-African reviews of regional and national groundwater management frameworks (e.g. Robins et al., 2006; Adelana et al., 2008; Braune and Xu, 2008, 2010; Knüppe, 2011), groundwater resources, except in countries totally dependent on them, (i) still suffer from an under-evaluation of their importance and significance, (ii) are often managed separately from surface water and (iii) management institutions (governments, communities, NGOs, consultants) are largely fragmented and lack a central strategy. Groundwater information services, i.e. databases and systematic long-term monitoring, are non-existent or of inadequate quality and fragmented. The involvement of stakeholders, including communities, in decision-making processes and resource utilisation is insufficient, under-acknowledged by managers and governments and requires urgent capacity building of all parties, from individual to institutional (e.g. BGR, 2007; Foster et al., 2008; Braune and Xu, 2010).

Efforts towards the integration of groundwater management within holistic water management frameworks, such as river basin organisations have only emerged recently, mainly through national Integrated Water Resource Management (IWRM) frameworks (Global Water Partnership, 2000, 2002; World Water Council, 2006) that aim to address these deficiencies and contribute to the Millennium Development Goals (MDGs). Nonetheless, groundwater management appears subsumed under broader policy, legal and institutional frameworks dealing with the management of water resources; hence the integration of groundwater into national policy requires development of adequate cross-sector dialogue within government (Mumma et al., 2011; Foster et al., 2012). The management of coastal groundwater poses a further challenge due to its vulnerability to seawater contamination and the specific physical and socio-economic characteristics of the coastal zone. The review of Steyl and Dennis (2010) is one of the very few works that provides insights on common issues with regards to groundwater management in coastal aquifers of Africa. There is a notable gap in the literature regarding the inter-disciplinary aspects of the management of coastal groundwater resources in Sub-Saharan Africa and the regionally-specific socio-environmental drivers.

In the East African coastal region, demographic change has led to an overall increase in groundwater abstraction, with increased drilling of deep boreholes with higher abstraction rates than traditional dug wells and shallow boreholes. High abstraction rates and concentrated well fields are incompatible with the nature of coastal aquifers. These aquifers are mainly low-lying with shallow water tables and are susceptible to seawater intrusion if not carefully managed, regardless of aquifer productivity or recharge rates (Robins, 2013; Werner et al., 2013). The abstraction of inland groundwater, by way of contrast is generally only limited by aquifer productivity and available recharge.

The geology of much of the East African coastal aquifers is young (Mesozoic to present), composed of soft or unstable sediments and volcanic deposits, which need supporting during and after drilling to avoid collapse and bloc fall. Though slower and labour intensive to construct, large diameter traditional wells are more suited to such environments; causing less drawdown than boreholes and giving access for clearance of debris (e.g. Bourhane et al., 2015). A larger number of shallow wells widely distributed across an area is effective in minimising the risk of seawater intrusion. Such strategies, however, pose a management challenge in urban areas (Edmunds, 2012) where high densities of abstraction points may be necessary, initial drilling costs are high and risk of contamination is considerable.

East Africa is identified as one of the regions at greatest risk globally from the impacts of climate change (Hinkel et al., 2012). Most coastal areas are low-lying and will experience significant inundation even with modest rises in sea level. The most recent climate change projections (IPCC, 2014a; Cai et al., 2014) anticipate an accelerated rise in global mean sea level in coming decades (Watson et al., 2015) combined with an increase in rainfall during the wet seasons and higher annual temperatures. These may increase potential evapotranspiration and increase seawater intrusion in low-lying coastal

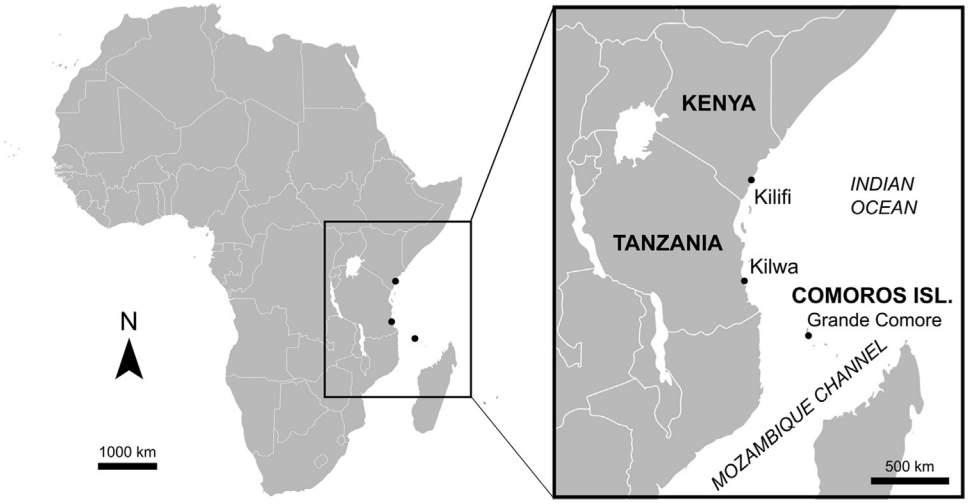

Fig. 1. Location of the three study sites in the coastal zones of the Comoros Islands, Kenya and Tanzania.

settings and islands (Comte et al., 2014). According to the latest report of the Intergovernmental Panel on Climate Change (IPCC, 2014a, 2014b), the available information or evidence on projected impacts of climate change on coastal aquifers is globally limited. More specifically, the impact on aquifer recharge in East Africa remains poorly constrained (Döll, 2009) due to a lack of hydrometric monitoring which could be used to inform forward modelling and proactive development of management approaches (Robins et al., 2006; Adelana, 2009; Steyl and Dennis, 2010).

The combined effects of demographic, socio-economic, climatic and political changes on coastal groundwater resources negatively impact both the availability and sustainability of potable groundwater. Although an adverse impact is expected, the extent of the problem is not well established because of the large number of driving factors involved and the paucity of data with which to test them. Better understanding requires the implementation of integrated multidisciplinary research and expertise (including hydrogeologists, hydrologists, geographers, and socio-environmentalists) in order to improve the knowledge and understanding both of the vulnerability of coastal groundwater and its long-term response to change. This will permit identification of appropriate management strategies to mitigate negative impact on resources. This constitutes a necessary and major step towards the sustainable development and management of water accessibility for people in coastal East Africa.

2. Aims and objectives

A suite of investigations was undertaken at three contrasting coastal areas in East Africa; Grande Comore (Ngazidja) Island (11°40′S; 43°20′E) in the Comoros Archipelago, Kilifi County, North of Mombasa, in Kenya (3°37′S; 39°50′E), and Kilwa, a rural area in southeast Tanzania (8°55′S; 39°30′E). These represent three of the lowest-income countries (LIC) (as classified by the World Bank, 2014b) of the East Africa/South-western Indian Ocean zone (Fig. 1) and are exemplars of the physical, social and cultural diversity of the coastal fringes of the region. An important component of the work was testing whether the concerns raised by Steyl and Dennis (2010), regarding the sustainable management of African coastal groundwater resources, apply consistently to the three study areas.

Three research sites covering the (1) societal, (2) environmental and (3) hydrogeological status of the study areas were established and within each a consistent work programme was applied. The overall research programme aimed to understand the physical and societal aspects of groundwater accessibility, to provide up-to-date regional groundwater databases and identify critical aspects of groundwater access as well as knowledge gaps that will require further longer-term monitoring and research. In this paper we focus on the hydrogeological outcomes of the research, framed within a summary of the principal societal and environmental issues identified in each area. Issues relating groundwater management with governance and institutional frameworks in the study areas would be addressed in detail in another publication (Obando et al., in preparation) focussing specifically on the socio-economic aspects of this research programme.

3. Study areas-overview

3.1. Comoros Islands—Grande Comore (Ngazidja) (see map in Fig. 2 a)

In the Comoros archipelago, the island of Grande Comore (1148 km^2) was selected for the study. As the most populated island in the region, and growing at over 2% per annum (~400,000 inhabitants estimated in 2015), more than half of the population is concentrated within 5 km of the shoreline due to the steep gradients of the elevated and afforested interior of

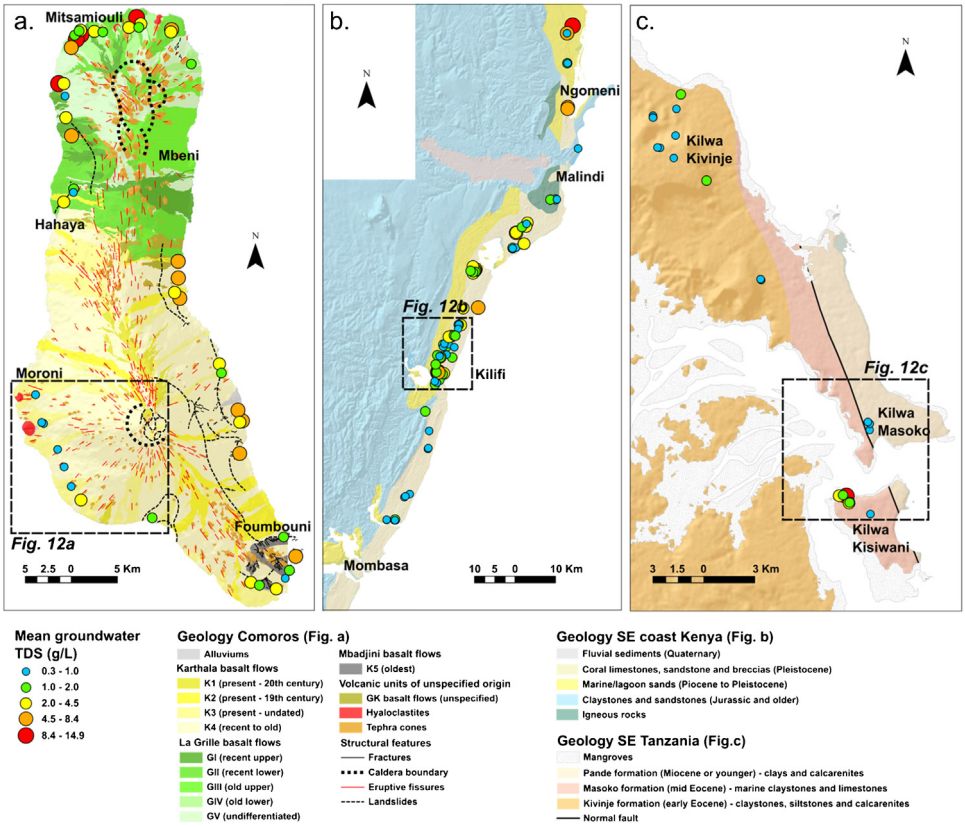

Fig. 2. Overview of the study areas, including the main geological units and groundwater salinities of surveyed wells in (a) Grande Comores Island (Comoros), (b) Kilifi region (Kenya) and (c) Kilwa district (Tanzania). See Fig. 1 for the general location on these sites in East Africa. Dashed boxes indicate more detailed areas plotted in Fig. 12.

the island. About 65% of the population do not have permanent access to groundwater and primarily harvest rainwater from roofs into tanks, which are only sufficient during the wet season and have issues with bacterial contamination. During the dry season, water use is rationed. For families that can afford it, freshwater is distributed by water trucks delivering from the few fresh abstraction wells on the island. These comprise 54 wells drilled in the volcanic aquifers of the coastal zone which supply 20 localities representing about 35% of the island's population (Mohamed and Othman, 2006). Fewer than 30% of the wells provide groundwater of acceptable quality, i.e. Total Dissolved Solids (TDS) < 1 g L^{-1} (Bourhane et al., 2015) and consequently the local drinking water salinity guideline is usually taken at 3 g L^{-1} instead of 1 g L^{-1} as recommended by the World Health Organisation (WHO, 2003). Wells with higher salinity continue to be used for irrigation, livestock or washing. This situation is not projected to improve in coming decades with anticipated population growth (demand is increasing at about twice the rate of groundwater development) and projected climate change (observed decrease in rainfall; Vincent et al., 2011). The large variations in groundwater salinity are locally responsible for community conflicts with regard to water costs.

