J. Trop. Resour. Sustain. Sci. 12 (2) (2024): 74-80
https://doi.org/10.47253/jtrss.v13i2.1480

Journal of Tropical Resources and Sustainable Science

journal homepage: jtrss.org

Modeling the impact of urbanization and climate change on groundwater flow pattern in Warri-Effurun area of the western Niger Delta

Ohwoghere-Asuma Oghenero[1,*], Esi Emmanuel Oghenevovwero[2], Ovwamuedo Glory[1], Onyemaechi Chukwudubem Prince[1], Atiti Prince[1] and Ophori Duke[3]

[1]Laboratory Department of Geology, Delta State University, Abraka, Nigeria
[2]Department of Physics, Dennis Osadebe University, Asaba
[3]Department of Earth and Environmental Studies, Montclair State University, Upper Montclair, New Jersey, 07043, USA

Received 2 October 2023
Accepted 6 March 2024
Online 23 December 2024

Keywords:
climate change, groundwater flow pattern, heavy pumping, aquifers, Niger Delta

⌧*Corresponding author:
Ohwoghere-Asuma, Oghenero
Department of Geology,
Faculty of Science, Delta State University, PMB 1 Abraka, Nigeria.
Email: ooasuma@delsu.edu.ng

Abstract

Warri-Effurun is one of the oil regions in the Niger Delta and has experienced industrial expansion with upsurge in population growth in the last five decades. The attendant effect of such growth is synonymous with more groundwater pumping needed to satisfy domestic, industrial and other purposes. The consequence is the subjection of aquifers to intensive abstraction of groundwater to meet the water needs of the inhabitants. The high demand for groundwater may be worsened by the climate change. The impact of climate change on groundwater is complex but can better be understood by modeling. The study used groundwater modeling software to understand groundwater flow pattern under high groundwater over-abstraction under climate change conditions. Model scenarios output revealed that pumping is sustainable when the aquifer was recharged with 2*10-4mm/year of precipitation and pumping rate of 6.1776m3/day, groundwater flow is towards the Warri River. However, flow direction was reversed when pumping rate was increased geometrically to 13,590.72m3/day with zero net recharge (drought conditions precipitated by climate change). The reversal in the flow direction is indicative of interaction between groundwater and river water. The implication is that contaminants may be transported from the river into the aquifer, consequently compromising groundwater quality and thus making it unsuitable for drinking. The study concludes that groundwater modeling is a better tool in understanding how stressed aquifer under the influence of climate change may respond to heavy groundwater over-pumping.

© 2024 UMK Publisher. All rights reserved.

1. INTRODUCTION

The world population is currently estimated at 7.9 billion people, this number according to the United States Census Bureau (2012), has increasingly double in less than 50 years. About 55% of the 7.9 billion people live in urban cities (UN, 2011). By 2030, it is estimated that 83% and 53% of the most developed and less developed economics of the world would have their respective populations living in urban cities (Cohen 2004). The attendant effect of urbanization is the competition for natural resources induced by urban cities expansion. The entire population of the Niger Delta principally depends on groundwater as the core source of water for potable, domestic and other diverse purposes. In the last four decade, there has been unprecedented increase in the number of boreholes drilled to meet the water supply needs of the increasing population. This is consequent upon the absence of public water supply schemes in the region. This has propelled individual ownership of boreholes. The influx of people into Warri is attributable to its strategic position as an oil province next to Port Harcourt, which is characterized by activities of more oil companies involved in the production and exploitation of oil and gas.

Urbanization intensifies land use such that land cover are cleared and converted to sites for buildings and pavements construction for provision of shelters and roads. This has significantly resulted in the reduction of available land spaces required for the recharge of aquifer. Constructed sites create impervious surfaces which have effect on runoff. Runoff from urban areas may be enriched in toxic substances that may find their ways into streams and rivers. Contaminants emanating from non-point and point sources from urban surface can change the quality of urban rivers, wetlands and streams. Studies have revealed that soil nutrients such as sodium, nitrates and phosphorus, heavy metals and rubber residues from roads are found in runoff (Tong and Chen 2002, Carey et al., 2013). Construction sites and sites in which soils are compacted are mostly responsible for the reduction in the quantity of

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.

water from precipitation that may end up recharging aquifers (Gregory et al., 2006; McGrane 2016).

