GROUNDWATER PARAMETERS ESTIMATION FOR NZOIA BASIN USING NAM MIKE 11 RUNOFF MODEL

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Abstract

A little over 50 years ago, we finally ventured to the moon. For the very first time, we looked back at our home planet. Never before had the interdependence of systems across the globe been laid out so visibly. None more so than the hydrological cycle. It was clear that this cycle, one of the cornerstones of life, could only be truly visualized in a global scale. It had numerous systems, all interdependent on each other in complex and entwined relationships. Science, Technology and Innovation provided a vital tool for understanding this system a little better and using this information for the benefit of humanity. Satellite radar measurement and video information, for instance, proved invaluable in monitoring and predicting meteorological events. This information was, and still is, essential in weather prediction and in early warning systems. One of the most crucial elements in the hydrologic cycle is groundwater. Containing 98% of all freshwater globally, it is clear that understanding of this system will be essential for securing humanity's future. This is, however, no mean feat. Complex underground channels and routes exhibit flowpaths so complex that simple equations cannot accurately describe them. Here, Science, Technology and Innovation have come to the rescue again, represented by the use of tools and simulations to provide a picture of how the system behaves. Among these are the rainfall-runoff computer models. By iteratively varying groundwater and surface water parameters till values of runoff estimated by the model match actual observations in the field, it is possible to acquire groundwater parameters for a particular watershed. This study aimed at obtaining groundwater parameters for Nzoia basin. Accuracies of a RMSE of 460 and water balance of 0.98 was obtained when the NAM Mike11 model was used, thus proving the feasibility of the study.

Keywords: Groundwater, Calibration, Hydrology, Freshwater, Radar measurement, Data manipulation.

1 Introduction

Groundwater is water that occurs below the surface of the earth, wherein it occupies all or part of the void spaces in soil or geologic strata. These voids usually constitute of pore spaces in soils or fractures in rock formations. Normally, groundwater is only considered as water flowing through shallow aquifers. In the technical sense, however, it can also include soil moisture, permafrost (frozen soil), static water in very low permeability bedrock and deep geothermal or oil formation water.

The hydrological cycle considers groundwater as a very key component of this natural system. It is naturally recharged from the surface by infiltration and percolation, finally discharging naturally at springs and seeps. It is therefore very important to always visualize subsurface and surface water as one entwined system with precipitation and evaporation as the main input and output processes respectively; and the sun as its main source of energy.

Globally, the importance of groundwater cannot be overstated. It constitutes 98% of the earth's freshwater supply, and currently provides a third of all total water consumed (Parletta, 2019). This attributes for the water supply of about 2 billion people. It also supplies majority of water for agricultural and industrial use. With the new space exploration era, scientists have also been made aware of the fact that groundwater is not exclusively found on earth. It is possible that the formation of some landforms on Mars may be influenced by groundwater, and evidence has been found pointing towards the existence of subsurface water on Jupiter's moon Europa.

In addition, groundwater provides a buffer against water shortages in droughts, effectively acting as a water reservoir. This is becoming more important especially in the current weather fluctuations due to climate change. This is made possible by the fact that residence times for subsurface water may range from days to millennia (Gleeson, Befus, Jasechko, Luijendik, & Cardenas, 2016). Deep groundwater quite distant from the surface recharge can take a very long time to complete its natural cycle. Therefore groundwater volumes may remain steady for a long time compared to short term natural reservoirs like the atmosphere and fresh surface water whose residence times range from minutes to years.

Aquifers antedating the formation of deserts may remain unaffected by increases in aridity with the passage of time. The Great Artesian Basin in Eastern and Central Australia is one of the largest confined aquifer systems in the world, with some of its water having been retained for more than a million years. The Sahara desert also boasts of the Nubian Sandstone Aquifer System (NSAS) which is the largest known fossil water aquifer system. Reservoirs like these provide vital lifelines by providing virtually the only source of water for living things in their respective habitats. This might occur by natural means like the upwelling of NSAS water at Kufra Oasis or by artificial extraction like drilling of boreholes as observed in most Australian arid towns.

