

Article

Impact of Population Growth and Climate Change on the Freshwater Resources of Lamu Island, Kenya

Cornelius Okello ^{1,2,*}, Bruno Tomasello ³, Nicolas Greggio ¹, Nina Wambiji ⁴
and Marco Antonellini ¹

¹ Integrated Geoscience Research Group (I.G.R.G.), University of Bologna, Sant'Alberto 163, Ravenna 48123, Italy; E-Mails: nicolas.greggio2@unibo.it (N.G.); m.antonellini@unibo.it (M.A.)

² University of Cadiz, Polígono San Pedro s/n, Aulario Norte, Puerto Real, Cadiz 11519, Spain

³ Environmental Management Research Group (EMRG), Centro Interdipartimentale di Ricerca per le Scienze Ambientali (CIRSA), University of Bologna, Sant'Alberto 163, Ravenna 48123, Italy; E-Mail: bruno.tomasello2@unibo.it

⁴ Kenya Marine and Fisheries Research Institute P.O. Box, 81651, Mombasa 80100, Kenya; E-Mail: nwambiji@kmfri.co.ke

* Author to whom correspondence should be addressed; E-Mail: cbokello@gmail.com; Tel.: +39-342-083-7373.

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Abstract: Demand for freshwater is rising with factors, such as population growth, land use change and climate variations, rendering water availability in the future uncertain. Groundwater resources are being increasingly exploited to meet this growing demand. The aim of this study is to identify the influence of population growth induced by land use change and climate change on the future state of freshwater resources of Lamu Island in Kenya where a major port facility is under construction. The results of this study show that the “no industrial development” population scenario (assuming the port was not constructed) would be expected to reach ~50,000 people by 2050, while the projected population upon completion is expected to reach 1.25 million in the same year when the Lamu Port-South Sudan-Ethiopia Transport Corridor Program (LAPSSET) port reaches its full cargo-handling capacity. The groundwater abstraction in 2009 was 0.06 m³ daily per capita, while the demand is expected to raise to 0.1 m³ by 2050 according to the “LAPSSET development” projection. The modelling results show that the Shela aquifer in Lamu, which is the main source of water on the island, will not experience stress by 2065 for the “no industrial development”

population scenario, whereas for the “LAPSSET development projection” population scenario, it will occur sooner (between 2020 and 2028). The modelling results show that the Representative Concentration Pathways (RCP) climate change scenarios will have a smaller impact on the effective water volume reserves than Special Report on Emissions Scenarios (SRES) for the “no industrial development”, while the impact is expected to be similar for the “LAPSSET development”, suggesting that population growth exacerbated by land use change will be a more significant driving force than climate change in affecting freshwater availability.

Keywords: freshwater; groundwater; population growth; climate change; water stress

1. Introduction

Freshwater is a scarce resource: only 2.5% of the total water volume on Earth is freshwater, with the largest portion of it lying underground [1]. Demand for freshwater is rising with factors, such as population growth, water pollution and economic, as well as technological progress [2], demonstrated by Jevon’s paradox, which postulates that, contrary to expectations, increased (rather than decreased) water use efficiency does not necessarily lead to decreased consumption [3]. Together with land use change, a complex process affected by both natural processes and human activities [4] and climate variations, many of these factors are expected to undergo substantial changes in the near future [2]. This is bound to render freshwater availability in the future uncertain [5–7]. Water resources are therefore indisputably declining at an alarming rate all around the world [8].

Urbanization, defined as the increasing share of a nation’s population living in urban areas and, thus, a declining share living in rural areas [9], is one of the most extreme forms of human-induced land use change resulting from the intricate actions of various physical and socio-economic factors. Urbanization leads to increased pressure on freshwater resources as people become more concentrated in one area through the transformation of once natural landscapes to urban water-impervious lands, which limits available freshwater resources [4]. Urban uses currently account for an average of 10%–20% of the total water withdrawals in developing world basins, with demand increasing rapidly as a direct result of population growth in urban areas [10]. This can be attributed to the fact that most of the growth in the world’s population is taking place in urban areas in low and middle-income nations, and this is likely to continue [11].

Other than population growth, demand is also expected to be influenced by economic development and projected changes in water use efficiency as urban areas grow [12]. This is a major concern for many developing countries that have seen their economies undergo rapid transitions from rural to urban settings during the last half of the twentieth century [13], especially since the world population tripled while the use of water increased six-fold in the past century [14]. A special report by the Intergovernmental Panel on Climate Change (IPCC) [15] indicated that rapid urbanization and the growth of megacities in developing countries have led to the emergence of highly vulnerable urban communities [16]. Population growth particularly will limit the amount of water available per person, because an increase in per capita water consumption driven by development will intensify water demand, straining the local water supply [17].

Groundwater is being extensively used to supplement the available surface water in order to meet this ever-increasing water demand in the world, especially in Africa, where groundwater is a major source of drinking water. Despite this, there is little quantitative information on groundwater resources on the continent, with groundwater storage capacity being consequently omitted from freshwater availability assessment reports [18]. When considering groundwater resources in areas bordering seas, coastal aquifers are a very important source of freshwater [1,19]. Freshwater stored in coastal aquifers is particularly susceptible to degradation due to its proximity to salty seawater, as well as higher population densities of coastal zones that lead to intensive water demand [20]. Climate variations (that cause fluctuations in sea level) and groundwater pumping also impose dynamic hydrologic conditions, which are inter-related with the distribution of dissolved salts through water density-salinity relationships [21].

Freshwater resources are also susceptible to projected climate change impacts. If the observed changes in climate in the last decades persist into the future, the potential impacts on water resources are likely to increase in magnitude, diversity and severity [22,23]. Studies show that as demand for water increases across the globe, the availability of freshwater in many regions is likely to decrease because of climate change [24]. The African continent, whose countries' economies are mainly natural resource-based, has been identified as particularly susceptible to the changing climate due to its envisaged low adaptive capacity [25]. Given the already large spatial and temporal variability of climatic factors in areas such as sub-Saharan and Southern Africa [26], climate change impacts on water resource availability are likely to be more pronounced in the near future than previously foreseen [6,23].

With growing water scarcity, one thing that exacerbates the situation is the mismanagement of the available water resources [8]. Proper management of groundwater resources in the face of a changing climate and land use requires a reliable knowledge of their availability, recharge and demand [27]. The key to determining changes in groundwater systems lies in the interactions between physical and human-induced processes and need to be incorporated in the broader environmental change scenarios [5], particularly by policy makers who are concerned with the future availability of water supplies and the sustainability of water use [6]. Though it is widely accepted that the combined effects of population growth and climate change will challenge future freshwater availability, water demand driven by an amalgamation of these factors has barely been explored in coastal aquifers [4]. Therefore, for coastal aquifers to continue being used as operational freshwater reservoirs, the development of better tools that facilitate the prediction of aquifer behavior under climate change conditions and human interference is required [1,19].

The Water Resource Management Authority (WRMA) already recognizes that the main driver of challenges in the context of water resources in Kenya, particularly, is the growing population with accompanying increasing demand in goods and services, which is a good step forward [28]. Pietersen [29] corroborates Morris *et al.* [30] argument that the conventional approaches to groundwater management in developing countries need to be reassessed, as most of them presume the existence of institutional, legal and technical preliminaries that are simply not in place. Management policies and practices should be aimed at improving the human-water relationships through harmonization of the equilibrium between humans and natural water resources by recognizing the urgent need for the reversal of this negative human impact through political action at both the national and local levels [31]. Water development and management should also be based on a participatory approach, involving users, planners and policy makers at all levels [27]. Groundwater management, therefore, needs a holistic

long-term approach, supported by legislation, agreed quality standards and international finance for projects [27].

Lamu is of particular interest to coastal groundwater managers, because it is the site for a new port under the Lamu-South Sudan-Ethiopia Transport Corridor (LAPSSET) project, whose implications on groundwater need to be investigated. Its selection for the LAPSSET project is based chiefly on its location along the Kenyan coast further north of the existing port of Mombasa, placing it closer to Sudan and Ethiopia, the other stakeholders and financiers on the project. Okello *et al.* [32] were able to characterize and quantify the size of the Shela aquifer in Lamu Island (Kenya). They determined the shape and volume of the freshwater lens, the elevation of the water table and expected changes resulting from changes in recharge and sea level rise driven by climate variations for Special Report on Emissions Scenarios (SRES) A1b and A2. This study aims to build on those results by first replicating the methodology used to determine potential recharge of different future climate change scenarios, volume lost by abstraction and resultant up-coning and, finally, the effective volume of the aquifer. It goes a step further by introducing new calculations for Representative Concentration Pathways (RCP) 2.6 and 8.5 using the same methodology. It further seeks to identify the contributions of population growth (human development) in the context of these climate change scenarios to the future state of freshwater resources available on Lamu Island. The study provides the quantitative information for the Shela aquifer required to characterize the groundwater resources in useful ways that will inform adaptive strategies for growing water demand associated, not only with population growth, but also climate change [18].

2. Study Area

The Lamu Island (Figure 1) is located between Lat 2°24' S and Lat 2°34' S and between Long 40°81' E and Long 40°92' E. It has a total land surface of about 50 km². Of this, about 19 km² is covered by a double row of longitudinal sand dunes located along the entire length of the southern coastline [32]. The primary source of water for the entire island is the Shela aquifer, whose unconfined section lies underneath these sand dunes. The groundwater is extracted from a well field located on the eastern side of the aquifer that comprises 30 wells. The dunes have a height ranging from 20 to 65 m and are almost entirely covered with fine–medium-grained Pleistocene carbonate sands, as well as loamy sands and pink coral limestone sediments. The area is underlain by sand, silt and silty clay deposits, as well as by weathered to fresh corals, which are, in turn, overlaid by coral breccia. The mild dune relief combined with the good infiltration capacity of the sandy soil at the top increases the amounts of vertical recharge and prevents surface run-off [32,33]. The recent establishment and development of the beach resorts together with a strong population increase has adversely reduced the recharge area of the groundwater catchment [33].

