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Investigation of Dominant Hydrological Processes in Chania Catchment at a Temporal Scale

Sharon Omollo[1*], **Jeremiah Kiptala**[2], **John Mwangi**[3]

[1, 2, 3]Civil Engineering Department, Jomo Kenyatta University of Agriculture and Technology P.O. Box 62000 Nairobi

Abstract: ***This study investigates the dominant hydrological processes governing the temporal variability of stream flow in Chania catchment. The study area is located within the upper Tana catchment which is the main source of Nairobi's water and hydropower supply downstream. The hydrology of this area is poorly understood because of inadequate information due to the ungauged nature of the catchment. Temporal dynamics of parameter sensitivity of the Soil and Water Assessment Tool was used to achieve this objective. The results show that the parameter sensitivity varies temporally. High sensitivity for two groundwater parameters; (base flow recession constant and groundwater time delay), one soil factor (available soil water capacity) and one evaporation parameter (soil evaporation compensation factor) were observed. The soil evaporation compensation factor dominates in re-saturation and baseflow segments of the streamflow hydrograph while, groundwater time delay and base flow recession constant are dominant during the peak and recession segments. Flow duration curves (FDC) were also used to relate sensitivities to certain magnitudes of streamflow. Runoff parameters were mostly sensitive in the Q0-Q5 segment while evaporation parameters are mostly sensitive in the Q5-Q20 and Q20-Q70 segment of the FDC. Highest sensitivities of two ground water parameters (base flow recession constant and ground water time delay) are detected in Q70-Q95 and Q95-Q100(low flow) segments.***

Keywords: hydrological modeling, hydrological processes, parameter sensitivity, SWAT, TEDPAS

1. Introduction

Nowadays, research tends to focus on accurate stream flow simulation with the aim of assisting in sustainable environmental management and to avail the necessary and relevant information for the management of water resources. Unfortunately, many catchments in the world are poorly gauged consequently dominant hydrological processes governing the occurrence of streamflow are poorly understood.

Hydrological models are very useful tools in describing the existing hydrological conditions and to predict the future situations in a catchment [1].

The output of the hydrological model can be evaluated for the whole time series or for smaller portions of the hydrological period [2]. Due to the variation of dominant hydrological processes over time for example between dry and wet periods, the dominant components will change temporally [2], [3]. Assuming that dominant hydrological processes are described sufficiently in the corresponding model components and their relevant model input parameters, the dominant hydrological processes can be effectively determined by use of temporal dynamics of parameter sensitivity (TEDPAS) [4].

The commonly used form of sensitivity analysis is a parameter sensitivity, which evaluates the effect of changes of model parameters on the model results. The parameter(s) causing the largest change in the output of the model for the period of investigation is identified [5], [6]. The other sensitivity analysis is the component sensitivity where the discharge sensitivity is assessed with a change in model component such as temperature or evaporation. In hydrological analyses, sensitivity is mostly used for calibration purposes with the aim of identifying the most relevant parameters over the time series of interest. An analysis of TEDPAS on the other hand is focused on identification of dominant model components and model parameters at a high temporal scale. The goal of TEDPAS differs from the common use of sensitivity analysis for calibration purposes.

2. Study Area

The area of study is the Chania catchment located within the Upper Tana catchment. It covers an area of approximately 533.87km^2. It lies between longitudes 36.58E and 37.076E , and latitudes 0.753S and 1.04 S.

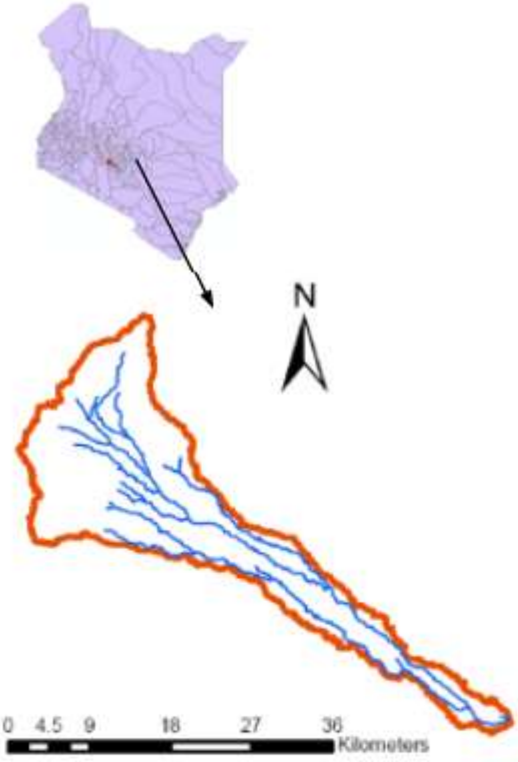


Figure 1: Map showing area of study

Chania River is served by; Kariminu, Nyakibai, Mataara and Kimakia, as the main tributaries all forming a dendrite drainage pattern. Besides the tributaries the catchment has several streams, springs, wetlands, boreholes and Dams. The river forms a confluence with Thika River near Blue Post Hotel in Thika.