Being of such relevance, mismanagement of groundwater may lead to disastrous results. Despite being such a steady supply, groundwater is usually very sensitive. Being part of the hydrological cycle at large means that any disturbance will ricochet throughout the system. The slow residence times and the shear expanse of the groundwater system means that these effects are bound to be expansive and long lasting. One recent example to show how disastrous results can come about from mismanagement was the Cape Town water crisis.

Among the primary consequences from subsurface water mismanagement is groundwater depletion. This defines the pumping out of groundwater at a faster rate than is replenished over the long term. Among the first impacts of this overabstraction is drawdown. Once this happens, a myriad of negative consequences are sure to follow. Lowering of the water table might mean that wells begin to dry out, and deeper wells may require to be dug, increasing costs as well as leading to a water crisis.

Geological implications are also likely to be witnessed. One of the most recorded geological aftermath of overdrafting groundwater is land subsidence. In a phenomenon known as depressurization, the loss of hydraulic pressure which supports some of the weight of overlying sediments leads to compression of the ground. Extreme cases include the San Joaquin valley in California that has sunk 8.5 meters in some places since the 1920s (Sneed, Brandt, & Solt, 2013). When visualized, this represents the height of a standard power distribution pole!! The city of New Orleans is also currently below sea level partly thanks to overabstraction (Dokka, 2011). Places on river deltas also seem to exhibit subsidence associated with groundwater overuse, including Venice in Italy (Tosi, Teatini, Strozzi, & Lio, 2014) and Bangkok in Thailand (Aobpaet, Cuena, Hooper, & Trisirisatayawong, 2013). Mexico City, located on a former lake bed, also exhibits subsidence rates of up to 40 centimeters per year (Aroyo, et al., 2013).

Seawater intrusion is generally considered to be a natural process. However, it can be aggravated by groundwater extraction from nearby aquifers. High risk areas involves places with high coastal populations like Mombasa and Kilifi in Kenya or the Australian coastline.

With exception of dissolved substances from rocks and traces of old seawater, groundwater in its natural state is generally free of pathogenic organisms and pollutants with no purification for industrial or domestic use necessary. However, it is at risk of chemical pollution from fracking, agricultural chemicals, leaking of unfit landfills and septic tanks, and other point and non-point pollutants. This pollution is less visible but very expensive and often more difficult or impossible to clean up compared to surface water. To further compound this issue, movement of groundwater within an aquifer causes the pollutant to advance in all directions from the source of pollution by a boundary known as a plume edge. This may not only intersect with groundwater wells, but also seeps and springs and thus effectively contaminate the entire area's water supply. The consequences for both humans and wildlife may be severe.

The complex nature of groundwater means that there is constant need for research into its nature to better understand the relationships guiding its behavior. The general understanding takes subsurface water as a reservoir system with an output and an input. Any water percolating into the water table is regarded as recharge (input), while any water either escaping or being abstracted from the water table is regarded as an output. Natural output systems provide little danger of depletion, and can be determined. It is artificial abstraction by man that poses the real threat. Discharge from this can also be determined by calculating and summing up total outflow rates from abstraction wells and boreholes. Recharge estimation is the most complex of the above procedures due to the many routes water may take to get to the aquifer. Furthermore, this system is extremely delicate and can be affected by the simplest of human activities like changes in land use. By determining both rates of recharge and abstraction, and taking the rest of the system and other factors to behave as expected, it is possible to determine the amount of abstraction recommended for a specific water year without depleting this renewable resource.

Current groundwater recharge estimation methods involve the soil-water balance, Chaturvedi formula, seasonal recession method (Meyboom method), and the well level data method. The soil-water balance and the Chaturvedi formula relies on climate data, the Meyboom method on streamflow data, while the well level method relies on observation well levels. The Chaturvedi and Meyboom methods are generally more effective for use in tropical regions. They also do not allow for negative values, which gives them a distinct disadvantage. On the other hand, well level and soil-water balance seem to do well in sub-humid continental climates (Badr, 2016). The soil water-balance is however the most popular of these due to the ability to use climate data in its estimation. Being in a sub-humid zone close to the equator, Nzoia basin automatically demands for use of the soil-water balance method. However, the problem of data scarcity seriously plagues its use in the region.

