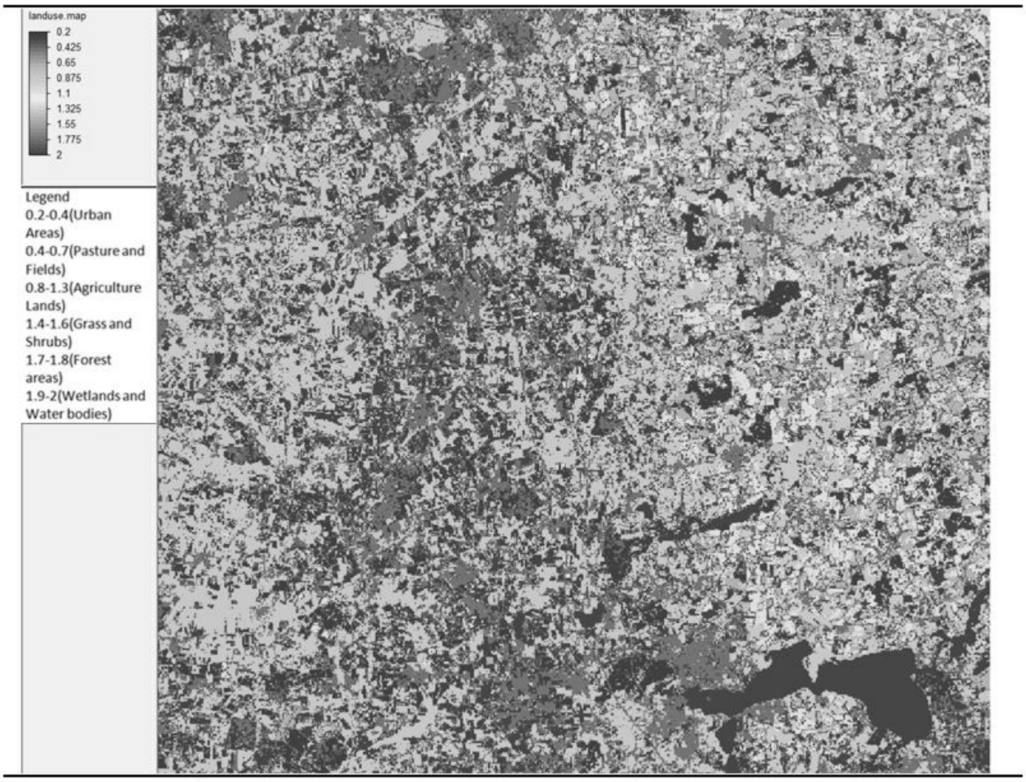
CHRISTIAN-ALBRECHTS-UNIVERSITAT KIEL

Digital Spatial Analysis

Hydrological Modelling- Kielstau Catchment



(Landuse Map Legend)

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ABSTRACT

A hydrological model for the Kielstau catchment of Schleswig Holstein in Northern Germany was developed in order to simulate discharge. Particular focus is placed on different estimation of evapotranspiration (ET) based on type of plants and how discharge is sensitive to these variations. Impacts on actual evaporation, soil water content, runoff and ultimately discharge is also analysed. Discharge results are then calibrated, interpreted and compared to observed values for further analysis. This model is developed based on measured field data, remote sensing data presented in the form of maps as well as estimated values. PC Raster is the modelling software used in this study.

CONTENT

1. INTRODUCTION

The Kielstau catchment is intercepted with different kinds of vegetative cover underlined with variations of soil types. The heterogeneous nature of this area allows the ecological states of water bodies to be influenced by numerous factors both internally and externally. These factors include precipitation, Evaporation, plant cover type, soil capacity to retain water, groundwater levels and elevation. In addition to these, the Kielstau water quality is also influenced by the predominating agricultural land use as well six municipal wastewater treatment plants (Schmalz et al., 2010).

Hydrological modelling has the potential not only to generate data which cannot be measured directly, but to determine existing and future development by the adjustments of variables and parameters to create different scenarios. The increase availability of spatial data and remotely sensed imagery has vastly increased the prospects for hydrological modelling both spatially and temporally and is crucial for catchment management (Dubayah et al., 2000).

The complexity of many hydrological models accompanied with low availability of input has not gone unnoticed. Hörmann et al., (2007), asserts that simple models are easy to setup, achieve results in shorter hours and most importantly easy to calibrate for non-hydrologists. In view of this the adaptation of a simple model is used for in this study.

The aim of the paper is to create a simple model of the catchment, based on the estimation of evapotranspiration of different plants (both increasing and decreasing) and how these variations affect other parameters in the model. The sensitivity of discharge to evapotranspiration is also articulated. In addition to this, discharge values from the model are calibrated and compared to observed values from the catchment to determine the quality of the model.

2. MATERIALS AND METHODS

2.1. Study Area

The area of study is located in the Northern part of Germany, the region of Schleswig-Holstein (Figure 1.). As part of the drainage area of the Treene, the Kielstau catchment has an area of 50 km² with smaller tributaries and agricultural drainage contributing to its main water flow. Located at the upper part of the catchment area is a nature conservation zone known as the Winderatter See (Tavares, 2006). With a total length of 17km, the Kielstau River has two important tributaries, the Moorau and the Hennebach (Lam et al., 2011).

