REPORT

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Constraints and solutions for groundwater development, supply and governance in urban areas in Kenya

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Abstract

Based on a five-town case-study cohort in Kenya, a conceptual framework has been developed to enable the formulation of holistic and effective strategies that encompass the national aspirations and regional to global sustainability agendas, and which can be used to monitor progress in achieving set objectives. The approach is flexible, scalable and transferrable, so that it can be applied in different contexts and using different indicators, based upon the same construct. Insufficient technical knowledge of urban aquifers and their interplay with the wider social-ecological system constrains the development of holistic, effective and robust management systems to ensure their sustainability for intended uses. The objective was to consider governance and management solutions that could promote water security for urban towns in Kenya through the sustainable use of groundwater in the context of its complex hydrogeology, water access disparities, competing uses and future risks. The in force national and county water policies, strategies, and plans for the case study areas were critically reviewed. The status of aquifer knowledge, water access disparities, competing uses, and risks was evaluated from critical literature reviews and data compilation, fieldwork, and analysis of indicator datasets from the Kenya 2009 census. Key aquifers need urgent characterisation to reverse the current situation whereby development proceeds with insufficient aquifer knowledge. Private sector and public participation in management should be enhanced through decentralised management approaches. 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.

Keywords Arid regions · Conceptual models · Groundwater management · Urban groundwater · Kenya

Introduction

The urban population of Sub-Saharan Africa (SSA) is growing at a faster rate than any other region of the world. It has been observed that the shift from rural to more urban societies is a global trend, and by 2050, 64–69% of the world population will be living in urban areas (Seto et al. 2014). Thus, Kenya with slightly over 30% of its population currently living in urban areas (MEWNR and JICA 2013) is not an exception. The cities and towns are occupied predominantly by low income households, with generally more than 50% of the population categorized as poor. The new constitution of 2010, which effectively changed the Kenya governance structure from a centralised one to one where some key functions were devolved to the newly created county governments, has all the ingredients to rapidly accelerate urban growth in the 47 towns that host the county government headquarters. Population redistribution through sedentarisation, migration and urbanization is a key dynamic in the East Africa region (Few et al. 2015). Now, the prospect of many more new economic growth centres other than the two main and established ones, Nairobi and Mombasa, becomes another component of the key dynamics driving population redistribution.

Water supply sources for the town dwellers include boreholes, shallow wells, unprotected and protected water springs, treated piped water (from lakes, rivers and/or springs), and water vendors (who sell water from all sources at different prices); in some cases, one source may dominate, while in others a hybrid variety of sources is accessed, which tend to have widely variable quality, from human-potable and

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livestock-potable to saline and non-potable. It is ironical that some of these towns suffer from a shortage of clean water though they may lie next to freshwater lakes and rivers, or close to groundwater sources. The patterns of urban water scarcity in large cities (>750,000 people) have been found to be influenced by geographical and financial limitations (McDonald et al. 2014) and this is also partly the case for Kenya's urban centres. Water service providers and water and sanitation infrastructure are struggling to keep pace within the rapidly growing urbanisation context (Dominguez Torres 2012; Hove et al. 2013; Wright et al. 2013) so that insufficient water supply is becoming the norm (Hove et al. 2013), forcing more urban dwellers to turn to wells and boreholes, among other water supply sources, which may offer unsafe drinking water due to lack of maintenance or protection (Dominguez Torres 2012). Water quality may be adversely compromised by geology (e.g. fluoride in the rift system, Olago et al. 2009; Olaka et al. 2016), but there is widespread contamination of urban/peri-urban water resources from closely located shallow water wells and pit latrines, solid wastes (Henry et al. 2006; Osman et al. 2014; Wright et al. 2013; Okotto et al. 2015), as well as domestic, industrial, and rural or peri-urban agricultural activities. Short water supply and poor sanitation frameworks which characterise many of the towns create situations where semi-treated or untreated sewage is in some areas discharged directly into water courses, especially in informal settlement areas. It is estimated that 80% of all communicable diseases are directly or indirectly linked to insufficient access to water and sanitation facilities and hygiene practices (Ministry of State for Planning 2007), so that the health burden can be significantly reduced and the quality of life can be significantly improved when there is safe, affordable, accessible and adequate quantity of potable water supplies.

The limited evidence on groundwater quality in urban areas in Sub-Saharan Africa (SSA) constrains the development of robust long-term policies on the development and management of urban groundwater resources (Lapworth et al. 2017). This is compounded by the dearth of knowledge (Xu 2008) on the characteristics of these urban aquifers and others that can potentially supply urban areas such as their geometries, transmissivities and storage capacities, which can contribute to the development of more precise and aquifer-specific strategies for their sustainable management. This report explores the challenges and proffers some solutions to promote water security for urban towns in Kenya through sustainable use of groundwater in the context of (1) complex hydrogeology and hydrogeochemistry, and (2) water access disparities which relates the source to the users who are an important consideration in sustainable groundwater supply and management.

Materials and methods

The case study sites and their hydrogeological setting

Kenya is characterised by bimodal rainfall distribution (March–May and October–December), except in the Lake Victoria basin region where there is a third subdued rainfall peak in August. The country's rainfall and surface water are highly variable in time and space, and drought is common. Five towns in Kenya in which the author has had substantial field experience have been selected as a multitown cohort of case studies for this report: Kisumu City and the town of Nakuru are in the sub-humid zones; Lodwar and Wajir towns are in the arid zones; and, the town of Msambweni is in the semi-arid zone. The towns are assessed in the context of the scale of their peculiar regional groundwater settings, not in terms of the sensu stricto administrative boundaries. Kisumu City lies on the shores of Lake Victoria's Winam Gulf. It is one of the study areas for the AfriWatSan project (AfriWatSan 2015) that seeks to develop the scientific evidence to inform policies and practices sustaining low-cost, on-site water supplies and sanitation systems in urban Africa and to strengthen the capacity of individuals and institutions to conduct this vital research. The town of Nakuru, bounded by Lake Nakuru to the south and the Menengai Crater to the north, was one of the sites for the MAWARI project (2006–2010, supported by CIFEG, France) which focused on sustainable management of the groundwater resource in the East African Rift System. The town of Lodwar and its environs is one of two observatories in Kenya for the global REACH programme (REACH 2015) which aims to determine how water supplies can be expanded and sustained for present and future generations in the face of uncertainties related to climate variability, extremes and change, rapid urban demographic growth, as well as growing demands from industry, agriculture, commercial and hydropower enterprises. The town of Wajir has been investigated through environmental impact assessments for petroleum exploration activities, while the town of Msambweni, the smallest town of those selected for the case studies, is within an area where there are huge demands for water from large-scale agriculture and mining concerns, alongside municipal and domestic urban and rural water demand. Here, the Gro-for-GooD project (Gro-for-GooD 2018) aims to develop a groundwater risk management tool that integrates natural and social data to promote improved groundwater governance that balances economic growth, groundwater sustainability and poverty reduction.

Kisumu City

The city is located at 34.77°E and 0.08°S at an altitude of 1,134 m asl. The mean annual rainfall varies from less than 1,000 mm/year along the lake shore to over 1,800 mm/year at

the top of the Nandi Hills, while potential evaporation ranges from 1,800 to 2,200 mm/year and in most months, exceeds the monthly rainfall (DHV 1988). The geology of this area and its environs comprises rocks and sediments that range in age from Nyanzian (Precambrian) to recent times (Saggerson 1952; Mboya 1983). Kisumu City lies within the Nyanza (formerly Kavirondo) graben which is bounded on the north and south by the east−west trending Nyando and Kendu faults, respectively. To the west of the Nyando fault are the Kisumu faults (three parallel faults) which trend NE–SW, and separate the Nyando fault from the E−W Kisian fault (Pulfrey 1952). The most westerly faults in the area are the NE−SW Seme faults whose northernmost extent abut the Kisian fault (Fig. 1). The strike of the Nyanza rift valley therefore changes from an E−W orientation in the east, to a NE−SW alignment in the west (Mboya 1983). Synthetic (and antithetic) faults extending into the graben from the major flanking faults have not yet been described, though Pulfrey (1952) postulated the likelihood of such faults, forming two E−W fault zones. On the upthrow side of the Nyando fault, the geology is dominated by granites, but moving south towards

the lake and the graben floor, phonolite flows overlain by lateritic soils characterise the area to the west, while alluvial sediments and deep calcareous black cotton soils underlain by lacustrine deposits characterise the area to the east (Fig. 1). The volcanic rocks tend to be jointed, with vertical and horizontal joints, and are, less commonly, faulted with the faults following the regional trend. Where they occur, they are often covered by laterite or lateritised soils and there are rare exposures of weathered coarse phonolitic regolith on the footslopes of the Nandi Hills.