Use of Science Technology and Innovation provides an easier way for groundwater investigation techniques. Radar and sonar, for instance, have provided a window into which we can peer into the ground strata and observe the water percolating within. Runoff models also give the ability to simulate the behaviors of water in the hydrologic cycle by use of a computer. By determining ‘rules’ governing how much time water is estimated to spend at each step of the cycle, it is possible to write an algorithm completely describing movement of water in a watershed. These rules are known as runoff parameters. This study seeks to determine the parameters guiding the flow of water in the hydrological cycle for Nzoia basin, and therefore providing a reliable alternative for estimating groundwater.

Study Area

The study area considered for the basin is Nzoia river basin. By delineating the basin from Rwambwa pour point using ArcGIS program, the area of the basin was found to be about 12,640 km^2. Geographically, the basin lies within longitudes 33.5^0 E and 36^0 E and latitudes 1.5^0 N and -0.2^0 S. Nzoia basin drains into Lake Victoria, which subsequently drains into the Nile river system. This ultimately empties into the Mediterranean Sea.

From a physiographic and land use point of view, the basin has four distinct zones; a mountain zone, a plateau zone, a transition zone and a lowland zone. The mountain zone is forested. However, it suffers severe land degradation. The plateau zone is the major farming zone in the basin. The transition and lowland areas are characterized by small scale farming. The lowland areas is flood prone, and is generally flat and swampy. The figure below shows the basin zones based on elevation depicting the highland zones, the plateau zone, and the lowland area;

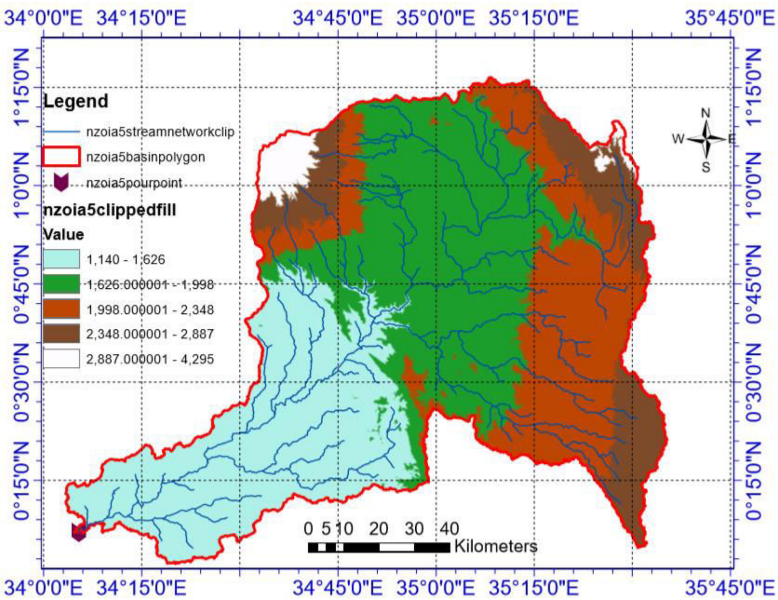

Figure 1: Nzoia basin

Main Objective

The main objective of this study was to determine the various soil, surface and subsurface strata parameters governing the flow of groundwater recharge in Nzoia basin.

Specific Objectives

1 To setup and calibrate a rainfall-runoff model for Nzoia basin.
2 To determine performance of the rainfall-runoff model for the basin.
3 To establish groundwater flow parameters for Nzoia basin.

2 Methodology

On collection, the rainfall, temperature and observed runoff were to be checked for quality by statistical analysis. A runoff model was then to be used to estimate groundflow parameters that best approximate our observed runoff from input rainfall and temperature data for Nzoia basin.
Below are the procedures employed:

2.1 Catchment Delineation

Catchment delineation was to be achieved in order to give an overview of the catchment and its parameters. These were helpful in hydrological modeling for the basin. For instance, catchment area is an important requirement in the runoff model. Delineation was also particularly useful in the choice of stations since it gave the spatial distribution of the stations with respect to the basin. The Arc map software from ArcGIS software were used to process the basin at this stage.

