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Brination of Coastal Aquifers: Prospective Impacts and Future fit-for-use Remedial Strategies in Tanzania

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Abstract
Over centuries, coastal societies have merely depended on the groundwater as their main source of portable water supply, while other sources remained uncertain. Intensive exploitation of coastal groundwater than its restoration capacity reverses groundwater-seawater hydraulic head that resulted to brine intrusion in the coastal aquifers. The applications of electrical resistivity, chloride ion concentration and taste techniques have proved brine contamination in the coastal aquifers. In 2012 an extended intrusion up to 1 km from the coast of Dar es Salaam city was reported. Also fresh ground waters from some deep wells in the city were reported to be salty after operating for a long time. Yet, long-term impacts of groundwater brination and sustainable restoration tactics are indistinct meanwhile the problem intensifies. Therefore this article intends to investigate the extent of brination on the coastal zones of Tanzania, address potential impacts as well as investigation of fit-for-use future remedial strategies.

Keywords: Brine contamination; Environmental Impacts; Salinity; Groundwater; Coastal Aquifers

Introduction

Fast growing coastal cities of the world face insufficient supportive environment due to high population growth rate, destruction, failure of the available infrastructures and budgetary issues. Population growth and its management is a challenge associated with high rate of exhaustion of natural resources, environmental pollution as well as poverty class, unemployment, corruption, slums, trafficking drug of abuse as well as vulnerability to natural disasters. These scenarios are mostly common in third world countries, where coastal cities of Tanzania are among them. Looking into 2012 Tanzania household sensor with population growth rate of about 5.6%, 2.2%, 2.2%, 1.2% and 0.9% in Dar es Salaam, Tanga, Coast, Mtwara, and Lindi regions respectively, there is an obvious struggling for resources[1]. The ultimate resource for all families is fresh water for domestic, industrial, commercial and even recreational purposes. Therefore investment in sustainable portable water supply projects in Tanzania is compulsory.

The Kimbiji as well as Ruvu stations are the major sources of fresh water supply in Dar es Salaam city and its neighborhoods. Yet Ruvu stations experience decreasing levels for the last 40 years as reported by Mtoni[2]. Recently, Kimbiji deep wells with about 1000 km^3 of received fresh groundwater have been a potential substitute, with a production capacity of 500 m^3/h. Also the Mtoni water pumping station located at Mbagala is another potential source of fresh water in the city. However with these four major sources, they are yet sufficient as the average households with access to safe water supply is yet to be 100%[1]. Moreover, connection to these water sources mostly covered parts of middle to upper class of the city while slums and other unplanned areas lack tap water connection. Hence, severe exploitation of groundwater is the one which supports both the lower and some medium class societies[3]. Among other reported means of withdrawing groundwater from aquifer, historic shaduf, qanats, saqiya and the Archimedean screw and/or current windmills, sanction pumps and/or powered pump[4] have been useful.

The high rate of extraction of groundwater greater than its replenishment causes drawn-down

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of the water table. This process reduces the hydrostatic pressure, depleting neighborhood rivers and causes subsiding of the land[2,5,6]. As the result of imbalanced equilibrium, saline intrusion in the coastal aquifers counterbalances the effect. Brine intrusion has negative effects such as lowers groundwater portability, make it unfit for use and hence induces water scarcity[7,8]. Salinization of groundwater is also linked to increased levels of mercury resulted from the formation of stable Hg-Cl complex[9]. Therefore the insight of brine contamination, impacts and relative remedial approaches in the context of Tanzania is inevitable.

Salinization of Groundwater

Normally fresh groundwater flows from highlands to the seas and oceans; nevertheless continuous extraction of coastal groundwater faster than its recharging rate reverses the process to counterbalance the effect. In other word, it involves movement of seawater to refill coastal aquifers, the process known as brination of groundwater. Brination of groundwater is also contributed by storm surge, rising of sea levels, concentration gradient, leachates, anthropogenic activities, salt domes and connates[7],[10]. The process is natural, and involves lateral bulky movement of seawater via cracks. `Among other sources of groundwater brination along the coastal areas, seawater intrusion is the dominant one due to close proximity to the ocean, while evaporation of surface water and infiltrations are negligible[11]. The common classification of saline contaminated groundwater is shown in Table 1.