Nakuru town

The town is located at 36.06°E and 0.28°S at 1,850 m asl. Rainfall on the rift shoulder escarpments ranges from 1,000 to 1,400 mm/year, while on the rift floor it is highest on the high rift point at Menengai (ca. 700 mm/year), and declines to the north and south (Olago et al. 2009). Nakuru lies within the central Kenya Rift, and is bounded by the Bahati fault to the east and the Mau fault zone to the west (Baker et al. 1988). The geology of the Nakuru area comprises a succession of
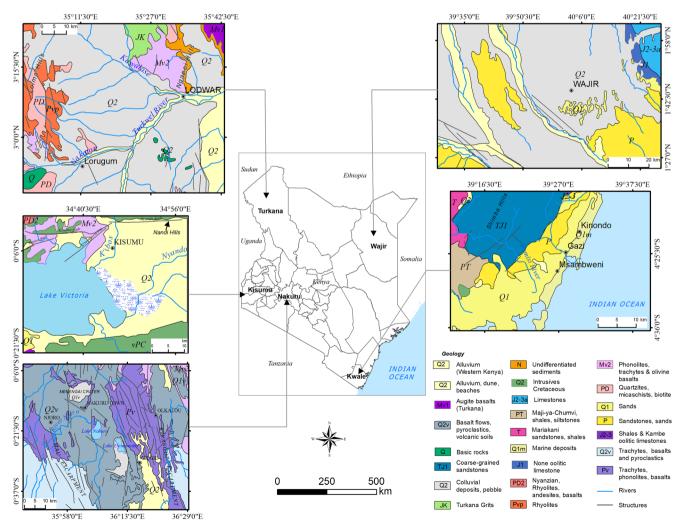

Fig. 1 Geological setting of the study sites, redrawn from the 1987 map of the geology of Kenya (Ministry of Energy and Regional Development 1987)

Miocene–Pleistocene volcanics, primarily phonolites, trachytes and basalts, with pyroclastics and intervening lacustrine beds being more widespread in occurrence during the Pleistocene (McCall 1967; Baker et al. 1988). Much of the rift floor area is draped by Holocene pyroclastics, basalt flows, and volcanic soils (McCall 1967); grid faults that occur in this section of the rift (Baker 1986; Schlüter 1997; Woldegabriel et al. 2016) are masked by the superficial materials. One outstanding feature is the Menengai crater which is just north of the town and the highest part of the rift floor. It consists almost exclusively of strongly peralkaline oversaturated trachytes (Clarke and Woodhall 1987). As assessment of borehole geo-logs in Olobanita, Kabatini and Baharini (next to Lake Nakuru on the north-eastern side) areas indicate that the top brown soils and sediments are on the order of 10 m thick or more. Below them are lava flows of rhyolites, basalts, trachytes or phonolitic trachytes, with varying thicknesses, from thin (10 m or less) to thick (sometimes 30–40 m), that alternate with consolidated pyroclastic materials such as tuffs, agglomerates, ashes and their derivatives comprising loose tuffaceous sands or pumiceous gravels. These also comprise layers that are thin (5 m or less) to thick (>50 m). This series occurs up to depths exceeding 200 m (Mogaka 2010). The town of Nakuru is supplied by groundwater from three major well fields, namely Kabatini, Baharini, and Olobanita (15,000 m³/day) well fields. However, the development of the groundwater supply has been proceeding without proper knowledge of the aquifer structure and lithology, and is affected by the collapsing of boreholes during drilling operations (Mogaka 2010).

The town of Lodwar

The town is located at 35.62°E and 3.14°N at an altitude of 477 m asl. The mean annual rainfall is about 217 mm (Opiyo et al. 2014) and the annual potential evaporation is about 2,300 mm (Ferguson and Harbott 1982). The wider Turkana area developed from Cretaceous through Eocene-Oligocene to Plio-Pleistocene times (Mugisha et al. 1997; Morley et al. 1999; Hautot et al. 2000; Tiercelin and Lezzar 2002; Tiercelin et al. 2004). However, the beginnings of the modern Turkana basin started in the Early Pliocene (Feibel 2011) and is characterised by a pattern of N−S oriented half-grabens (Dunkelman et al. 1988). To the west of Lodwar are the Loima hills which comprise Precambrian age metamorphic rocks including gneisses, quartzites and amphibolites as well as Pliocene rhyolites. Immediately north of Lodwar are the upper Miocene phonolitic Ngapoi Hills, to the north of which are outcrops of the Upper Jurassic-Cretaceous Turkana grits. East of the Ngapoi Hills are also some outcrops of upper Oligocene to lower Miocene augite basalts. Much of the areas surface geology, including that around Lodwar, is masked by an extensive cover of Holocene colluvial deposits, pebble sheets, soils and alluvium along the Turkwel River and the ephemeral streams. The Plio-Pleistocene sequences consist of a complex of alluvial fan, fluvial, deltaic and lacustrine deposits and volcanic rocks, tuffs and ash (Bowen and Vondra 1973; White and Harris 1977; Owen and Renaut 1986; Feibel 2011). East of Lodwar is the coastal plain, which, from over 100 m above the lake level, dips gently eastwards to Lake Turkana and shows a number of well-defined platforms marking former lake levels (Walsh and Dodson 1969). Consequently, most of the coastal plain is covered by fine-textured and powdery, often diatomaceous, sands derived from the lake sediments. Planned large-scale irrigation schemes along the Turkwel River (scaling up from about 2,000 ha currently to 10,000 ha potential, Ocra 2013) and increased demand for water from the rapidly increasing urban populations, commercial establishments, and incipient oil development activities, introduces an unforeseen demand for very large supplies of water in an arid region. Lodwar is supplied by up to 10 boreholes that are situated within a 10-km radius of the town centre.

The town of Wajir

The town coordinates are 40.06°E and 1.75°N. It has an average annual rainfall of 372.8 mm and an annual evaporation rate (pan B) of 2,630 mm (MWI 2005). It lies at an altitude of 250 m asl in the NW−SE trending southern Anza graben that formed in the Lower Cretaceous or possibly in the Upper Jurassic through to the Palaeogene (Bosworth and Morley 1994). Geophysical and exploratory drilling data indicate that the graben is characterised by an 8–10-km-thick sediment infill (Dindi 1994). Continental sedimentation dominated in most of the Anza basin during the Cretaceous, but at least one marine incursion has been documented in the Ndovu-1 well (Bosworth and Morley 1994). During the Palaeocene-Miocene a thick sequence (locally more than 3,000 m) of fluvial and lacustrine sediments was deposited (Bosworth and Morley 1994). Continental Pliocene sandstones outcrop in the west and southeast parts of the area, while in the northeast part there are outcrops of mainly Middle Jurassic marine limestones with sandstones and shales. Various superficial unconsolidated sediments of Quaternary age mask the graben's tectonic structures (Dindi 1994). These Pleistocene to Holocene deposits, in the vicinity of Wajir, include surface deposits of arenaceous limestone, calcareous sandstone, marl, and gypsum, representing arid to semi-arid depositional environments (Swarzenski and Mundorff 1977). Since its shallow groundwater is prone to contamination and deep groundwater does not provide good quality water, there is a plan to pipe water from the Merti aquifer in Habaswein area, 110 km south of Wajir, which will relay a total of 2.2 million cubic metres per year (MCM/year) of potable water to Wajir (Luedeling et al. 2015). This plan illustrates the significant role of groundwater storage in water security assurance (Foster and MacDonald 2014), particularly in the ASALs.

The town of Msambweni

The town is located at 39.48°E and 4.42°S on the Indian Ocean coastline. The rocks in this area strike approximately NNE−SSW and dip towards the sea at low angles (~5–10°); they become progressively younger from the west eastwards to the coast (Caswell 1953, 1956; Oosterom 1988). They comprise seven formations: Taru Formation (Upper Carboniferous to Middle Permian, mainly fluviatile sandstones and conglomerates), Maji ya Chumvi Formation (Mid-Permian to Mid-Triassic, mainly lacustrine gritty shales and sandstones), Mariakani Formation (Middle–Upper Triassic, mainly deltaic facies sandstones and shales), Matolani Formation (Upper Triassic to Lower Jurassic, deltaic facies feldspathic sandstones), Mazeras Formation (Lower–Middle Jurassic, mainly quartzo-feldspathic deltaic to aeolian sandstones), Kambe Formation (Middle–Upper Jurassic limestones with interbedded calcareous shales), and Mtomkuu Formation (Upper Jurassic–Upper Cretaceous sandy and calcareous fossiliferous and thin lenticular limestones; Rais-Assa 1988). There is an erosional hiatus from the Palaeocene to Miocene (Caswell 1953; Rais-Assa 1988). The Pliocene Magarini sands and Pleistocene corals complete the sequence. There are a number of normal faults that follow two dominant trends: NNE−SSW (marine Jurassic Rocks and Mazeras Sandstone) and WNW−ESE (the stepping of outcrops; Caswell 1953) and which formed from possibly as early as the Upper Jurassic through to mid-Pliocene times (Caswell 1953; Rais-Assa 1988). Msambweni is supplied mainly by surface water; groundwater is used for domestic purposes other than drinking.