2.2 Hydrological Runoff Model

Hydrological models available in current software employ the use of a cascade/series of linear reservoirs where every reservoir/storage empties into the next until runoff is obtained.

Software for hydrological modelling include;

Table 1: Hydrological models

Software	Description
SMART	Includes agricultural, subsurface drainage flow, in addition to soil and ground water reservoirs to simulate flow path contributions to streamflow.
Vflo	Uses radar rainfall and GIS data to generate physics based, distributed runoff simulation.
WEAP	Models runoff and percolation from climate and land-use data, using a choice of linear and non-linear data.
RS MINERVE	Simulates formation of free surface runoff flow and its propagation in rivers or channels
NAM mike 11	Balances input and storages on a basin to determine runoff from a basin

Hydrological runoff modelling can be carried out using NAM mike 11 with only rainfall and temperature data. By varying input and storage parameters till observed discharge resembles simulated discharges, the model is calibrated for the basin. It requires 3 input data; temperature, rainfall and observed discharge. These input parameters were readily available to the researcher. Therefore, NAM mike 11 model presented a suitable model for the study. It was therefore chosen.

NAM mike 11 is a deterministic conceptual runoff model that balances the inputs and storages of a basin to determine the runoff from a basin. In the case of this project, NAM was prepared with 9 parameters representing the surface zone, root zone and ground water storages.

2.3 Calibrated Runoff Model Groundwater Parameters

The following is a description of the parameters used (Danish Hydraulic Institute, 2007).

Surface Rootzone

The following parameters represent the surface runoff and storage parameters of the basin in consideration:

Maximum water content in surface storage (Umax)

Represents the cumulative total water content of the interception storage (on vegetation), surface depression storage and storage per area in the uppermost layers (a few cm) of the soil.

Maximum water content in root zone storage (Lmax)

Represents the maximum soil moisture content in the root zone per area which is available for transpiration by vegetation.

Overland flow runoff coefficient (CQOF)

Determines the division of excess rainfall between overland flow and infiltration.

Time constant for interflow (CKIF)

Determines the amount of interflow, which decreases with larger time constants.

Time constants for routing overland flow (CK 1, 2)
Determines the shape of hydrograph peaks. The routing takes place through two linear reservoirs (serial connected) with the same time constant (CK1 = CK2). High, sharp peaks are simulated with small time constants whereas low peaks, at a later time, are simulated with large values of these parameters.

Root zone threshold value for overland flow (TOF)
Determines the relative value of the moisture content in the root zone (L/Lmax) above which overland flow is generated. The main impact of TOF is seen at the beginning of the wet season, where an increase in the parameter value will delay the start of runoff as overland flow.

Root zone threshold value for interflow (TIF)
Determines the relative value of the moisture content in the root zone (L/Lmax), above which interflow is generated.

Groundwater

To cover a range of special cases, NAM applications range from irrigation to river level variations to time taken for constant routing.

However, for most applications, and also this project, only the two overall parameters were required;

Time constant for routing baseflow (CKBF)
Can be determined from the hydrograph recession in dry periods. In rare cases, the shape of the measured recession changes to a slower recession after sometime. To simulate this, a second groundwater reservoir may be included.

Root zone threshold value for groundwater recharge (TG)
Determines the relative value of the moisture content in the root zone (L/Lmax) above which groundwater recharge is generated. The main impact of increasing TG is less recharge to the groundwater storage.