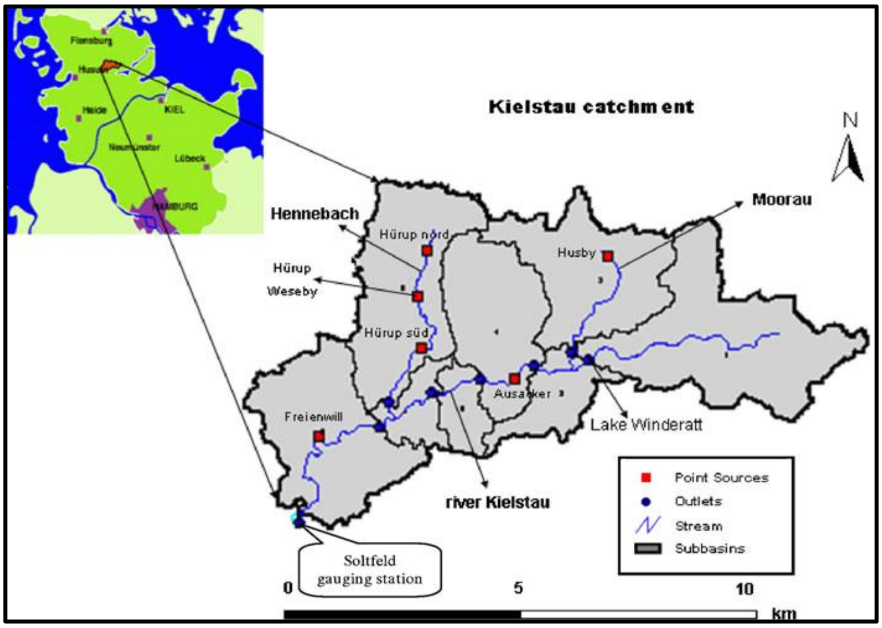

Figure 1: Location of the Kielstau catchment and Gauging Station (Lam et al., 2011)**.**

The Kielstau is located in the landscape unit of the "Östliches Hügelland" which is one of the three predominant nature areas, along with the "Geest" and the "Marsch" areas, in Schleswig-Holstein (Tavares, 2006). The topography of the catchment is generally flat but relatively uneven, with a maximum height difference of 42m. The mean annual temperature in this region is 8.2°C accompanied by frequent rain and fog (Lam et al., 2011). The soils are dominated by haplic and stagnic luvisols with the river valleys consisting of peat soils (Figure 2.). With the presence of few villages and detached farms, arable land and pasture dominates the Landuse (Schmalz et al., 2010). Application of fertilizers on farms as well as animal husbandry leads to a diffuse source pollution of nutrients which influences the stream water quality significantly. Zhang, X et al, (2008), asserts that hydrology in the Kielstau is such that monthly discharges are not always in positive correlation with rainfall volumes, which can be attributed to near surface ground water and a large wetland area. The wetland fraction of the Kielstau is estimated at 0.3 with a mean precipitation at ca. 800mm and evaporation of app. 400mm (Hörmann et al, 2007). Discharges for the catchment are measured at the Soltfeld station (Figure 1).

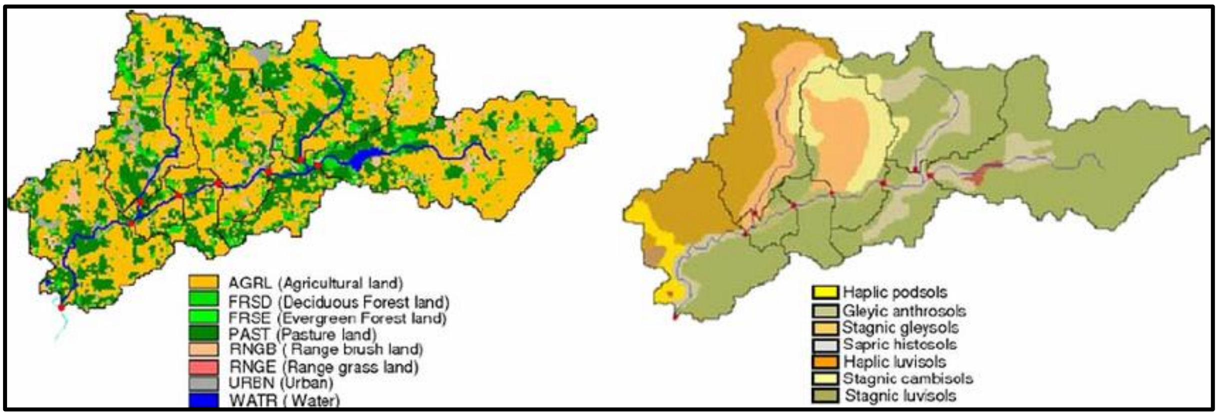

Figure 2: Soil and Landuse types of Kielstau Catchment (Lam et al., 2011).