The study area lies along the equatorial coastal climatic zone characterized by two monsoon winds. The climate is generally warm with average, unequally-distributed precipitation that varies between 550 and 1100 mm per year. There are two distinct rainy seasons; the long rain period between March and May; and the short rain period from mid-October to mid-December. The temperatures are usually high, ranging between 23 and 33 °C. The hottest months are from December to April, while the coldest are from May to July. The mean annual potential evapotranspiration is high and amounts to 2257 mm per year ([33,34], Kenya Meteorological Department (KMD)). The Lamu Island has no rivers, and

groundwater recharge is derived from local precipitation and infiltration processes. The sand dunes are the most important recharge areas and are able to store freshwater, which is harvested for domestic use [35].



Figure 1. Map showing the location of the unconfined part of the Shela aquifer under the sand dunes south of Lamu Island, Kenya (adapted and modified from [36]).

The choice of the study area was based on it being chosen as the location of a new port, which is part of the LAPSSET project; Lamu Island will experience population growth at an unprecedented rate. The assessment of its impact on the limited water resources is of utmost importance for policy makers and water resource managers. Lamu is the site for Kenya's second harbor, which is currently under construction, and is expected to increase the demand on this already overexploited freshwater source. The port is part of the LAPSSET, which also consists of a port at Manda Bay (Lamu), a railway line (from Lamu to Juba and Addis Ababa, the South Sudanese and Ethiopian capitals, respectively), a road network, oil pipelines (to South Sudan and Ethiopia), oil refinery at Bargoni, three airports (Lamu, Isiolo and Lokichogio) and three resort cities (Lamu-Mainland, Isiolo and Lake Turkana shores). The LAPSSET project is an integral part of the "Vision 2030" initiative that aims to make Kenya an industrialized country by 2030. It will radically change the landscape of the entire Lamu area from a once predominantly rural setting to a completely urban center. New jobs will be created by the project, attracting migration into the area, while the new transport systems will further open up the area to tourism among other economic activities [37].

3. Materials and Methods

A methodology for the quantification of the change of volume of the freshwater lens in the Shela aquifer through time was built by combining three different types of models, one physical and two demographic, in the context of climate change. Using these models, the total effective freshwater volumes (Table 1) in the aquifer for four different climate change scenarios—SRES A1b and A2 [23] and RCP 2.6 and 8.5 [38]—were calculated. Two future population growth patterns were also calculated: a “no industrial development” population growth trajectory based on past population growth trends; and the “LAPSSET development projection” population (Table 1) expected upon completion of the port. The two demographic models were then compared with the physical model. Expected water demand and abstraction rates were also determined in relation to past per capita demand and increased demand in the future driven by urbanization. A water stress assessment was carried out to put all results in context.

Table 1. Definitions of some terminology used throughout the study. LAPSSET, Lamu-South Sudan-Ethiopia Transport Corridor.

Terminology		
Term	Definition	Symbols
Total effective volume	The actual amount of water available in the freshwater lens of the aquifer	V_{fw}
Exploitable volume	The maximum amount of water that can be abstracted from an aquifer under prevailing economic, technological and institutional constraints and environmental conditions without causing stress on the aquifer	Ω
“no industrial development”	A theoretical situation where the port in Lamu is not constructed, there is no urbanization and the future population growth follows historical trends	N
“LAPSSET development projection”	The expected situation in Lamu once the port is completed	M

The components of the model are (see Figure 2):

(1) A physical model that quantifies the total effective volume of the freshwater lens of the Shela aquifer following its natural evolution without any abstraction, which is dependent on the annual climate variables and is independent of any anthropogenic interference:

$$V_{fw} = f(w, R, K, G, L) \quad (1)$$

where V_{fw} (theoretical initial total effective volume of the freshwater lens) is a function of potential recharge w , aquifer width R , hydraulic conductivity K , the density ratio of fresh and saltwater G and the longitudinal length of the aquifer L [32].

The permanent freshwater volume of the aquifer was calculated for every subsequent year after 1955 using the formula in Equation (2):

$$V_{fwi+1} = V_{store} \pm \Delta W_i \quad (2)$$

where V_{fwi+1} is the final effective volume (permanent + temporary) volume, V_{store} is the stored volume from previous years and ΔW_i is the difference between V_i and V_{store} ; where $i = 1955, 1956, 1957 \dots 2065$.

In this model, we assume that, in any given year, the temporary change in aquifer reserves is limited to 10% of the previous year's aquifer total reserves, while the remaining 90% is permanent. Therefore, if ΔW_i were greater than or equal to 10% of V_i for any given year, it was added to the V_{store} to get the effective volume for that year. Conversely, if ΔW_i were smaller than 10% of V_i for any given year, the V_{store} became the effective volume for that year. This assumption is based on analytical transitory flow solutions for unconfined aquifers (see the formulas reported by Kresic (2005) page 90–92 [39]) that show how the decay of hydraulic head accumulated by recharge in a coastal aquifer over a time period of one year (an aquifer with the geologic and geometric characteristics of that under examination) cannot cause a change in aquifer volume larger than 10%, because of the time delay it takes for recharge water to flow to sea.

The year 1955 was used as the reference year for all volumetric calculations, as it represents the beginning of exploitation in the Shela aquifer.

(2) Demographic models that quantify the anthropogenic influence, *i.e.*, the current population and expected changes, as well the impacts of population growth on water demand, abstraction rates and, ultimately, the effective volume of the freshwater lens [32]:

$$V_{fwi} = V_{fw} - V_{absi} - V_{swi} + V_{store} \quad (3)$$

where V_{fwi} is the total effective volume for a given year i in response to abstraction V_{absi} and resultant saltwater intrusion caused by up-coning V_{swi} ; where $i = 1955, 1956, 1957 \dots 2065$.

Abstraction V_{absi} is a function of population and water demand:

$$V_{absi} = f(N, Pcd) \quad (4)$$

with:

$$N = N_0 \cdot e^{\alpha t} \quad (5)$$

where N_0 is the initial population, N is the expected population, α is the rate of population change based on past population growth rates and t is the elapsed time (in years).

Additionally:

$$Pcd = Pcd_0 \cdot e^{\beta t} \quad (6)$$

where Pcd is the expected annual per capita demand, Pcd_0 is the initial annual per capita demand, β is the rate of per capita demand change, an exponent that is obtained by inverting the exponential relationship to fit per capita demand in the year 2065 and t is the elapsed time (in years). The per capita demand of water follows an exponential relationship based on the initial demand in 2009 and that expected in 2065. The use of an exponential growth rate was based on the assertion by Kremer [40] that an increase in population would lead to an increase in technological change, driving water increase demand at a similar rate.

Whereas, volume lost to saltwater intrusion V_{swi} is a function of abstraction as computed by Okello *et al.* [32]:

$$V_{swi} = f(V_{absi}) \quad (7)$$

The reference year for the demographic models was 2009, as the most recent official population data was from the official census carried out that year by the Kenya National Bureau of Statistics (KNBS).

The abstraction rate of 2009 according to data obtained from Lamu Water and Sewage Company (LAWASCO) was used as the base for this study.

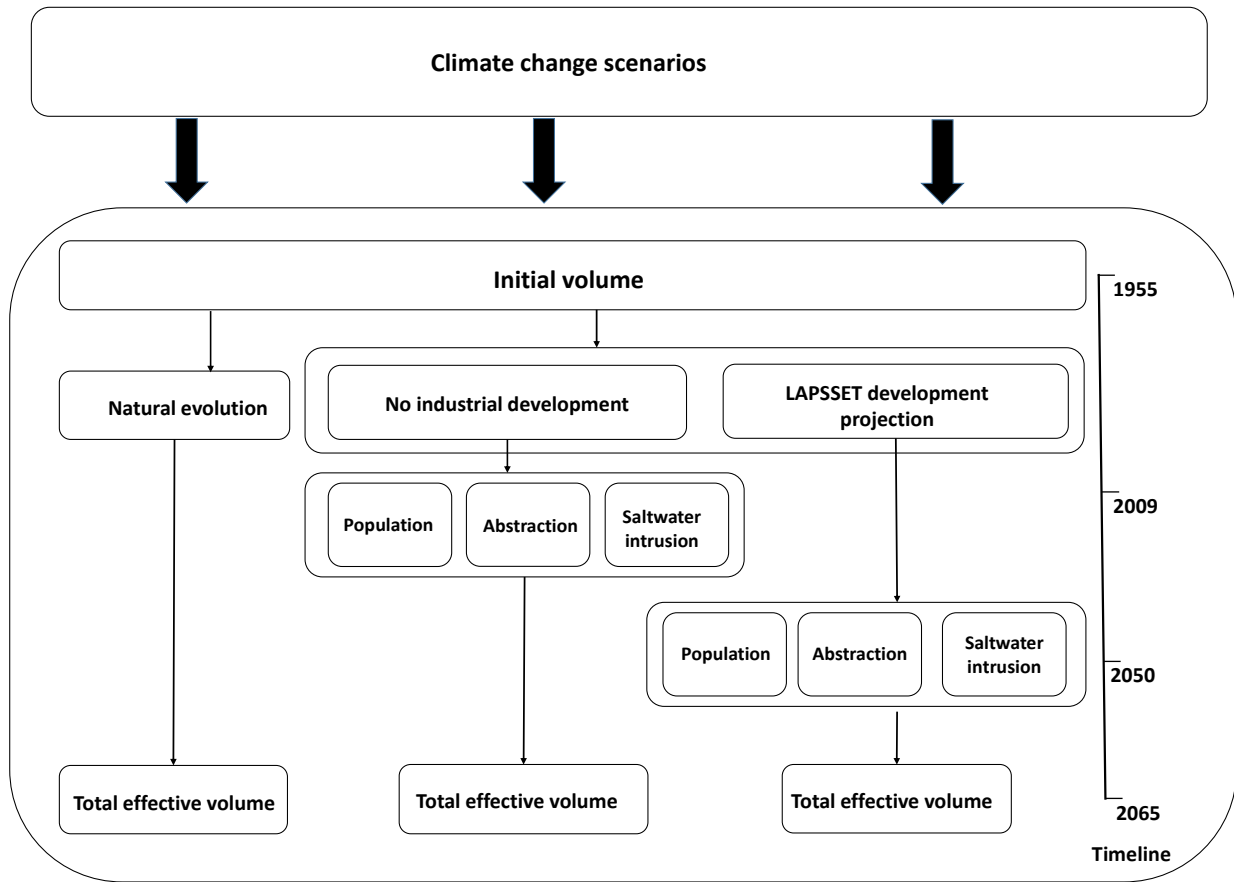


Figure 2. Graphic representation of the physical and two demographic models in the context of different climate change scenarios.