Methods

The general settings of the towns in terms of their wider hydrogeological contexts are described as follows: Kisumu Regional Aquifer (KRA, Kisumu), Greater Nakuru Aquifer (GNA, Nakuru), Lodwar Aquifer (LA, Lodwar), Wajir Town Aquifer (WTA, Wajir) and Msambweni Aquifer (MA, Msambweni) in conformity with the most commonly used descriptors in the literature.

Hydrogeology and groundwater quality

This aspect is based on a critical review/assessment of the literature and personal observations in the field spanning a 15-year period. For hydrogeology, the fieldwork comprised geological mapping at all sites coupled with some geophysical surveys using both vertical electrical sounding (VES) and electrical resistivity tomography (ERT) in Nakuru and Msambweni, and geo-log assessments for Nakuru. However, a generalised approach to avoid double reporting of hydrogeology and groundwater quality data is taken since there are currently ongoing geological, geophysical and groundwater quality surveys, amongst others, in three of the towns (Kisumu, Lodwar, and Msambweni) and their environs which will be the subject of comprehensive papers. Currently, no hydrogeological maps, sensu stricto, exist for any of these sites (Mumma et al. 2011; Kuria 2013). The groundwater quality data is based on consolidation of data from analyses of samples collected in the field as well as published and reported values (indicative only as a lot more unpublished and difficult to access data exist than have been covered here). The parameters presented are electrical conductivity and the concentration ranges of nitrate, fluoride, thermotolerant coliforms (TTC) and *E. coli* since, with respect to potable water quality, these are the parameters that are of most concern in Kenya's groundwaters.

Water access disparities

Data on the sources of water used in the various towns of interest was obtained and compiled from the joint Kenya National Bureau of Standards and the Society for International Development – East Africa county reports that were published in the year 2013, and based on the Kenya Census of 2009, which is therefore used as the base year in this report. In the reports, this data was not delineated by towns, but by rather by county, constituency, and ward, in descending hierarchy of administrative jurisdictions. Consequently, the data was derived on this basis, and therefore there are some variances with the census urban "core" and "peri-urban" categories. For the town of Msambweni, the population figure of 22,633 persons for Kinondo Ward was taken to represent the town and its peri-urban population, since the town lies within that ward. This differs from and is larger than the census tabulation of the core urban population of 12,503 persons; however, it is considered more representative since the census denotes the peri-urban population for the town as zero, suggesting that those areas immediately adjacent to the core were considered as rural settings. For Kisumu, the total population of 439,009 persons for Kisumu Central, Kisumu East and Kisumu West was used, compared to the census total of 383,444 persons in the urban core and peri-urban areas. The three constituencies are considered to be town affiliates, not belonging to the rural category, and therefore the derived population number is more representative. In Lodwar, the total population of 54,549 persons in Lodwar Town Ward and Kanam Ward was used, compared to the census total of 47,101 persons for the urban core and peri-urban areas. For Nakuru, the total population of 298,254 persons for the Nakuru Town West and Nakuru Town East constituencies was used, compared to the census total of 367,183 persons for the urban core and peri-urban areas. Finally, in Wajir, the total population of 51,729 persons in Wajir Ward and Wagberi Ward was used, compared to the 82,106 persons recorded in the 2009 census. Of this number, almost 70,000

are listed in the census as being in the peri-urban category, suggesting that this zone is quite diffuse. Where two or more wards or constituencies were used, the proportional percentages accessing different sources of water were recalculated from the primary datasets to get the correct proportions for the combined totals.

The contributions by volume of shallow well water to domestic water supply in the towns was garnered from the literature. Gaps were noted, including only localised or old assessments, and there was no published data for Nakuru, Lodwar and Msambweni. Data on per capita daily water consumption, nonrevenue water or unaccounted-for water were extracted from the literature and here again, there were clear data gaps.

Governance and management framework

The in-force national water policy and strategies, and county integrated development plans for the case study areas were critically reviewed to assess gaps and potential synergies in terms of how they deal with the issues of governance, management and risk. Although three strategy documents are outlined in the Water Act 2002, the focus in this report is on the following two: the National Water Resources Management Strategy (NWRMS) and the National Water Services Strategy (NWSS). The third one, the Catchment Management Strategy, is subsidiary to the NWRMS (MWI 2007a, b). These two strategies in the Water Act 2002 were also assessed against the equivalent strategies outlined in the revised Water Act 2016, where they are referred to as the National Water Resource Strategy (NWRS) and the National Water Services Strategy (NWSS; MWI 2016). The other strategy document included in this analysis is the National Water Master Plan 2030, which was formulated in 2013. The first CIDPs were developed for the period 2013–2017, and are the counties development blueprints. Other national policies and strategies that are in force are referred to, where relevant. Based on this analysis and considerations from the other findings of this report, outlined in the following, coupled with personal observations and experience, a governance and management framework to guide resource assessment, strategy formulation, and monitoring is proposed.

Findings

The complex hydrogeology

Regional hydrogeological characteristics

There are similarities and significant differences in the hydrogeological settings of the various towns. Msambweni, Wajir and Lodwar areas are within essentially sedimentary settings associated in part with marine (Msambweni and Wajir) and lacustrine (Lodwar) systems, while Kisumu and Nakuru are in rift settings that are partly associated with lacustrine systems. All these areas have, however, been affected by rifting during their geological history, which influences their modern-day hydrogeological setting. The types of aquifers that occur are: groundwater in the weathered zone of hard rocks, weathered contacts between lava flows, groundwater in faults and fractures/fissures in hard rocks, and groundwater in sediments of various types (alluvial, lacustrine, marine, pyroclastics). Rift-related volcanism complicates the hydrogeological setting save for Msambweni and Wajir areas where it does not occur. Fieldwork in Nakuru, Kisumu and Msambweni areas has revealed that a few rocks have been wrongly identified, and that some key geological structures such as contact zones, faults, fractures and joint patterns, all of which have an influence on the groundwater expression, are missed out on because of the mapping scale. Geophysical studies have also assisted in location of buried paleochannels and conductive faults in Msambweni and Olobanita, respectively.

The groundwater flow direction in KRA east of the city is from the highland recharge areas to the east, north and south into the central area of Kano plains and then southwest towards the lake, while to its north and west it flows from north to south (DHV 1988). The lake shore abuts the southwest border of the city. No flow paths are indicated for the confined aquifer layers. Further, as noted by Wright et al. (2013), groundwater flow patterns are difficult to determine due to the area's complex lithological and structural relationships. The setting of the GNA is broadly similar to that of KRA. Here, piezometric plots and isotopic evidence suggest that groundwater is mainly derived from rainfall on the flanks of the north−south trending rift, both to the east and west (Allen et al. 1989; Allen and Darling 1992), and is modified by faults, and surface and buried lava flows within the rift floor (Olago et al. 2009). There is also some significant local recharge of intermediate to deep aquifers through the permeable pyroclastic materials, faults and fissures (Olago et al. 2009; Kuria 2013). A consequence of localised study, three aquifers have been identified in Nakuru drainage basin which include Olobanita, Bahati and Baharini aquifers, each of which has a well field (Kuria 2013). Within the rift floor of the GNA area, effective high recharge takes place every 10 years or so and lasts about 3 years, while low recharge periods had a duration of 6–10 years in response to either the effects of the interannual variability of El Niño Southern Ocean (ENSO) oscillation in East Africa, or to an underlying decadal-scale drying cycle (Olago et al. 2009). The evidence obtained by Taylor et al. (2012) in their study in central Tanzania, based on a 55-year record of groundwater-level observations, corroborates the Nakuru assessment. They found that there was a highly episodic occurrence of recharge resulting from anomalously intense seasonal rainfall that was associated with ENSO and the Indian Ocean Dipole.

The Lodwar and Wajir town aquifers do not have the benefit of direct recharge from remote high rainfall zones and so are reliant on local rainfall recharge, which is generally low because of the low rainfall (MAR <250 mm) received. The groundwater flow direction is generally from north to south in WTA (Swarzenski and Mundorff 1977; MWI 2005) and west to east in LA. For Lodwar aquifer, an additional key recharge is from the quasi-perennial Turkwel River whose source is Mount Elgon a few hundred kilometres to the south west, and its tributaries, and the ephemeral streams that flow west to east from the Loima Hills towards Lake Turkana. The geometry of LA has not been defined, but RTI (2013) outlines a fault-controlled structure of an intermediate to deep aquifer (which they call Lodwar Basin Aquifer) about 5 km east of the town of Lodwar. Kuria (2013) proposes that the WTA shallow aquifer circulates in small localised flow systems because of low local recharge, coupled with an assumed heterogeneity of the shallow limestone beds, numerous cones of depression around wells, and randomized variation in water quality. In the MA, the major recharge zone for the intermediate to deep aquifers are the Shimba Hills that border the area to the west. The shallow groundwater is recharged by runoff from the higher grounds to the west, and local rainfall. It is further be enhanced by two inferred fault lines on the coastal plain covered by the Magarini sands. Groundwater flow is essentially west to east, from the highlands to the Indian Ocean. The two faults, and a third which is further west on the foot plateau, likely contribute to the recharge of the deeper confined aquifer layers.