Urbanization essentially give raise to corresponding increase in the demand for groundwater. Heavy pumping of groundwater impacted by increase in population has attendant consequences in causing reversal in the direction of groundwater flow. In coastal areas, like the twin city of Warri-Effurun, heavy pumping of groundwater may trigger inflow of river water into groundwater. This may result in the contamination of groundwater when such river is contaminated. The interconnectivity of the surface and subsurface intensifies the rate and the concentration of contaminants that are transported into groundwater (Jackson and Pringle 2010).

Understanding the impact of climate change in forcing the water cycle is the most essential factor influencing the quantity and quality of water resources (McGrane 2016). The hydrological cycle is affected by the temperature, atmospheric CO2 and distribution of precipitation (Yang et al., 2019). Factors driving climate change has direct effect on evaporation and runoff. These two forms the most important components of the hydrological cycle (Jung et al., 2010). Climate change has both positive and negative effects on the distribution pattern of precipitations both globally and locally. It has the tendency of increasing and reducing amount of precipitation. Its contribution to drought as source of water resources scarcity and attendant effect on agriculture are well known. Consequently, climate change variables either reduces or increases the amount of precipitation that finally reaches the aquifer.

Groundwater resources are under serious threat from effect of climate variables and over-pumping to meeting the increasing demand for water. The understanding of this threat is best studied and illustrated by the use of modeling. Several studies have used different scenarios for describing the response of groundwater resources to these threats. Excessive over-pumping of the Isfahan-Borkhar aquifer, which was used for irrigation of farmland was modeled by Ostad-Ali-Askari and Shayannejad (2021). Their model revealed that groundwater levels have decreased from 0.5 to 0.1m/s annually. Urbanization of Semarang City in Indonesia requires groundwater to meet the water needs of the population. From modeling of the effect of urbanization on groundwater, Lo et al., (2021) demonstrated from modelling that groundwater levels in deep aquifers have declined drastically due to excessive pumping. Furthermore, in the coastal area of the Niger Delta, Ohwoghere- Asuma et al., (2021) simulated over-extraction of groundwater and one of the climate change variables, decreased precipitation have led to lateral movement of saltwater into inland coastal aquifer. Similarly, Kerrou et al., (2010) depicted in the 3D MODFLOW modeling of the Korba aquifer that influx of saltwater was triggered by over-abstraction of groundwater. They also showed that it would take up 150 years of no pumping in order to restore the aquifer to its pristine condition. On impact of climate change on coastal aquifer, Rajaveni et al. (2016) used FEFLOW software to establish the response of hydraulic heads to groundwater abstraction and precipitation variation. The model output showed that 10% increase in recharge and 10% decrease in abstraction of groundwater resulted in 3m and 6m increase in hydraulic heads. In coastal regions, the incursion of saltwater from the sea not only deteriorate the quality of groundwater but also responsible for drastic reduction in fresh groundwater quantity. Subsequently, De Biase et al., (2021) modelled the combine effect of reduction in recharge and sea level rise as climate change variables on groundwater quantity from the use of 3D density dependent and heterogeneous model. It was revealed that these two variables reduced groundwater quality and quantity by 16%.

Recent study that analyzed data of temperature spanning 102 years revealed that Warri urban city was warmed by 1.3 °C (Efe and Ojoh, 2013) and it is expected to increase in the future to 1.4 °C These temperature data arguably suggested evidence of climate change. The sustainability of groundwater resource in urban cities requires maintaining a balance between the quantity abstracted and quantity recharged by precipitation. For a twin urban city like Warri-Effurun that relies solely on groundwater requires water balance maintenance to thrive. It is appropriate therefore, to understand how groundwater is affected by one of the climate change variables of precipitation and that of over abstraction on its interconnectivity with the river in the area. For this reason, the objective of this paper is to use groundwater modeling software (GMS) to simulate the impact of excessive groundwater withdrawal and climate change on the flow pattern of groundwater.