The catchment mainly experiences two rain seasons, long rains from March to May and short rains from October to December. It receives an average rainfall of 1200-1500mm per annum. The hydrology of the catchment is greatly influenced by climate variability, topography and the land use among other factors which has impacted the water resource quality and quantity.

Main land cover in the area includes forest, subsistence agriculture, tea, coffee, water and settlements.

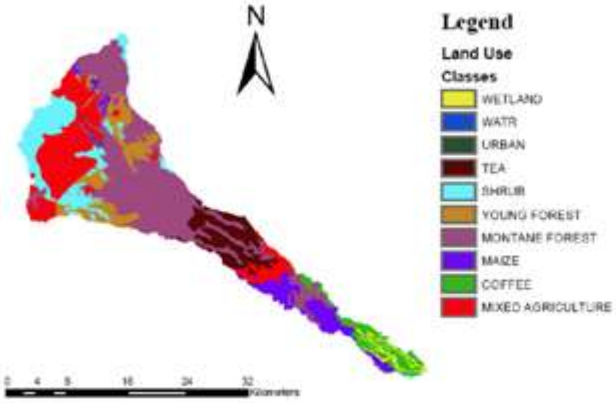


Figure 2: Map showing land use classes

Table 1: Area under each Land Use for the year 2000

Land Use	*Area (km^2)*	*Percentage*
Forest	192.04	35.97
Coffee	26.75	5.01
Shrubs	67.51	12.64
Tea	44.23	8.28
Wetland	8.83	1.65
Urban	0.24	0.05
Maize	38.39	7.19
Water	1.03	0.19
Mixed Agriculture	105.56	19.8
Young Forest	49.24	9.22

Soils in Chania River catchment vary with elevation and parent material. Deep in the Aberdare forest the soils are well drained, dark reddish brown, very friable, silt clay loam, with humic top soil of mollic andosols combined with well drained, very deep, dark reddish brown to very dark greyish brown, friable and slightly smeary clay, with a humic topsoil of andocurvic phaeozems. Soils in the eastern side of the Aberdares forest are well drained, deep to very deep, reddish brown, friable clay, with acidic humic top soils (ando-humic acrisols). Lower into the catchment soil comprise of Humic Nitisols and Cambisols.

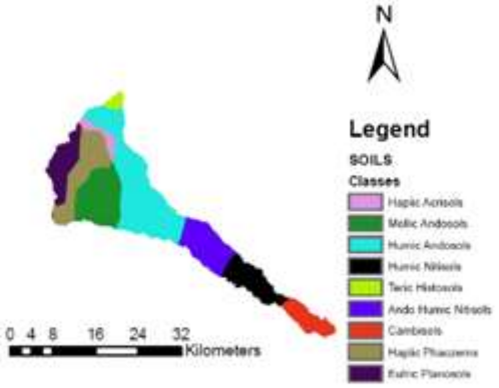


Figure 3: Map showing soil classes (Kenya Soil Survey)

3. Materials and Methods

3.1 Description of the Model

The Soil and Water Assessment Tool (SWAT) is a basin-scale model that was developed by Dr. Jeff Arnold for the USDA Agricultural Research Service. SWAT has been chosen for this study for its ability to focus on modeling the hydrology of a catchment, while specifically accounting for the interactions between regional soil, land use and slope characteristics [7].

SWAT first divides the basin into sub-basins based on the topography of the area, followed by further discretization using soil type and land use. Areas with the similar land use and soil type form a Hydrologic Response Unit (HRU); a simple computational unit which is assumed to be homogeneous in hydrologic response to land cover change.
Mostly water enters in the SWAT watershed system in form of precipitation. Parameters influencing flows and water quality are directed in the model on the basis of HRU to each sub basin and subsequently to the watershed outlet. In the present study SWAT model integrated with Arc GIS techniques was used to simulate water yield of the Chania catchment.

SWAT performs a day to day mass balance and contains eight modeling components – hydrology, weather, plant growth, nutrients, soil temperature, land management and pesticides.

The hydrologic component of SWAT partitions precipitation into four control volumes:
(1) The surface, (2) the soil profile or root zone, (3) the shallow aquifer, and (4) the deep aquifer. SWAT hydrologic simulations are based on the water balance equation 1:

$$SW_t = SW_o + \sum(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1)$$

SW is the soil water content (mm water) at the end of time step t (days),
SW_0 is the initial soil water content on day i(mm water),
R_{day} is the amount of precipitation on day i(mm water),
Q_{surf} is the amount of surface runoff on day i(mm water),
E_a is the amount of evapotranspiration on day i(mm water),
w_{seep} is the amount of water entering the vadose zone from the soil profile on day i
(mm water), and

Q_{gw} is the amount of base flow from the shallow aquifer on day i(mm water).