The regional transmissivity values in Table 1 are from a transmissivity map that was constructed using the Ministry of Water and Irrigation database (Kuria 2013). The aquifer layers are defined by depth below ground level (bgl) as follows: shallow (0–30 m), intermediate (30–100 m), deep (>100 m). The transmissivities are quite variable. Higher transmissivities occur in the soft rock terrains (LA, MA) except for WTA where it is the lowest of all the five aquifer systems, and lower transmissivities occur in the dominantly volcaniclastic and faulted terrain of GNA and the igneous-sedimentary-volcanic rocks of the KRA. Thus, transmissivities are enhanced by faults and fractures in the KRA, GNA and MA, but this aspect is uncertain in the LA and unknown for the deep layer of the WTA. Presently, although much work has been undertaken, none of these aquifer systems have yet been definitively defined and characterised.

Shallow groundwater aquifers

Unconfined shallow groundwater occurs at all sites, but less frequently in Nakuru because of the widespread underlying permeable and thick pyroclastic deposits and the associated grid fault system that channels the recharge into deeper aquifers. In KRA, the shallow aquifers are found at depths of 5–25 m (DHV 1988; Okotto-Okotto et al. 2015) with the relatively deeper ones sited in the Kano plains east of the city (DHV 1988), yielding 2–18 m^3/day (DHV 1988). The LA comprises mainly alluvial sediments in and along the seasonal and ephemeral streams that characterise the area. In Wajir, a fine sand aquifer located 2–10 m below ground level (bgl; MWI 2005) with an average water table that is about 6 m bgl (Kuria 2013), occurs within the Wajir beds which comprise jointed arenaceous limestone with calcium carbonate concretions and solution cavities, and mixtures of calcareous silty and clayey sand, clay, marl, and gypsum with a total thickness of 20–25 m in the Wajir area (Joubert 1963; Swarzenski and Mundorff 1977; Mailu 1997). The limestone itself is 2–15-m thick (Swarzenski and Mundorff 1977; Mailu 1997). Early estimates of its areal extent were that it lies within a radius of 15 km from the town of Wajir (706 km^2; Swarzenski and Mundorff 1977). Based on geophysical profiles, it was estimated to be about 40 km^2, with its boundaries, relative to the town centre, at 15 km to the northwest, 4.3 km to the north, 5.7 km to the east, and not specified to the south (MWI 2005). Kuria (2013), however, suggested that tentative boundaries of this aquifer can be set at approximately 7–8 km north and 20 km west of the town of Wajir based on outcrop geology and absence of shallow wells, respectively, but was uncertain about the boundaries to the east and south. Shallow wells are typically dug to 10–20 m (Swarzenski and Mundorff 1977). The shallow water aquifer is underlain by sandy clays that are over 150 m thick (Mailu 1997). The shallow aquifers are generally low-yielding, with >5 m^3/h in roughly 40% and 2 m^3/h in 60% of tested wells (Kuria 2013), and show both pronounced local variation with higher and lower yielding wells sometimes in close proximity and rapid response to rainfall (Swarzenski and Mundorff 1977; MWI 2005; Kuria 2013). In MA, the water table is normally between 15 and 25 m bgl, but since about 65% of the aquifer sands are held above mean sea level, the risk of saltwater intrusion is reduced and higher drawdowns are acceptable during abstraction (Kuria 2013). Wells dug in the fossil coral reef next to the shoreline encounter both fresh and saline water, depending on location.

Intermediate-depth groundwater

The western part of KRA has groundwater from 25 to 60 m in faulted and fractured hard rocks as well as in sediments along the gulf (DHV 1988). In the central part of Kisumu area (town), there are perched aquifers that underlie the fractured phonolites (Okotto et al. 2015). To the east in the Kano plains, the thicknesses of individual aquifers were determined from a combination of drill cuttings and geophysical well logs; it was established that the individual aquifers ranged in thickness from about 2–10 m with two aquifer levels usually found between 30–80 m depth (DHV 1988). In the central and western parts of the area, medium depth groundwater (25–60 m)

Table 1 Transmissivity values in the aquifer systems

Aquifer system	Shallow aquifer (m²/day)	Intermediate aquifer (m²/day)	Deep aquifer (m²/day)	Regional (Kuria 2013) (m²/day)	References
KRA	1–20, central and south. 20–60, north and east	1–20, central and south. 20–60, north and east	Likely higher than intermediate aquifer	1–100	DHV (1988)
GNA	–	1–108	1–108	50–100	Mawari Project
LA	–	–	–	50–400	–
WTA	<80 to 300[a]	None	–	1–20	Kuria (2013)
MA	–	4 to 700	–	20–200	Gro-for-GooD Project

[a] Apparent transmissivity

occurs in faulted and fractured hard rocks and in sediments along the gulf (DHV 1988). In the Olobanita and Kabatini areas of the GNA, thick loose sands and pyroclastic successions at depth, some which are over 150 m in thickness, are the main sources of groundwater for Nakuru and its environs. South of Nakuru, the yields are mainly between 7 and 15 m³/h (Allen et al. 1989; Odero and Peloso 2000). The LA is hosted within predominantly alluvial sediments with fractured intervolcanic layers; exploratory boreholes drilled to 47 and 61 m into the aquifers show almost no seasonal groundwater level variation (RTI 2013), suggesting that the system is multilayered and extensive. One of the Lodwar boreholes gave a stable yield of 27 m³/h of potable water (RTI 2013). In Wajir there is a fine sand aquifer at 29–36 m bgl that has low water yields and very large drawdowns when pumped (MWI 2005), though this aquifer is not referred to in Mailu (1997). In MA, the sandy aquifer is estimated to have a thickness of 16−59 m, with expected yields of 10–20 m³/h for the thinner sections and 40–60 m³/h for the thicker section (Kuria 2013). It was estimated in 1999 that 17,800 m³/day was being abstracted through 251 shallow boreholes (Kwale CIDP 2013).

Deep groundwater

Geo-electrical soundings in the Kano plains of KRA indicate that relatively thicker and better developed aquifers occur below a depth of about 150 m, but this has not yet been physically proven (DHV 1988). Boreholes in the Olobanita area of the GNA give very high yields of 40 to over 60 m³/h. In the LA, a well dug to a total depth of 128 m penetrated two highly conductive coarse sand aquifer layers at 104–118 m and 119–128 m, respectively (RTI 2013). The deeper Lodwar borehole was tested to have initial yields of 40 m³/h at a depth of 120 m, but the water was slightly mineralised with slightly elevated F and Na. In the Wajir area, the deep groundwater aquifer consists of a coarse sand lens between 100 and 120 m depth (Mailu 1997), whose recharge zone is possibly 30–50 km north of the town where the contact between the sandy clays and the underlying Precambrian rocks is exposed at the

surface (Joubert 1963; Mailu 1997). Kuria (2013), based on a critique of the literature and analysis of recent borehole logs, noted that there were uncertainties in the geology of the area at depth. He proposed that the Mansa Guda Formation may extend further southwestwards than previously thought and might occur under Wajir at a depth of 120 m, and that Merti bed equivalents underlie the Wajir beds in the area. The MWI (2005) indicates the presence of another aquifer layer at about 260 m bgl, but makes no reference to the one described by Mailu (1997).

Groundwater quality

The electrical conductivity and concentration ranges (minimum, maximum) of rivers and groundwater in the five case study areas, based on the accessed data, are given in Table 2. It should be noted that the datasets have strongly right-skewed distributions, and the median values lie between the 5th and 20th percentiles. The rivers generally have low conductivities; however, slightly higher conductivities are observed at a few sampling points along the Njoro River within the GNA area that are attributed to industrial effluent discharges, while the exceptionally high values in the MA area are found in the Ramisi River where there is a strong Indian Ocean tidal influence that extends some kilometres inland (Table 2). In the KRA, there is a wide saline zone where flow paths converge in the area east of the Lake Victoria shoreline within the Nyanza rift (DHV 1988) which precludes a connection between shallow groundwater flows from the north and east (Nandi fault highlands and Kericho hills) with that from the south (Kendu fault highlands). Further, higher salinity shallow groundwater occurs all along the lake shore margin than in areas further away (DHV 1988). The deep boreholes that are closer to the lake in the saline zone demarcated by the unconfined aquifer also have electrical conductivities slightly over 1,000 μS/cm. These data suggest that there is little connectivity between the groundwater and the lake. High electrical conductivity values in the GNA deep boreholes are due to rock−water interactions, while in the MA they are found in boreholes that are close to the coastline, and reflect saline water intrusion. Fluoride levels are naturally

Table 2 The ranges for electrical conductivity values and the concentration ranges {or average values} for nitrate, fluoride, thermotolerant coliforms (TTC) and *E. coli* in the surface and groundwaters in the case study regions. The *GNA* and *LA* regions have high groundwater dependency for piped water supplies. In the *MA*, the Ramisi River has a several-kilometre-long tidal reach so concentrations of the parameters are given separately in *square brackets*