3.1. Future Population Growth Projections

A “no industrial development” scenario to establish the prevailing anthropogenic influence on the aquifer where Lamu maintains the same level of development (the port is not constructed, there is no urbanization and the population growth follows historical trends) was investigated. This was done in order to highlight the impact that the port would have on the population dynamics and subsequent demand and abstraction rates. The “no industrial development” population growth N was calculated using past data from KNBS and its future population growth based on past trends calculated using the law of growth equation (Equation (5)) [41].

With the construction of the port already well underway, the population growth estimates (denoted by M) for the “LAPSSET development projection” were carried out by the Government of Kenya through the Ministry of Transport as part of the feasibility assessment of the LAPSSET project. This was done by establishing the growth ratio correlation between port cargo volume and population increase in Mombasa (a port city ~240 km southwest of Lamu). This correlation (growth ratio) was used as a base to extrapolate possible future population growth for Lamu, as both Mombasa and Lamu are largely similar port cities (Table 2) [42].

Table 2. Correlation between port cargo volume and population in Mombasa and the projection of port cargo volume and population in Lamu based on the growth rate ratio of the Mombasa port. The growth ratio is the rate of change of cargo volume and populations over time.

Cargo Volume/Population	Mombasa		Growth Ratio	Lamu		Growth Ratio
	Year			Year		
	1980	2009		2009	2050	
Cargo Volume (tons)	7,800,000	19,062,000	2.43	0	24,000,000	2.43
Population (persons)	400,000	1,000,000	2.5	~25,000 (census)	1,250,000 (projected)	2.5

Both *N* and *M* were used in Equation (4) to calculate the abstraction rate of both projected scenarios where *N* was used to calculate for “no industrial development” while *M* was substituted for *N* in the equation to calculate for “LAPSSET development projection”.

3.2. Estimating Future Water Demand

Initial annual per capita water demand Pcd_0 for the reference year (2009) was determined by multiplying the daily per capita demand statistics (0.06 m^3) obtained from LAWASCO with the number of days in a year (365) to obtain the annual demand.

As land use is expected to change and Lamu becomes urbanized, it was assumed that the water demand would eventually rise to be as high as other urban areas in Kenya upon completion of the port. This future per capita daily demand was extrapolated from current demand of two of Kenya’s biggest metropolises, Nairobi and Mombasa, found within the Athi catchment. The daily domestic demand of both Mombasa and Nairobi were calculated by dividing the total domestic demand (Pcd_{tu}) of the catchment area that totaled 316 million m^3 by the total population of the catchment (N_u), 8.5 million people [42]:

$$Pcd_{2065} = Pcd_{tu}/N_u \tag{8}$$

where Pcd_{2065} is the projected future daily per capita demand (0.1 m^3).

An exponential growth equation for the per capita demand between 2009 and 2065 was constructed by inverting the exponential relationship to fit Pcd_{2065} to obtain β (0.003%) in Equation (5).

(3) The physical and demographic models were run considering past climate conditions, as well as different future climate change scenarios to assess the effect exerted on the aforementioned physical and demographic models (Equations (1) and (2)), with the value of recharge *w* expected to vary with each climate change scenario:

$$w = f(P, T, PET) \tag{9}$$

where *w* is a function of temperature, *T*, precipitation, *P* and potential evapotranspiration (PET). PET is calculated using the Thornwaite [43] method and climate data provided by the Kenya Meteorological Department (KMD) for the past, present and future estimates from the [37] report as highlighted by Okello *et al.* [32].

3.3. Climate Change Scenarios

In the past, several sets of scenarios have been used as a basis for assessment of possible climate impacts and mitigation options and associated costs, including the scenarios from the Special Report on Emission Scenarios (SRES) [44,45]. When the SRES needed updating, the scientific community was commissioned to develop a new set of scenarios [23]. The scenario development process aimed to develop a set of new scenarios that facilitated integrated analysis of climate change across the main scientific communities [46]. This led to the introduction of the Representative Concentration Pathways (RCPs). The new climate change scenarios are classified as follows: RCP 8.5 is considered a high emission, highly energy-intensive scenario as a result of high population growth and a lower rate of technology development [44]. It was based on a revised version of the SRES A2 scenario, where the storyline emphasizes high population growth and lower incomes in developing countries. The RCP 2.6 is the lowest emission and radiative forcing scenario representative of mitigation measures aiming to limit the increase of global mean temperature to 2 °C [47].

This study concentrates on the two extreme RCPs, 2.6 and 8.5, selected to explore the entire range of RCP scenario variations and compared with emissions-based SRES A1b and A2. Projected seasonal temperature and precipitation changes for the SRES scenarios were downscaled from global averages to local level estimates by McSweeney *et al.* [48] regional climate model for Kenya using statistical downscaling [49]. The RCPs are yet to be downscaled to the local level; therefore, the regional-scale climate information from IPCC [37] was used. Although such information can be obtained directly from global models their horizontal resolution was often found to be too low to resolve features that are important at regional scales. High-resolution atmospheric global climate models (AGCMs), variable-resolution global models and statistical and dynamical downscaling (*i.e.*, regional climate modelling applied to a limited area) were used to complement coupled atmosphere-ocean global climate models (AOGCMs), as well as to generate region-specific climate information for the RCPs [37]. Climate data provided by KMD were used to calculate a monthly average for ten-year time series (2000–2009). The climate data were grouped into seasons in compliance with the future predictions and the percentage of seasonal variation calculated. These percentages were then applied to the individual months to get the expected monthly changes in the future (2021–2030 and 2051–2060). Monthly averages for these time series were calculated from existing climate data provided by KMD. Projected changes in average monthly temperature and precipitation up to 2100 were derived from IPCC [36] and used to calculate expected values for 2016–2035 and 2046–2065 time series.

According to McSweeney *et al.* [48], the average temperature is expected to increase annually by 1.2 °C for the 2021–2030 time period in both SRES A1b and A2 scenarios. For the 2051–2060 decade, it is expected to increase by an annual average of 2.3 and 2.4 °C for A1b and A2, respectively. For the RCP 2.6 scenario, the temperature increase projected by IPCC (2013) [37] is 0.3 °C for 2016–2035 and 1 °C for 2046–2065, while the RCP 8.5 temperature is projected to increase by 0.7 °C and 2 °C for the same time period. The precipitation is expected to increase annually by 4 and 3 mm on average for the 2021–2030 time period in both SRES A1b and A2 scenarios, respectively. For the 2051–2060 decade, it is expected to increase by an annual average of 7 mm for A1b and 5 mm for A2 [48]. For the RCP 2.6 scenario, the IPCC (2013) projects a 0.6% increase in precipitation for 2016–2035 and 2% for

2046–2065, while the RCP 8.5 precipitation is projected to increase by 3.5% and 10% for the same time period 4.

3.4. Uncertainties

The uncertainties of the models were taken into consideration by determining the linear regression of the effective volumes of the scenarios and the equations of the determined lines (Equation (10)). The standard deviation (95% confidence) was then calculated. The upper and lower bounds were calculated by adding and subtracting (Equation (10)) the standard deviation from the equations of the linear regressions, respectively. Below is an example of the methodology for the physical model up to 2009 based on available climate data (Figure 3).

$$y = (-0.0082x + 18.43) \pm \sigma \tag{10}$$

where σ is the standard deviation.

The above calculations were replicated for all models.