Table 1: Classification of water based in salinity content (Stuyfzand) and (USGS)

Main type	Stuyfzand [Cl^{-1}] mg/L	Main type	USGS [Cl^{-1}] mg/L
Fresh	30-150	Fresh water	< 1,000
Fresh-brackish	150-300	Slightly saline water	1,000-3,000
Brackish	300-1,000	Moderately saline	3,000-10,000
Brackish-salt	1,000-10,000	Highly saline water	10,000-35,000
Salt	10,000-21,000	Ocean water	35,000

As seawater contains approximately 35,000 mg/L of dissolved bedrocks, runoff ions and evaporation enriched ions whose chloride concentration is about 19,000 mg/L, it is denser than fresh water and extremely taste salty[12]. Consequently this composition facilitates brination by creating pressure that pushes saline water to the inland underneath freshwater zones. Apart from saline movements, possibility of bulky movements of other chemical contaminants such as emerging contaminants and inorganic contaminants prevails too.

Measurement of groundwater densities, chloride concentration as well as electrical conductivity determine possibilities of saline contamination[10,13]. Further assurance of exact sources of groundwater salinity is achieved by quantification of ratios of major ions namely hydrogen, oxygen and strontium isotopes[14].

Study Area at Glance

The coastal line of Tanzania is in the Eastern of Tanzania, East Africa bordered to the Indian Ocean. It is about 900 square km, covering 5 regions namely Dar es Salaam, Tanga, Coast, Lindi and Mtwara, with exclusion of Zanzibar. The population growth rate and other demographic data of these regions as indicated in Table 2 are higher than inland regions due to local migrations, business centers, fishing, various forms of accessible transportation, developed infrastructures and tourism. The existing resources are insufficient to this population thus searching for alternatives are important. For instance, groundwater suffices lower and middle class population which is large compared to the upper class that rely on the tap water.

Table 2: Population and Water Supply in Figures

Region	Dar es Salaam	Tanga	Coast	Lindi	Mtwara
Population	4,364,541	2,045,205	1,098,668	864,652	1,270,854
Population density	3,133	77	34	13	76
Population growth rate	5.6	2.2	2.2	0.9	1.2
%DGP Contribution	15.6	5.6	1.9	1.9	2.4
% Tap water supply	51.8	38.2	32.0	19.2	32.4

(Sources: Summary of Key Indicators by Region – Tanzania, 2012 Census, [15])

There are enough evidences of effects of sea level rise and brination of groundwater; these are such as intensive soil erosion along Kunduchi and Bahari beaches, reported in 2004 that, some residential houses, mosque and fish market were completely destroyed after headwater intrusion of 200 m for 6 decades. Also the abandonment of water wells due to saline intrusion in various parts of Dar es Salaam[16],[2] are reported as the evidence of brination of coastal aquifers.

Impacts of Brine Contamination

The effects of global warming are predicted to raise sea level from 0.5 up to 1.5 m by 2100 because of oceanic thermal expansions and glacial melting[17]. If no mitigation measures by 2100 all coastal regions of the world will be in severe catastrophe. Mtoni[2] reported an intrusion up to 2 km in the coast of Dar es Salaam, while research information from other coastal regions of Tanzania are scarce, though the effect might be closely related. The corresponding impacts of groundwater brination are heterogeneous in these regions as far as geographical location, economic activities, population density, climatic changes, season of the year and management practices are concerned. These impacts are such as health, ecological, local migration, collapsing of concrete infrastructure and economic declines.

Health Effects

Saltwater intrusion increases the amount of chloride, sodium and sulfate ions in the water. An intrusion of about 1% into groundwater make it unfit for drinking by increasing hardness and brackishness of groundwater[7]. Water with chlorine concentration less than 150 ppm is considered as fresh water while greater than 10,000 ppm becomes salty water[18]. Mtoni[2] reported 15,478 ppm of chloride concentration at DSM which is, therefore, proof of brine contamination. Apart from drinking, other roots of exposure to saline water include bathing, occupational hazards and through cooking. Elevated amounts of sodium and chloride is unsafe for salt food restricted people, and can lead to health effects like high blood pressure and heart diseases, miscarriages, skin and respiratory diseases[19]. The presence of chloride increases corrosiveness of metals which increases the amounts of metals in the water that through food chain get into humans. Extended impacts like failure of oxygen and nutrient supply into aquatic organisms are certain[20]. Consumption of saline water may lead to anxiety and stress to the society since salt water lack taste and society may experience a state of fear upon long term unrevealed effects. A stressed person may suffer from muscle tension, headaches, and insomnia, and if intensive may lead to depression.