3.2. *Kenya–Kilifi County (see map in Fig. 2b)*

Kilifi County (13,006 km^2) lies along the Kenyan coast between Malindi to the north and Mombasa to the south, with a total population of 1,109,700 growing at a rate of 3.1% per annum. The area experiences a semi-arid climate, with irregular wet seasons and frequent drought (Onyancha et al., 2010). Although much of the piped water supply in the county is currently supplied from surface water sources, it is expected that reliance on groundwater in the area will increase as the demand for domestic and agricultural water increases. Groundwater yields vary along the coastal zone with poor quality and low yields in areas of Jurassic shales and Pleistocene coral limestones and higher quality and yields in Triassic sandstone and Quaternary sands. Excessive abstraction has already resulted in water contamination and saline intrusion (Musingi et al., 1999; Munga et al., 2006). Surface water sources in the county are generally inland or to the north where the Athi-sabakia and Tana rivers, which originate in the Kenyan highlands, flow towards the Indian Ocean. The security of these sources is currently threatened by planned large-scale agricultural projects in the Kenyan interior and plans for dams upstream. Most of the water supplied to the densely populated Kilifi township and the linked coastal zone, which is the focus of this study, is piped from these rivers and inland lakes. Daily water demand in the township is estimated to be 200,000 m^3 against the available

130,000 m^3 (NEMA, 2010) and is leading to pressure and conflict in the area. The contrast between tourist developments and affluent coastal residences and the amenity-poor, densely populated urban zone is pronounced. Many of the existing boreholes yield either saline or brackish water, and the remaining freshwater aquifers are in danger of overexploitation and are susceptible to pollution.

3.3. Tanzania—Kilwa district (see map in Fig. 2c)

Kilwa district (19,998 km^2) is a largely rural, low-lying coastal and island environment in south-eastern Tanzania consisting of coral limestone to the east and clays in the west, which dip eastward. Overburden comprises weathered lateritic soils and some Quaternary to Recent deposits of blown sand which are the dominant water bearing formations. The district is predominantly agricultural focussing on crop production such as cashews, simsim and coconut with some livestock rearing. Kilwa Masoko is a growing urban centre, the centre of local administration, with a developing tourism industry. In 2012 it was designated a service port for the gas pipeline installations to the north at Songo Songo island. The population has grown in recent years (currently ~15,000), fuelled by migration from the coastal hinterland. Water demand exceeds supply in the town and across the district. Currently the town is supplied by 4 public supply boreholes at a well field at the centre of the urban area, about 2 km from the coast, supplying approximately 1500 m^3/day. Demand is twice this volume so additional piped water is taken from open springs 15 km to the north at Mpara, with more wells under construction. The islands of Kilwa Kisiwani and Songo Mnara are historic stone-built towns (12thC) now designated a UNESCO world heritage site and a tourist attraction. Only Kilwa Kisiwani (area 17 km^2) is populated, with about 850 people settled in the more elevated (15 m) northwest of the island. The island is composed of coral limestone, overlying marls and clays (Nicholas et al., 2006). Groundwater occurs in shallow lenses, replenished during seasonal rains. Drainage is localised with no rivers or streams. The main employment is subsistence farming and fishing. Water shortages are major issues for the island community. The current sources of water are open shallow wells, the less saline dating from the 12th Century, which were added to by installation of boreholes and hand pumps in 2006 (Marobhe and Songo, 2006). All but one of the boreholes are saline or collapsed and the hand pumps are broken.

4. Methodology

Systematic investigations were undertaken in each of the study areas and hydrometric monitoring infrastructure installed at each site. The societal component of the study targeted issues of accessibility facing local communities and stakeholders in each area. An environmental characterisation, covering land use change and examination of existing data sets on sea-level and climate provided insight into the potential factors limiting groundwater availability and sustainability both at present and in the future. The hydrogeological component aimed to establish a quantitative and qualitative background status of coastal groundwater resources.

4.1. Societal constraints on water accessibility—perspectives of stakeholders and user groups

Gaining a local perspective on issues affecting access to water was one of the core objectives. Surveys of water users (householders, farmers and industries) and stakeholders (e.g. drilling companies, water managers) provided valuable complementary data to existing demographic observations and census data. Direct interviews with households (a total of 142 households in Kilifi, 154 in Kilwa and 185 in Grande Comore) were undertaken using a stratified random sampling method to select households within local electoral areas. Focused group discussions with community members and health providers were used to identify sources and quality of water supply and public health issues including common waterborne and water-related diseases.

Local stakeholder groups in each target area were established and a Participatory Action Research PAR (Pretty and Vodouhê, 1997) approach used to understand and address the social-economic and environmental factors of water resource management (Van Niekerk and Van Niekerk, 2009; Mapfumo et al., 2013). This involved working with the selected communities through an inception workshop followed by community workshops and meetings and a final dissemination workshop. The PAR included use of questionnaires, Focused Group Discussion (FGD), in depth interviews and visioning (all in a participatory manner) where the stakeholders (youth groups, women's groups, elders) reflect on the past, look at the current situation and develop a 'vision' of what should be in the future.

The outputs provide an overview of: (a) existing issues with water access in each study area and perceptions of causes; (b) societal issues affecting water resources management; (c) current water resources management strategies and environmental factors affecting the same; (d) past practices and traditional methods of water management; (e) community stakeholder analysis on best practices of water resources management; (f) community perceptions on changing water resources and effects on their livelihoods; and (g) water resources management and environmental health.

4.2. Environmental change—land use change and climatic trends

For each study area available secondary data sources on climate, land use and recharge were compiled, and supplemental monitoring implemented where data gaps were identified. An automatic weather station provided rainfall and potential evapotranspiration time-series data at hourly intervals to promote understanding of borehole and well level and electrical conductivity monitoring.

Land cover and use were mapped from available aerial imagery for each area, and validated in the field. Temporal change was evaluated by comparison of the most recent aerial imagery with past imagery of equal resolution. Sources were limited by budget and as such the period varied depending on the availability of imagery for each site. Land use change was mapped and classified within a Geographic Information System (GIS) to provide information on settlement growth/decline and the clearance of land for agriculture, industry and infrastructure.

Long-term trends in temperature and rainfall in the study areas were examined, including the frequency and intensity of rainfall events, and temperature trends. Weather data for available coastal synoptic stations across Kenya, Tanzania and Comoros were acquired from the British Atmospheric Data Centre Global Weather Observation data sets over the period 1984–2014. The sampling time-step for the stations was normally every 3 h but quality and completeness of the data sets varied considerably among sites, with marked improvements from the late 1990s onward.

4.3. Hydrogeology and groundwater resources

Hydrogeological investigations were carried out to assess the current hydrogeological conditions and the aquifer vulnerability to seawater intrusion across each area.

Comprehensive baseline surveys were undertaken to establish the existing water well infrastructure. Existing datasets were used to map the location of wells and compile their technical characteristics, their use, pumping rate and records of changing salinity. A strong collaboration with local water services was initiated to ensure a continuous exchange and updating of borehole databases.

Baseline geophysical investigations, using 2D Electrical Resistivity Tomography (ERT), were carried out at each site, to characterise the aquifer structure and the current extent of saltwater intrusion. One to two profiles were undertaken at each site, perpendicular to the shore, using boreholes or wells with existing hydrogeological information to inform the interpretation.

Additional well monitoring was carried out to provide an indication of the groundwater variability in both space and time. Spatially, water levels, Electrical Conductivity (EC) and temperature profiles of wells were measured across a subset (dependent on density and accessibility) at each site, for a number of campaigns (2 per year corresponding to the dry and wet seasons). Temporally, in 1–3 strategic boreholes/wells at each site, a borehole datalogger was installed to acquire high-resolution temporal data on temperature, EC and water level, to investigate recharge processes and aquifer diffusivity.

5. Results

5.1. Societal—community and stakeholder perspectives

5.1.1. Results from analysis of census data

Analysis of the available census data, from at least 2 decadal censuses, for each site provides an overview of demographic change (Fig. 3) and associated pressures on groundwater infrastructure (Table 1).

5.1.1.1. Demographic changes. In Kilifi, Kenya, the analysis focused on the township to the north of the estuary and found that population and household densities have grown rapidly. The population in this area more than doubled over the 20 year period, increasing from 255 persons km^{-2} in 1989–535 persons km^{-2} in 2009, and a household density of 54 households km^{-2} in 1989–111 households km^{-2} in 2009.

Population growth in Kilwa district, Tanzania was weaker by contrast; increasing by 10% between 2002 and 2012. The area is still predominantly rural with a population density of 13 people km^{-2}. The urban population increased from 8% to 10% of the total over the decade. In the urban centre of Kilwa Masoko, which has seen some growth in tourism and the development of the port for servicing the gas pipelines to the North.

In Grande Comore (Ngazidja) the population increased by 62% over the 23 years between 1980 and 2003 (last census). The population density was about 250 people km^{-2} in 2003. In 2005 72% of the population was rural, against 76% in 1991. The capital Moroni's population (13.5% of the island's population in 2003) more than doubled between 1980 (17,267 people) and 2003 (40,050 people) and is currently estimated at over 50,000 people. Tourism is as yet embryonic in the Comoros but has potential and is expected to develop in the next decades (Shaaban et al., 2013) due to the many natural and cultural assets.