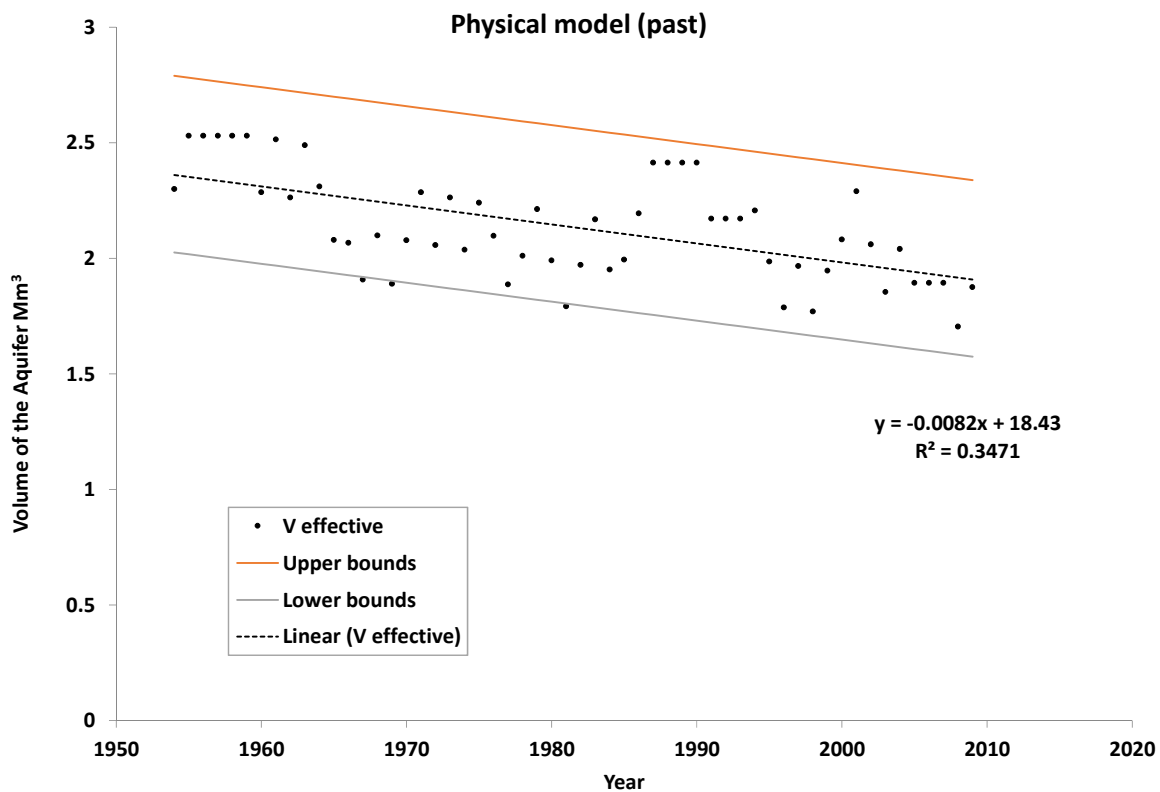


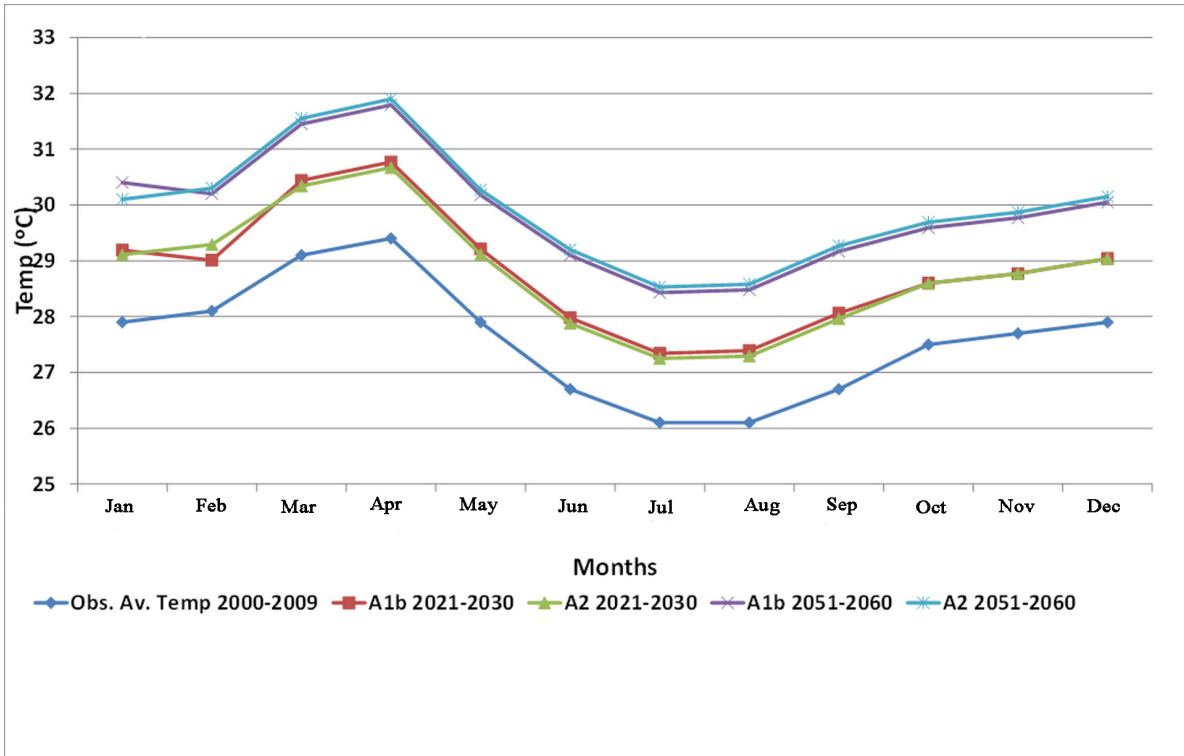
Figure 3. A graphical representation of the physical model based on past data with the uncertainties represented.

4. Results

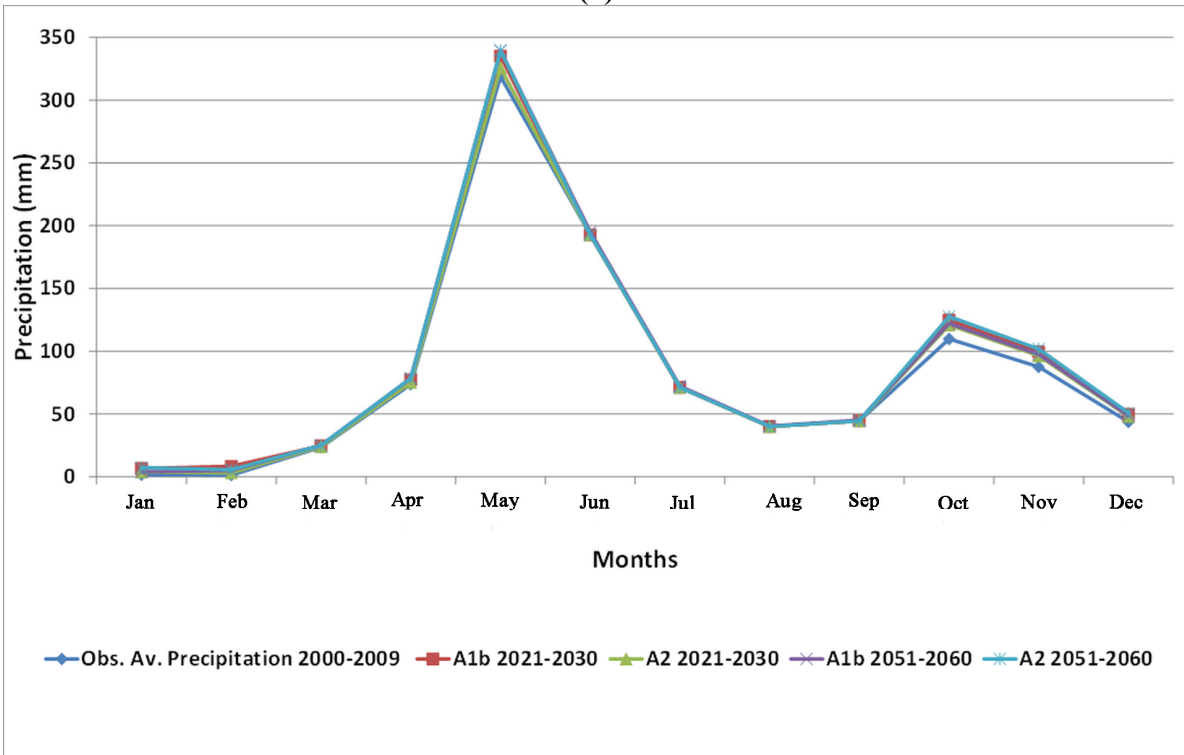
4.1. Climate Change Scenarios

A summary of the monthly temperature and precipitation value expected results for Special Report on Emission Scenarios (SRES) A1b and A2 scenarios for the near-term (2021–2030) and long-term (2051–2060) time series are presented in Table 2, and the monthly values of the same for Representative

Concentration Pathways (RCPs) 2.6 and 8.6 for the near-term (2016–2035) and long-term (2046–2065) times series are presented in Figure 4a–d.

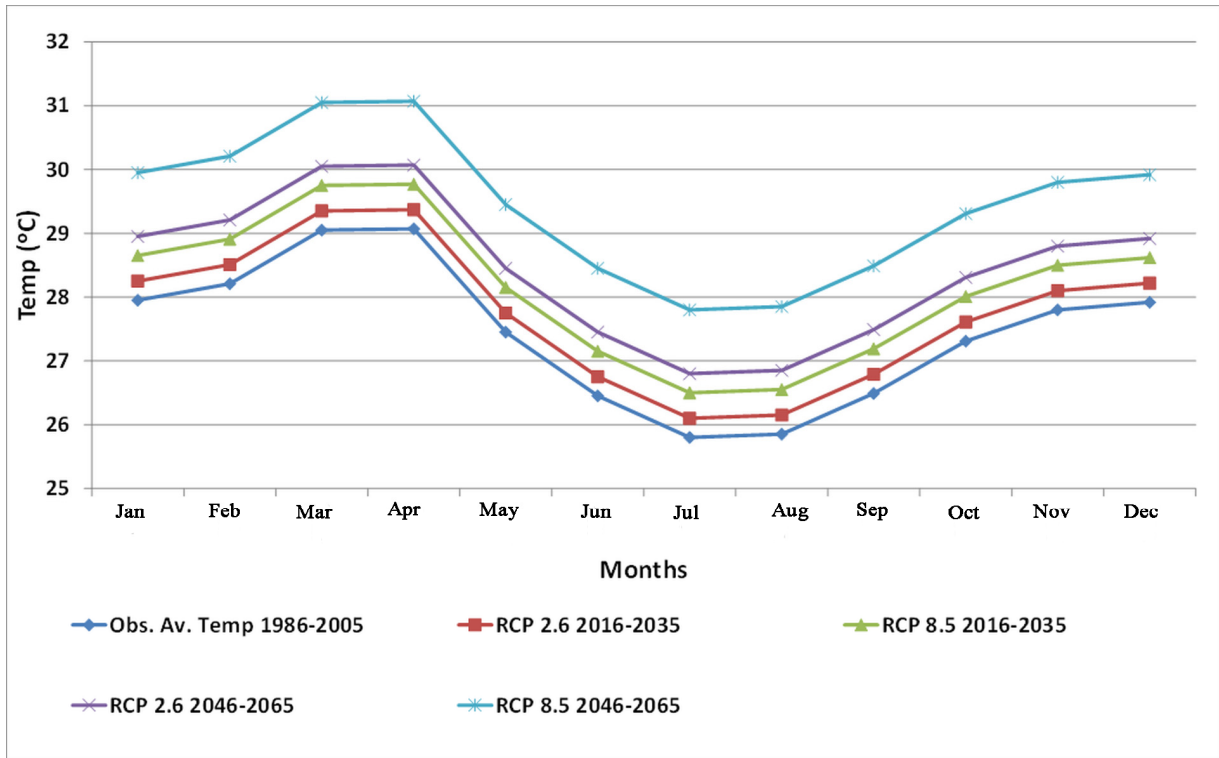


(a)