A water balance is computed for each HRU at every time step. A summary of the resulting water balance at the end of each (daily) time step can be viewed in the HRU output file. SWAT simulation divides precipitation that falls on the soil surface into surface runoff (Q_{surf}) and infiltration with other options for water movement in SWAT, including recharge to the shallow aquifer and subsequent groundwater discharge. Surface runoff is calculated using the empirically derived SCS Curve Number (CN) method (USDA-SCS, 1972), with the amount of infiltration determined as the difference between the amount of precipitation and the amount of surface runoff. SWAT provides an option for modeling infiltration explicitly using the Green-Ampt method .The USDA Soil Conservation Service (formerly SCS; now NRCS) CN method is an infiltration loss model which aggregates (lumps) spatial and temporal variations into a calculation of “direct runoff” for a given storm depth and drainage area. Developed in 1954, the SCS CN method is used for estimating runoff volumes. The equation for determining direct runoff fusing the CN method (USDA-SCS, 1972) is given as equation 2:

$$Q_{surf}=\frac{(R_{day}-0.2S)^2}{R_{day}-I_a+S} \qquad (2)$$

Q_{surf}= Accumulated runoff
R_{day}= Rainfall depth for the day, mm
I_a= Initial abstractions which includes surface storage, interception, infiltration prior to runoff, mm
S= Retention parameter, mm.

The retention parameter is dependent on changes in land use, soil, management and slope and temporarily due to changes in water content. The retention parameter is defined using 3 as:

$$S=25.4\left(\frac{1000}{CN}-10\right) \qquad (3)$$

Where CN is the curve number ($0 \le CN \le 100$).

The initial abstraction, I_a, is commonly approximated as 0.2S and 2 becomes

$$Q_{surf}=\frac{(R_{day}-0.2S)^2}{R_{day}+0.8S} \qquad (4)$$

3.2 Model Set-Up

The data required for SWAT model were collected from various sources. A 30m x 30m Digital Elevation Model from Regional Centre for Mapping Resource for Development was used to provide topological data. Africover 2000 Land use map was prepared using SWAT land use codes. The Kenya Soil and Terrain database (KENSOTER) was used to derive soil characteristics of the area. Precipitation and temperature data for the 2000-2010 period were obtained from the Kenya Meteorological Department.

All these data was converted to a format compatible with SWAT. The multiple HRU option was used for this study resulting to a total of 647 HRUs.

3.3 Temporal Parameter Sensitivity

According to Saltelli, there are different goals of sensitivity analysis [8]. Factor prioritizing is useful in identifying dominant model components along a time series [3]. The factor fixing option on the other hand focusses on parameters that have the least effect on the output of interest and can be fixed to any value without upsetting the calibration process. Factor mapping option is used in calibration studies like the generalized likelihood uncertainty estimation (GLUE) method [9].

Sensitivity analysis can also be classified broadly in two categories with respect to methods. These are local and global sensitivity analyses. Local sensitivity analysis takes into consideration the effect of variation for a given parameter combination, without considering a larger parameter range. The One-at-a-time method of sensitivity analysis falls under this category. However, the output acquired from a single-parameter combination is not a true reflection of the whole parameter space [10], [3]. Additionally, methods like the one-at-a-time method do not take into consideration how the parameters interact. Global sensitivity analysis investigates the whole parameter range but it is more intensive computationally and requires a higher number of model runs. Van Griensven [11] combined the Latin hypercube with one-at-a-time method to come up with an efficient and robust screening method that considers the whole parameter range. A number of methods which take into consideration non linearity and also determine the output of parameter interactions have been developed. [Sobol’s method and (extended) Fourier amplitude sensitivity test (FAST) [8],[12],[13],[3],[10].

Commonly, the application of a sensitivity analysis is to rank input model parameters according to their sensitivity for a given output variable of interest. Such sensitivity is mostly determined for model performance indicators such as the Nash–Sutcliffe efficiency index (CE) and usually do not consider the temporal dynamics of parameter sensitivity [3].An analysis of TEDPAS has a different goal from the common use of sensitivity analysis for calibration purposes. TEDPAS determines the parameter sensitivity of the model output for every time step. The purpose of this is to determine the dominance of different model components and parameters for different periods [14], [15]. Identification of dominant model components is associated with the factor prioritization setting of sensitivity analysis. This is best solved through methods that estimate the first-order partial variance to measure sensitivity [8]. Partial variance-based methods modify the parameters at the same time. This method investigates how the variance of the model output depends on these parameter modifications in 12[3]. The first-order partial variance is defined as the variance resulting from changes in a certain parameter divided by the total variance V over all model runs [3].