Parameter	Site type	Case study region				
		KRA	GNA	LA	WTA	MA
Electrical conductivity (μS/cm)	River	61.0–110.0	97.0–1,057.0	143.0–300.0	No river	80.0–404.7 [5,647.0–35,300.0]
	Well	280.0 ≥ 2,500.0	–	–	1,124.0–3,900.0	67.0–5,000.0
	Borehole	160.0–1,280.0	230.0–3,420.0	380.0–538.0	–	200.0–7,000.0
Nitrate (mg/L)	River	1.2–8.2	0.0–20.6	0.03–25.5	None	0.9–6.0 [52.0–268.0]
	Well	1.2–188.3 {18.1–70.3}	5.9	0.01–0.07, Turkana central	78.0–222.0 in town; 0.0–106.0 in county	0.2–68.0
	Borehole	1.7–8.4	0.1–36.0	3.3–6.8	0–443 in county	0.2–32.2
F (mg/L)	River	0.3–0.5 {0.8}	0.3–3.4 {0.8}	<0.01–1.32	None	0.0–0.6 [1.3–5.4]
	Well	0.9–3.5 {3.5–6.2}	–	0.1–3.8, Turkana Central	0.2–0.8	0.0–0.2
	Borehole	0.3–7.3	0.6–20.0 {6.2–6.7}	0.1–0.4, town; 0.2–1.2, Turkana Central	0.2–8.2	0.1–0.4
TTC (cfu/100 ml)	River	152–210	–	24, 2,400 (two samples)	None	3–37 [123–1,150]
	Well	894–2,183	–	–	3 ≥ 1800 {1048}	5–10
	Borehole	0–144	–	–	–	3.3–81.0
E. coli (cfu/100 ml)	River	–	–	2,000 (one sample)	None	8–22 [13–817]
	Well	<10.0 to >100,000 {654[a]}	–	–	0–275 {41}	0
	Borehole	–	–	–	–	0 (majority)−18
Data sources		DHV 1988; Orwa 2001[a]; Wright et al. 2013; Okotto-Okotto et al. 2015; Wright et al. 2013; Ong'or and Long-Cang 2007; AfriWatSan Project	Olago et al. 2009; Njeru and Alukwe 2017; Mawari Project	LOWASCO (REACH Project Partner); unpublished data	Swarzenski and Mundorff 1977; Osman et al. 2014	Chalala et al. 2017; Gro-for-GooD Project

TTC range < 10 to >100,000 in Okotto-Okotto et al. 2015 datasets. Average F concentration in the water supplied from Nakuru Water and Sanitation Services Company (NAWASSCO) taps was 7.05 mg/L (Njeru and Alukwe 2017). In Msambweni area only the groundwater sources of Milalani Primary School Borehole and Tuliani Borehole were contaminated with faecal coliform. High nitrate concentrations relate to the downstream portion of the Ramisi River (Chalala et al. 2017). Pb in the town of Wajir is a major issue (0.00–0.03 mg/L vs WHO guideline of 0.01)

[a] *E. coli* in Manyatta Estate

high in the alkaline volcanic rocks of the rifts in Kenya and are mobilised into the water system through processes such as weathering, leaching, cation exchange reactions, and interaction with geothermal or hydrothermal fluids (Edmunds 1996; Olago et al. 2009), and are thus found in the KRA, GNA, and LA regions where volcanic rocks occur. It is ubiquitous and heterogenous in distribution (Olaka et al. 2016) with no clearly discernible pattern in terms of location, depth and confined or unconfined status of the aquifer layer (Table 2). Some deep boreholes in the WTA area also have elevated fluoride values whose origin remains debatable, but Swarzenski and Mundorff (1977) suggest some interaction with possibly buried volcanics.

Nitrate levels in the rivers are within permissible values, except for the Ramisi River in the MA which has high nitrate concentrations from the ocean tidal influence. Nitrate contamination has been of ongoing concern in the KRA shallow wells (DHV 1988; Orwa 2001; Wright et al. 2013) and the WTA shallow wells and deep boreholes (Swarzenski and Mundorff 1977; Mailu 1997; Table 2). It is partly attributed to the wells being closely located with leaky onsite sanitation (Ong'ang'a and Righa 2009; Okotto et al. 2015). A significant correlation between nitrate and chloride levels in shallow wells and the density of pit latrines in wells within a 100-m radius of the latrines was noted in Manyatta and Migosi estates within

Kisumu City (Wright et al. 2013). Nitrate concentrations in well water tend to peak during rainfall events (Okotto-Okotto et al. 2015), indicating that enhanced diffuse leakage, burst sewers, and sometimes pit latrine flooding and overflow during flood events contribute to the contamination (Ong'ang'a and Righa 2009). However, in the central and western parts of the KRA, outside the city, the quality of the groundwater is much better (DHV 1988). The high nitrate concentration in Wajir shallow wells is due to contamination by surface wastes and backflows (Mailu 1997) and possibly also remobilisation from shallow palaeosols (Swarzenski and Mundorff 1977). Microbial contamination is of greatest concern in shallow aquifer layers, but a few deep boreholes are also contaminated and in most cases this is attributed to poor wellhead completion and protection. Thus, poor water quality constrains the use of the groundwater resource and exacerbates water stress (Currell 2014). Better water quality has been demonstrated to be strongly related to the protection of groundwater and treatment of piped water (Bain et al. 2014), including abstraction through pump-equipped wells rather than by bucket (Mailu 1997).

Knowledge gaps

There are challenges with the existing monitoring, data, and information system (MDIS) for groundwater in Kenya, including incomplete records (Kuria 2013) and a huge gap between stored information (less) on water resources and the real field data (more) (Bakker 1997). The problem of insufficient knowledge of aquifer systems (Table 3) is not unique to Kenya (cf. Robins et al. 2006; Bates et al. 2008; Xu 2008)—for example, recharge and sustainable yield values, which are critical for resource assessment and management (cf. Scanlon and Cook 2002) continue to be estimated based on assumptions that may or may not be justified because empirical evidence is lacking but immediate decisions must be made about the resource. In the NWMP 2030, the sustainable yield of groundwater is "estimated" to be 10% of its recharge value. It is, however, followed with a caution that such values should be carefully determined based on more detailed studies (MEWNR and JICA 2013). Fortunately, the knowledge problem has been recognised for some time now at the highest policy and management levels, and was aptly outlined in the NWRMS 2007 through its specification of the aspects that needed further study (Table 3).

The fact that groundwater resource resilience depends on aquifer storage volume, transmissivity and long-term recharge (Foster and MacDonald 2014) is, however, not readily appreciated. The aquifer knowledge is hierarchically and spatially stratified, ranging from poor in many to fair in a few, and better in those in areas with dense populations compared to those with sparse populations in remote locations. Aquifer knowledge is lagging behind aquifer development, instead of the other way around, so that development decisions are being made with insufficient evidence. Thus, focused and intensive studies to characterise the key groundwater aquifers need to be carried out urgently to guide aquifer development and management.

Water access disparities

While households receiving piped water supply into dwellings rely on it almost solely for all domestic water requirements, those living in informal settlements or low-income urban areas rely on a wider range of water sources such as boreholes, springs and shallow wells that have different quality and prices for different domestic uses including drinking, cooking, and washing (e.g. Philip and Stevens 2013). However, planned low income areas and parts of the informal settlements do receive piped water into yards. Though the right to clean and safe water is recognised in Article 43 of the Constitution of Kenya 2010, it has been a key objective of the government since independence, and the slogan "Water for all by the year 2000" was well known by the public (Nyanchaga 2016).

There are some similarities and differences as to how water from the different sources is used depending on one's income level (Table 4). Water from shallow wells is commonly used for other purposes other than drinking and cooking, such as washing clothes due to ease of access, affordability and constancy of supply (Okotto et al. 2015). It was, however, noted that spring water was often used for drinking and cooking even though households seemed to be well aware of the health risks posed from consuming water from shallow wells (Okotto et al. 2015). Shallow well and spring waters in low income and poor urban areas are often contaminated by human wastes due to conjunctive use of the sub-surface for water and sanitation. In recognition of this, the Kenya Environmental Sanitation and Hygiene Policy 2016–2030 (Ministry of Health 2016) states that "household or private sector or any other eligible entity, when establishing environmental sanitation facilities, shall ensure that the wastes from such environmental sanitation facilities do not pollute the environment and water bodies, including groundwater aquifers".

Groundwater yield data for LA and GNA was not available in the accessed literature. In Kisumu's (KRA) urban estates of Manyatta A and Migosi, the overall contribution of shallow well water to the domestic water supply was estimated to be 381 and 91 m^3/day, respectively (Okotto et al. 2015), but shallow wells dot all the unplanned settlements. Considering these estimates by Okotto et al. (2015), and converting into daily per capita supply using the area populations and assuming that there is no significant variance in usage between different areas, the total amount of shallow groundwater used in all Kisumu City unplanned settlements (MajiData 2018) is between 1,177 and 1,748 m^3/day or more.