The table below represents the various runoff parameters used in the project;

Table 2: Hydrological model parameters

Characteristic Represented		**Parameter**	**Units**	**Range**
Surface rootzone characteristics	Storages	Umax	mm	5-35
		Lmax	mm	50-350
		CQOF	N/A – reps a fraction	0-1
	Runoff parameters	CKIF	Hours	500-1000
		CK1,2	Hours	3-72
		TOF	N/A – reps a fraction	0-0.99
		TIF	N/A – reps a fraction	0-0.99
Groundwater characteristics		TG	N/A – reps a fraction	0-0.99
		CKBF	Hrs.	500-6000

3 Results and Discussion

3.1 Introduction

The data available to the researcher covering both the satellite and observed values was from 1982 to 2009. This was considered as the time period for the study.

Choosing rainfall stations was based on the percentage completeness. Complete stations lead to more accurate results due to the availability of data. They are also easy to interpolate since only few values are to be determined. The stations that were 90% complete provided a suitable spatial distribution for most of the basin, apart from in the North West part. Therefore, Keiyo-Marakwet rainfall station at 80% completeness limit was added to the stations used in the study to provide an even spatial distribution.

For temperature data, only three stations were available to the researcher and thus they were adopted.

The spatial distribution of temperature and rainfall stations within Nzoia basin is described in the figure below;

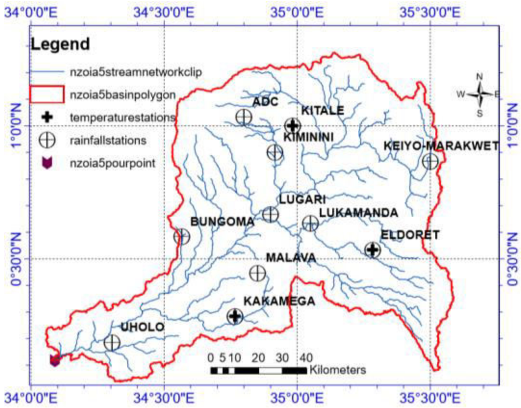

Figure 2: Stations chosen for the study

3.2 Catchment delineation

Theissen polygons were used to determine the area of influence of the various stations considered. This area of influence is important in future determination of the total average values affecting the entire basin. These average values represent the input data for the runoff model.

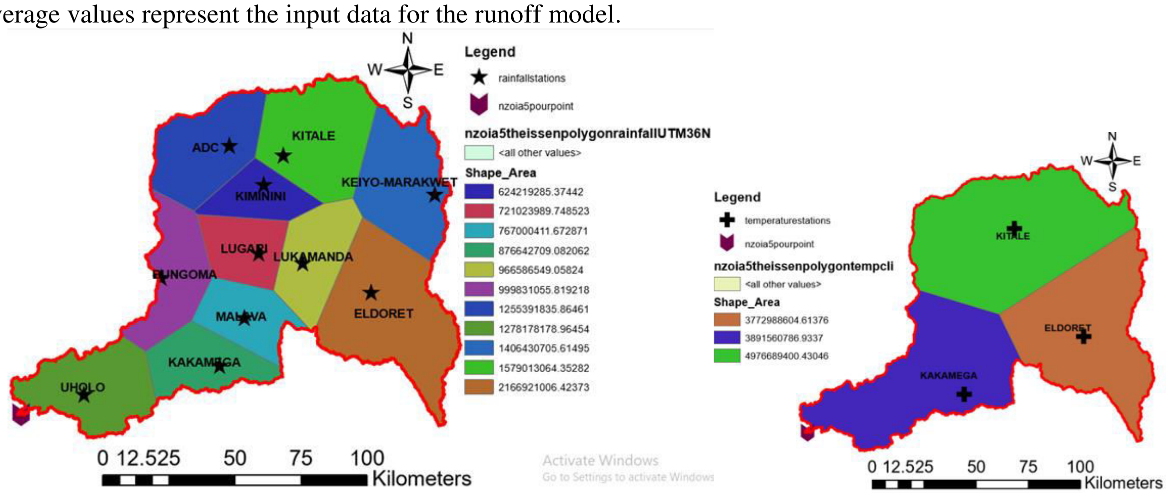

Figure 3: Catchment Delineation

3.3 Calibration of the Runoff Model

This generally involved changing of the parameters for Nzoia basin till the output that is simulated is similar to the observed discharge (from field observations thus representing the most accurate data and acting as our baseline for calibration).