5.1.1.2. Water use and evolution of infrastructures. Data on water use (Table 1) were obtained from census records in each country (Kenya, Comoros Union and Tanzania) at the highest resolution available for each study area (respectively, Kilifi County, Grande Comore island and Lindi Province in which Kilwa district is located).

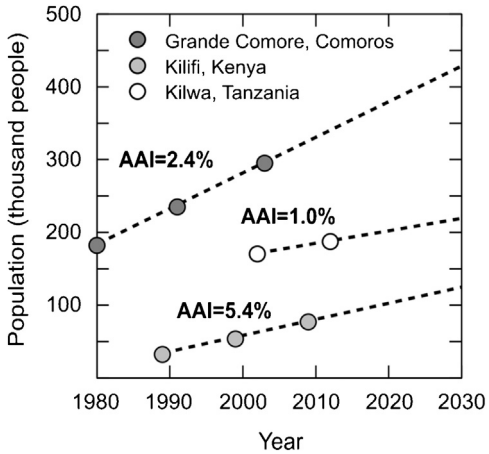

Fig. 3. Population changes in the three study areas over the last three decades (from the most recent available census data). AAI = average annual increase; dashed lines are linear projections by 2030.

Table 1
Main source of water used in the three regions as compared to the whole country and change over time.

% (Rounded to upper%)	Remotely piped water	Protected well/spring	Unprotected well/spring	River/pond/dam	Vendors (e.g. trucks)	Rainfall tank/Jabias	Other
Tanzania (excl. Zanzibar) 2012	34	20	31	14		2	
Tanzania (excl. Zanzibar) 2002	37	18	29	11		5	
Lindi Region 2012 (Tanzanian coast)	19	14	53	10		4	
Lindi Region 2002 (Tanzanian coast)	13	17	55	15		1	
Kenya 2009	30	36		27	8		1
Kenya 1999	30	33		33	2		3
Kilifi County 2009	57	24		19	1		1
Kilifi County 1999	50	25		24	1		2
Grande Comore 2014	0.0	20[a]/2[b]	0.0	2	5	59	18[c]
Grande Comore 2000	0.0	15[a]/2[b]	0.0	3	3	70	10[c]
Comoros Union 2014	0.0	33[a]/3[b]	0.0	3	No data	30	29[c]
Comoros Union 2000	0.0	20[a]/2[b]	0.0	4	No data	40	24[c]

Kenya values from KNBS.
[a] UNDP deep wells.
[b] Private wells.
[c] Public fountains supplied by groundwater (protected wells).

In Kenya, reliance on piped water supply is high in Kilifi with 56.8% of households surveyed in 2009 using piped water over other supplies. There was an increase of 7.1% in piped supplies from 1999 and a corresponding decrease in the use of well or spring supplies. The Kilifi region has no permanent rivers and the piped supplies are abstracted from River Tana and Athi-Sabaki rivers originating from the Kenyan highlands that flow into the Indian Ocean. Currently the supply from inland is inadequate to meet demand and is supplemented by groundwater abstraction, supplying a combined total of 130,000 m^3 daily towards an estimated demand of 200,000 m^3. The decrease in groundwater as a supply (24.5–23.2% between 1999 and 2009) may be linked to the high salinity of coastal aquifers in the area combined with water pollution, environmental degradation and recurrent droughts of wells (Marete, 2006; Onyancha et al., 2010); which make piped supplies preferable where they can be afforded. Similar patterns were observed in the county during the surveys and FGDs undertaken as part of this study. The use of water vendors and supply trucks has increased by 6.5% in the county over the decade (up to 2009) while the use of water from rivers, ponds and dams directly by households declined by 6.5%.

Piped water is less commonly used in Lindi Region, of which Kilwa is the easternmost district, accounting for 19.1% of use in 2012 (Table 1). This is still low in comparison to the percentage of households with access to piped water at national level (Tanzanian mainland), which was 33.5% in 2002 and reflects the rural character of the area. The increase in piped water use in Lindi from 2002 is attributed to some improvement in infrastructure and a larger urban population in proximity to existing piped networks. Potentially linked to this is the decline in households obtaining water from boreholes, wells and springs from a combined total (unprotected and protected) of 72.1 to 66.9%. Some 79% of all wells/springs in Lindi were considered unprotected in 2012 compared to 76% in 2002. Growth in use of alternative water supplies such as rainwater and supply by water vendors from 0.4% in 2002 to 7.0% in 2012 may reflect the growing urbanisation of the population and increasing demand driving alternatives to traditional well sources as well as a growing perception of water vending as a rewarding business opportunity.

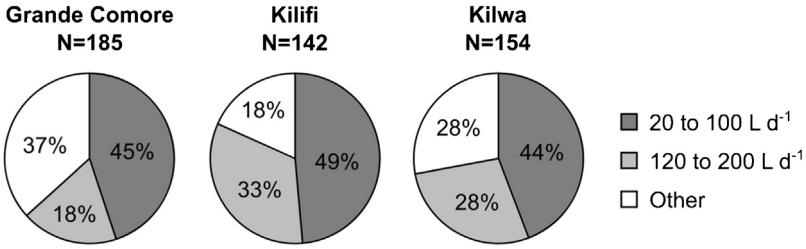

Fig. 4. Daily volume of water used per household (mean size of 6 persons) in the three regions. *N* = number of households surveyed.

Water supply in Grande Comore Island relies exclusively on local aquifers and on rainfall harvesting. Supply from boreholes and wells more than doubled between 1985 and 2010 as a result of the commissioning of 54 new wells drilled in the early 1980s (UNDP, 1987). Groundwater is currently estimated as supplying just over a third of the island's population with safe water. Alternative water supplies such as rainfall harvesting have decreased as a consequence, from 70% to 59% between 2000 and 2014. Water supply by tanker trucks from operating wells has strongly increased (from 3% in 2000 to 5% in 2014) particularly in the last decade and has become a highly lucrative business (Mohamed, 2012).

5.1.2. Results from household surveys, water stakeholder and community meetings

Further to the available census data, local observations at each of the study areas were undertaken through a combination of household questionnaires, stakeholder and community meetings. For brevity a summary of the key findings is presented here; the detail of the socio-economic work programme will be covered elsewhere.

5.1.2.1. Water accessibility. In terms of water access, results from the household survey (Fig. 4) established that less than half of households in Kilifi, Kilwa and Comoros used between 20 and 100 L day^{-1} (mean household size = 6 persons). This falls short of the basic water requirements of 20 L person^{-1} day^{-1} recommended by the World Health Organisation (WHO, 2003). Furthermore, less than a third of households used between 120 and 200 L day^{-1} which is classed as 'reasonable access' but still falls below the 50 L person^{-1} day^{-1} which is considered adequate for domestic use (Gleick, 1996). The primary factors contributing to poor water access across all three areas based on the household surveys and community discussions were: lack of finances to purchase greater quantities or purchase storage/harvesting equipment, insufficient storage capacity, water budgeting/rationing in certain areas or during the dry seasons and a failing or inadequate infrastructure.

Across all three sites the common issues raised in community and stakeholder meetings and discussions were inadequate and intermittent supply, water scarcity, increased salinity, poor quality and high cost. The causes of these issues were attributed to drought (lack of rainfall/changing weather patterns), poor water sector management and governance, sea water intrusion and failing infrastructure. Issues with water quality result primarily from contamination of unprotected wells and poor source protection, with unregulated dumping highlighted as an issue in all areas. In Comoros there is a problem with unregulated use of agricultural fertilisers and sediment erosion due to deforestation.

5.1.2.2. Participation in water resources management. Across the three study sites the stakeholder and community discussions raised issues with governance and disproportionate resource allocation, highlighting failures at district and national levels. Effective water governance requires active participation of all the stakeholders in management of water resources. This can be determined by the proportion of the local community which actively contributes to water resource decision making through membership of social groups and being involved in leadership roles contributing to the decision making process. Findings from the survey indicate that less than half of the households surveyed were members of social groups relating to water resources (Fig. 5a) or involved in meetings for decision making in relation to water resources (Fig. 5b). Furthermore, less than 25% in Kilifi and Grande Comore and less than 5% in Kilwa had received any training relating to groundwater or surface water management, water quality or water use (Fig. 5c). Additionally, 10–20% of households surveyed identified poor water sector management as a major water problem (Fig. 5d), which needs to be addressed.

5.1.2.3. Strategies for management. In summary it was noted that community members were aware that groundwater resources are being depleted and that salinity is a key water quality issue. The community members are willing and ready to engage in water resources management and to pay for water of good quality.

Several strategies were proposed for sustainable management of existing groundwater resources during the meetings including the implementation of effective water resources management to provide water of good quality that is properly and the provision of appropriate infrastructure for water storage, especially for rainwater harvesting. Furthermore, there should be proper siting of boreholes and wells, with regular maintenance programmes, that should involve women as major stakeholders at micro level and encourage alternative sources of water supply. Traditional knowledge systems should be integrated with modern technologies. The need for awareness and training on water issues is still critical (see Fig. 5c). Micro-finance and social networks are also vital as avenues for capacity building of community for effective management

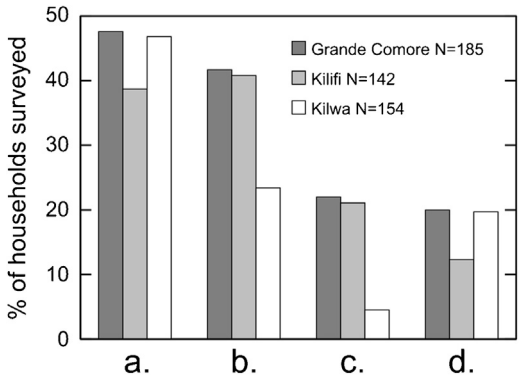

Fig. 5. Participation of end-user households in water resources management. (a) Membership of a social group relating to water access; (b) participation in community meetings for decision-making relating to water; (c) water related training received; (d) identification of poor water sector management as a major water problem.

Table 2
Summary of community aspirations based on focussed group discussions on water resource management across the 3 study areas.