Ecological Impacts

Salinity range between 2 to 3 parts per thousand induces ecological stress to aquatic plants whereas concentration greater than 5 parts per thousand results to noticeable physical impacts[21]. Ecologically, brine contamination increases salinity content of the soil eventually affects the rate of plants growth[22]. For example, the Pangani communities in Tanzania are continuously moving inland seeking for less saline arable lands and freshwater as the result of seawater intrusion. Also, some water wells at Oysterbay and Gerezani were abandoned for irrigation in the dry season as it affected vegetation[2]. Less productive coastal wetlands due to salinization of groundwater bring food insecurity and un-employment which affect family income and its well-being. Lack of productive lands directly affects animal keeping, induce soil nutrients imbalance that later may result into abandonment of the lands. Only few macro and microorganisms prefer such kind of saline land. Bare lands are extremely vulnerable to coastal erosions, land sliding, infertility, less productive and inhabitable[23].

Local Migration and Conflicts

The loss of productive lands as a result of water brination causes migration of people searching for arable lands. In the course of movements, farmers and animal keepers who are looking for grazing, shelter, and cultivation lands may happen in the same area, once they meet in the arable lands conflicts are unavoidable consequence. In turn, a trembling community security, human hunting, and destruction of crops, killing domestic animals and house burning are common. The said local migrations can cause illegal inversion into reserved lands and national parks leading into ecological destructions and eventually poaching[24,25]. Apart from farming migration remains to be human nature once need arises[26]. Local migration and conflicts create fear, while women and children are the vulnerable group.

Collapsing of Concrete Structures

Concrete structures erected in the seawater or in the areas which are contaminated with seawater experience both physical and chemical forces which later degrade them. The hydraulic pressure experienced between wet part of concrete immersed in the salt water and dry part in the air increases the rate of the structure collapsing. Magnesium and sulfate which are among composition of common cement react at certain pH values. Thus the variation of pH of the water and various chemicals present in the saline water corrode concrete structure by attacking magnesium and sulfate, while thermal expansion and contraction cause cracks[27,28]. At last concrete structure collapses, leaving behind social and economic effects.

Economic Impacts

In the next century, most of the coastal regions will face acute economic impairment as they will less be touristic attractive. Saline water causes corrosion, blackening and induces unrequired salts into food and drinking staffs which interfere with industrial production[29]. Practices of urban agricultural including vegetables, cassava, legumes and sweet potatoes growth will be affected since saline tolerance differs among vegetation. For instance, rice is classified as tolerant to saline water up to 2400 mg/L of chloride, potatoes are considered relatively sensitive to chloride concentration up to 600 mg/L while fruits are classified sensitive with chloride tolerance of 300 mg/L. Based on 15,478 ppm of chloride concentration that were found at some areas in Dar es Salaam city, urban agricultural activities which rely on the groundwater will be highly affected [29]. When linking these observations with the intensive extraction of groundwater, it is the hypothesis that there will be a severe brine contamination making domestic water expensive. Health effects and impaired socio-economic life of the communities due to brine contamination shall interfere with individual incomes [30]. Food insecurity from poor coastal region crops production will speedup illegal fishing and potentially reduce habitable lands like Pangani[31,32,33]. Moreover, the rising of the sea level of about 0.5 m is expected to increase seawater intrusion leading to an estimated loss of about US$ 48-82 million in the Dar es Salaam city alone[34], therefore if sea level rises to 1.5 m will be a tragedy in the coastal regions of Tanzania.