2.2. Data and Methods

Parameter inputs for Hydrological models such as Digital Elevation Models, Landuse and Soil maps are derived from Remote Sensing data and techniques (Gangodagamage, 2011). In this model, pre-processed Landsat 8 data was derived from the www.earthexplorer.usgs.gov/ and used as input data to develop a Landuse map. Data processing, correction, sub setting and classification among others were performed using the ENVI software to develop a Landuse map for the Kielstau Catchment. Landuse and other data were provided in the form of maps and time series by Georg Hörmann and the information was analysed using PC Raster Nutshell (version 4.87). Preparation of graphs for visual analysis was done using MS Excel, 2010. “No_evap” in displayed graphs represents a hypothetical situation where there is no evaporation, “base” represents the base model, “Landuse” the Landuse map, “Field” open fields with not plants; and the other names represent their various vegetation types. The basis for the base model, parameter values used as well as modifications would be elaborated in this chapter.

2.3.Base Model

Precipitation and evaporation values served as measured input for the discharge model. This data was presented in time series and was collected and measured at a single station which is the Soltfeld station; however values are modelled for the whole catchment area. The script for the Digital Spatial Analysis lecture (Hörmann, 2017) clearly illustrates the various parameters and variables necessary for developing a basic hydrological model based on the water balance expressed in Figure 3 below. A brief description of these variables based on presentation in the base model script, especially in conjunction with evaporation is highlighted. Values set for the various parameters in the base model are expressed in Table 1. The time step of the model was adjusted to 9860 steps out of precipitation and evaporation data collected from 1989 to 2014.

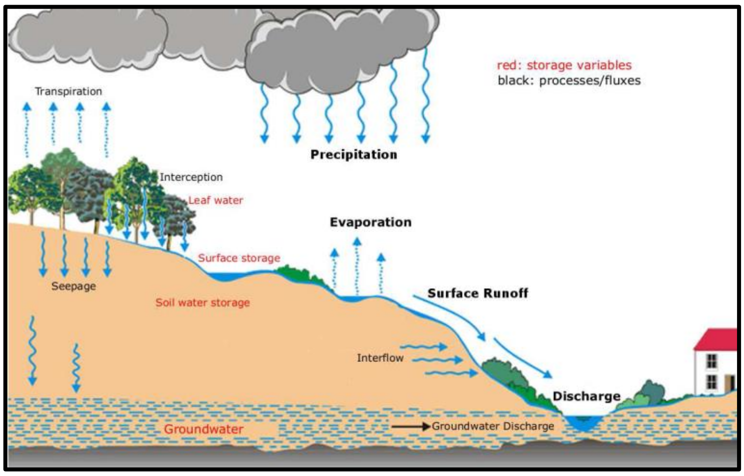

Figure 3: Water Balance (Hörmann, 2017)

Interception and ‘rest’ variables

Interception is basically the rainfall which does not reach the soil due to vegetation interfering in its path. Vegetation has different interception capacities based on their LAI, type of vegetation as well as volume (Toba et al., 2005). These factors among determine volume of precipitation prevented from reaching the soil surface. When the capacity is exceeded, the rest is then transferred to the next layer and finally to the soil surface. Interception for this model was set as a constant value for all surfaces. Evaporation of intercepted precipitation occurs according to the potential evaporation of that vegetation and the higher the potential evaporation the likelihood for all the water of the bucket to evaporate.

The amount of evaporation and precipitation which is transferred to the soil is the content of the rest variables; “rest_et” and “rest_precipitation” respectively. Rest_et is calculated by subtracting evaporation from interception, whereas rest_precipitation is precipitation minus interception.

Actual Evaporation and Soil properties

Actual Evaporation (ETa) is influenced by variables such as the soil properties and interception values and is an important water balance component. ETa is based on the premise that when there is the presence of sufficient water in a soil; ETa is equal to ETp, however as the soil begins to dry up ETa also becomes less than ETp. Here the ETa takes a linear form, based on the soil properties and continues to wilt towards zero.

In view of this, salient physical soil parameters have to be included in the development of the model. Soil field capacity is one of such parameters and it expresses the water content at field capacity which is basically the highest volume of water a soil can contain. Soil start reduction is the point in water content where ETa becomes lesser than ETp showing an onset decline in both evaporation and soil water content. For this model, ETa was calculated such that if soil water content is higher than start reduction then ETa is equal to rest_et. If not, ETa becomes rest_et multiplied by the value of Soil water content divided by Soil start reduction.

Soil water content is essentially the water present in the soil and this can be calculated firstly by adding rest precipitation to already existing water content. Initial surface runoff has already been subtracted from this rest precipitation before being added. Infiltration of the soil which is basically the ability of water to penetrate through the soil, determines the volume of precipitation which runs off immediately. In addition to this, evaporation, overflow of water as water storage fills up as well as groundwater flux is also subtracted, leaving the resultant value as the final Soil Water Content.

In a situation where soil water content becomes more than soil field capacity there has to be an outlet where excess water flows. In order to achieve this, a water flux to the groundwater is developed (gw_flux). Storage groundwater also releases a portion of its water towards the surface and this is determined by the groundwater factor (gw_factor), leaving the remaining values as the final ground water content. Finally the discharge is calculated using the Kinematic wave approach. A virtual gauging point is created as the outlet for estimated discharge.