Current state	Desired state
Not all community members receive high quality water	All community members receive high quality drinking water
Not all community members have adequate supply of water particularly shortages in dry season	All community members have adequate supply of water in relation to the demand during all seasons
Not all community members can afford to pay for water—prohibitive cost	Affordable water pricing
Waiting too long to fetch water	Sufficient water points per unit of population
Long distances to water source	Water source near dwelling or piped water—enhance connection of water
Community not aware of the water issues, particularly the poor	Participation of community in water governance
Poor water resource management	Effective water resources management

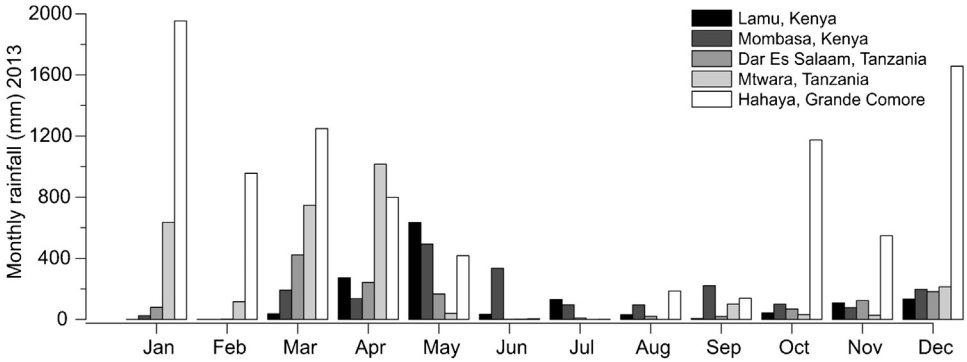

Fig. 6. Comparative monthly rainfall totals for 2013 indicating the annual variation in rainfall across seasons from Lamu in northern Kenya to Mtwara in southern Tanzania and Hahaya on Grande Comore island.

of water resources. From the visioning conducted with the community members the desired state for selected aspects of water resources management was captured in Table 2.

5.2. Environmental change

5.2.1. Regional climatic data

Seasonal rainfall varies across the region. The rainy seasons occur during boreal spring and autumn; the long rains occurring in spring and short rains in autumn. The strength of the rainy seasons varies with latitude and changes in circulation patterns over the Pacific and Indian Oceans. Orographic influences are particularly strong in Comoros where volcanic massifs create a topographic high that results in high variability across the island.

From the regional synoptic stations (Fig. 6), average annual rainfall in Mombasa, 20 km south of Kilifi, is 1800 mm (average over 2007–2013) with the majority falling in May and June, and generally some rainfall in all months, though little in January and February (<25 mm in 2013). Seasonal rainfall decreases to the north with an average annual rainfall in Lamu, the most northerly district on the Kenyan coast, of 1700 mm over the 2007–2013 period, for which the record is almost complete. Since the 2005–2008 period, during which Kenya experienced extremes of drought and rainfall (Hastenrath et al., 2010) with

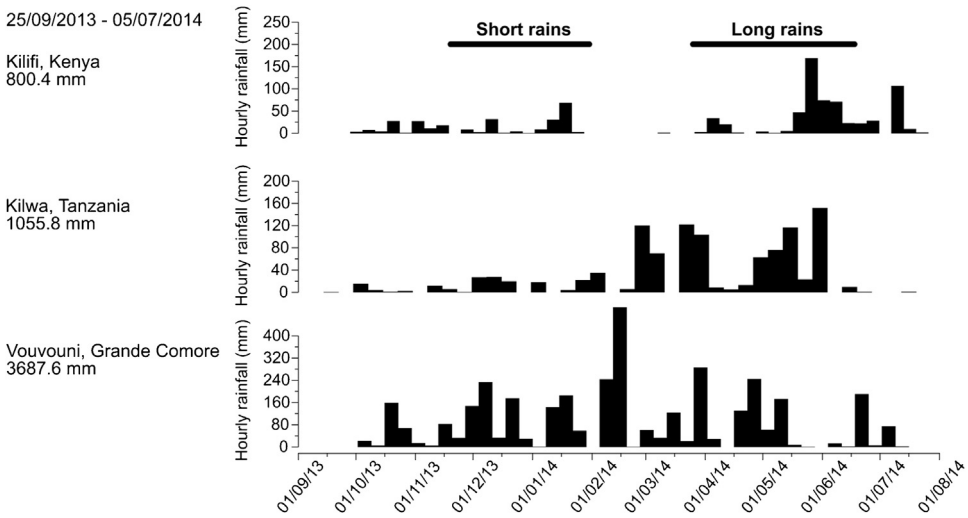

Fig. 7. Rainfall over the period 25/09/2013–05/07/2014 at the weather stations at Kilifi, Kenya; Kilwa, Tanzania; and Vouvouni, Grande Comore.

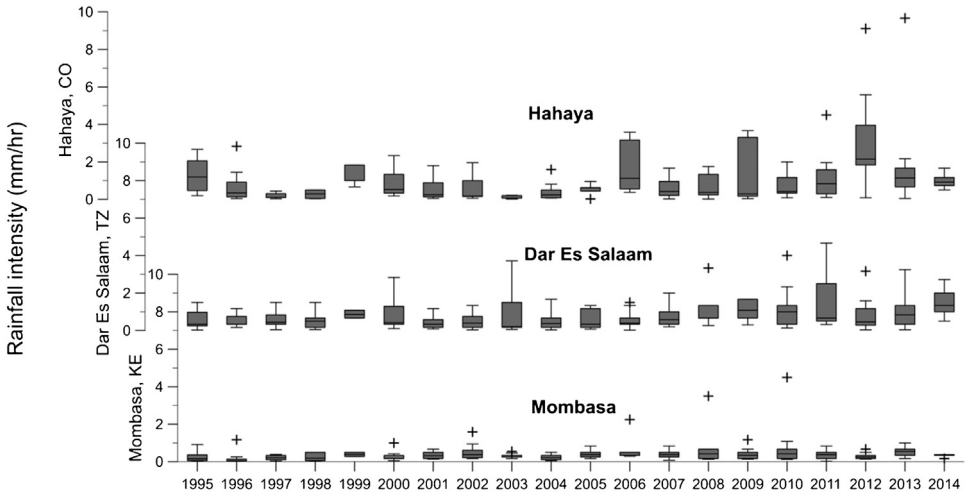

Fig. 8. Box whisker plots of monthly rainfall intensities calculated for the closest synoptic stations in each country.

3160 mm recorded in 2008 at Mombasa, annual rainfall has not exceeded 2000 mm, with 2011 particularly dry at 1140 mm. The low rainfall pattern has been linked to variability in both the Indian and Pacific Oceans and to the El Niño-Southern Oscillation (Ummenhofer et al., 2009; Clark et al., 2003). The effect of prolonged droughts places increases pressure on groundwater resources in the region as surface water dries up.

To the south at Dar es Salaam in Tanzania, which lies 100 km north of Kilwa, seasonality is more pronounced with clear rainy seasons and almost no rainfall in June, July, August and September and February (43 mm total over these months in 2013 in Dar es Salaam). Average rainfall recorded in Dar es Salaam over the 2007–2013 period was 2570 mm. At Mtwara 170 km south of Kilwa, Tanzania the average annual rainfall was 2430 mm over the 2007–2013 period. In Grande Comore, an average of 4395 mm rainfall was recorded over the same period.

Observations at the weather stations installed at each of the study sites agree well with the patterns at the national synoptic stations overall (Fig. 7). Over the period 25 September 2013–5 July 2014, for which a complete record exists for all three sites, 800 mm of rainfall was recorded in Kilifi (maximum rainfall = 40.8 mm h^{-1}, median rainfall 0.8 mm h^{-1} with rain recorded 5% of time), 1056 mm in Kilwa (maximum rainfall = 46.2 mm h^{-1}, median rainfall 1 mm h^{-1}, with rainfall recorded 4.5% of the time) and 3688 mm in Vouvouni in Grande Comore (maximum rainfall 97.6 mm h^{-1}, median rainfall 1.4 mm h^{-1} and rain recorded 11% of time).

In Comoros, and particularly in Tanzania, which in late April 2014 experienced heavy rainfall and extensive flooding across the north east of the country, the number and magnitude of large rainfall events in recent years was a frequent comment in the social surveys undertaken in the study areas. An analysis of rainfall intensities based on the 3 hourly synoptic station data supports this (Fig. 8) with increasing magnitude events recorded in the last decade at sites (Hahaya, Dar es Salaam and

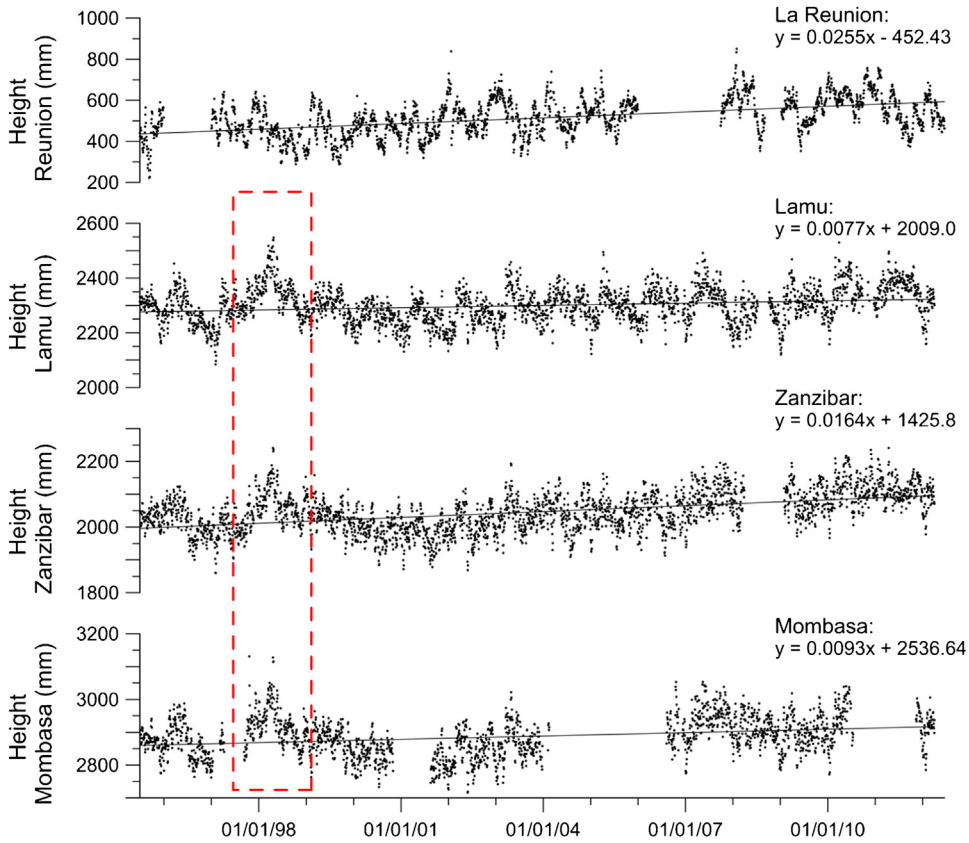

Fig. 9. Tidal gauge data for the Western Indian Ocean region proximal to the study area. An upward trend is noted for all sites excepting a peak (red dash box) recorded at Lamu, Zanzibar and Mombasa circa 1998.