1.1 Study area description

The area under study is Warri-Effurun metropolis in Delta State and its geographical location lies between latitude 50 30’N–50 45’N and longitude 50 15’E – 50 50’E (Figure 1). It is situated along Warri River and 40km from the Atlantic Ocean. It is the second hub of oil activities in the Niger Delta region of Nigeria, and as such a host to several multinational and local oil companies.

The area is a low land with an average elevation of 5m above sea level. It is characterized by a tropical equatorial climate; the annual temperature is 27.44 °C (Efe and Ojoh 2013) and precipitation amount slightly less than 4000mm per annual. Every month in Warri-Effurun metropolis experiences rainfall but peaks in the months of July and September, and two weeks break in August. The dominant wind system is the Tropical Marine Air. The air influences distribution of rainfall and humidity of the areas.

eISSN Number: 2462-2389 © 2024
UMK Publisher. All rights reserved.

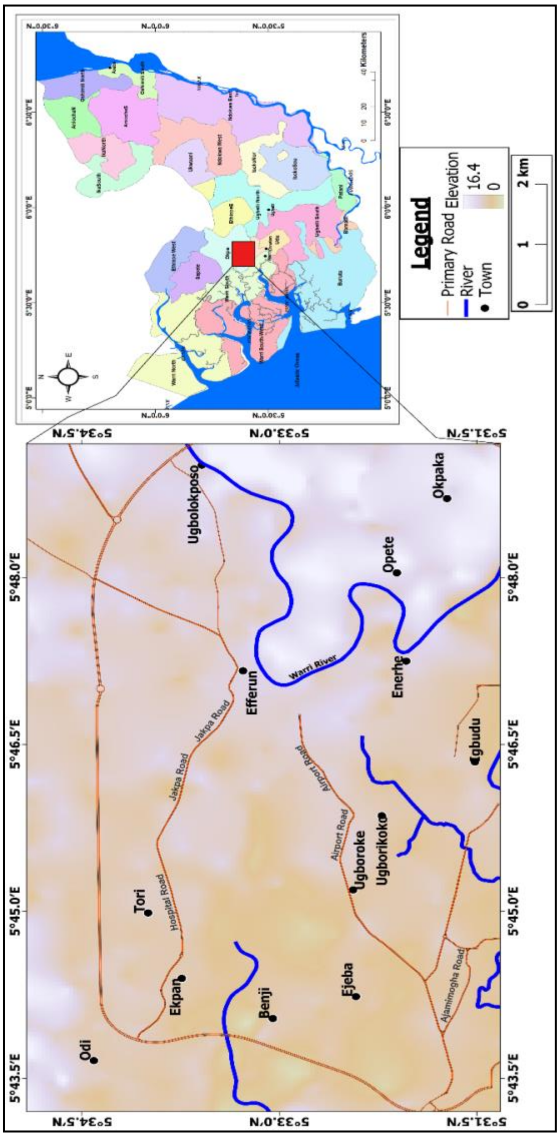

Figure 1: Map of the study area.

The vegetation is predominantly mangrove and freshwater swamps forests, which can be found along the Warri River.

1.2 Geological and hydrogeological setting

The Niger Delta basin was formed from the thermal cooling of the separation of the South American from the African plate, and the subsequent opening of the South Atlantic Ocean. The Niger Delta basin consists of sediments deposited in different depositional environments. Its basin fills were controlled by sediment supply and subsidence, climate change and variation in sea levels. The sequence of deposition of the three litho-stratigraphic units in terms of decreasing age are Akata, Agbada and Benin Formations. The basal unit of stratigraphy is the Akata Formation mantled by the basement rock of Cretaceous age. Characteristically, its sediments are made up of shale of open marine origin, which is abnormally over-pressured. Deposited along with the shale are dome and diaper shaped lowstand turbidities sands. Like the shale, they are also highly pressured and mobile (Reijers, 2011). They were initially deposited on the slope of the continental shelf and through gravity flow they were subsequently deposited basin ward. Overlying the basal Akata Formation is the Agbada formation, whose shale and sand deposits are sources and reservoirs for oil and gas, respectively. The shale and sand alternate each other in the sequence. The sequence of clay and sand were deposited during cycles of transgression and regression of the sea. The shales are product of marine deposits and the sands are of transitional marine and shoreface depositional environments. The Benin Formation tops the 3 lithostratigraphy of the basin fills of the Niger Delta. It is the fresh groundwater bearing formation of the three. The sediments that make up this formation are silt, clay, shale and gravel, and occasionally peat and wood fragments. The sediments originated from terrestrial environmental and deposited by fluvial flowing processes.