Table 1: Parameters and values set for base model

	Parameter	Base Value
1	Interception Capacity(Inter_cap)	1mm
2	Soil field capacity	200mm
3	Reduction point(soil_start_reduction)	100mm
4	Infiltration factor(Infil_fac)	0.3
5	Groundwater factor(gw_factor)	0.1

2.4. Modification of Base Model and Simulated Models

The main focus of this study was to estimate evapotranspiration (ET), both plant specific as well as increasing evaporation and analyse how these alterations would affect other parameters and sensitivity of discharge to it. A total of eight simulate model runs including the base model are produced in order to test the sensitivity of the model to these alterations.

Different crop coefficient values are assigned to different plant types for this analysis. In reality, crop coefficients are influenced by factors such as crop type, stage of growth, health of plants, canopy, temperature, soil moisture and cultural practices among others (Allen et al., 1998). However in these simulations, such data is unavailable hence co-efficient assigned where conjectured developed based on evaporation characteristics displayed by different plant types postulated by different scientist (eg. Zhang et al., 2001, Wang et al., 2012). Using the simple estimation method ("ET=Kc x ETo", where for this study "Kc" is the proposed coefficient and "ETo" is Potential evapotranspiration (ETp)), evapotranspiration for different plant type is estimated (Allen et al., 1998).

Forest, Grass, Shrub, and Agricultural Crops are taken into consideration for this analysis. Forest is known to have a higher potential ET than other vegetation types such as grass, pasture and crops; this is due to plant water available capacity (Nepstad et al., 1994). In view of this the highest co-efficient was assigned to forest, with grass closely following it. Moisture levels for grass and shrub are relatively lower than forest but higher in grass than shrubs (Wang et al., 2012). Estimated ET was higher in grass than shrub for this simulation. Agricultural crops are mostly intercepted with bare grounds and not totally covered as in the case of vegetation like grass or forest and this account for relatively lower amount of interception, hence the relatively lower ET (Chen et al., 2010). Among all the four plant used in the model runs, "Crops" where estimated to have the least values of evapotranspiration. To also asses the effects of extremely low ET values, bare field with no vegetation is also modelled. Different Coefficient values are also assigned to various landuse types in the Landuse map derived. A legend of the map is included in the files presented. This Landuse map is then used as a coefficient for one of the simulated models. A simulation with no presence of ET was also modelled as an extreme case and how hypothetically no evaporation at all affects other parameters. Table 2 below highlights the actual weights applied to the different vegetation type which where multiplied by potential evaporation while Figure 4 shows the graphs of output of these weights applied from 2011-2013.

Table 2: Coefficient values for vegetation and simulations

	Vegetation/Simulation	Coefficient Value
1	Base	1
2	Forest	1.8
3	Grass	1.6
4	Shrub	1.4
5	Crop	1.2
6	Field	0.5
7	No evaporation	0
8	Landuse	0.2-2

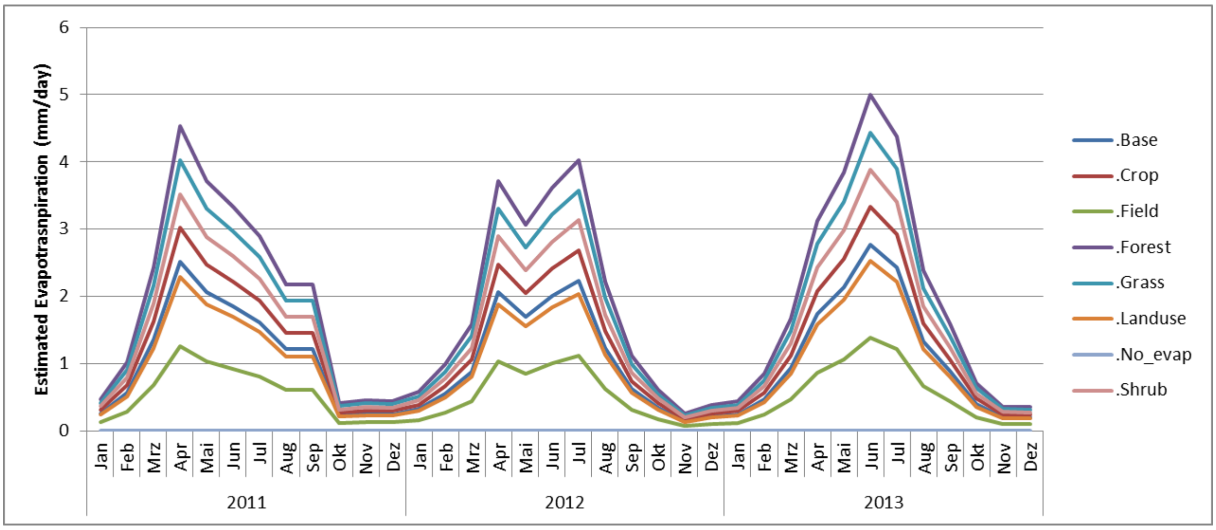

Figure 4: Actual Estimated ET in mm/day from 2011-2013

The figure above shows the estimated evapotranspiration created from the weights applied to the observed ET. These values are the start ET attributed to different plants which influences the outcomes of the other parameters to be analysed.