Mombasa) for which the data record is almost complete and where potentially erroneous measurements were filtered based on the Quality Check scores attached to the record. Due to large data gaps and omissions the period prior to 1995 was not included in the analysis. An increase in the extremes of rainfall is apparent from 2005 onward for Hahaya in Comoros and Dar es Salaam, Tanzania. There is less indication of change for Mombasa, which experiences lower annual rainfall.

Many projections exist for the impact of climate change on Global Mean Sea-level (GMSL). The rate of change has been widely debated, with recent work (Watson et al., 2015) which corrected for errors in satellite altimetry data over recent decades, indicating that the actual rate of sea-level rise has accelerated. At a regional level, tidal data (Fig. 9) were obtained from the University of Hawaii Sea Level Center (http://uhslc.soest.hawaii.edu/data/download/rq) for the Western Indian Ocean region (gauges at Mombasa, Kenya; Lamu, Kenya; Zanzibar, Tanzania and Pointe des Galets, Réunion Island). Data gaps are present in almost all data sets but from 1986 to 2012 a comparable section from each time series was extracted and a linear fit applied to data during this period for each station. Not accounting for issues with gauge maintenance and instrument drift a clear positive trend is common to all with estimated annual increases for the gauges ranging from 3 to 9 mm. The potential implications for the coastal communities in this area are clear: accelerated coastal erosion, inundations of low-lying land and resulting inland extension of saltwater intrusion which will impact on the availability of freshwater resources.

5.2.2. Land use change

Change in land use across each study area provided an indication of the effects of demographic change and the potential impact on recharge and groundwater quality. Clearance of vegetation for agriculture affects evapotranspiration and recharge and where bare earth remains there is increased potential for soil erosion during intense rainfall events. Increased sediment entering surface waters through erosion affects their use as water sources and with intensification of agriculture comes a risk of contamination from pesticides and herbicides, animal faecal material and chemical fertilisers. Pressure for space in urban areas leads to dispersion and enlargement of the urban periphery. New houses require water and where piped water supplies are not available new wells are necessary or the amount of time spent per day on collecting water increases.

Mapping was undertaken within defined areas at each study area. The focus was on mapping ground cover (extent of vegetation) and urban areas. Buildings were digitised from aerial imagery in order to provide an indication of changing housing and population patterns in the study areas. All buildings within selected areas, including houses, business establishments

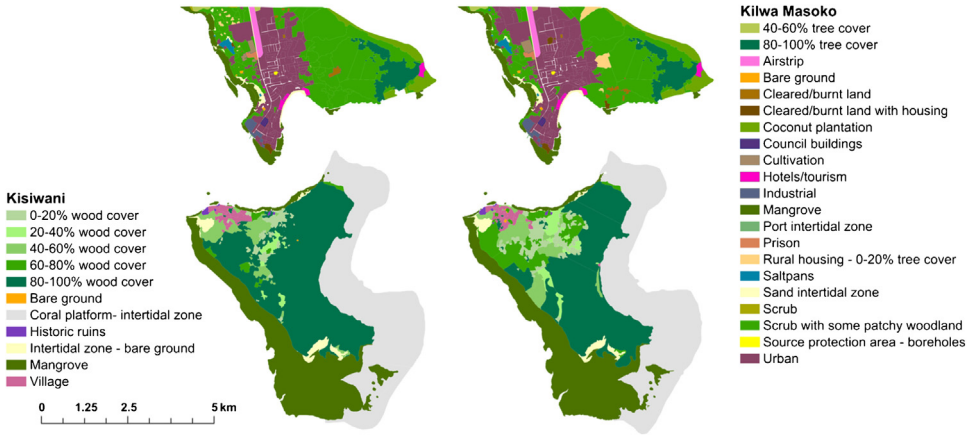

Fig. 10. Land use change in Kilwa Masoko (mainland) and Kisiwani (island), Tanzania between 2006 (left) and 2013 (right).

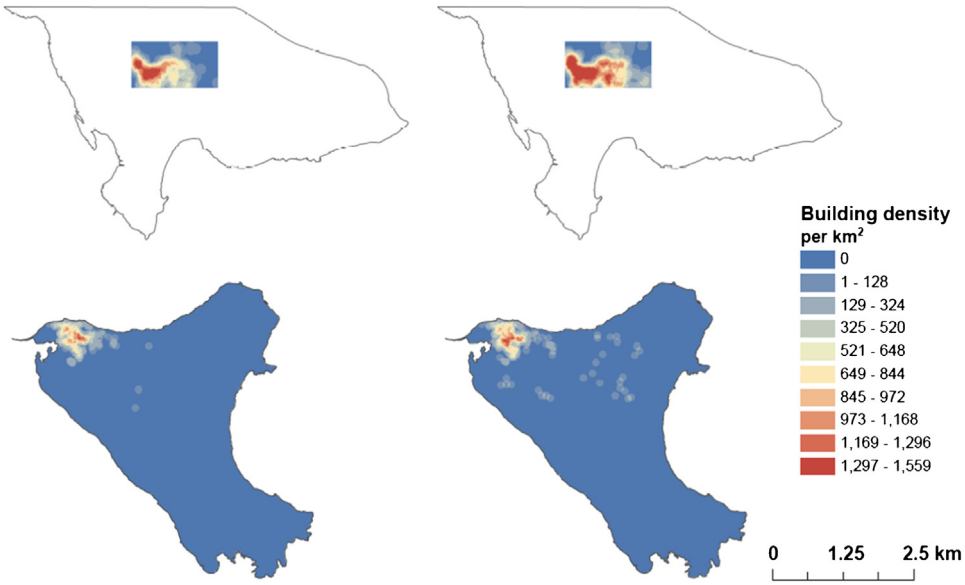

Fig. 11. Building density in Kilwa Kisiwani (island) and for a sub-area on the urban periphery of Kilwa Masoko, Tanzania in 2006 (left) and 2013 (right). Density is expressed as number per km^2.

and public buildings were mapped. Land use and housing density change is presented for Kilwa, Tanzania over the period 2006–2013 (Figs. 10 and 11). The comparatively rural situation in this study area makes alterations in the landscape easier to map; the quality of imagery available was high.

Within dense urban areas, such as Kilifi, the quality of imagery available limited the extent to which change could be mapped. However across the area an increase in land enclosure was noted.

In Kilwa Kisiwani clearance of land for cultivation and to provide fuel has reduced tree cover on the island over the 2006–2013 period (Fig. 10). Areas of formerly dense woodland to the south and east of the village have been thinned and cut for firewood and to provide land for cultivation, with new houses established. Areas with wood cover in the range 80–100%, which made up 35% of the island area in 2006 had reduced to 27% in 2013. The density of housing in the village increased over the period (Fig. 11) and traditional huts were replaced with block built houses. On the mainland, in Kilwa Masoko, the built area increased by 8% over the period, with large areas to the north of the town on both sides of the road cleared for construction. Housing densities increased during the period in formerly low density areas. New housing is largely block-built.

5.3. Groundwater resources

5.3.1. Geological structure and spatial patterns of groundwater salinity

The hydrogeological investigations provided baseline information on aquifer characteristics and on groundwater quality across the three study areas (Figs. 2 and 12).

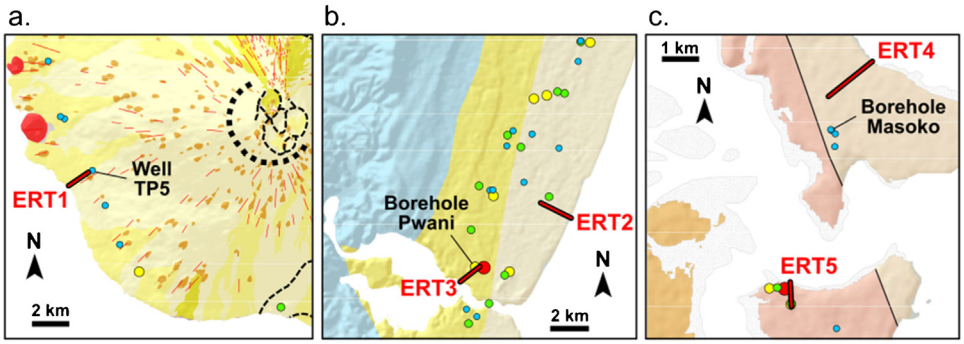

Fig. 12. Areas of more detailed hydrogeological investigations, including geophysical profiling (ERT) and high frequency temporal groundwater monitoring in (a) well TP5, Vouvouni area, Grande Comore island; (b) Pwani borehole, Kilifi area and (c) Masoko borehole, Kilwa Masoko. See Fig. 2 for geological legend and borehole colour legend. ERT profiles 1–5 are presented on Fig. 13.

In Grande Comore island (Fig. 2a), aquifers are composed of young volcanic rocks organised in three volcanic massifs of different ages (Bachelery and Coudray, 1993). The Mbadjini massif is the oldest of these (Miocene) and outcrops at limited locations in the south-east of the island. It is characterised by deep weathering, which makes it difficult to distinguish the individual lava flows. The La Grille massif is of intermediate age (Mid-Pleistocene) and outcrops in the north of the island. The degree of weathering varies from moderate to low depending on the chronology of flow emplacement. The Karthala massif is the youngest (Quaternary), and active, volcano on the island characterised by a low degree or absence of weathering of the lava flows.

Water wells on the island are mostly deep (50–100 m), hand-dug, large-diameter wells excavated in the 1980s. Very large spatial variations in groundwater salinities are observed among the wells, which can be related to some extent to geological heterogeneity. In Grande Comore, all wells are located within a few kilometres of the coast due to the much higher topographic gradients compared to hydraulic gradients. This necessitates a large increase in well depths with distance from the coast to reach water, and much higher associated costs. In the Mbadjini massif, groundwater salinity is generally low ($<2\,g\,L^{-1}$) due to the intensity of weathering resulting in reduced aquifer permeability and, therefore, reduced seawater intrusion due to higher hydraulic gradients. In addition, the weathering of the Mbadjini massif promotes the development of perched aquifers within more recent lava flows that overlie and are disconnected from the basal aquifer which has been subjected to seawater intrusion (Bourhane et al., 2015). In the La Grille and Karthala massifs, water wells have higher salinities (generally above $2\,g\,L^{-1}$) except on the western flank of the Karthala massif which experiences higher rainfall. Seawater intrusion in those two massifs is promoted by the high permeabilities of the lava flows and limited weathering; it is reduced by the rainfall intensity notably higher on the western flank of the Karthala volcano due to its exposition to dominant south westerly winds and its high elevation. Important spatial variations of salinities can be noted and attributed to the complexity of imbrication of lava flows of different ages resulting in different degrees of weathering and associated permeabilities.