The environment of deposition and the thickness of clays and sands determine hydraulic performance of aquifers in the region. Multi-aquifers systems are abundance but are more in floodplains of the Warri River and in the coast. The yield of aquifers is relatively high due to the unconsolidated nature of gravel, coarse and medium sands which impact high permeability and porosity on the aquifers. The pore spaces are interconnected which leads to high hydraulic conductivity and consequently promotes easy transmission of groundwater. Groundwater is sourced from hand-dug wells, shallow boreholes and occasionally deep boreholes. Some aquifers are characterized by dissolved iron, which occasionally has resulted in abandonment of boreholes. The non-continuity of aquiferous layer or its termination against clay layers, and intercalation and admixture of clay with sand may result in heterogeneity, which has effect on the horizontal and vertical hydraulic conductivities.

Groundwater table vary from 0 in areas close to rivers and wetland to 5m in other areas. It's not static as it being influenced by the different seasons prevalent in the area, wet and dry seasons respectively. During raining season, water level rises toward the ground surface in certain areas and decreases downward in dry season. Groundwater flow naturally towards the nearest rivers and wetland as discharges points. It is recharged by infiltration and percolation of rainfall. The Climate is characterized by two seasons, wet and dry seasons, respectively. The area receives rainfall throughout the year with annual rainfall slightly below 4000mm. More rainfall is experienced in the wet season, especially in the months of May to October, and occasional rainfall in November to April. The season controls the hotness and coldness of the area. In the dry season, maximum temperature of 34 °C is common and 26 °C in the wet season. The watershed of the areas is drained majorly by the Warri River, its distributary, wetlands and swamps.

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.

2. MATERIALS AND METHODS

2.1 Conceptual model

Lithological information obtained from borehole logs (Figure 2) and geophysical data were used in conceptualizing the hydrogeology of the areas model into 3 layers of fine sands, silty sand and clayey sand. These layers characterized by different grains sizes and hydraulic conductivities for the various layers which constitutes the aquifers and the confining layers. The known source of water to the model is infiltration of precipitation, surface water leakage, returned flow from septic tanks and groundwater leaves through abstraction, evapotranspiration and discharge into surface water of rivers, wetlands and freshwater swamps. The direction of flow is towards the Warri River and discharge of groundwater through pumping which is temporary. The unconfined aquifer is extended to the soil surface and receives precipitation. The aquifers interconnected by using the linkage terms.