3. RESULTS AND DISCUSSION

3.1. Influences of estimated evaporation on other Parameters

In eight model runs, the parameter potential evaporation (ET) is altered using different plant co-efficient assigned to different vegetation types and simulations, with all other parameters being constant. In the first set of results, actual evapotranspiration derived from estimated ET is produced. Soil water content and runoff is analysed to determine how evaporation influences these parameters. In an attempt to show clear representation and disparity between different model runs, only three years (2011-2013) out of the total time step (1989-2014) calculated would be represented in the form of graphs.

Estimated Actual Evapotranspiration (ETa)

Model runs resulted in different values for ETa among the different types of plants and simulations. Results derived show a clear positive relation between ETp and ETa, where actual evapotranspiration increases with increasing potential evaporation. Plants and simulations which have higher co-efficient values (see Table 2), and as such higher estimated ET (see Figure 4) also record higher values for ETa (Figure 5).

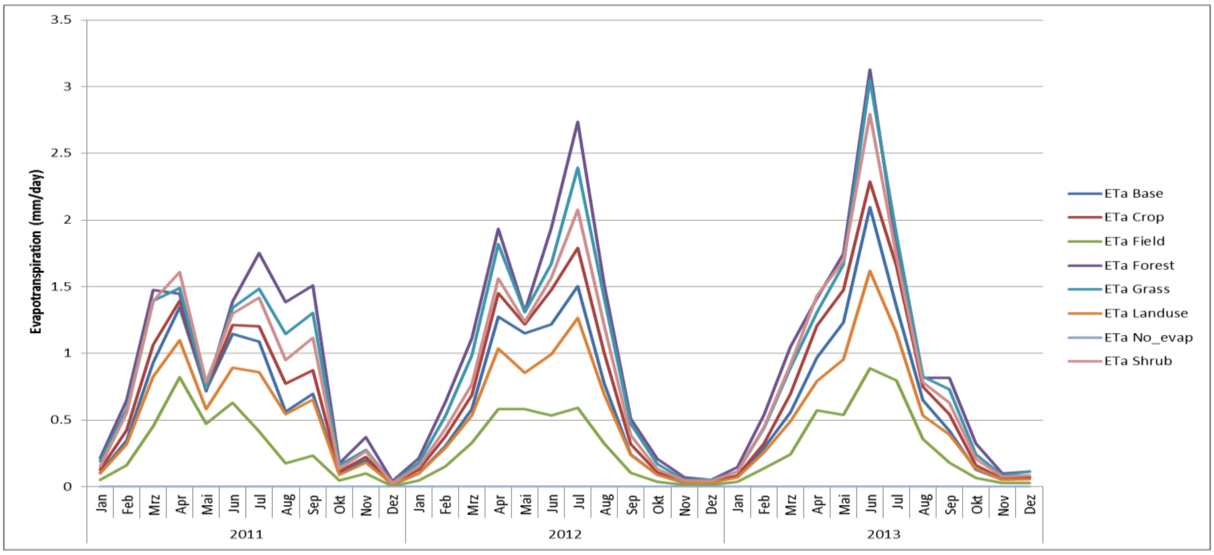

Figure 5: Monthly average of actual evapotranspiration in mm/day.

Figure 5 indicates the highest monthly average of 3.1mm/day found in forest with a closely followed 3.0mm/day in grass. The lowest obviously is “no evaporation" with field having 0.8 mm/day following at the bottom. A sum of all the evaporation from these years reflects the same disparity characteristics in Table 3. The graphs above show ETa from Landuse map as lower than the base model. This is due to the differences in land surfaces with different coefficients in the map, with some higher and lower than that of the base model. Majority of this surface being agricultural lands and pasture; leads to relatively lower coefficients depending on crop and surface type. (Legend of Landuse map illustrates this).

Table 3: Model results for sum of evaporation from 2011-2013 in mm.

Model Runs	Base	Crop	Field	Forest	Grass	Landuse	No_evap	Shrub
Sum	683	795	327	1076	990	573	0	920

Soil Water Content

The average highest soil water content recorded is from the model with no evaporation content and the lowest is that of forest. In this case, areas with the higher coefficients and values for ET tend to have lower soil content and vice versa. Figure 6 bellow illustrates this.