The Kilifi coast in eastern Kenya (Fig. 2b), is characterised by a 5–15 km wide band of generally highly productive Tertiary and Quaternary sediments overlying less productive Jurassic or older sediments. The Tertiary (Pliocene) and lowest units of Quaternary (Pleistocene) sediments are composed of relatively homogeneous fine-grained marine or lagoon sands. They are overlain by, or for the uppermost units laterally pass into, Pleistocene coral sandstones and limestones displaying variable degrees of karstification. All those formations are covered by Holocene sand dunes along a narrow fringe of about 1 km width along the coastline. Most of the water wells in the coastal zone are shallow (typically <20m) large-diameter wells intersecting late Tertiary and Quaternary aquifers. Groundwater is mainly used for irrigation and as drinking water. Measured salinities display large spatial variations, but remain generally lower than those measured in Grande Comore (2/3 of the surveyed wells in Kilifi region have salinities lower than $2\,g\,L^{-1}$ and 1/3 lower than the recommended WHO limit of 1 g/L; Fig. 2b). A gradient of increasing salinity also occurs from south to north reflecting the decrease in rainfall northwards in coastal Kenya.

Kilwa district, Tanzania, is composed of Tertiary to possibly Quaternary sediments comprising shale and silt (Nicholas et al., 2006) that are of little hydrogeological interest. However, calcarenite and coral limestone intercalations offer useful yields and are common in the Masoko formation (mid Eocene) that constitutes the western side of Kilwa Masoko peninsula and most of Kilwa Kisiwani island (Fig. 2c). A fault separates the Masoko formation on the west and the more recent (Miocene and younger) sediments of the Pande formation on the east. The moderately productive public boreholes providing drinking water for Kilwa Masoko are drilled in the Pande formation close to this fault. Measured salinities in Kilwa region are generally low, with 70% of wells providing water with less than 1 g/L of salt. This is the case for the majority of boreholes intersecting poorly productive shale and silt aquifers in the Kivinje and Pande formation. Wells drilled in the Masoko formation all occur on Kisiwani Island. They are mostly shallow large diameter hand-dug wells drilled in proximity to habitations on the northwest coast. They have much higher salinities ($1–9\,g\,L^{-1}$) except for one borehole in the centre of the island.

Fig. 12 shows more detailed, enlarged views of the areas investigated in the three countries. More detailed investigations included geophysical surveys and high frequency temporal monitoring of groundwater in selected wells.

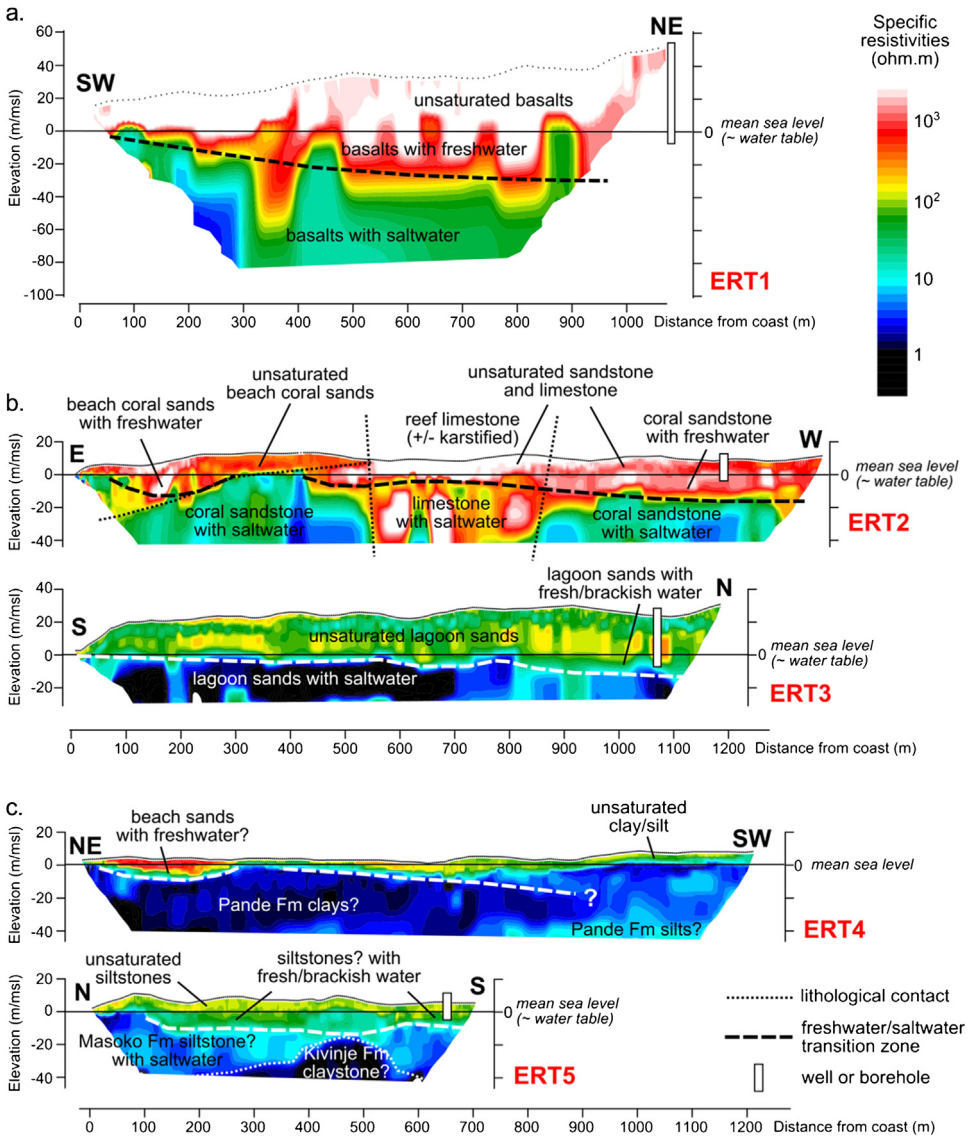

Fig. 13. Results of ERT investigations in (a) Grande Comore; (b) Kilifi area and (c) Kilwa Masoko (top) and Kilwa Kisiwani (bottom).

5.3.2. *Geophysical investigations*

Electrical Resistivity Tomography (ERT) was applied to all three study areas using similar acquisition methodologies. Several 2D resistivity cross-sections were obtained from selected transects run perpendicular to the coast; results are plotted on Fig. 13. All cross-sections show both the spatial organisation of different types of geological units and the spatial patterns of saltwater distribution in the aquifers. All results highlight the relatively high degree of aquifer salinization associated with the interface between freshwater and saltwater occurring at relatively shallow depths with a low angle of dip away from the coast. Such a low angle is consistent with a low hydraulic gradient resulting from the relatively large permeabilities of the coastal aquifers. Significant differences in mean resistivities are also observed between sites. Both the volcanic aquifers of Grande Comore (ERT1) and coral limestones/sandstones of Kilifi (ERT2) have much higher overall resistivities than in the marine/lagoon sands of Kilifi (ERT3) and clastic sediments of Kilwa (ERT4 and 5), which have lower resistivities overall due to a higher aquifer clay content. Because of these lower mean resistivities, the contrast between freshwater and saltwater is not as clear for those latter sites (ERT3, 4 and 5)

In the Vouvouni area, south west of Grande Comore Island (Fig. 13a), the volcanic aquifer is characterised by a thick (from 10 m at the sea cliffs up to 50 m at 1 km from the shoreline) and highly resistive (>1000 Ω m) unsaturated zone. The transition zone between freshwater-saturated and seawater-saturated basalts (50–1000 Ω m) dips towards the centre of the island at a low angle. Freshwater thickness reaches a maximum of 30 m at 1 km from the coastline. This is consistent with the average low salinity measured in well TP5 (~0.2 g L^{-1}) located at a few hundred meters upslope of the north east end

of the section and drilled within about 5–10 m below the water table. The Vouvouni area has the highest rainfall on Grande Comore (more than three times the average rainfall); therefore the freshwater thickness is less elsewhere on the areas of the island that are also underlain by the same young Karthala basalt flows.

Around Kilifi (Fig. 13b and c) resistivity signatures are different depending on the geological nature of the aquifer. Mean resistivities are generally higher in the Quaternary coastal units of the Pleistocene coral limestones and the Holocene sand dunes (Fig. 13b top) compared to the inland Tertiary marine/lagoon sands (Fig. 13b bottom). Coastal quaternary formations display a relatively high degree of heterogeneity. The Holocene coral sands (resistivities of ~20–1000 Ω m depending on the salinity of pore water and degree of saturation) overlie the Pleistocene basement with thickness increasing toward the sea (up to 30–40 m thick at the studied location) from about 500 m from the coastline.

The Pleistocene basement is composed of variability consolidated coral sandstones and breccias (2–1000 Ω m depending on salinity and saturation) with local occurrences of highly resistive reef limestone (10–10000 Ω m). A reef formation occurs between about 500 and 900 m from the coastline in the cross section of Fig. 13b (top). Strong internal variations in resistivities suggest karstification. Superimposed on the geological structure are different degrees of seawater intrusion.

Within the coastal Holocene sands, a freshwater lens (resistivity of 200–2000 Ω m) occurs reaching up to 20 m thickness at 200 m from the coastline. The maximum width of the lens is about 200–300 m. Seawater intrusion is reaching a greater distance inland in the underlying coral sandstones/breccias due to their higher permeability. A freshwater wedge (100–1000 Ω m) starts to develop at about 400 m from the coastline with thickness slowly increasing with distance, reaching about 20 m at 1400 m at the end of the ERT profile. Within this formation (500–900 m), the reef limestone displays extremely heterogeneous resistivities suggesting seawater intrusion is taking place within the karstified structures (10–100 Ω m) while the compact limestone remains relatively unaffected due to its low storativity (100–1000 Ω m). Generally, freshwater thickness appears lower within the karstified limestone than within the coral sandstone/breccias. The hydrogeological structure observed in this profile extends laterally, with similar structural patterns within Holocene/Pleistocene formations observed along the coastline north and south of Kilifi town.