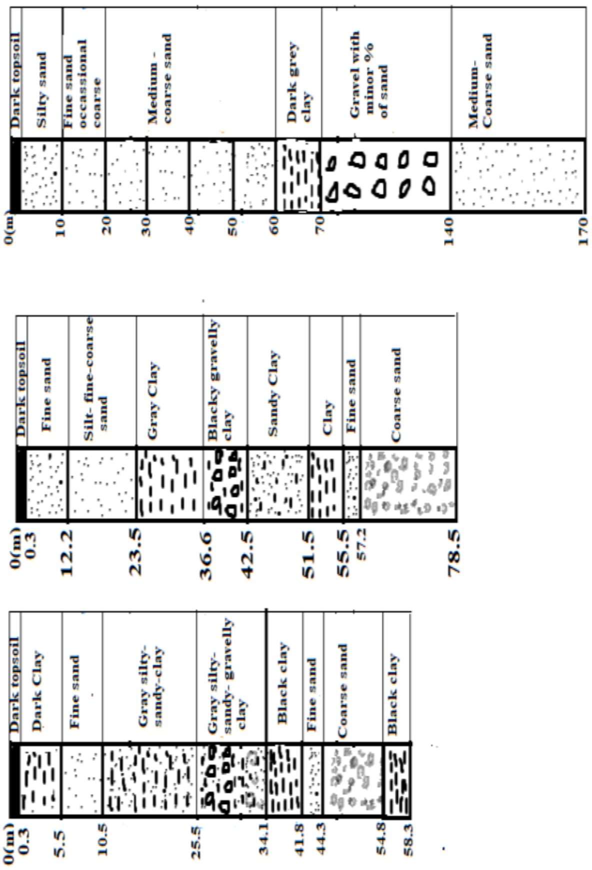

Figure 2: Lithological description of subsurface geology of some borehole logs (left and middle were drilled close to the Warri River) in Warri.

2.2 The numerical model

The conceptual model was converted to numerical model by groundwater modelling system (GMS) software. Digital elevation model (DEM) for the area was generated using QGIS. The model domain was discretized uniformly into 25 columns by 25 rows using the grid approach. The gridding is to enable the calculation of hydraulic heads at each cell in the model domain. The Warri River is a natural boundary and consequently a constant head equivalent to it water stage was assigned to the cells that represent it. The model bottom which is an impermeable layer was treated as no-flow boundary. The upper boundary layer which is the unconfined aquifer connected to the surface was design to receive specified amount of precipitation which infiltrate into the aquifer. The initial hydraulic head used was the average of heads computed from groundwater tables measured in boreholes while the hydraulic conductivity used are shown in Table 1. After the successful inputting of modelling parameters into the model, it was simulated under steady state condition.

Table 1: Initial and calibrated hydraulic conductivity.

S/N	Layer	Initial range md	Calibrated m/d
2	Silty clay	2.0	0.09
3’	Fine sand	8.0	6.0
4	Clayey sand	3.0	0.8

2.3 Model calibration and validation

In order to construct a useful model, it must be calibrated to be effectively used in the future for prediction purposes. This way the responses of aquifer to stressing is understood. The study area is without historical data required for the calibration. However, hydraulic heads were measured from groundwater water level in boreholes. To calibrate the model under steady state condition, hydraulic conductivities and recharge were adjusted repeatedly and the model was run. This was done severally till calculated heads obtained by model is correlate with the corresponding observed heads from measured boreholes. The model was subsequently validated by comparing contours flow map from calculated head to observed heads. The similarities in heads derived from model calculation with those measured suggest the model actually represent the hydrogeologic of the watershed and can be used for management purpose. The result of the initial and calibrated hydraulic conductivities for the three layers are shown in Table 1.

3. RESULT AND DISCUSSION

3.1 Groundwater flow direction

The direction of groundwater flow is apparently in conformable with the direction of flow conceptualized for the model (Figure 3). The heads range from 3.45 - 8m, which is in consistent with the heads observed for the area. Consequently, the model was used for scenario simulation of the excessive withdrawal and seasonal variation of rainfall as analogue of climate change.

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.

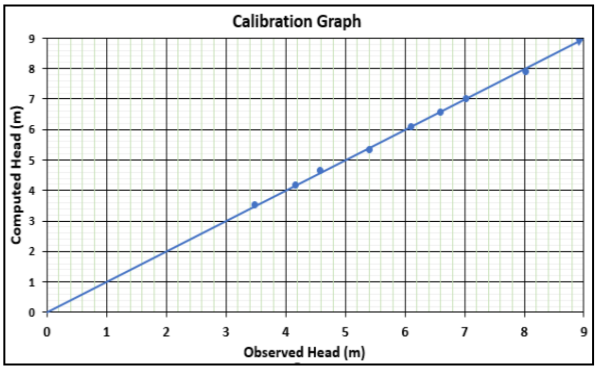

Figure 3: Graphical representation of computed heads against observed heads.

3.2 Effect of urbanization on groundwater flow pattern

In its pristine condition, groundwater flow in aquifer is driven by gravity, topography and geology. The discharge of groundwater from aquifer is another way by which groundwater flows, especially by pumping of a well.