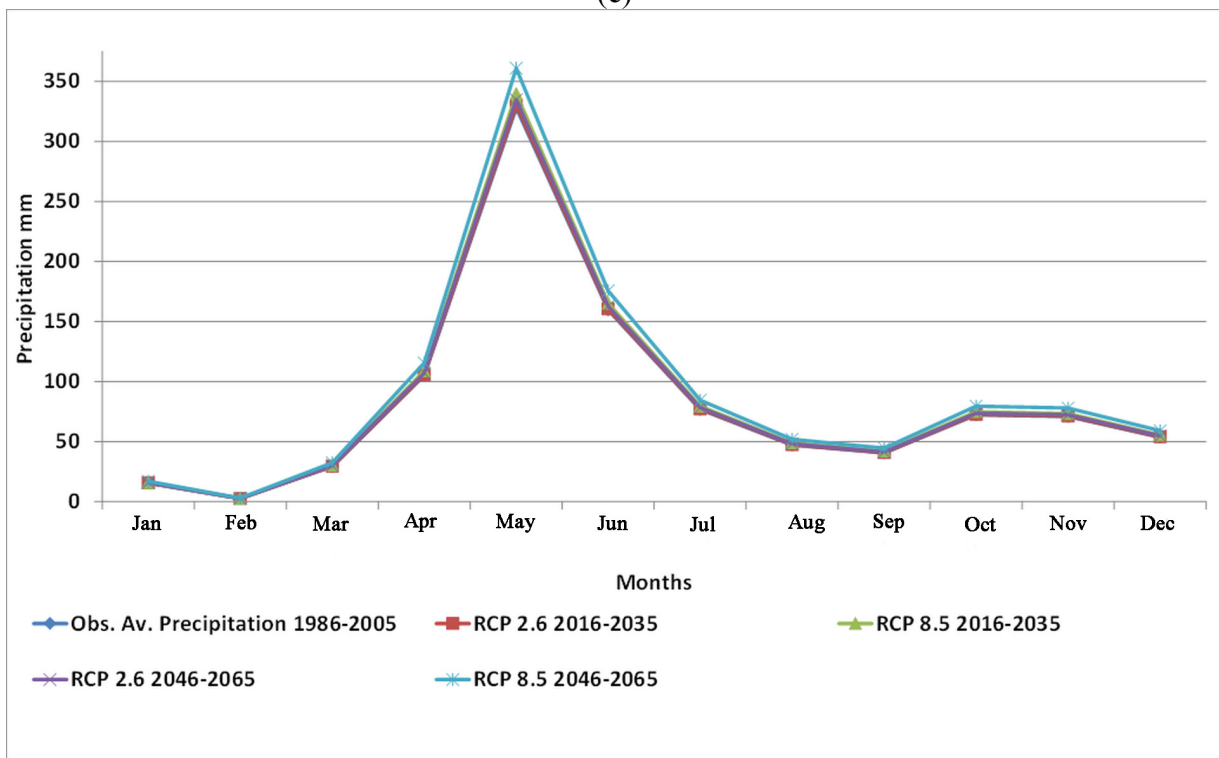


(b)

Figure 4. Cont.



(c)



(d)

Figure 4. (a,b) Monthly temperature and precipitation projections for Special Report on Emissions Scenarios (SRES) A1b and A2 for 2031–2030 and 2051–2060 based on McSweeney’s [48] estimated changes and KMD climate data for 2000–2009; as well as (c,d) monthly temperature projections for Representative Concentration Pathways (RCP) 2.6 and 8.5 for 2016–2035 and 2046–2065 based on IPCC [38] estimated changes and Kenya Meteorological Department (KMD) climate data for 1986–2005.

4.2. Physical Model

The total effective freshwater volume (V_{fw}) for the Shela aquifer from 1955 to 2009 ranges from 1.57 to 2.78 Mm^3 , averaging $2.1 \times 10^7 m^3$. The volume for all four climate change scenarios for up to 2065 does not vary greatly from these values, ranging from 0.9 to 2.2 Mm^3 (Figure 5).

Comparatively, the RCPs scenarios are expected to impact less on the freshwater volume than the SRES scenarios, as demonstrated by the results showing larger volume sizes for the RCPs (1.3–2.2 Mm^3 by 2065), as opposed to the smaller SRES volumes of 0.9–2.0 Mm^3 by 2060 (Figures 6 and 7).

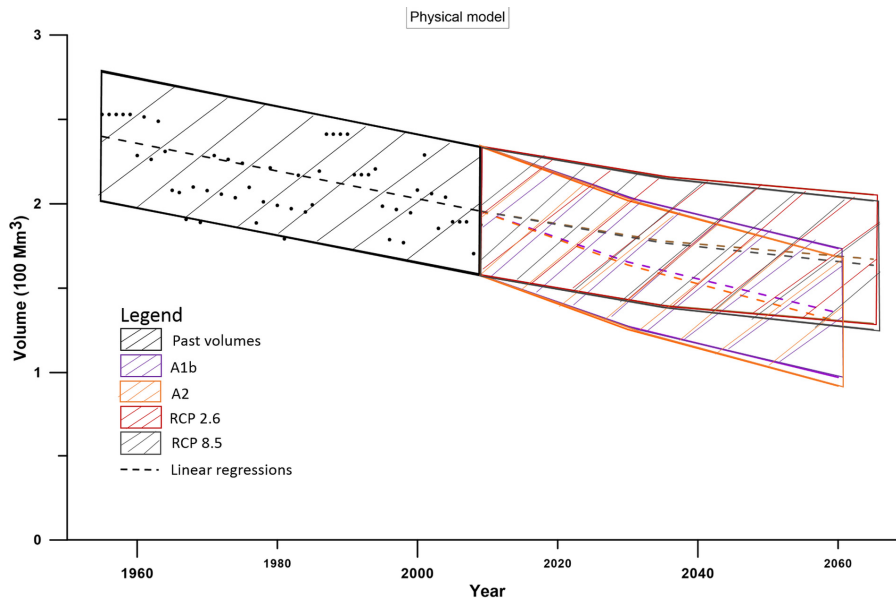


Figure 5. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for all four climate change scenarios, as well as the uncertainties.

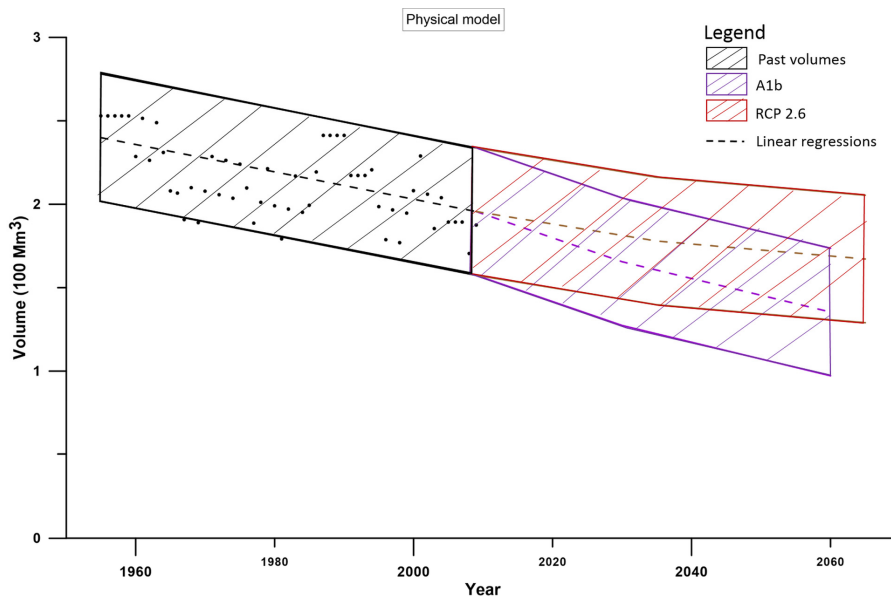


Figure 6. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A1b and RCP 2.6 climate change scenarios, as well as the uncertainties.

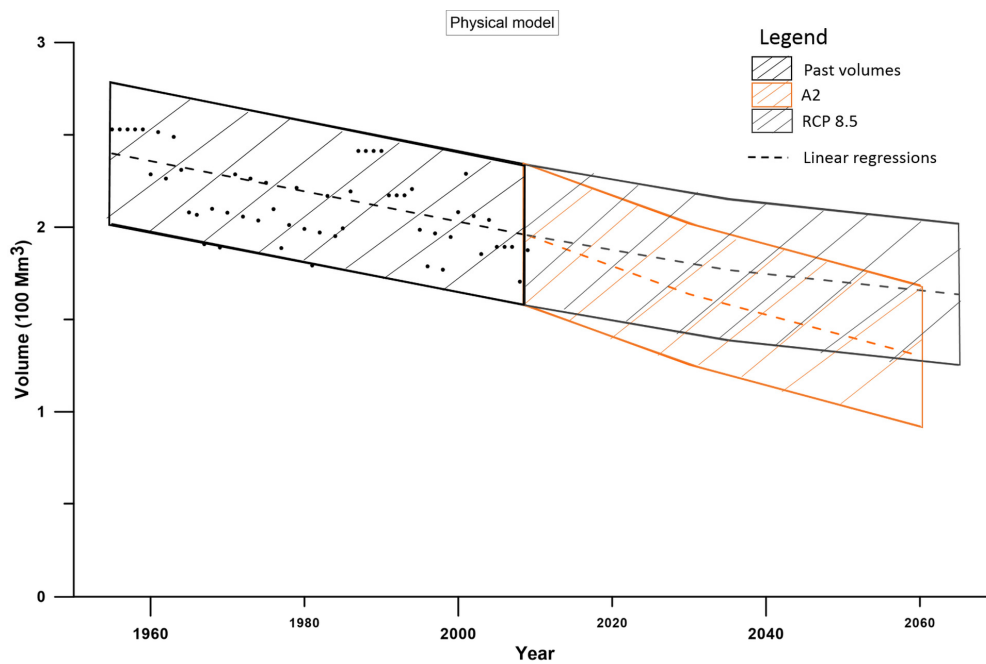


Figure 7. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A2 and RCP 8.5 climate change scenarios, as well as the uncertainties.