Coastal Aquifer Management

Recharging Groundwater

Seawater intrusion results from rebalancing process of lost groundwater-saltwater equilibrium. Natural and artificial recharging is the most widely adapted restoration approach. It involves construction of water reservoirs or reserved wetlands which collect free-from-pollutant surface and rain waters then allowed to slowly infiltrate and counterbalance extracted fresh groundwater. Water recharging reservoirs are placed in such a way they become barriers between sea and fresh water, also reported by Rao[35]. Sometimes rivers may be redirected or constructed towards groundwater recharging zones. Recharging is also achieved through rechanneling major rivers to smaller outlets which infiltrate open and paved lands. Instead of letting rivers to flow freely over kilometers, diversion barriers can be constructed to hold water for sometimes to allow gentle water infiltration. Induced recharge is as well useful and adaptable[36], where water wells are drilled close to the river just like Mtoni water pumping station where fresh river water is forced to infiltrate due to nearby groundwater extraction.

Controlled Abstraction

The basis of controlled abstraction aim at reducing unnecessary amount of used water in order to conserve the available groundwater. This is less mythical and more practicable by adapting wastewater recycling and reuse while observing ecological safety. Adaptation of planting less water consuming crops, shifting to drip irrigation, canal lining and sometimes adaptation of hanging gardens reduce water for irrigation. Reusing wastewater in recharging, cooling, washing and other related activities may reduce groundwater extraction. Public awareness on serving water to serve the future must be in line with these adaptations. Reduction of water loss during water distribution is within our will and control that serves energy, supplement the demand and reducing groundwater abstraction.

Scavenger Wells

Scavenger wells are dug deeper than and close to the abstraction well with the role of collecting saline water which is separately abstracted. Brine water is denser than fresh water and therefore gets into deeper scavenger well while freshwater remains in the shallow well. This method is cheaper and capable of separating both fresh and saline water [37]. By doing this fresh-salt water interface is rebalanced and controlled in order to prevent brination of abstraction well. The implementation of this technique is merely challenging particularly on the location and dimensions of scavenger wells to enable extraction of saline water while leaving behind soft water.

Hydraulic Barriers

Construction of hydraulic barriers creates artificial freshwater recharging bore holes between extraction wells and saline waters. The method is relatively expensive as it involved drilling of several wells and then followed by pumping or channeling in fresh water which shall counterbalance the replenished groundwater. Nevertheless, it is very important to establish the actual boundary of seawater intrusion. In such approach, groundwater is saturated with freshwater, therefore, no room for saline water intrusion. However affordability of this technique especially in the third world countries is frankly impossible.

Policies and Regulations

Restoration policies such as those of obstruction of human activities in the conserved areas such as water catchment, forests, flooding zones and coastal lines are inevitable. This goes hand-in-hand with defining specific distance for the location of water wells from the sea, i.e. the far the well the less the vulnerable to seawater intrusion it becomes. Regulations must be reinforced to each wastewater releasing body to abide with environmental management policies. These regulations, stakeholders and the government must consider water supply and sewage management as a service rather than commercial item, or run at reduced costs where people can share the cost with the government in order to prevent erruption of waterbone diseases. To date, the integration of the salinization issue in water safety, environmental topics, public speeches and planning matters is necessary in order to serve the future.

Data management System

Brination of coastal aquifers requires sufficient quantitative and qualitative data to avail sources and extent of the problem. These data are useful in monitoring the extent of contamination, performance of the control measures, and the extent of corresponding effects. Some of the important data include the understanding of the annual amount of groundwater abstraction and recharging rates, physical and geological makeup of the aquifers, climatic data, water level and water quality. Historical facts about the place, ecological nature of the place as well as rising and falling of sea level are crucial data too. It is through data where any other facts on seawater intrusion can be proved, supported, accepted, implemented and even financed for rehabilitation of affected zones.

Conclusion

The coastal regions of Tanzania like any other coasts are vulnerable to all impacts of seawater intrusion due to poor planning, poverty, unimproved infrastructures and closeness to the Indian Ocean. At first place, it is important for coastal resources managers to grow saline sensitive plants along the coastal lines as indicators of brine contamination. Establishment of monitoring centers for assessing the extent of brine contamination is recommended despite the heterogeneity of the coastal lands. Construction of desalination plants, lock separator and recovery wells are crucial and likely approach to mitigate the effects. Authorities must implement coastal resources management policies as a long-term plan for protection of vulnerable potential coastal areas.

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