Pumping of groundwater from an aquifer induces pressure difference which triggers flow. In area with river, the flow of groundwater is ether towards or away from it. Figure 4 shows the direction of groundwater flow is towards the Warri River, when the groundwater was abstracted at a rate of 1.23*103m3/day (0.858m3/min) with the model domain being recharged with 1.749ẋ10-3mm/year of precipitation. Also, on increasing the pumping rate to 1.85328m3/day with unchanged amount of recharge, the direction of flow remained unchanged. Though, no pattern change in the flow direction was observed by increasing the pumping rate, the amount of groundwater that may flow into the river is also reduced considerably.

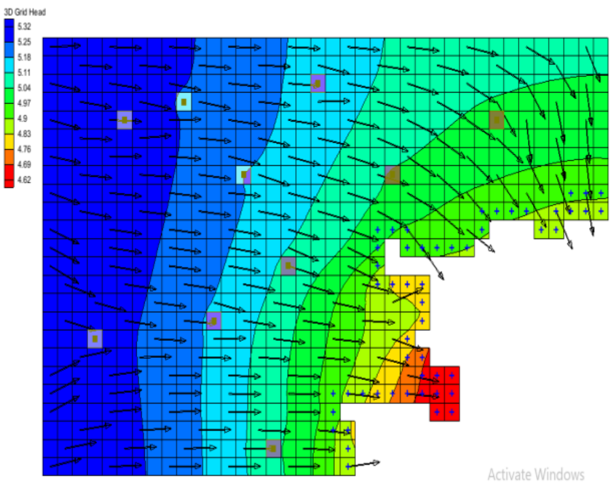

Figure 4: Groundwater flow pattern induced by moderating pumping (arrows indicate flow direction).

Figure 5 evidently shows flow pattern that is significantly different from Figure 4. This is may be due to geometrical increase in the pumping rate, which was increased from 1.85328m3/day to 6.1776m3/day and with recharge net amount that was increased from 1.749ẋ103mm/year to 2 ẋ10-4mm/year. The groundwater flow lines are concentrated towards the wells, again this will reduce the quantity of groundwater flowing into the river more than what is observed in Figure 4.

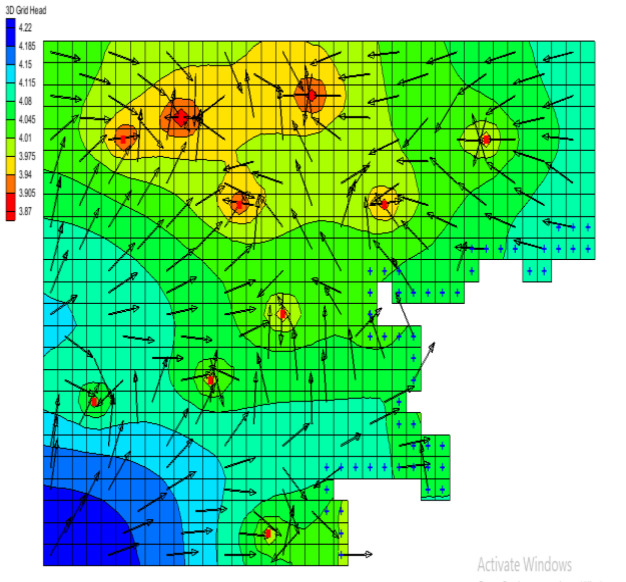

Figure 5: Slight change in groundwater flow pattern driven by increasing pumping rate and recharge reduction (arrow changed direction).

The reduction in aquifer recharge amount by precipitation is a resultant of the preponderance of pavements trigger by road construction and built infrastructures as well as deforestation arising from urban cities expansion. Their proliferation affects the precipitation amount that eventually reaches the aquifers. The explanation is that reduced recharge rate of 2 ẋ10-4mm/year and abstraction of 6.1776m3/day rates of groundwater abstraction from the aquifer are sustainable for the progressive growing population of the Warri-Effurun.