4.3. Demographic Model

The population of Lamu stood at 22,336 according to the results of the last census carried out in 2009 (KNBS). Further analysis of statistics from the past provided by KNBS show that the population had grown at an annual rate of 2.8% since 1969. In the event that the same level of infrastructural development in Lamu prevails in the foreseeable future, this average yearly population growth rate can be assumed to continue into the future. At this rate, the population will be ~50,000 in 2065. This represents the value of the “no industrial development” population growth, N , which is significantly less than the “LAPSSET development” projected population, M , which is expected to peak at 1.25 million in 2050 (Figure 8).

According to data for 2009 obtained from LAWASCO, the abstraction rate for the Lamu well field was 26 m^3 per capita, annually translating to $\sim 0.06 \text{ m}^3$ a day per capita, Pcd_0 . The same per capita demand is expected to be maintained for the “no industrial development” population, while the per capita demand for the projected population growth, Pcd_{2065} , would increase to 0.1 m^3 . While the total volume of freshwater needed daily to satisfy demand in 2009 is 1340 m^3 , it would be expected to increase to $\sim 2580 \text{ m}^3$ for the “no industrial development” population and $125,000 \text{ m}^3$ for the “LAPSSET development” projected population by 2065.

The total effective volumes for all four climate change scenarios in response to abstraction (V_{fwi}) in the case of “no industrial development” are expected to range from ~ 0.7 to 2.0 Mm^3 , as shown by the results (Figure 9). These volumes, as expected, are lower than those of the physical model, highlighting the effects of abstraction on the freshwater volume.

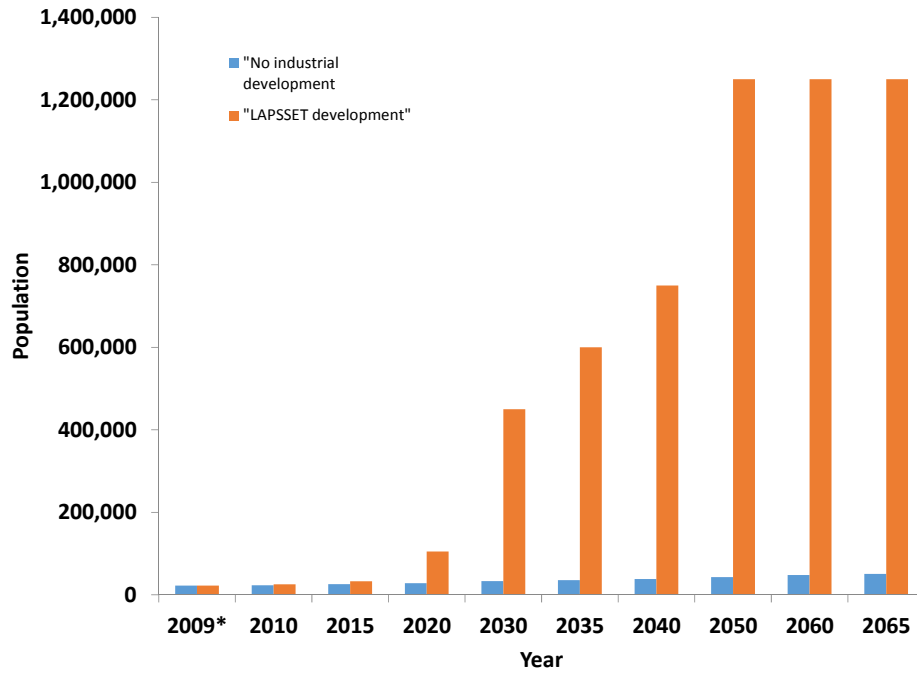


Figure 8. Graph showing the “no industrial development” and “LAPSSET development” projected population growth of Lamu Island against time (years) up to 2050. * 2009 population is official population data from the Population Census Report [50].

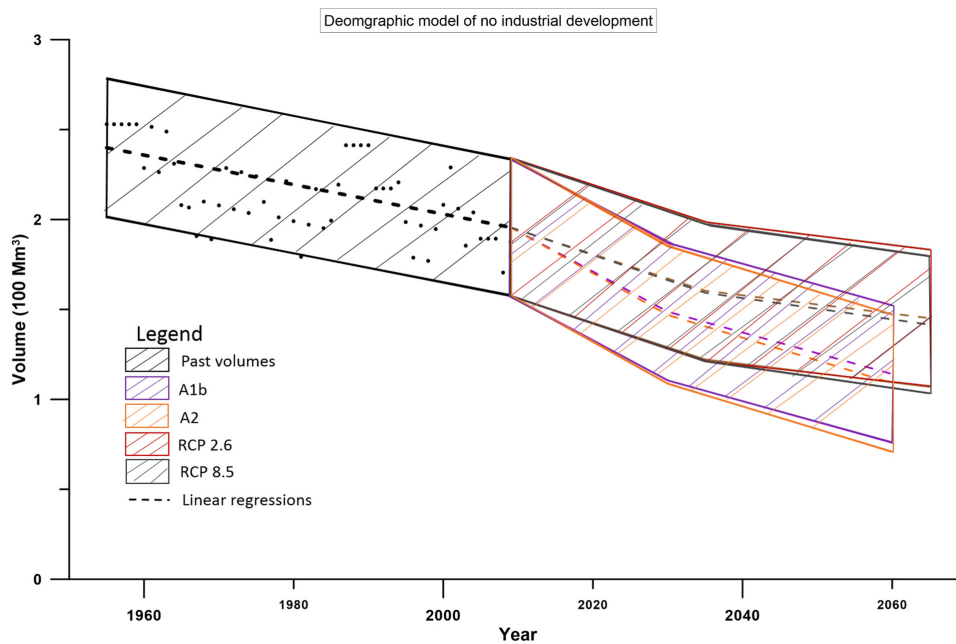


Figure 9. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for all four climate change scenarios, as well as the uncertainties for the demographic model without the port (“no industrial development”).

The freshwater volumes for the RCPs scenarios are expected to range from 1.0 to 1.8 Mm³ in 2065 compared to the smaller SRES volumes of 0.7 to 1.5 Mm³ in 2060 (highlighted in Figures 10 and 11).

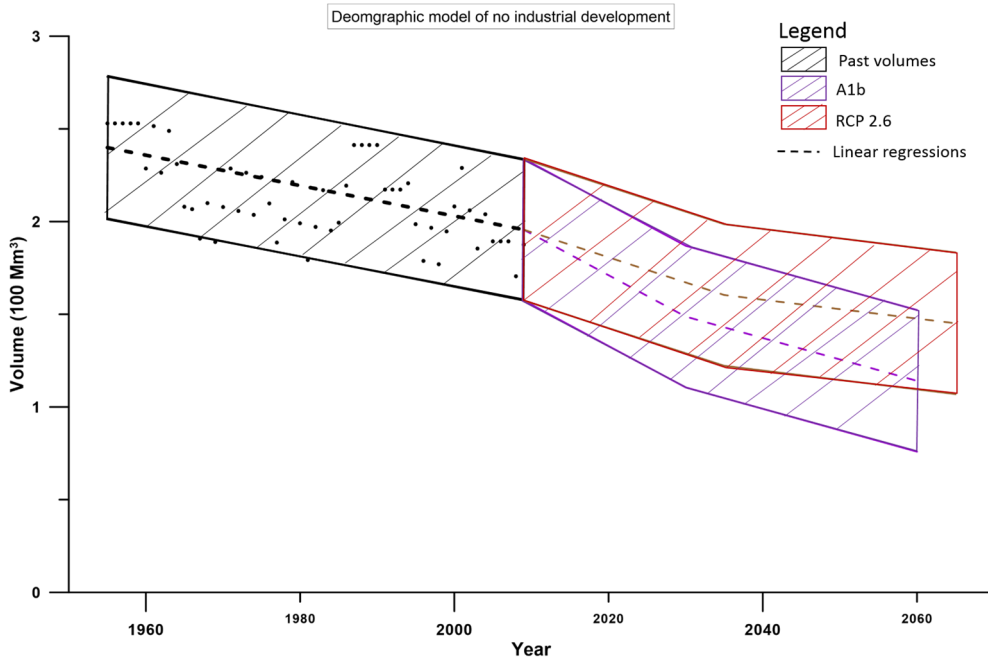


Figure 10. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A1b and RCP 2.6 climate change scenarios, as well as the uncertainties for the demographic model without the port (“no industrial development”).

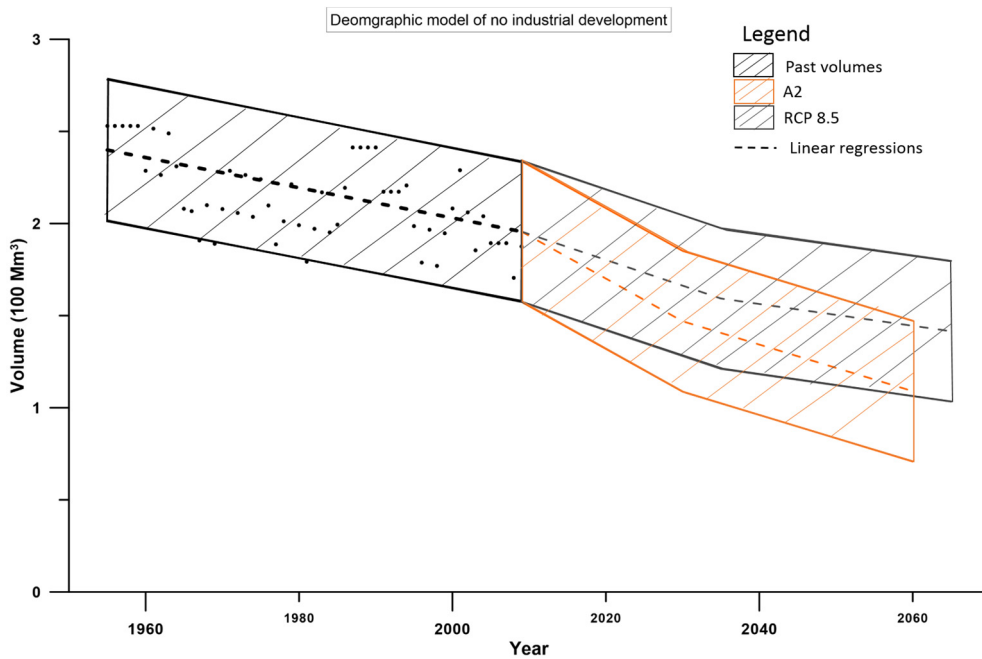


Figure 11. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A2 and RCP 8.5 climate change scenarios, as well as the uncertainties for the demographic model without the port (“no industrial development”).