The profile ERT3 (Fig. 13b bottom) trends north east from Kilifi creek within the Pleistocene/Holocene marine and lagoon sand units. Aquifer resistivities are much lower, relatively, than those observed in the Quaternary coral units. This is due to a finer granulometry and higher clay content. The unsaturated zone displays resistivities ranging between 10 and 200 Ω m because of horizontal lithological stratification within the sands. Below sea level, the aquifer displays very low resistivities: seawater intruded sands have values generally lower than 10 Ω m and lower than 1 Ω m in the most southern part of the profile close to the creek. There is a thin freshwater/brackish water lens of resistivity values ranging 10–100 Ω m reaching a thickness of only about 15 m at 1100 m from the creek. Presence of fresh/brackish water at this distance is confirmed by a well where groundwater electrical conductivity has been measured at 2500 microS/cm (corresponding to a salinity of about 1.4 g L^{-1}).

In Kilwa, south east Tanzania, the silt-clay dominant lithology of Tertiary sediments is responsible for low resistivities, typically less than 100 Ω m (Fig. 13c). Only coastal sands occurring on a narrow band of about 200 m along the western coastline have higher resistivities of up to 1000 Ω m (ERT4, Fig. 13c top). No clear resistivity contrasts are observable in the Pande Formation (ERT4, Fig. 13c top) except for the transition between the unsaturated (10–100 Ω m) and the saturated zone (<10 Ω m). Because of such low resistivities in the aquifer's saturated zone, it is difficult to distinguish between freshwater and seawater. However, a general decrease in resistivity towards the coast suggests diffuse saline intrusion. Kilwa Masoko public water boreholes drilled in this formation a few hundred metres south of the south west end of this profile provide freshwater with salinity of about 0.4 g L^{-1}; this suggests that low resistivities are primarily attributed to the clay/silt lithology rather than the saltwater content. This profile also suggests the presence of a thin freshwater lens of 5–10 m thick within or below the coastal sands.

Within the Masoko formation, profile ERT5 (Fig. 10c bottom) is characterised by slightly higher resistivities due probably to a more silty/carbonate lithology. The unsaturated zone clearly shows resistivities ranging 50–200 Ω. In the saturated zone, a fresh/brackish water lens of about 15 m thickness is suggested by slightly lower resistivities of 20–100 Ω m. The underlying seawater-saturated aquifer has resistivities lower than 10 Ω m. At the base of the profile, the even lower resistivities (<1 Ω m) could be attributed to the underlying Kivinje claystone formation, a clay facies within the Masoko formation, both saturated with saltwater. The existence of a well and a borehole at distance of about 600 m, where salinities were measured at 1.2 and 4.3 g L^{-1} is consistent with a brackish nature of the lens rather than freshwater.

5.3.3. *Controls of geology, distance to sea and rainfall on salinity distribution in groundwater*

Resistivity profiles clearly reveal a geological control on spatial patterns of seawater distribution in the various coastal aquifers. Other factors such as the distance to the coast and the average rainfall of the area also exert a control on distribution of saltwater within a specific geological unit. Both an increase in distance to the coast and increased rainfall should correspond to a decrease in groundwater salinity. Fig. 14 illustrates such correlations between the combination of distance to coast and amount of rainfall and the salinity observed in wells and boreholes. When all geological types are considered together across the three countries, a poor correlation is observed (Fig. 14a). However, in Grande Comore island (Fig. 14b), strong correlations are observed within the two dominant volcanic units of Karthala and La Grille, respectively with an exponential relationship with $R^2 = 0.68$ and a power law relationship of $R^2 = 0.85$. This suggests relative aquifer homogeneity within individual geological units with the magnitude of seawater intrusion predominantly controlled by the aquifer recharge from rainfall and distance to sea.

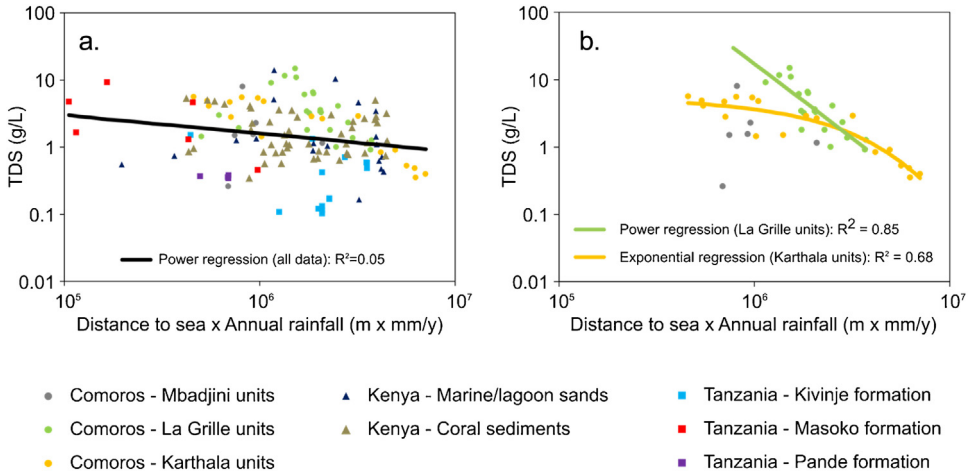

Fig. 14. Correlations between borehole/well salinity, geology, distance to coast and rainfall; (a) all data across the three countries; (b) Grande Comore.

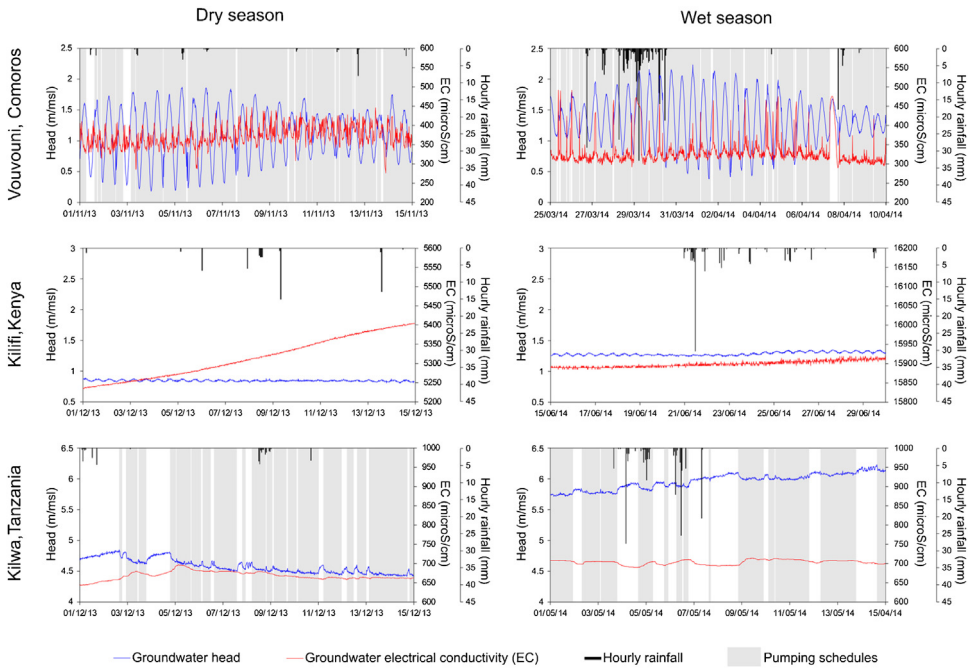

Fig. 15. time series of groundwater heads and electrical conductivities measured in monitored wells (Fig. 12) along with hourly rainfall and pumping schedules for dry and wet seasons.

In contrast to Grande Comore, the absence of clear correlation for the aquifers of Kilifi and Kilwa can be explained by three main factors: (1) a significant intra-formation aquifer heterogeneity; (2) the large variations of well/borehole depths resulting in large variations of salinity primarily due to the strong vertical salinity gradients in the aquifers; and (3) a large variability in abstraction rates resulting in different degrees of seawater upconing. However, for Kilwa and Kilifi, an analysis of the influence of well depth and pumping rate on salinity is not possible due to lack of available data.

5.3.4. Groundwater behaviour

Locations of temporally monitored boreholes in Comoros, Kenya and Tanzania are shown on Fig. 12. High frequency groundwater time-series recorded in those boreholes reveal large differences in temporal groundwater behaviour in the three studies sites (Fig. 15). In TP5 well in Vouvouni (Fig. 15a), both groundwater heads and electrical conductivity fluctuations are primarily controlled by semi-diurnal tidal fluctuations. The high water Table during the high tide is systematically accompanied by high electrical conductivity levels. This strong tidal control is promoted by high permeabilities and diffusivities in the volcanic aquifers (Bourhane et al., 2015). The short-term influence of rainfall is not visible, reflecting the large thickness of the unsaturated zone that results in diffuse recharge over time. Seasonal variations of heads and electrical

conductivity can be noted with slightly higher water tables and slightly lower electrical conductivity during the wet season as compared to the dry season. TP5 is one of the most intensively pumped wells in Grande Comore. Pumping schedules are designed to minimise drawdowns (about 10 cm, due to high permeability and large diameter of the wells). More interestingly, pumping failures result in a sharp increase in salinity. This is a similar effect to the tidal fluctuationsm—a general rise in the water column results in a rise of more mineralized water from the base of the well. Improving access to groundwater of acceptable quality might require considering different abstraction and management approaches (e.g. widespread low-rate shallow wells or horizontal tunnels). Currently, two programmes funded by the African Development Bank [ADB] and the French Development Agency [AFD], are prospecting for new groundwater resources in Grande Comore. The latter is considering drilling large diameter wells to supply rural communities in both coastal and mountain areas (Join et al., 2013).

Pwani University boreholes in Kilifi (Fig. 15b) also show the influence of semi-diurnal tides on groundwater heads and salinity fluctuations, but to a much lower extent than TP5 in Grande Comore. However, hourly rainfall does not show a visible effect on groundwater heads and salinity. As for Grande Comore, the thickness of the unsaturated zone (20–30 m) is likely responsible for diffuse recharge over time during the rainy season, i.e. a more seasonal impact of rainfall than in Grande Comore. This seasonality is seen during the dry season showing a progressive increase in electrical conductivity. Prolonged rainfall is also responsible for a slight rise in the water Table (a few cm) during the wet season. The datalogger had to be moved from one borehole to another nearby between the two dry/wet periods because a pump was installed in the original one. The second borehole was previously pumped causing seawater intrusion but pumping was stopped before the datalogger was installed. This explains the much higher EC recorded there during the wet season.