3.3 Effect of climate change on groundwater flow pattern

The sustainability of the aquifers to the attendant effect of increase in groundwater demand by surge in population due to urbanization is attributable to the regular recharge of aquifers by precipitation. Climate change causes uneven distribution of precipitation globally. Drought is one of the effects of climate change, during drought, aquifers are not recharged due to absence of rainfall for a period of time. The consequence is that

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.

aquifers may suffer from depletion of groundwater, especially those unconfined aquifers that are mostly shallow. A drought condition was simulated by increasing the pumping rate with zero net recharge of aquifer. Figure 6 clearly reveals the reversals in the groundwater flow direction caused by increasing the pumping rate to 13,590.72m3/day with no recharge.

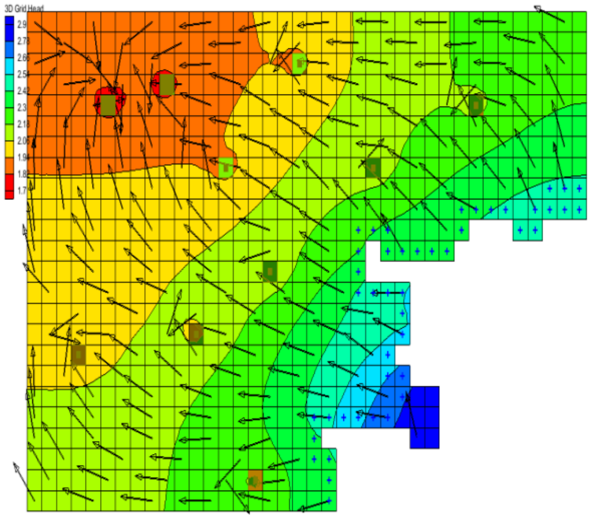

Figure 6: Groundwater flow pattern reversal induced by no recharge and over pumping.

The changes in the groundwater flow pattern underscored the strong interaction between the Warri River and the aquifer. In this case the river is actually contributing to the recharging of the aquifer. The implication of the reversal of the flow pattern is that there is tendency of the groundwater contamination caused by the influx of the river water in case of the river water has been contaminated.

4. CONCLUSION

The efficacy of models in understanding how groundwater responds to climate change and urbanization has been clearly and evidently demonstrated in the study. The prevalent of impervious surfaces in urban cities is demonstrated to have same impact on groundwater dynamics as climate change. The impact of urbanization may be small compared to climate change which may be global. The similarity of both is expressed in the reduction of groundwater recharge, however, climate change differs significantly from urbanization in that it may also results in increase in recharge of groundwater at the period of excess.

The study has also shown the effectiveness of using MUDFLOW in understanding hydraulic properties of aquifer and thus a tool for the management of groundwater resources. The groundwater in Warri-Effurun flows with respect to the topography of the land flowing from a higher hydraulic head to a lower hydraulic head and groundwater pumping. The groundwater flow direction is affected by the amount of discharge or pumped from the aquifer per day. In conclusion, as the discharge rate is increase there is a simultaneous reduction is the hydraulic head. This implies that the over extraction of groundwater in Warn-Effurun is not good for the inhabitants residing in twin city.

REFERENCES

Amodu, A., Oyetade, O. P., Fadiya, S. L., Fowora, O. (2022). Sequence stratigraphic analysis and hydrocarbon prospectivity of AMO Field, deep offshore Niger Delta, Nigeria. Energy Geoscience, 3(1), 80-93.

Anyiam, U. O., Uzuegbu, E. (2020). 3D seismic attribute-assisted stratigraphic framework and depositional setting characterization of frontier Miocene to Pliocene aged Agbada Formation reservoirs, deep offshore Niger Delta Basin. Marine and Petroleum Geology, 122, 104636.

Carey, R. O., Hochmuth, G. J., Martinez, C. J., Boyer, T. H., Dukes, M. D., Toor, G. S., Cisar, J. L. (2013). Evaluating nutrient impacts in urban watersheds: Challenges and research opportunities. Environmental Pollution, 173, 138-149.

Cohen, B (2004). Urban growth in developing countries: A review of current trends and a caution regarding existing forecasts. World Development, 32(1), 23-51. https://doi.org/10.1016/j.worlddev.2003.04.008.