$$V=\sum_{i} V_I+\sum_{i<j} V_{IJ}+\ldots+V_{1,2,3,\ldots,n} \qquad (12)$$

Where V is the total variance, Vi the variance of parameter θi (first-order variance) and Vij the covariance of θi (second-order variance) and θj higher-order terms. Any global sensitivity analysis method that can be used for factor prioritization can be used for TEDPAS. FAST was chosen for this research because of its computational efficiency and suitability for use in the presence of nonlinearity [16],[17],[18]. It requires fewer number of model runs compared with other methods, for example Sobol's method [19],[3]. Cukier [16]and McRae [20] gave more information about this algorithm. The algorithm was implemented in the R package FAST [21] using R studio. For eight parameters, the FAST method requires 243 model runs. The simulations were run in SWAT from the year 2000-2004. The year 2000 was used as warm up. The results were transferred to FAST in R package and used to generate the sensitivities as a time series.

3.4 Parameter Selection

The SWAT parameters shown in Table 2 and their ranges were selected based on literature review [22], [23] and landscape features – land use and topography.

A time of concentration of more than 1 day means that the entire amount of surface runoff will not get to the river on a given day. Decreasing SURLAG results in surface runoff being stored in the catchment, and this runoff process is delayed. The relationship of SURLAG with runoff is shown in 5[22].

$$Q_{surf}(t) = (Q'_{surf}(t) + Q_{stor}(t - \Delta t)) * (1 - exp(\frac{-SURLAG}{t_{conc}})) \quad (5)$$

$Q_{surf}(t)$-surface runoff to the river on day t
$Q'_{surf}(t)$-surface runoff generated in the sub basin on day t (mm)
$Q_{stor}(t-\Delta t)$-surface runoff storage from day
t_{conc}-time of concentration

The available soil water capacity (SOL_AWC) is a soil parameter. SOL_AWC is used to estimate the field capacity for each soil layer. It is added to the wilting point as shown in 6. The available water capacity influences the calculation of the percolation which takes place in the current soil layer. The soil water influences the occurrence of lateral and surface flow, evaporation and the percolation into the groundwater [22].

$$FC = WP + SOL\_AWC \quad (6)$$

Where FC is the water content at field capacity for the soil layer and WP the water content at wilting point for the soil layer. Two ground water parameters, base flow recession constant, ALPHA_BF and Groundwater time delay, GW_DELAY control the retention of the water in the soil passing through the groundwater to the river reach. The GW_DELAY is measured in days and it regulates the time delay for recharge of the shallow aquifer. ALPHA_BF delays outflow from the ground water to the reach of the river. Increasing ALPHA_BF implies a quicker response of groundwater flow. The influence of GW_DELAY on recharge is shown in 7 while ALPHA_BF's relationship to groundwater is shown in 8.

$$w_{rchrg}(t) = (-\exp(\frac{-1}{GW_{DELAY}}) * w_{seep}(t) + \exp(\frac{-1}{GW_{DELAY}}) * w_{seep}(t - \Delta t) \quad (7)$$

Where $w_{rchrg}(t)$ is the recharge flowing into the aquifer on day t (mm), $w_{seep}(t)$ the percolation from the soil on day t (mm) and $w_{seep}(t - \Delta t)$ the recharge flowing into the aquifer on day $(t - \Delta t)$mm.

$$Q_{gw}(t) = Q_{gw}(t - \Delta t) * (exp(-ALPHA\_BF) + w_{rchrg,sh} * (1 - exp(-ALPHA\_BF)) \quad (8)$$

Where $Q_{gw}(t)$ is the ground water flow on day t (mm) and $Q_{gw}(t - \Delta t)$ the ground water flow on day $(t - \Delta t)$ (mm).

The recharge resulting from percolation is distributed into two aquifers. The aquifer fraction coefficient (RCHRG_DP) determines how recharge is split between the shallow and deep aquifers as shown in 9[22].

$$w_{rchrg,sh} = w_{rchrg} * (1 - RCHRG\_DP) \quad (9)$$

Where $w_{rchrg,sh}$ is the recharge flowing into the shallow aquifer (mm).

CANMX represents the water capacity of the canopy storage. The canopy storage is dependent on the leaf area index of the crop represented by the land cover. Water from precipitation will only reach the soil after the storage of the canopy is filled completely [22]. CANMX is also incorporated during calculation the actual evapotranspiration.

$$can(t) = CANMX(\frac{LAI}{LAI_{mx}}) \quad (10)$$

Where $can(t)$ is the canopy storage at day t (mm), LAI is the Leaf Area Index and LAI_{mx} the maximum leaf area index. ESCO is a parameter representing evaporation from the soil. Evaporation losses from the soil occur only after canopy storage has been emptied [22].

$$E_{soil,ly} = E_{soil,zl} - E_{soil,zu} * ESCO \quad (11)$$

Where $E_{soil,ly}$ is the evaporative demand for the soil layer (mm), $E_{soil,zl}$ the evaporative demand for the lower layer end (mm) and $E_{soil,zu}$the evaporative demand at the upper layer end (mm).