In the case where the port is completed in time and becomes operational by 2030 (“LAPSET development” projected population), the volume for all four climate change scenarios again varied considerably from the initial volume, showing a great reduction in volume size (Figure 12).

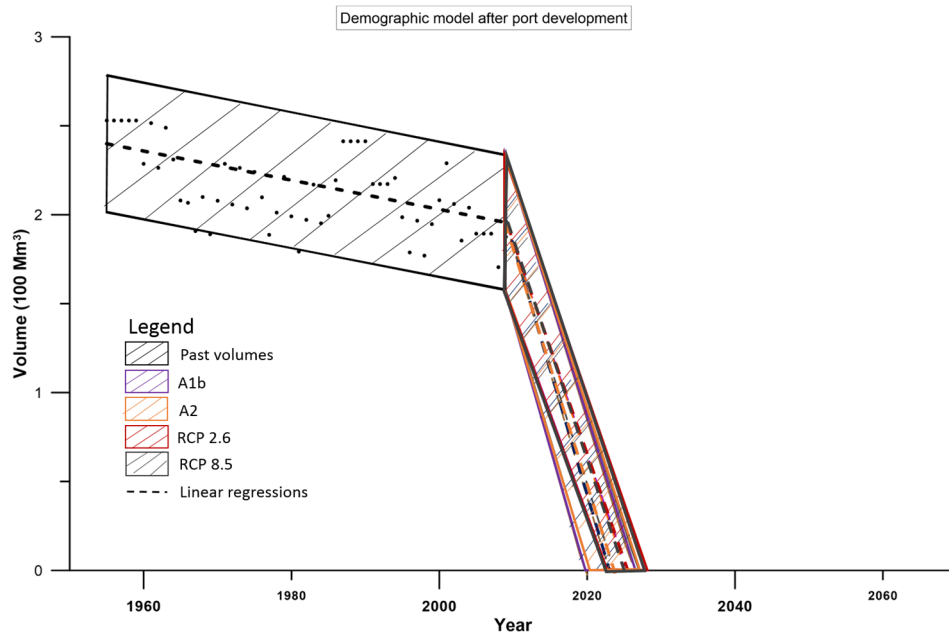


Figure 12. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for all four climate change scenarios, as well as the uncertainties for the demographic model with the port construction completed (“LAPSSET development projected”).

The results dramatically show that the effective volume of freshwater in the aquifer is expected to be exhausted, *i.e.*, be reduced to the zero level, in all climate change scenarios between 2020 and 2028. The freshwater volumes are expected to be exhausted between 2020 and 2026 for the A1b scenario, 2021–2027 for the A2 scenario, 2022–2027 for the RCP 2.6 scenario and 2023–2028 for the RCP 8.5 (highlighted in Figures 13 and 14).

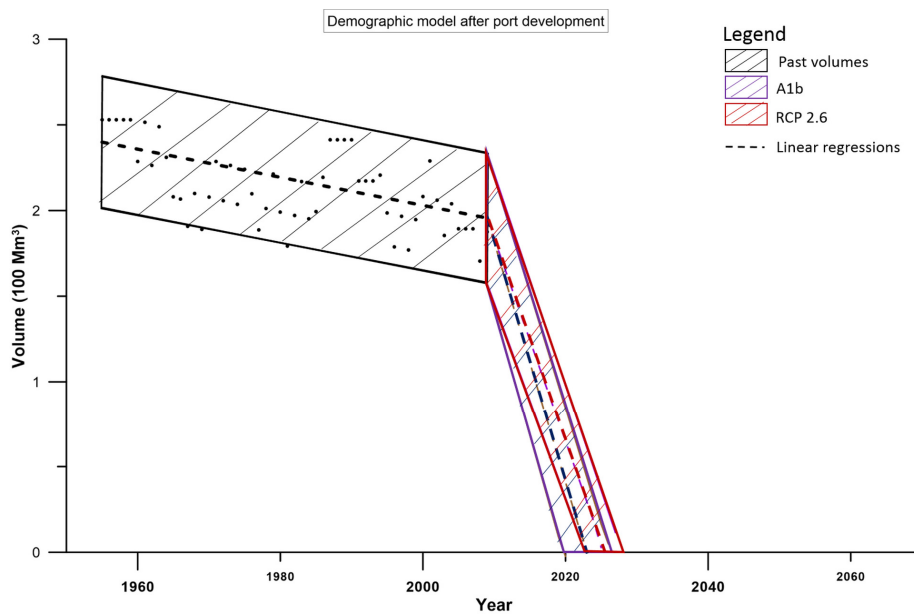


Figure 13. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A1b and RCP 2.6 climate change scenarios, as well as the uncertainties for the demographic model with the port construction completed (“LAPSSET development”).

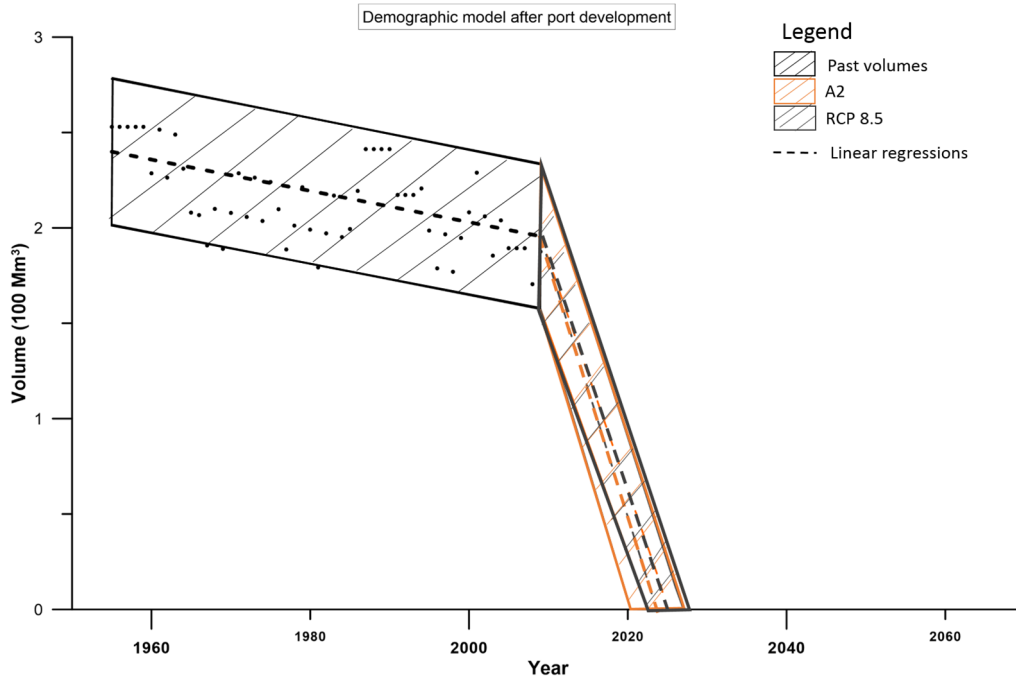


Figure 14. Graph, with the shaded areas representing the effective volume of Shela aquifer and projected volumes for A2 and RCP 8.5 climate change scenarios, as well as the uncertainties for the demographic model with the port construction completed (“LAPSSSET development”).

The evolution of the aquifer’s volumes for the near and long term are summarized in Figure 15.

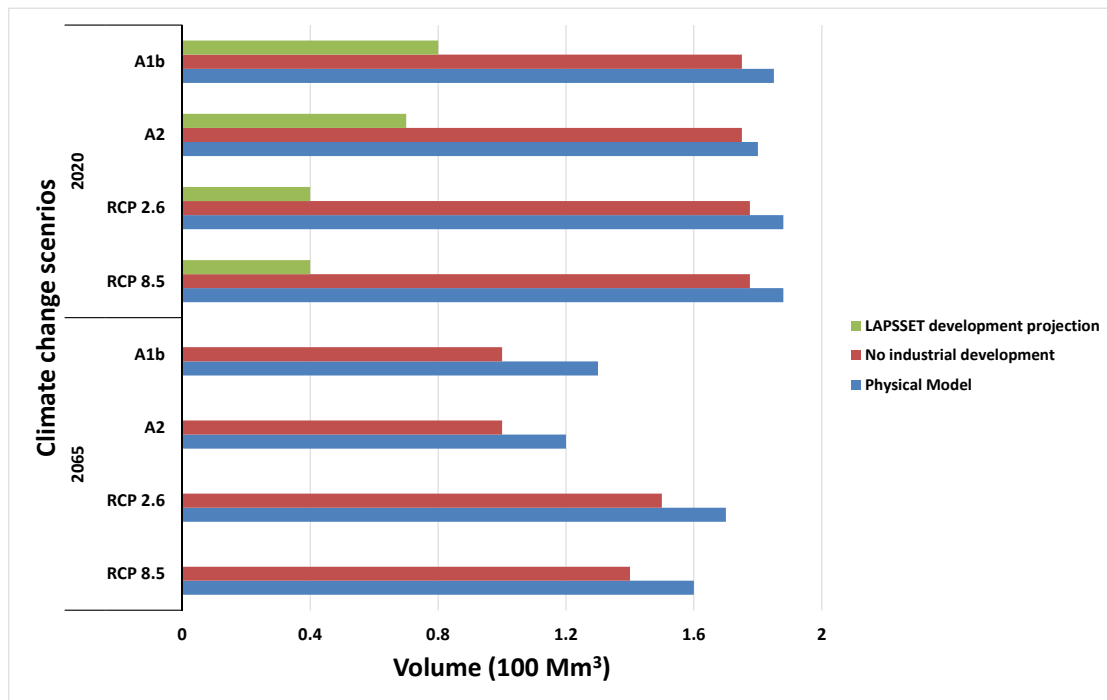


Figure 15. Graphical summary of the results in terms of water volumes vs. climate change scenarios for the near future (2020) and the long term (2065). The results highlight the complete depletion of the aquifer for the demographic model with the port completed (“LAPSSSET development”).