De Biase, M., Chidichimo, F., Maiolo, M., Micallef, A. (2021). The impact of predicted climate change on groundwater resources in a mediterranean archipelago: a modelling study of the Maltese Islands. Water, 13(21), 3046.

Edet, A., Abdelaziz, R., Merkel, B., Okereke, C., Nganje, T. (2014). Numerical groundwater flow modeling of the Coastal Plain Sand Aquifer, Akwa Ibom State, SE Nigeria. Journal of Water Resource and Protection, 6, 193-201.

Efe, S. I., Ojoh, C. O. (2013). Climate variation and malaria prevalence in Warri Metropolis, Atmospheric and Climate Sciences, 3(1), 132-140. http://dx.doi.org/10.4236/acs.2013.31015.

Gregory, J. H., Dukes, M. D., Jones, P. H., Miller, G. L. (2006). Effect of urban soil compaction on infiltration rate. Journal of Soil and Water Conservation, 61(3), 117-124.

Kerrou, J., Renard, P., Tarhouni, J. (2010). Status of the Korba groundwater resources (Tunisia): Observations and three-dimensional modelling of seawater intrusion. Hydrogeology Journal, 18(5), 1173-1190.

Jackson, C. R., Pringle, C. M. (2010). Ecological benefits of reduced hydrologic connectivity in intensively developed landscapes. BioScience, 60(1), 37-46.

Jung, M., Reichstein, M., Ciais, P. *et al.* (2010). Recent decline in the global land evapotranspiration trend due to limited moisture supply. Nature, 467(7318), 951-954.

Lo, W., Purnomo, S. N., Sarah, D., Aghnia, S., Hardini, P. (2021). Groundwater modelling in urban development to achieve sustainability of groundwater resources: A case study of Semarang City, Indonesia. Water, 13(10), 1395

McGrane, S. J. (2016). Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. Hydrological Sciences Journal, 61(13), 2295-2311.

Ohwoghere-Asuma, Oghenero., Felix Mensah, O., Duke, O. (2021). Simulation of saltwater intrusion into coastal aquifer of the Western Niger Delta. International conference on Mediterranean Geosciences Union. Cham: Springer Nature Switzerland, 2021.

Ohwoghere-Asuma, O., Essi, O. E. (2017). Investigation of seawater intrusion into coastal groundwater aquifers of Escravos, western

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.

Niger Delta, Nigeria. Journal of Applied Sciences and Environmental Management, 21(2), 362-369.

Ohwoghere-Asuma, O., Chinyem, F.I., Aweto, K. E., Iserhien-Emekeme, R. (2020). The use of very low-frequency electromagnetic survey in the mapping of groundwater condition in oporoza-Gbamaratu area of the Niger Delta. Applied Water Science, 10(7), 1-14.

Ojuri, O.O., Ola, S. A. (2010). Modelling LNAPL Plume breakthrough and saltwater intrusion for a coastal site in the South-Western Nigeria, AU J.T. 14(2): 119-130.

Ostad-Ali-Askari, K., Shayannejad, M. (2021). Quantity and quality modelling of groundwater to manage water resources in Isfahan-Borkhar Aquifer. Environment, Development and Sustainability, 1-17.

Reijers, T. J. A. (2011). Stratigraphy and sedimentology of the Niger Delta. Geologos, 17 (3): 133–162. doi: 10.2478/v10118-011-0008-3

Rajaveni, S. P., Nair, I. S., Elango, L. (2016). Evaluation of impact of climate change on seawater intrusion in a coastal aquifer by finite element modelling. Journal of Climate Change, 2(2), 111-118.

Tong, S. T., Chen, W. (2002). Modeling the relationship between land use and surface water quality. Journal of environmental management, 66(4), 377-393.

U.S. Census Bureau. International Data Base. Washington, DC. (2012). http://www.census.gov/population/international/data/idb/informationgateway/php

Yang, P., Wang, W., Xia, J. *et al*. (2022). Effects of climate change on major elements of the hydrological cycle in Aksu River basin, northwest China. International Journal of Climatology, 42(10), 5359-5372

eISSN Number: 2462-2389 © 2024 UMK Publisher. All rights reserved.