Several hundreds of wells have been drilled in the town of Wajir and the surrounding settlements to satisfy the water demand (Mailu 1997). In the 1970s, Swarzenski and Mundorff (1977) reported that water withdrawals from the shallow wells

Table 3 Status of aquifer knowledge as per the National Water Resources Management Strategy (NWRMS) 2007 specifications in 2011 and 2018

Activity proposed in the NWRMS	Achieved? (Mumma et al. 2011)	Present status (2018)	Achieved? (2018)
Define and describe groundwater bodies in Kenya	Yes	Groundwater bodies in Kenya only partially described from site-specific geologs done by qualified personnel, aquifer testing, and geophysical investigations; information insufficient for aquifer management and decision-making	Partially
Define and quantify the reserve for each groundwater body	No	Aquifer systems geometry, layer thicknesses and properties partially known from site-specific geologs, aquifer testing, and geophysical investigations, but critical boundary parameters such as empirically determined recharge values, groundwater/surface-water interactions, and sustainable yields remain unresolved	No
Identify groundwater bodies which are at risk of over abstraction or water quality deterioration	Yes	As in the preceding, in addition to lack of or insufficient well monitoring and abstraction data; some information on water quality but monitoring is infrequent and erratic while some monitoring parameters may be irrelevant and others, e.g. POPs excluded	Partially
Produce a hydrogeological map of Kenya	No	No hydrogeological maps yet produced for most of the known aquifers, so no possibility of upscaling to country level	No
Produce a groundwater vulnerability map of Kenya, in detail as and where required	No	Some maps have been produced using DRASTIC model, e.g. for Nakuru and Mombasa areas	Partially
Identify groundwater bodies that have been subject to significant pollution	No	Monitoring systems are in place but need to be improved, focused and representative for all aquifer systems	Partially
Develop a classification scheme for Kenya's groundwater resources	Yes	A classification scheme has been developed	Yes
Develop a monitoring network for groundwater quantity and quality	Partially	Monitoring systems are in place but need to be improved, focused and representative for all aquifer systems	Partially
Develop an overview of the status of groundwater quantity and quality in Kenya	No	This needs input from all the other factors previously mentioned to be achieved	No
Identify areas to be designated protected areas and groundwater conservation areas.	No	Baseline and monitoring data are required for evidence-based identification of designated protected areas; collaboration required with other sectors, e.g. forestry, land use planning	Partially

Yes, issue addressed; *No*, issue not addressed; *Partially*, issue partially addressed

in the Wajir area was already as high as 4,500 m³/day. In 2005, the estimated abstraction for the town of Wajir was 5,502 m³/day, with one fifth of it being used for irrigation (MWI 2005). This represents very little development over the past four decades, and suggests that the town of Wajir has been getting more and more water stressed with time. By 2014, Wajir County had over 182 boreholes, 5,000 shallow wells and over 300 water pans, but due to recurrent drought and mushrooming of settlements, the accessibility and availability of water was limited in most parts (NDMA 2014). Due to local variations in the character of the aquifer, there is high variability in water levels, yields (range is ca. 60−200+ m³/day) and water quality, even within a single group of wells (Swarzenski and Mundorff 1977).

In the MA unconfined layer, yields range from 12 to 192 m³/day, while in the confined layers it ranges from 7 to 480 m³/day (Gro-for-GooD Project). Furthermore, in many cases around the country, wells are poorly constructed and protected, and there is infrequent and irregular maintenance or repair if at all (Ong'ang'a and Righa 2009). It is noted that access to groundwater sources and improvement of the flow and safety of springs in particular can accrue multiple benefits to the users, particularly women, in terms of health, income, and security

(Philip and Stevens 2013). By channeling and protecting springs (and shallow wells), greater volumes of water are made available to residents (Philip and Stevens 2013).

As of 2010, the existing water supply system could provide only 36 L/day (L/d) of water on average in Kenya, though it is required to provide 60 L/day even for populations in low class housing, according to the national standard (Table 5). In Kisumu, only the high-income class exceeds the basic water requirement of 60 L/day, while on the lower end are the generally poor informal settlement residents who have a mean per capita daily water use of 22.5 L (Wagah et al. 2010). Too much water is being lost as nonrevenue or unaccounted-for water as listed in Table 5; the Water Services Regulatory Board (WASREB) has set a target of reducing NRW to 20%.

Governance and management framework

The concept of "governance" is understood very differently in different contexts (Norichika et al. 2014). In this report, the following definitions apply: "Governance" refers to the oversight and decision-making that provide strategic direction relating to policies, plans and strategies that provide guidelines for

Table 4 Sources of water and their treatment and uses by income group levels (low income group are not italicised; middle and upper income group are *italicised*) in the towns of—*Kis* Kisumu, *Nak* Nakuru, *Lod* Lodwar, *Waj* Wajir, *Msb* Msambweni (data from KNBS and SID 2013a, b, c, d, e; KDHS 2014; personal knowledge)

Source of water		Kenya urban	Kis	Nak	Lod	Waj	Msb	Low income group; middle and upper income groups
Surface water (%)	River	9.2	15.8	0.3	13.2	0.0	5.6	Domestic uses and drinking after treatment[a] and peri-urban agriculture; gardening
	Lake	0.5	1.9	0.0	0.0	0.0	0.0	
	Dam	0.7	0.5	0.0	0.4	0.0	0.0	*Peri-urban agriculture; Gardening*
	Pond	0.9	0.9	0.2	0.2	0.1	2.5	
Groundwater (%)	Spring (P)	4.0	2.8	1.0	1.2	0.3	1.1	Domestic uses and drinking after treatment[a] and peri-urban agriculture; gardening
	Spring (U)	1.9	2.1	0.1	0.6	1.3	0.8	
	Shallow well (P)	6.8	7.7	0.5	4.9	39.4	18.6	*Peri-urban agriculture; Gardening*
	Shallow well (U)	2.9	2.2	0.1	4.4	55.9	27.8	
	Borehole	10.7	14.5	7.1	18.6	0.5	41.2	Owned by landlords/*Individuals*; Domestic uses and drinking (*both*); Assumed to be uncontaminated, uncommonly treated; *treated (chlorinated/filtration)*
Piped water (%)	Piped	34.9	30.0	56.3	41.2	1.3	1.6	Domestic uses and drinking (*both*)
	Piped into dwelling	14.7	5.5	22.0	10.6	0.3	0.4	(not further treated, *sometimes boiled or filtered*)
Vended water (%)	Water vendor	11.8	15.0	12.2	4.0	0.1	0.4	Domestic uses and drinking after treating sometimes; *Domestic uses during piped water shortages; treated*
Rock catchment (%)	Rainfall/runoff	0.2	0.1	0.1	0.0	0.0	0.1	Not used (*both groups*)
Roof harvesting (%)	Rainfall	0.5	0.9	0.6	0.0	0.0	0.0	Rare for individuals; some rental residential units do harvest to boost supplies; Sometimes treated; *In areas with common water shortages or unserved areas*
Other (%)		0.1	0.0	0.1	0.5	0.9	0.0	Not used (*both groups*)
Total (%)		99.8	99.9	100.6	99.8	100.1	100.1	–
No. of people (millions)		11.844	0.439	0.298	0.055	0.052	0.023	–

[a] Treatment of water by: boiling; adding bleach or chlorine; strained through cloth, ceramic or other filter; solar disinfection; cover container and let settle

P protected; *U* unprotected

management, while "management" refers to the routine decisions and administrative work related to the daily operations of institutions or agencies mandated to implement the policies, plans and strategies.

Governance framework

The Water Act 2016 and related policies The Water Act 2002 has now been replaced by the Water Act No. 43 of 2016, which came into effect on 21 April 2017. It was necessary to revise the act to bring it into alignment with the constitution of Kenya 2010 and its devolved governance structure. The act states, in Article 63, that "Every person in Kenya has the right to clean and safe water in adequate quantities and to reasonable standards of sanitation as stipulated in Article 43 of the Constitution." Under the Water Act 2002, the purpose of the NWRMS was to specify how Kenya's water resources would be managed, protected, used, developed, conserved and controlled, and to provide for national monitoring and information systems on water resources. Under the same act, the NWSS was required to institute arrangements to ensure that at all times there is in every area of Kenya a person capable of providing water supply, design a programme to bring about progressive extension of sewerage to every centre of population in Kenya, and to provide for national monitoring and information on water systems and water services. The strategies were revised and aligned to Vision 2030 following its adoption by the government in 2007. Vision 2030 is Kenya's development blueprint for the period 2008–2030, by which time the country should have transitioned from a low-income country to a middle-income country. Consequently, every activity in the water sector since 2002 to 2017 has been guided by the two key strategy documents under the Water Act 2002.