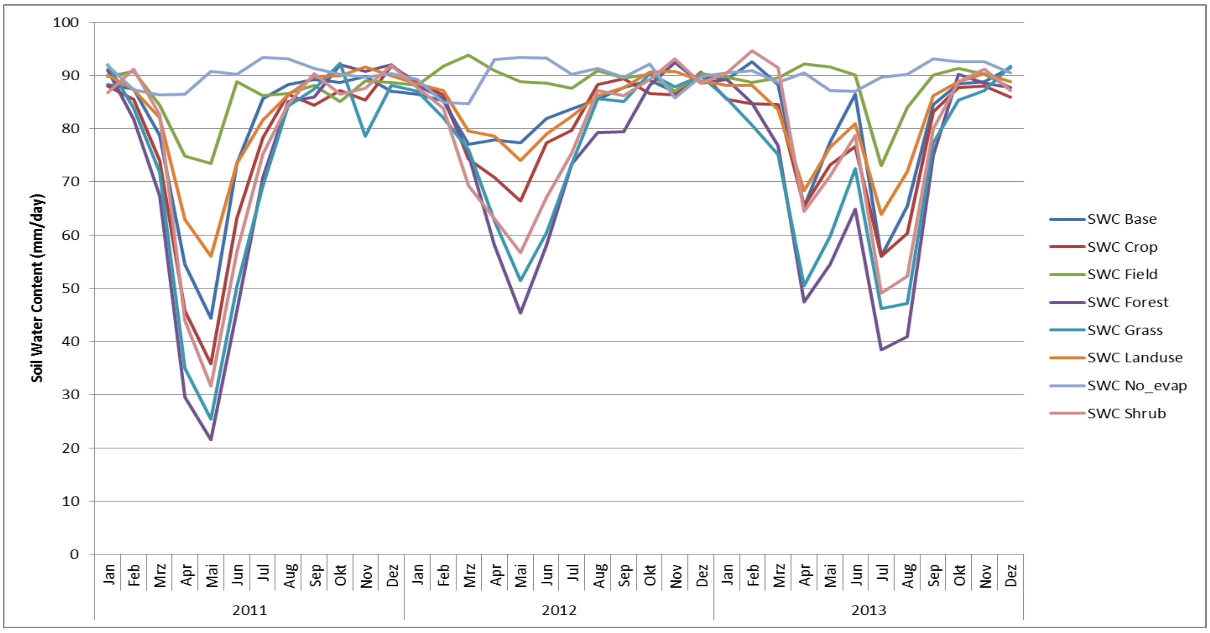

Figure 6: Monthly Average of soil water content in mm/day (2011-2013).

The "SWC No_evap" graph seems to be constantly high with no sudden depressions and troughs experienced in the other graphs, and this is because it is not influenced by evaporation. Evidently the relationship between soil water content and evapotranspiration is negative, where increased evapotranspiration results in decreased soil water content values.

However the disparity between soil water content are closely related than that of actual evapotranspiration. Table 4 sheds more light on this using total average for the three years.

Table 4: Model results for total average of evaporation from 2011-2013 in mm.

Model Runs	Base	Crop	Field	Forest	Grass	Landuse	No_evap	Shrub
Total Avg.	81.6	78.3	87.8	72.3	73.6	82.5	90.0	77.6

Surface Runoff

Surface runoff does not exhibit a clear pattern like the other parameters analysed so far. More often than not results show that surface runoff values for all the model runs are close to each other during certain periods (Figure 7).

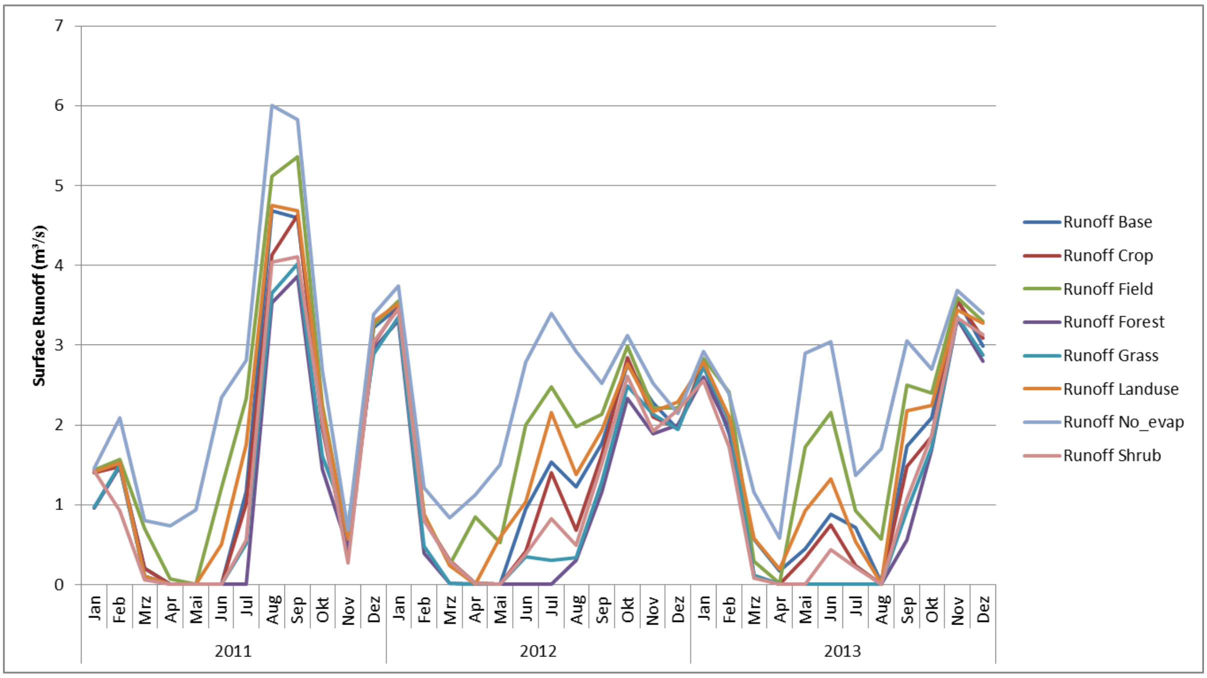

Figure 7: Monthly Average of Runoff in m³/s (2011-2013).