By changing parameters iteratively, it was possible to obtain the best or optimum parameters. The best parameters are those that give the least root mean square error with the following conditions met:

a. You do not exceed the maximum range of the considered parameters

b. The water balance lies within 0.95 and 1.05, i.e. the difference between the simulated and observed values does not stray to more than five percent.

The time period chosen for calibration of the rainfall-runoff model was 1982 – 1990. Leaving out a warm up of two years, the calibration of the runoff model began in 1984 and then the validation period followed the calibration period.

For calibration, the following were the results obtained from the optimum parameters;

Water balance = Simulated /Observed = 0.98

R square coefficient = 0.91

Validation of the optimum calibration provided an r-square coefficient of 0.8 in comparison to observed values. Thus, the effectiveness of the calibration was confirmed.

3.4 Groundflow parameters

The following are the parameters that govern how a water behaves upon landing on the Nzoia basin surface;

Table 3: Parameters describing water flow in Nzoia basin - Surface and Subsurface

Parameter	Description	Calibrated Optimal Value	Units
Umax	Describes interception storage, depression storage and storage in uppermost layer of the soil.	12.7	mm
Lmax	Describes maximum soil moisture content in the root zone per area. This is soil moisture available for transpiration by vegetation.	136	mm
CQOF	Determines ratio of overland flow to infiltration	0.2	N/A – reps a fraction
CKIF	Describes interflow amounts	1100	Hours
CK 1,2	Determines shapes of hydrograph peaks. R-squared is heavily dependable on this parameter	62	Hours
TOF	Describes value of moisture content in root zone above which overland flow is generated	0.25	N/A – reps a fraction
TIF	Describes value of moisture content in root zone above which interflow is generated	0.2	N/A – reps a fraction
TG	Describes value of moisture content in root zone above which groundwater recharge is generated	0.05	N/A – reps a fraction
CKBF	Time constant for routing base flow	2825	Hrs.

However, the assumptions were not exact due to one or a combination of the following reasons (model errors):

a. Shift in the days.

b. Record errors. Those recording discharge are humans and as is the norm, they are prone to making mistakes.

c. Missing values make it particularly difficult to accurately calibrate the simulated discharge to the observed discharge.

d. Change in land use land cover characteristics through the years may render the parameters less accurate.

5 Conclusions

Nzoia catchment experiences two rainfall peaks every year. The first peak comes from the months of April to June, while the second occurs from July to September. Comparatively dry months in the region range from December through to March. Compared to other basins in Kenya, the basin is considered to receive high rainfall, where average annual values vary between 1,000 to 1,500 mm. The characteristic river in the basin is Nzoia River. The river has its source in the forested highlands, namely Mt. Elgon, Cherengani hills, Nandi hills and Kakamega forest. The river is about 330 km up to its outfall in Lake Victoria, and its discharge into the delineated pourpoint was determined to be 1777 x 10^6 m^3/year. Nzoia basin experiences annual averages of 27^0 C maximum temperatures and 12^0C minimum temperatures. The highest temperatures are observed to occur in April for maximum temperatures and for minimum temperatures, they occur either around July or September depending on the location within the basin. Use of rainfall-runoff models was found to be suitable for Nzoia basin, with r-squared between daily simulated runoff data model and observed weather station data meeting the threshold (0.7). R-squared values comparing simulated data with observed discharge for the calibration period was found to be 0.9 for daily data. For the validation period, it was found to be 0.8 for daily data. The optimal runoff model parameters observed were 12.7 for Umax, 136 for Lmax, 0.2 for CQOF, 1100 for CKIF, 62 for CK 1, 2, 0.25 for TOF, 0.2 for TIF, 0.05 for TG and 2825 for CKBF. These gave a water balance of about 0.98 and root mean square error of about 460. This proves that the model parameters that gave the above results were suitably accurate in simulating the behavior of water upon precipitation. However, one on one correlation could not be achieved due to the various model errors and uncertainties

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