The Water Act 2016 addresses some of the weaknesses in the 2002 Act that became apparent as the

policy was implemented. Two key strategy documents have been clearly specified as necessary in the act. The broad objective of the National Water Resources Strategy (NWRS) is to "provide the Government's plans and programs for the protection, conservation, control and management of water resources", and that of the NWSS is to "provide the Government's plans and programs for the progressive realization of the right of every person in Kenya to water". These objective statements are followed by detailed descriptions of their respective strategic scopes. It expanded on or elaborated the scope of the objectives of the strategies under the Water Act 2002.

The National Water Master Plan 2030 The National Water Master Plan (NWMP) 2030 (formerly the NWMP 1992), which incorporates the relevant elements of Vision 2030, is the key document against which the strategies are benchmarked. It aims to develop the country's available surface and groundwater resources to the maximum to meet the water demands through multipurpose development, interbasin transfer, intra-basin transfer, water saving, reuse of water, and by promoting other approaches such as roof and rock catchments for water harvesting to supplement supplies and mitigate drought impacts (MEWNR and JICA 2013). The aim of the NWMP 2030 is to ensure that all people living in urban areas will have access to piped water (whether into dwelling or to shared water points such as a yard) by the year 2030. In addition, it proposes the development of small-scale rural water supply systems (SSRWSS) that include construction and improvement of boreholes, wells, and springs on a personal and community basis. The rural areas that are in proximity with urban centres may therefore end up competing for the same water resource. This rural-urban linkage in the water management regimes is considered a key vulnerability, particularly during droughts (Field et al. 2014).

Management framework

Under the Water Act 2002, a decentralised management system was devised and implemented through the creation of institutions such as the Water Resources Management Authority (WRMA) to effect the NWRMS, and the Water Services Regulatory Board to effect the NWSS. The Water Appeals Board was set up to resolve any water-related disputes. The 2016 Act reorganised existing institutions and their respective mandates, and established new institutions—for example, rainwater harvesting was not included in the 2002 Act, but in the 2016 Act it has been given a lot of prominence, with the establishment of a National Water Harvesting and Storage Authority. Groundwater recharge, previously not mentioned in the 2002 Act, is now recognised and has been brought under the permitting regime. The 2016 Act has also taken cognisance of public

participation in the formulation and periodic revision of the strategies, and private sector participation in water development and services provision. Under the 2016 Act, the new Water Resources Authority (WRA) is mandated to develop the NWRS, while the top policy-making level, the Office of the Cabinet Secretary for the Ministry of Water and Irrigation formulates the NWSS with the WASREB tasked with monitoring and assessing its implementation, like the arrangement under the 2002 Act.

The influence of the NWMP 2030 on the institutional set-up outlined in the Water Act 2016 is evident, with the formation of the National Water Harvesting and Storage Authority, and the establishment of water works development agencies whose mandates include undertaking the development, maintenance and management of the national public water works within their areas of jurisdiction. Other aspects have also been incorporated such as the NWMP 2030 call for institutional strengthening of the WRMA and catchment-based organisations to improve on governance, and the formulation of development master plans for subsectors, such as water and sanitation, irrigation, hydropower, urban development, and regional development, in order to quantify the future water demands more clearly.

Challenges and gaps

Three issues stand out from analysis of national versus county policies, plans and strategies with respect to water, and groundwater in particular: (1) the translation of national policies and strategies into county contexts, (2) lack of expert advice or capacity in water for the formulation of County Integrated Development Plans (CIDPs), and (3) lack of structures and capacity to collect county water data that would be aggregated and assessed at the national level. Indeed, it has been noted that the development of groundwater and its efficient use for urban water supply in the developing world is sometimes hindered by existing institutional and administrative arrangements (Foster et al. 2011). The five CIDPs assessed lack a proper reflection of the national policies, plans and strategies. They focus primarily on Vision 2030, and other national policies are generally inadequately addressed. None of them mention NWMP 2030, and only the Nakuru CIDP alludes to the development of a county water master plan. The mention of the terms "groundwater" or "underground water" appears only once in the Kisumu CIDP in relation to its contamination where septic tanks are used. In the Nakuru CIDP, there is no mention at all, but there is a lot of focus on water projects incorporating borehole drilling in the logframe, similar to the Turkana CIDP where "groundwater harvesting" is thrice referred to but only in the logframe. Technically wrong or misleading statements and quantitative data relating to water appear in some of the CIDPs. This suggests that at the county level, the technical and/or institutional capacities to manage water resources are low and concerted efforts need to be made to rectify this situation.

Table 5 Per capita daily water use, nonrevenue water (NRW) and unaccounted-for water (UFW) in the case study regions

Usage	Year	Kenya	Kisumu	Nakuru	Msambweni	Lodwar	Wajir	Data source
Per capita daily water use (L)	–	45.2	32.9	–	–	–	–	Wagah et al. 2010
Served populations (L/day)	2014/2015	–	47	34	–	10	–	WASREB 2016
NRW or UFW (%)	2014/2015	–	49 (5 towns served)	37 (4 towns served)	–	40	–	WASREB 2016
	2010	45	53	50	50 (5 towns/areas served)	–	–	MEWNR and JICA 2013
	2010	–	66	–	–	–	–	Wagah et al. 2010
NWMP urban water supply (domestic, L/day)	2030	100	146	119	119	119	119	MEWNR and JICA 2013

In all its geological terranes, the estimates of Kenya's groundwater endowment in terms of "safe yield" has been rising with each assessment, from 632 MCM as given in the National Water Master Plan 1992 (GoK/WWAP 2005) to 1040 MCM in 2007 (Mumma et al. 2011). The National Water Master Plan 2030 of 2012 provides a sustainable yield estimate of 1927 MCM (MEWNR and JICA 2013). The safe yield is defined as "the amount of water that can be abstracted without causing undesirable effects to the aquifer" (GoK/ WWAP 2005), a concept which Mumma et al. (2011) view as being vague, essentially undefined, and contentious. More recent studies in Turkana County by RTI (2013), however, suggest that the latest sustainable yield estimate of groundwater (taken as 10% of the groundwater recharge amount) given in the National Water Master Plan 2030 may be a gross underestimation, but the huge deep aquifers that they postulate, e.g. in the Lotikipi Basin (ca. 207,000 MCM) and the Lodwar Basin (ca. 10,000 MCM) are yet to be proven and are more likely than not, palaeo-groundwaters except for where the systems are shallow (>50 m) alluvial types that and can be linked to present-day river recharge. The shallow groundwater is sensitive to rainfall fluctuations, and during the dry season the water levels in wells that tap this source fall rapidly.

Implementation of the NWMP 2030 faces many challenges—for example, the target water source for urban water supply systems in the NWMP 2030 is surface water and only about 5% of the total demand is to be met by groundwater (MEWNR and JICA 2013). However, towns in sub-humid areas such as Nakuru are partially dependent on groundwater, while those in ASAL areas such as Lodwar and Wajir are almost totally dependent on groundwater. While interbasin transfers of surface water are proposed and are being implemented in some cases, such transfers would be extremely difficult and prohibitively costly to implement in ASAL towns due to distance, terrain characteristics, land easements, community interests, resettlements, and compensations. The NWSS 2007 to 2015 only mentions groundwater once, with respect to prioritising environmentally friendly sanitation to "…enhance acceptance among the users and limit the risk of polluting of groundwater" (MWI 2007a, b). This demonstrates that there is lack of cross fertilisation between it and the NWRMS to address interlinkages, which is critical if the NWMP 2030 is to be successfully and sustainably implemented. Further, the water sectors' strategic targets were not being met by the institutions that were supposed to implement them (Mumma et al. 2011).

Discussion

The constraints and challenges have been presented in the preceding findings section. The NWMP recognizes that, in order to be able to define a robust and practical framework of water resources management and to have proper regulation of water resources at the national and regional levels, it is necessary to establish a credible, transparent, accountable, scientific and quantitative management of water resources that is trusted by stakeholders.

A planning framework

It has been noted that groundwater and surface water should not be managed separately (Levy and Xu 2012). A generic planning framework that can be used to assess and address holistically the central need for "safe and clean water for all by the year 2030", and to this end guide the formulation of governance and management systems that work effectively has been developed here as shown in Fig. 2. It uses indicators that are common and embedded in the country's decision-making processes relating to water governance, planning and management so that radical reorganisation, which tends to be associated with time, financial constraints, as well as institutional and capacity-building drags, is circumvented. The diagram presents a way of rapidly being able to see where interventions in the water sector are needed with respect to location, related water sources, and the water access disparities that exist there (Fig. 2). The diagram construct is based on: (1) the sources of water indicator that is commonly used in the country in government, practitioner/user, commercial/industrial and research circles, (2) the central need

(policy objective or optimal condition) which is "clean and safe water", (3) the waterscape condition, and allowing for conjunctive use of resources (4) the desired infrastructure for development and conveyance of safe water and its reach (piped system of protected and treated water), and (5) the enveloping conceptual model for framing the issues that need to be considered for a targeted, practical and robust governance and management framework. Further, the peculiarities of the urban centres can be clearly differentiated and are location-specific, so that customised rather than planned blanket or uniform programmes and management schemes can be devised using such a planning framework. The approach is scalable, both upwards (e.g. to regional level) or downwards (to county level or even to sections within one urban centre), and flexible so that different indicators can be used based on the same construct. It therefore also presents a useful basis for monitoring progress via stepped time intervals.