Results from October of 2011 to February of the following year show that values are almost the same which is replicated from October, 2012 to February of the following year as well (Figure 7). This suggests a pattern which can be attributed to other parameters such as climate (precipitation and temperature), ground water and infiltration. This suggests that evaporation is not as strong an influencing factor in this parameter.

3.2.Sensitivity analysis of Simulated Discharge to ET

This second set of results looks at simulated discharge from all the model runs and how altering the parameter evapotranspiration (ET) influences this as well. Values in the table below represent data gathered for simulated discharge from 1989- 2014 for all the model runs representing 9353 data sets (Table 5).

Table 5: Model results for simulated discharge in m³/s from 1989-2014.

	Parameter/ Vegetation	Mean Discharge (m^3/s)	Total Discharge (m^3/s)	Maximum Discharge (m^3/s)
1	Base	8.33	77948.07	157.81
2	Forest	6.10	57091.58	250.66
3	Grass	6.53	61109.80	262.59
4	Shrub	7.10	66456.21	223.07
5	Crop	7.68	71851.01	254.88
6	Field	10.56	98752.20	170.83
7	Landuse	9.03	84485.63	164.03
8	No evaporation	13.42	125517.66	127.29

Mean discharge values for all model runs range from 8-13 m^3/s and these are relatively high. Comparing discharge of base with other simulations, three of the model runs have higher discharge than the base with 61% higher with no evaporation, 26% increase for open fields and, 8% for increase in Landuse. On the other hand lower discharge than the base is recorded for the remaining four with 7.8% lower for crop, 14% lower in shrub, and 21.6% lower in grass and finally 26.76% lower in forest. Despite the fact that total discharge follows a pattern of being higher with lower evaporation, maximum discharge varies with grass being the highest as opposed to the expected forest. Minimum values where not displayed in the table because values where really similar and close to absolute 0. The graphs in Figure 8 show the clear variations in discharge for entire model runs which cannot be identified only with the statistical data.

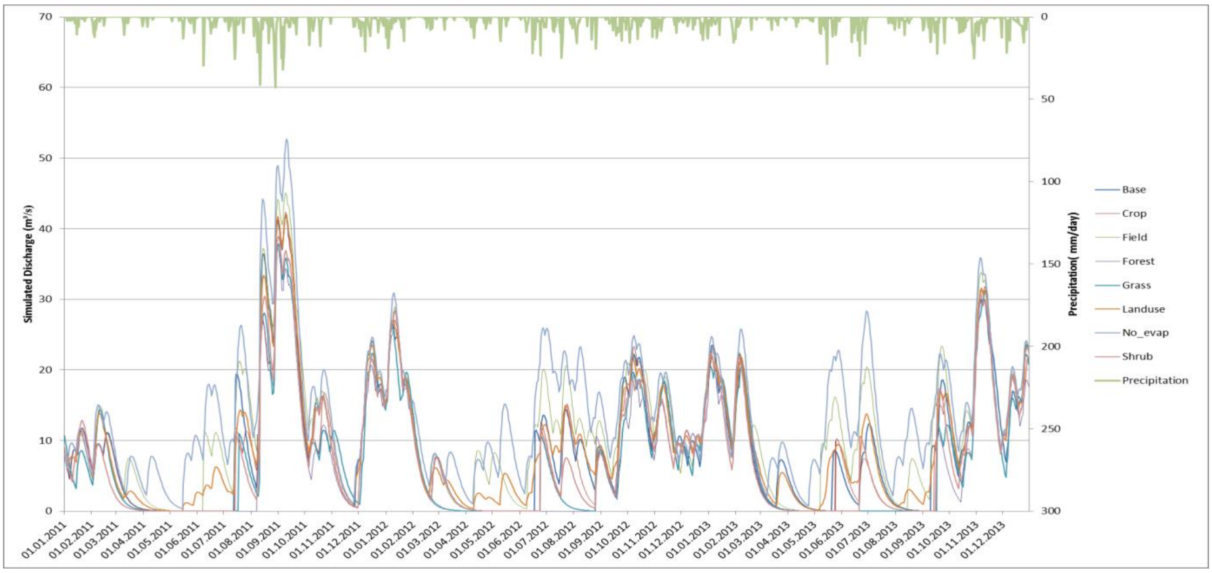

Figure 8: Daily Precipitation and Discharge values for model runs (2011-2013).

Despite the variations, discharge values are similar more often than not for all simulations; these similarities can be seen from August, 2011 to March, 2012 as well October, 2012 to April, 2013. The uniqueness of daily discharge is that, it does not conform to a particular pattern based on the highest or lowest evaporation. Some days for instance values for field are higher than no evaporation and vice versa. In conclusion discharge is sensitive to changes in ET, however it competes with other factors like infiltration and temperatures, hence does not have a very strong influence as majority of the graphs and values recorded are still close to that of the base model unlike that of ETa and soil water content (Figure 5).