The selected parameters represent different relevant hydrological processes. For the 8 selected parameters, 243 parameter sets were generated using FAST algorithm for the parameter boundaries indicated in Table 2. Each set was run in SWAT model and the results were saved. These 243 sets of results were then used in FAST algorithm to determine the sensitivities of each of the 8 parameters over the required period of four years (2001-2004).

Table 2: Selected SWAT parameters and their ranges

Parameter	Full Parameter name	Process	Lower Boundary	Upper Boundary	Type
CN2	curve number	Surface runoff	-15	15	Add
Surlag	surface runoff time lag	Surface runoff routing	0.1	2	Range
Canmx	maximum canopy storage	Interception by canopy	0	4	Add
ESCO	soil evaporation compensation factor	Evapotranspiration	0	1	Range
SOL_AWC	available soil water capacity	Soil	-0.01	0.2	Add
Rchrg_dp	aquifer fraction coefficient	Ground water	0	0.3	Range
Gw-delay	groundwater time delay	Ground water	2	30	Range
Alpha_BF	baseflow recession constant	Ground water	0.01	0.2	Range

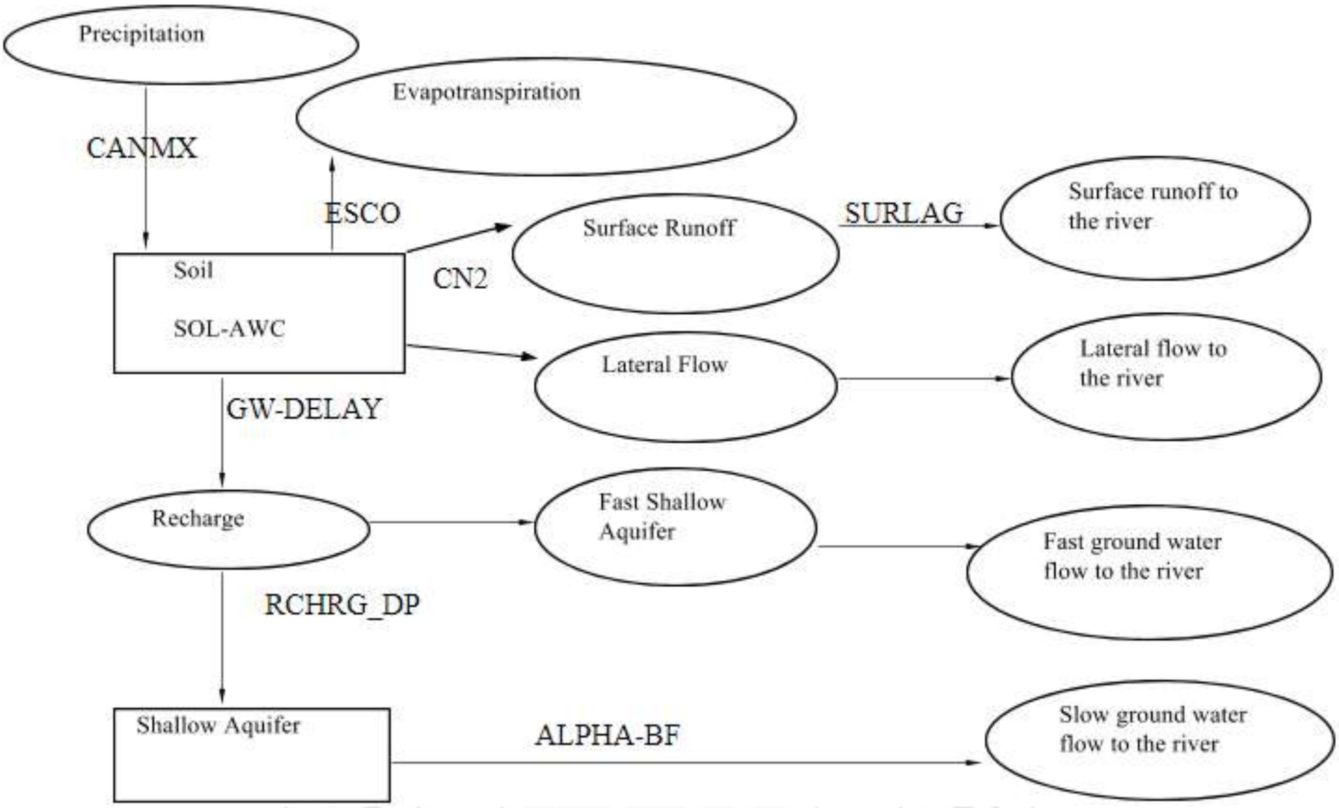


Figure 4: Chart showing hydrological processes and selected parameters

4. Results and Discussion

4.1 Temporal Parameter Sensitivity

4.1.1Runoff processes

Curve number and surlag are sensitive for short periods as shown in figure 5. Their sensitivity is mostly high during rainfall events shown in figure 6. This is because curve number is dependent on rainfall and soil moisture conditions.