There are also a number of broader considerations that should be taken into account as indicated in Fig. 2. The intricate interconnections between groundwater, surface water, climate and the environment, how the interactions affect groundwater quality and quantity, and how these changes impact on the social-ecological systems over space and time and ultimately on the policy objective, which is "safe and clean water", are important considerations for the planning framework (Fig. 2). Further, specific plans and programmes should take into account the four sustainability dimensions (WCED 1987)—safeguarding long-term ecological sustainability, satisfying basic human needs, and promoting intragenerational and intergenerational equity. The Sustainable Development Goal 6 on water is broadly incorporated in the Water Act 2016, and the related water strategies are under revision. However, the act and current strategies are silent on the special consideration of vulnerable groups other than women (goal 6.3); this should be included in the revision of the strategies and plans. It is also important to differentiate and quantify to the extent possible the potential effects of the risk factors and their scales of influence (Foster and MacDonald 2014). Evaluation of risks, uncertainties and adaptation options through integrated (biophysical and socioeconomic) scenario analyses should accompany decisions made on groundwater management (SEI 2009; Mumma et al. 2011)—for example, climate change may lead to higher costs for water supply related to falling surface and groundwater levels (Bates et al. 2008), which may affect the on-boarding of more users. Periodic drought may also become common, meaning that even the less efficient aquifers will become vital components in small-town-water-management strategies (Mumma et al. 2011). Decision-making in development should also consider uncertainty in project benefits and the risks of project failure (Luedeling et al. 2015), as well as the potential impacts of rural-urban connections (Field et al. 2014) such as a shared water resource.
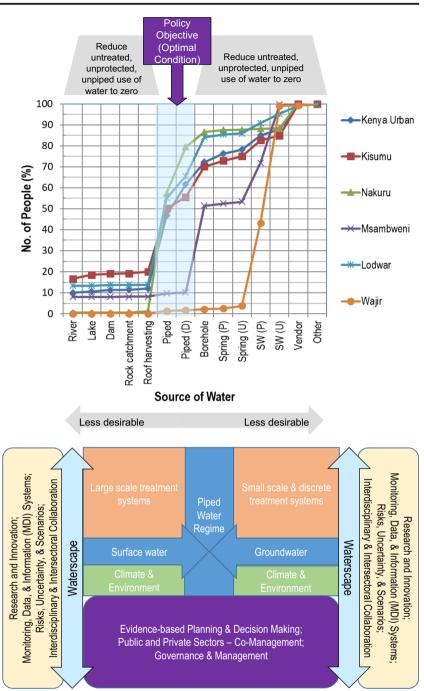
Translation of the policies and strategies from national to regional levels

There is increasing recognition that sectoral policies, plans and strategies need to be aware of where they need to create synergies or coordinate functions between themselves. It is essential that strong coordination structures are established between national and county institutions to ensure a two-way flow of information so that water sector development is undertaken in a structured and cohesive manner, even though there may be different approaches in different areas.

Considerations for improvement of groundwater management

It has been noted that whilst professionals in their interactions reflect the cross-boundary interactions needed for transition management, scientific outputs do not indicate an actual system level shift towards transdisciplinary modes of knowledge production to address the complexity of urban water systems management (Wen et al. 2015). Interdisciplinary research needs to be encouraged (Currell 2014; Barthel et al. 2017) and the capacity of researchers and scientists in the various government, research institutions and agencies, including the private sector, to produce and communicate such outputs should be enhanced. Partnerships between the government, private sector and research institutions should be enhanced (Barthel et al. 2017) in areas such as resource survey and development, while communities and the public sector should be encouraged in conservation, protection and co-management of the resource. Water management boards should take up the propositions by IPCC (2014) on adaptive water management, which includes scenario planning, learning-based approaches, flexible and low-regret solutions, reduction of non-climate stressors on water resources; strengthening of institutional capacities for demand management, groundwater assessments, integrated water-wastewater planning, integrated land and water governance, and sustainable urban development to create and build resilience to uncertain hydrological changes and impacts due to climate change. It is necessary, therefore, to build the institutional and technical capacities to address these issues, as well as the technological capacities required for groundwater development.

Given the growing policy emphasis on reducing inequalities with respect to water and sanitation, an important question is the extent to which such interventions can be considered pro-poor and how the incidence of benefits from, e.g. well upgrading might vary across different socio-economic groups (Okotto et al. 2015). In addition, groundwater resources are not amenable to centralized regulation and management (Mumma et al. 2011). Therefore, water infrastructure and technologies should be fit for purpose in application and scale, and the pro-poor focus adopted in the strategies should be underpinned by appropriately focused management regimes. Water resources

Fig. 2 Proposed framework for assessment and strategy development for the governance and management of the groundwater resources in Kenya. The graph is based on the cumulative trend of the percentage of people accessing the diverse water sources of water for each urban centre, with the objective (in this cased piped into dwelling or yard) at the centre and moving out progressively to the lesser desirable water sources. An "hysteresis loop" is generated, which contrasts, both between and within, those urban centres that are groundwater-dominated with those that are surface-water-dominated in terms of source and the percentage of people accessing them

management has tended to be under-funded relative to water supplies, and it has been suggested that this is because the resources management side hardly generates any income (Bakker 1997). Some institutional or agency funds should be ring-fenced for research and monitoring and pegged to well-defined and costed objectives. Further, some resources should be committed towards a process that seeks to set strict and enforceable minimum standards for any new water management projects that incorporates issues of sustainability, access rights and natural resources management (Mude et al. 2007).

Conclusions

The objective was to consider governance and management solutions that could promote water security for urban towns in Kenya through the sustainable use of groundwater in the context of its complex hydrogeology, hydrogeochemistry, and water access disparities among the users. The in-force national and county water policies, strategies, and plans for the case study areas were critically reviewed. The status of aquifer knowledge, water access disparities, competing uses, and risks were evaluated from critical literature reviews and data

compilation, fieldwork, and analysis of indicator datasets from the Kenya 2009 census. Analysis of national versus county policies, plans and strategies with respect to water, and groundwater in particular showed that there was need to bridge the gap in the translation of national policies and strategies into county contexts, and that the technical and/or institutional capacities to manage water resources was low, requiring concerted efforts to build them up to required levels.

Lack of cross fertilisation between the NWMP 2030 and the NWRMS reflects one weak aspect that would retard the attainment of the 2030 water vision of Kenya. The aquifer systems are insufficiently studied to properly guide interventions; each is hierarchically and spatially stratified and the depth of knowledge about them ranges from poor in many to fair in a few, and better in densely populated areas as compared to less populated ones. Aquifer knowledge lags behind aquifer development, so that development decisions are made without sufficient basis. The convergence of climate shocks, urban population explosion, infrastructure expansion, resource mining, refugee fluxes, and other factors, presents significant (and differentiated depending on location) but uncertain risks and opportunities for the evolution of small towns in Kenya, with the towns in the ASALs being particularly more vulnerable to these factors, singly and collectively. Key risks are related to rapidly increasing demand for water for various purposes, as well as land degradation and climate change, both of which threaten the quality and quantity of the groundwater resource. These will have ramifications on sustainable supplies, with attendant social and economic costs.

A flexible, scalable and transferrable holistic governance and management framework has been developed to guide the formulation of governance and management systems that work effectively and that ensure sustainability. It incorporates the country's water aspirations, the four dimensions of sustainable development and the sustainable development goals, specifically goal 6 on water. It uses indicators that are commonly applied in the country's decision-making processes in the water sector, and so can be immediately applied. Focused and intensive studies to characterise the key groundwater aquifers need to be carried out urgently to guide aquifer development and management. Water resources, supplies and management strategies should clearly involve the public and private sectors in roles where they can add value such as in conservation and aquifer development, respectively. In addition to their pro-poor focus, the strategies should also incorporate other vulnerable groups other than women who are already included. The National Monitoring and Data information system should expand, through collaboration with stakeholders, its scope on knowledge and data capture, institute quality control and assurance measures from capture through archiving to dissemination nodes, increasingly adopt automated monitoring systems, and update its indicator dataset to expand its capacity to monitor the condition of the resources, and thereby design effective

protection and control measures. The evaluation of risks, uncertainties and adaptation options through integrated (biophysical and socioeconomic) scenario analyses should underpin decisions made on groundwater management. Structures should be put in place to guide intra- and intersectoral as well as national-county coordination to better govern the groundwater resource. Counties in particular need capacity-building programmes to ensure that their institutional and technical capacities to manage groundwater resources are up to par. Water infrastructure, technologies and management regimes should be fit-for-purpose in application and scale, and the funding base for all the activities envisaged in the strategies should be secured based on clearly outlined action plans.

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