5. Discussion

The population of Lamu by 2009 was considerably low due to underdevelopment, *i.e.*, the prevailing rural conditions of the area. This can be attributed to Lamu Island (and the district as a whole) being fairly isolated from the rest of Kenya, primarily because of poor transport infrastructure. However, with the establishment of the new port and ensuing developments, the population is expected to increase at an unprecedented rate (Figure 8). The creation of employment opportunities and the expected high migration flux into Lamu will translate into high population growth that has yet to be experienced anywhere else in the country [37]. Population growth is expected to impact freshwater availability: as the population grows, overall demand for water will increase (as domestic demand for water is determined by demographic factors), and pressure on the Shela aquifer will intensify. Increased abstraction from the Shela aquifer to meet growing demands will lead to increased sea water up-coning, salinization and overall degradation of the water quality [32]. Therefore, a population increase of up to 1.25 million people by 2050, which represents a ~5500% increase, is bound to destroy the aquifer, thereby completely exhausting the Lamu groundwater resources.

The amount of water each person uses is also expected to increase as income grows and consumption increases [51]. It is worth pointing out that population growth will lead to an increase in the total demand of water, whether or not the per capita demand increases. The results of this study demonstrate this by indicating that the total demand by 2065 is expected to be greater than that of 2009 for the “no industrial development” model. An effect on the abstraction rate will therefore be experienced as more freshwater is needed to satisfy increasing demand. Moreover, with land use expected to change from rural to urban upon completion of the LAPSSSET project, per capita water demand is bound to increase chiefly because urban populations tend to have a higher domestic per capita water demand [52]. As Lamu moves from a more rural setting and turns into a metropolis, it is expected that this trend of increasing freshwater demand should be followed; the per capita demand will almost double according to the results. The expected impact of this is a much greater total demand of water for the “LAPSSSET development” projected population than what would have been expected for the “no industrial development” population growth, further lending evidence of the impact of population growth. Given that this is an aquifer located on a coastal island, the problem is further compounded by the threat of salinization. Increased pumping to meet growing demand would lead to more up-coning, forcing sea water into the freshwater lens and further degrading the water quality [53,54].

The results of this study further show that the RCP scenarios have lesser impacts on the aquifer size than the SRES, as demonstrated by overall larger freshwater volumes of the RCPs (Figures 5–15). This is chiefly because, unlike SRES, RCPs possess inherent mitigation scenarios and climate policy, making them more representative of the full range of possible emission developments [47]. Water demand based on population growth for both the “no industrial development” and “LAPSSSET development projected” scenarios was applied to these climate change scenarios to further determine the impact that population-driven abstraction would have on the effective volume (by juxtaposing the results against those of the physical model). The effective volume of the physical model for all climate change scenarios was well within the range of the initial volume, not veering too far away from the average (Figures 4–6). However, both demographic models demonstrated a reduction in the total volume, with some of their volumes going to zero, suggesting complete exhaustion of the freshwater lens.

The “no industrial development” model was found to have a lesser impact on the effective volume than the “LAPSSET development” projected population across all four climate change scenarios. Furthermore, the results indicate that under the “no industrial development” scenario, the Shela aquifer would serve the residents of Lamu Island as a freshwater reservoir for longer before getting stressed by the overexploitation and subsequent salinization. These suggest that a low, consistent increase in the number of inhabitants will have a smaller impact on the groundwater resources as opposed to the rapid projected population growth that is expected once the port construction is concluded (“LAPSSET development projected”). This serves as evidence that the port and the resultant population growth will contribute greatly to the stressing of the Shela aquifer. This has also been witnessed in arid and semi-arid regions around the world, the same agro-climatic zone that Lamu falls under, where the increased use of groundwater has led to the overexploitation of groundwater resources, mostly causing water tables to drop at an alarming rate, often 1–3 m a year [14].

A review of these results suggests that increased population growth will be the strongest driver in the future, regardless of the climate change scenarios modelled, especially for a coastal aquifer like the one in Lamu. This implies that, as much as climate change impacts the recharge rate, the impact is dwarfed by the effect of demand driven chiefly by population growth, *i.e.*, that population growth particularly influenced by the construction of a new port and consequent urbanization will be a more significant driving force that will affect the availability of freshwater than climate change. This is unlike some studies that consider climate change as the main driving force affecting both the temporal and spatial variability of water availability [6]. According to [8], a possible explanation for the difference between this study’s results and that of Gain and Wada [6] is that: (1) Lamu will be entering the stage of evolution of human-water relationship where human development is seen to negatively affect the environment causing the relationship between human and water to become increasingly hostile; and (2) like all coastal aquifers, effects of water abstraction are more dire in Lamu due to the resultant up-coning and saltwater intrusion [19,53]. However, this does not completely negate the impact of climate change. It merely suggests that in Lamu, population growth will have a greater impact, regardless of the differences in climate change scenarios.

The National Development Plan (2002–2008) [55] recognized Kenya as a water-scarce country, whereby the water demand exceeded renewable freshwater sources. The total national water withdrawal was estimated to be just over 2.7 km³ by the year 2000, while the demand was projected to increase to 5.8 km³ by the year 2010. On Lamu Island, the average annual abstraction for the years 2008 to 2012 was 574,089 m³, which exceeds the annual demand of 489,815 m³ (calculated from raw data provided by LAWASCO). This is set to change in the next 15 to 35 years, as demonstrated by the results of this study. Currently, groundwater issues are addressed through the same frameworks as for surface water [56]. New water management policies that take into consideration these expected changes in population, increased demand and abstraction and their contribution to salinization of coastal aquifers, as well as changing climate should be formulated and implemented in order to conserve the Shela aquifer’s status as a freshwater reservoir.

While the results demonstrate that stress will be expected to be experienced as early as 2020, the feasibility study carried out for the LAPSSET project recommends long-term mitigation measures to be implemented from 2030 and beyond, a whole decade after stress is expected to be experienced. The three most feasible solutions for the long-term water supply opportunities suggested are:

(1) conveying water from the Tana River delta; (2) obtaining water from the High Grand Falls Dam (HGFD) project with an uptake at the Nanighi Barrage (weir) and pumping to Lamu, which is approximately 185 km away; and (3) desalination of sea water. The second option has been considered most suitable, and a pipeline system (of a yet to be determined volume of water) is designed as part of the LAPSET project's master plan [37]. However, this plan does not address the water scarcity between 2020 and 2030, when, according to the results of this study, the water resources are expected to be initially stressed. Mitigation and management measures therefore need to be in place before the year suggested by the feasibility study.

The best solutions that can be put in place to deal with water stress and shortage are: to maximize the efficiency of water management, reuse, desalinate or import [27]. Importing water from a secondary location is also another feasible option to offset the increasing demand. These measures can be used to either offset the domestic demand, therefore reducing abstraction from the aquifer, or to artificially recharge the freshwater lens, or both [27]. Reuse and sea water desalination can cost less than groundwater or imported water, depending on the groundwater pumping costs [17]. A number of sea water desalination technologies have been developed during the last several decades to augment the supply of water in water-scarce regions of the world. However, due to the constraints of high desalination costs, many countries are unable to afford these technologies [7]. This technology is currently being used across Africa, e.g., in Libya [57–59] and Algeria [60–62], and would be a good investment for the Government of Kenya.

6. Conclusions and Recommendations

The results of this study show that the “no industrial development” population is expected to reach ~50,000 by 2065. The population is projected to reach 1.25 million by 2050 when the port reaches its full cargo-handling capacity (“LAPSET development projected”). The groundwater abstraction as of 2009 was 0.06 m³ daily per capita, while the results of the exponential growth equation shows an annual growth rate of 0.003%, resulting in a daily per capita demand rise to 0.1 m³, as recorded in Mombasa and Nairobi. The RCP climate change scenarios will have a lesser impact on the effective volume than the SRES. The overall results suggest that population growth exacerbated by land use change will be a more significant driving force that will affect the availability of freshwater than climate change. The aquifer is not expected to experience any stress by 2065 for the “no industrial development” population, while for the “LAPSET development” projected population, it will occur much sooner (between 2020 and 2028). New water management policies that take into consideration these expected changes should be formulated and implemented in order to conserve Shela aquifer's status as a viable freshwater reservoir. Barring this, the aquifer is in danger of being exploited to its full capacity. Import of water from a secondary location and desalination of seawater are feasible options to offset the increasing demand, which should be considered as viable alternative water supplies. The choice of method should be informed by the cost of the necessary infrastructure, the availability of funds, as well as the efficiency of the technology.

The models used in this study provide sound data analysis and interpretation methods needed by policy makers regarding coastal groundwater assessment, monitoring and mitigation against overexploitation globally. A more encompassing water stress analysis using an indicator that combines

the effects of climate change, sea level rise and the anthropogenic contribution (population growth and urbanization) would give a better risk assessment to freshwater degradation through saltwater intrusion, providing policymakers a clearer analysis of the situation needs to be carried out to augment the findings of this study. The water management policies of the Kenyan coast generally and the Lamu area specifically should explicitly take into account the effect that the new harbor will have on population dynamics and land use changes. The mitigation measures highlighted by this study should also be investigated further to assess their viability, both ecologically and economically. Furthermore, a monitoring program of the water quantity and quality in the well field should be established as soon as possible to serve as an early warning against the deterioration of the freshwater lens.

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Author Contributions

Cornelius Okello and Marco Antonellini conceived of and designed the overall concept and work plan for the research. Bruno Tomasello consulted on and conceptualized the demographic models alongside Cornelius Okello and Marco Antonellini. Nicolas Greggio, along with Cornelius Okello and Marco Antonellini, conceptualized the physical model and helped with running the simulations for all three models. Cornelius Okello and Marco Antonellini analyzed the data. Nina Wambiji was the liaison between the first author and the Kenyan authorities and played a critical role in the data collection in Kenya. Cornelius Okello wrote the paper. This study, research and paper are part of Cornelius Okello's PhD thesis, with Marco Antonellini being his principle supervisor, and Nina Wambiji is the second supervisor.

Conflicts of Interest

The authors declare no conflict of interest.

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