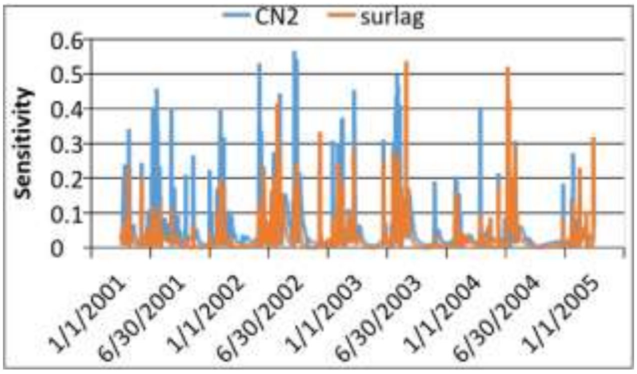


Figure 5: Temporal Dynamics of Sensitivity of CN2 and Surlag

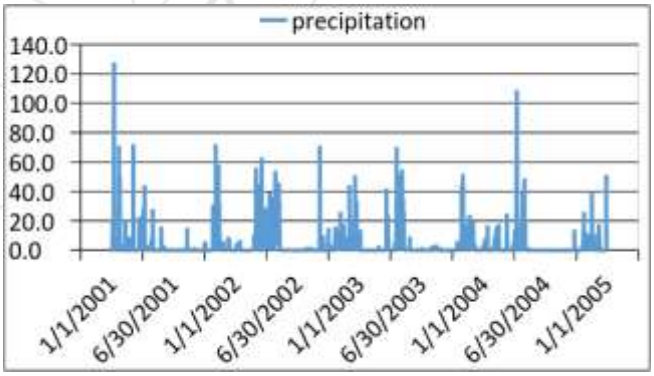


Figure 6: Precipitation

4.1.2 Evapotranspiration process

Canmx and Esco are dominant at different periods as shown in figure 7. When Canmx is highly sensitive, ESCO is a bit low. Once the canopy storage is empty soil water can be used for evaporation. It is characterized by the depth of soil evaporation (ESCO).

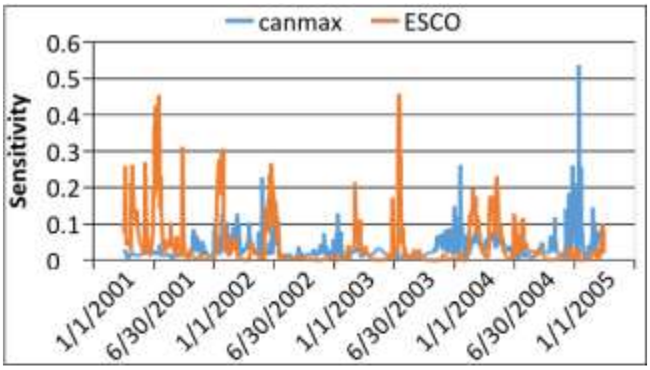


Figure 7: Temporal Dynamics of Sensitivity of Canmx and ESCO

4.1.3 Groundwater processes

Groundwater parameters are sensitive for a longer duration of time as shown in figure 8 and 9.

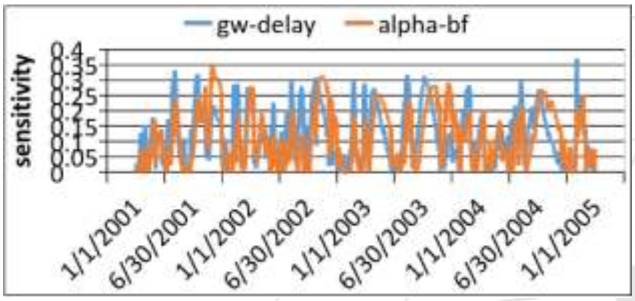


Figure 8: Temporal Dynamics of Sensitivity of Gw_delay and Alpha-bf.

4.1.4 Soil and Groundwater

SOL_AWC has periods of dominance and also periods of low sensitivity. Periods of high sensitivity are mostly detected during peak flows.