Groundwater records on the Kilwa Masoko boreholes (Fig. 15 bottom) do not show any clear influence from tides. Instead, the influence of pumping is clearly visible on both heads and electrical conductivity: pumping periods are characterised by a drop in head, of about 20 cm, and a rise in electrical conductivity of up to 50 microS/cm. This simultaneous response of both heads and salinity can be attributed to seawater upconing below the boreholes; the drawdown of the water Table is accompanied by a rise in the freshwater/seawater transition zone. Seasonality of rainfall also impacts both heads and salinity, with a progressive decrease in head/increase in salinity during the dry season and increase in head/decrease in salinity during the wet season. Short-term rainfall also shows a slight impact on heads, with highest hourly rains causing a water Table rise of a few cm (e.g. on 4 May 2014).

In summary, the groundwater (heads and salinity) temporal behaviour in the volcanic aquifers of Grande Comore appears to be primarily controlled by the tidal fluctuations and secondary by the pumping regime. In the Kilifi marine/lagoon sands, the same parameters appear to be primarily controlled by seasonality and secondly by tides (monitored boreholes were not pumped at the time of monitoring). In the clayey/calcarenite sediments of Kilwa Masoko, they are primarily controlled by the pumping regime and secondly by both short-term rainfall and seasonality.

6. Overall synthesis, discussion and state of understanding

The results of the various investigations carried out in the three countries provide an overview of the status of the groundwater resources and demand for water as well as the challenges faced with regard to expected environmental and societal changes. They also highlight strong similarities as well as notable differences across the three areas. The status of the groundwater resources and water supply is summarised as follows:

- Groundwater resources are important, and often safer sources of domestic and agricultural water across the whole region; used by over 50% of the population in Tanzania and Comoros (including direct supply from groundwater or indirect supply through water truck delivery) and over 20% in Kilifi region, Kenya (in Kilifi about half of the water supply is imported from other catchments and dams on remote major rivers);
- The observed increase in population of 1.0–5.4% in average annually regards predominantly urban centres and is causing an increase in demand; which is not met by increases in water availability and supply infrastructure;
- There is widespread salinization of wells and boreholes in all areas studied across the region. This is the main limiting factor on the quantity of groundwater availability and was highlighted as a key water quality issue by the community members and stakeholders;
- Fresh groundwater resources in coastal areas systematically occur as thin lenses or wedges; with the freshwater/salt water transition zone is inclined at a low angle so that salt water occurs at relatively shallow depths for a considerable distance inland. This limits the depths to which wells can be bored and the abstraction rates that are possible if fresh water supplies are to be maintained;
- The spatio-temporal variability of groundwater quality is well-correlated with the spatio-temporal distribution of rainfall and geology; in particular, variations in geology are reflected in the temporal response of wells to drivers such as tidal fluctuations (volcanic aquifers of the Comoros), pumping schedules (lower productive sedimentary aquifers of Tanzania), or seasonality (coral aquifers of Kenya);
- Long-term monitoring data for groundwater are lacking across the region and in cases where data are available there are often inconsistencies due to the methodologies used at different times so that comparisons are difficult and trends unclear;
- Well construction strongly influences water quality and long-term sustainability. Traditionally constructed wells are wider and shallower, have better water quality (lower salinity) and are more sustainable (less collapse/failure and more eas-

ily refurbished); however unprotected open wells are more likely to have faecal contamination due to dirty collection buckets/ropes (Tanzania and Kenya) and ingress of debris such as animal waste;
- The time-constrained nature of funding and of groundwater development projects are issues, often causing a disconnect where deliverables are required within the short (2–3 years) duration of a project. This results in the prioritisation of delivering a set number of mechanically-drilled production boreholes and rapid speed of installation regardless of the known benefits of hand dug, large diameter wells;
- The importance of local researchers with expertise/experience in coastal hydrogeology and having established links with local water stakeholders is recognised by researchers, stakeholders and communities in order to facilitate literature and data compilation necessary to conduct regional resource assessments.

The environmental drivers (climate and land use) that have potential to affect groundwater resources and their accessibility are:

- An overall change in climate across the region, that is indicated in long-term hydrometric observations and reported by local people who are noticing changes in weather patterns, seasons, dynamics of plants and animal behaviour;
- A clear increase in the extremes of rainfall in the last decade is recorded in Comoros and Tanzania, but is not as clear in Kenya which is drier and less seasonal;
- A clear increasing trend of sea level was recorded over the last two decades ranging from 3 to 9 mm/year across the region and comparable with global estimates for the Indian Ocean region;
- Increasing urbanisation is leading to land clearance for housing and increased demand for wood as a fuel. In areas subject to high intensity rainfall events (Tanzania) this leads to increased potential for runoff and soil erosion and can reduce infiltration to groundwater;
- Tourism developments and modern plumbed housing place strains on existing water infrastructure through the volume used compared to local housing
- Demand for land in coastal areas is leading to increased enclosure of land (particularly in Kenya) with loss of grazing ground for pastoralists and increased stocking densities on land which is accessible.

The socio-economic drivers and governance affecting groundwater resources and access are:

- Low levels of education, income and limited livelihood characterises the region; all indicate a need for strategies to address poverty in the region;
- Communities feel strongly that it is the responsibility of government to solve water issues and identify shortcomings in governance;
- There are low levels of participation to decision making community meetings and training/education related to water resources management, although community members are keen to engage and voice their opinions; they want to be actively involved in water resource management, identify it as a critical issue and a direct link with daily life;
- Community members are critical of researchers who commonly do not return/share project findings;
- Gender issues and equality are getting increased recognition: women are the main stakeholders at community-level, but rarely involved in discussion, decision and future activities;
- Most users are willing to pay for water, however some resist because water quality is poor (i.e. salty);
- Researchers, managers and communities recognise that technical decisions should be bottom up by local communities and incorporate local knowledge and skills; international/national funding agencies are culpable for perpetuating unadapted and unsustainable groundwater infrastructures;
- Student training is viewed as key for water management as they will be the future decision makers in many areas;
- Particularly in Kenya and Tanzania, which are much larger than the Comoros Islands, the lack of centralisation of basic information on wells and boreholes is pointed out, which causes difficulties in accessing crucial hydrogeological literature and reports.

Overall, stakeholders have recognised the need to understand how the available groundwater resource works so that sustainable management and development plans can be adopted. Also, the investigations as well as the dissemination events strongly pointed to the important role of engagement both with the stakeholder and community and the importance of education as to how coastal groundwater and aquifers work and why they need stakeholder safeguarding.

Recent and specific figures for integrated management of groundwater and coastal aquifers within IWRM frameworks in Sub-Saharan Africa are not yet readily available, though projects relevant to East Africa are in progress (e.g. UNEP, 2012; Mehta and Movik, 2014). Governance aspects of groundwater management in East Africa lack the mechanism for coordination and for fostering cross-sector linkages. For example, deficiencies have been identified in key areas under existing policy, legal and institutional frameworks in Kenya (Mumma et al., 2011). Given the lack of consideration of groundwater, as pointed out by previous studies (e.g. Braune and Xu, 2010; Knüppe, 2011), one can expect progress to be made on managing coastal groundwater resources in East Africa.

The results of this study provide a detailed regional perspective that complements the previous continent-scale review of coastal aquifers by Steyl and Dennis (2010). It confirms the fundamental importance of coastal groundwater resources for the

development of the region and the urgent need for matching the rate of water development with the rate of demographic change, including urban expansion and economic growth. Despite the geological diversity of the region, the sustainable provision of safe groundwater is limited in all areas by both seawater intrusion (rather than aquifer productivity) and the lack of adequate local to national management plans and a policy framework adapted to the specificities of these coastal situations. The positive development of national and inter-African consciousness and leadership with regard to water development mentioned by Steyl and Dennis (2010) must however be accompanied by a realisation of the fundamental importance of implementing coastal groundwater development strategies that are different to those of other physical settings where borehole productivity is the target.

International development projects still fail to provide sustainable groundwater infrastructure and fresh (i.e. non salty) groundwater in coastal regions. Drilling campaigns are often deemed successful once productive boreholes with good quality water are obtained without consideration to future salinisation due to over-pumping. Those strategies, which systematically target a limited number of deep and productive boreholes rather than promoting the development of multiple shallow, large diameter wells, have proven unsuccessful in the long-term. Sustaining the use of large numbers of shallow wells through, for example, modernisation, rehabilitation or deployment of traditional wells however poses significant management challenges requiring a strong collaboration of stakeholders at different levels of society, from communities to providers, consultants, NGOs and regulators. Those collaborative aspects must be embedded or strongly enhanced in the design and implementation of future development projects. In particular, the developing, and lucrative, water trucking business in Kenya and Comoros proves that communities are willing to pay for quality water, which suggests that community/associative management frameworks based on paying for quality water from local wells have potential as a local alternative for water management.

7. Conclusion

The coastal aquifers of East Africa are major water resources for domestic supply, industry and agriculture. They currently require development programmes to support the high rate of population increase in the region, including strong urban development. The region is also experiencing clear trends in long-term environmental change, common to all three countries and probably also shared by many other African coastal countries. Those changes include an increase in rainfall intensity without a clear increase in average rainfall together with significant land clearance and urbanisation. This is expected to have a negative long-term impact on groundwater recharge. Sea level is also showing a consistent rise during the last two decades that may increase coastal erosion and lead to seasonal flooding of low-lying areas, which ultimately will decrease fresh groundwater availability.

Notwithstanding, geological controls across the three areas, groundwater quality from wells and even more from narrow boreholes is broadly poor due to saltwater intrusion, and freshwater availability is low despite highly productive aquifers. Fresh groundwater is often limited to thin freshwater lenses/layers requiring a large number of shallow wells with low abstraction rates. The experience shows that traditional (or modernised) shallow large diameter wells are less saline and are more sustainable than deep boreholes. Observed trends of changes in demography, climate, sea level and land use are not expected to improve the availability of fresh groundwater. Recent and current development projects do not account for hydrogeological requirements for drilling more and shallower wells rather than deep boreholes. Communities as wells as stakeholders are often left with wells having inadequate water quality that are abandoned, opening up business for costly water trucking. Communities are willing to pay for water and to engage in local groundwater management framework provided that groundwater is of appropriate quality.

The recent progress in social consciousness and education on groundwater vulnerability in African coastal regions must be strengthened and rapidly accompanied by the establishment/improvement of national strategies for both groundwater development and management. Those strategies will need to take better account for the specificities of coastal groundwater resources as well as their anticipated changes and will also require enhancing the involvement of communities in the management processes. They also have to be supported by improved knowledge of coastal aquifers and long-term monitoring data, which are lacking in the region.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ejrh.2015.12.065.

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