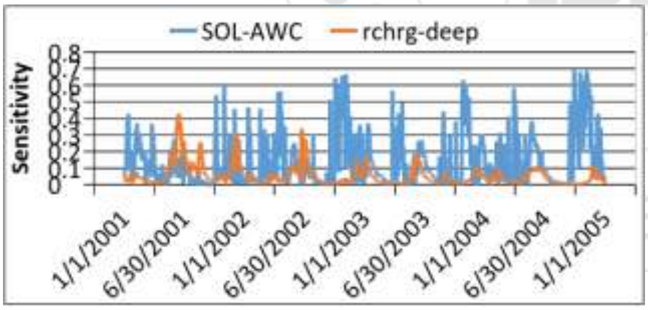


Figure 9: Temporal dynamics of Sensitivity of SOL-AWC and Rchrg-dp

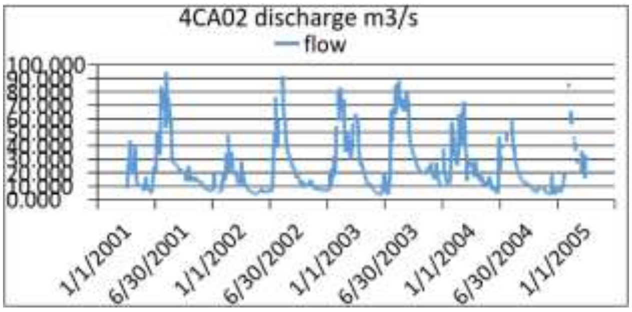


Figure 10: Discharge at the outlet of the catchment

4.2 Comparison of Flow Duration Curve (FDC) to Sensitivities

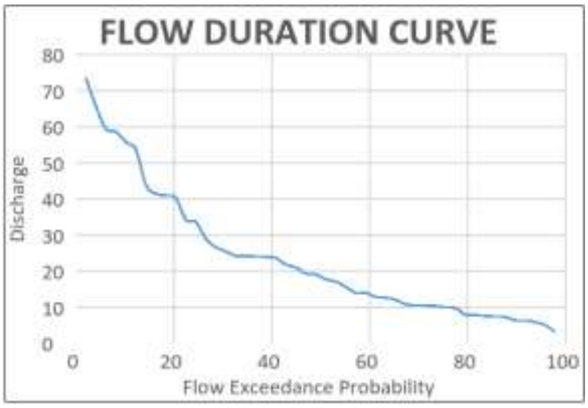


Figure 11: Flow duration Curve

The FDC was divided into five segments using the flow exceedance probability at the 5%,20%,70% and 95% points as boundaries. The sensitivities for each segment of the FDC are shown in figure 12a-12e.

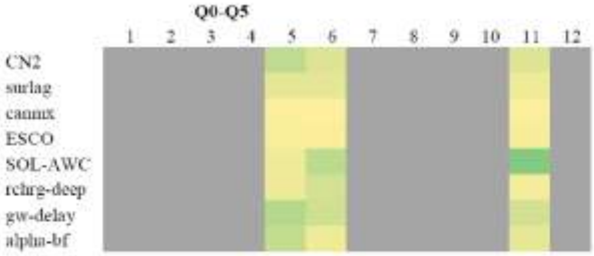


Figure 12a

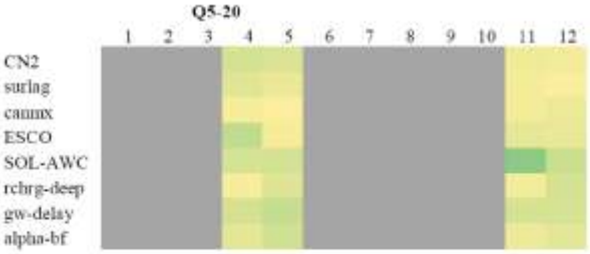


Figure 12b

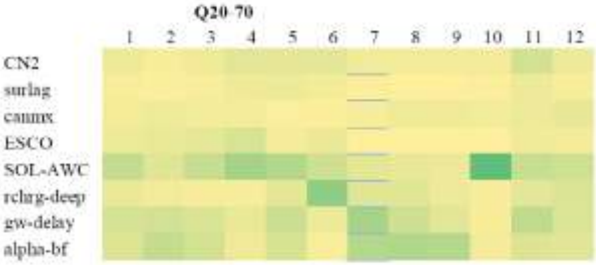


Figure 12c

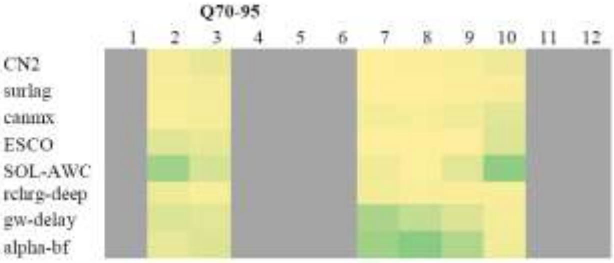


Figure 12d

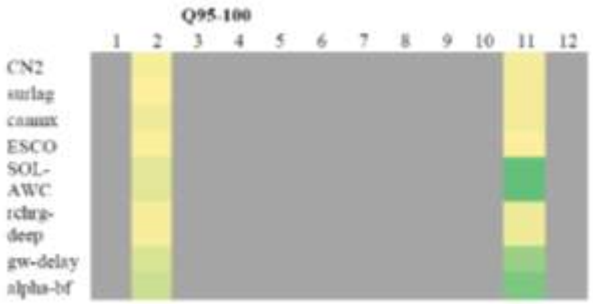
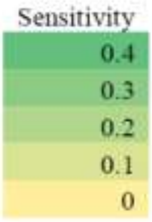


Figure 12e



Key

For the first segment of the FDC curve,Q0-Q5, the lowest sensitivities are seen for canmx and ESCO. CN2, Surlag, Rchrg_dp, Gw-delay and alpha-bf are relatively sensitive. The highest sensitivity is detected for SOL-AWC.

For Q5-20 the lowest sensitivities are seen for Canmx. All other parameters are relatively sensitive with the highest sensitivity being detected for SOL-AWC.

For Q20-70, the lowest sensitivities are detected for CN2, surlag, canmx and ESCO. All the other parameters are more sensitive with the highest sensitivity occurring for SOL-AWC.

For Q70-95 the least sensitive parameters are Surlag, CN2, Rchrg deep and Canmx. Gw-delay, alpha-bf and SOL-AWC are most sensitive.

For the low flow, Q95-100, SOL-AWC is most sensitive followed by alpha-bf and gw-delay. Rchrg-deep, CN2, surlag canmx and Esco are least sensitive for this flow regime.

5. Discussion

Whereas CN2 controls the magnitude of surface runoff, SURLAG controls its timing in contributing to stream flow. These parameters are sensitive for short periods, especially during precipitation events because runoff processes are faster compared to groundwater processes. When compared against the streamflow hydrograph in figure 10, these runoff parameters are relatively sensitive during high magnitudes of stream flow. No sensitivity is detected during low flow conditions. The occurrence of surface runoff increases in periods with high-precipitation and high-soil-moisture conditions as per the curve number method. SURLAG is sensitive also in the same phases.

Gw-delay and alpha-bf are sensitive most of the time especially at peak flows, during the start of the recession phase and the transition to base flow. For TEDPAS, their sensitivity is for longer periods compared to runoff parameters. Their sensitivities are detected in all five segments of the FDC. The highest sensitivities are detected in Q70-Q95 and Q95-Q100 segments.

Rchrg _dp is not as sensitive as the other ground water parameters during low flows .The sensitivity of RCHRG_DP increases directly as discharge increases. RCHRG_DP is the fraction of the recharge that is split between the shallow and the deep aquifer therefore its sensitivity will increase with increasing recharge values. RCHRG_DP has some periods of high sensitivity in the Q20-Q70 segment of the FDC.

High sensitivity of ESCO is noted when the streamflow is increasing towards a peak. When canmx is highest, ESCO is low and vice versa. Canmx peaks are mostly detected during and after rainfall events. This is because during this time water is intercepted by plant canopies. This water is then lost through evaporation. Only after the canopy storage is empty will the soil water used for evaporation. This explains their antagonistic nature. ESCO and Canmx are relatively sensitive in the Q5-Q20 and Q20-Q70 segments of the FDC.

For TEDPAS, SOL_AWC has periods of dominance and also periods of low sensitivity. This parameter is also sensitive in all five segments of the FDC. This pattern is detected because SOL-AWC controls occurrence of surface and lateral flows. It also controls how water percolates into ground water. Periods of high sensitivity are mostly detected during peak flows. This is because the initial conditions of the soil will affect the movement of water through the soil.

6. Conclusion

For every flow magnitude there is sensitivity for a groundwater and soil parameter. This means that ground water and soil processes are most dominant in Chania catchment.

The results show that ground water and soil processes are a main contributor of streamflow during low flows. However, ground water processes are affected by the prevailing land cover in the catchment. Practices such as deforestation which is the current trend in the catchment should be controlled. This is because these practices reduce the amount of precipitation water which is converted to groundwater. It is therefore important that Water Resources Management Authority promotes policies and practices that will protect ground water processes.

7. Acknowledgement

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Author Profile

Sharon Omollo is a postgraduate student at Jomo Kenyatta University of Agriculture and Technology pursuing a Masters degree in Civil Engineering (Water Engineering option). Her area of specialty is in hydrology and water engineering.

Jeremiah Kiptala is a lecturer at the Civil Engineering department in Jomo Kenyatta University of Agriculture and Technology .His area of specialty is in Irrigation and Water resources engineering.

John Mwangi is a lecturer at the Civil Engineering department in Jomo Kenyatta University of Agriculture and Technology .His area of specialty is in Hydrology and Water resources engineering.