3.3.Comparison between Simulated and Observed data

In order to compare simulated and observed data there are indices which can be used to calculate the errors and differences. Average error (AE=P-O) is one of these method, where O represents observed and P predicted values. Results of these in addition to two other indices, Mean absolute error (MSE) and regression co-efficient (r^2) are displayed in Table 6 below. It is important to calculate for r^2 in addition to other error methods since it provides a definite range between 0 and 1; where 1 represents a perfect correlation, hence easier to analyse (Dawson et al., 2007).

Table 6: Model results for error between observed and simulated discharge from 1989-2014.

Calculation	Base	Crop	Field	Forest	Grass	Landuse	No_evap	Shrub
Regression (r^2)	0.32	0.30	0.25	0.36	0.33	0.31	0.17	0.33
Mean abs. error	0.96	0.89	1.22	0.70	0.76	1.03	1.56	0.82
Average error	7.8	7.1	10.1	5.5	6.0	8.6	13.1	6.7

The high error between measured and simulated values can be identified, with the largest error found in the simulation with no evaporation and the smallest in that of the forest (Table 6). The regression results validates that majority of the modelled base data did not fit the observed one.

The simulated discharge value used for visual comparison is the one from the base model and Landuse map (Figure 9). The base model because it is the model in which all other models where modified from and as such influences their output and to identify how close it actually is to observed data. In the case of landuse, measured data is influenced by different spatial factors similar to the one represented with the landuse map.

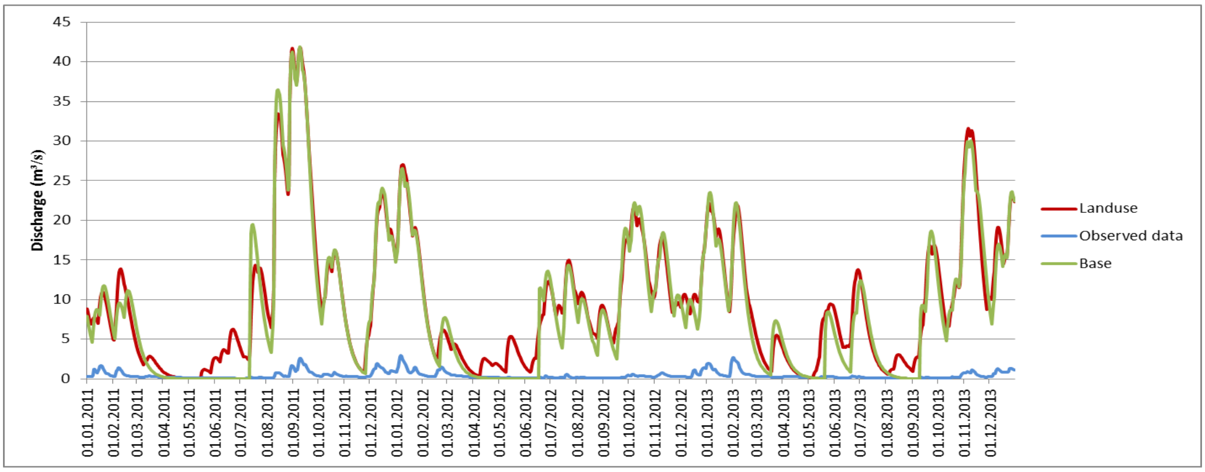

Figure 9: Daily Discharge values for model runs and Observed values in ms³/s (2011-2013).

The result clearly indicates that the calibration of the base model is not optimum and as such reflects on the other results from other models as well. Regardless of the huge numerical differences between observed and predicted base values, they possess similar peaks and troughs at similar time periods. This can be attributed to climatic conditions such as precipitation, temperature as well as evaporation patterns.

4. CONCLUSION and OUTLOOK

The outcome of model runs and analysis clearly conveys the importance of hydrological modelling in determining the extent to which environmental factors affect the phenology of water bodies. To test the effect of evapotranspiration (ET) in plants on natural water balance, estimation of ET was done using conjectured crop coefficients.

Results from this study, highlighted the fact that evapotranspiration has a strong influence on other parameters such as ETa, soil water content, runoff and ultimately discharge. Models with higher estimated ET (higher coefficient) displayed higher ETa values as well. On the hand soil water content and runoff generally displayed a negative correlation where they reduced with increasing evapotranspiration. Discharge values despite its similar patterns as runoff did not always conform to the differences in ET suggesting that other parameters such as precipitation, relief and temperature has a much stronger influence on discharge.

Comparing observed discharge and predicted base discharge confirms the importance of parameter estimation and modification. Selection of parameter values for the base model influences the quality of model outputs as well as models developed based on it. The use of diverse indices to calculate errors allow for the calibration of models to produce accurate results. Calibration indicated that values set of the base model was not optimum hence results where divergent from observed data.

Other factors affecting evapotranspiration, hence its estimations were not considered for this model. In subsequent studies, using a well calibrated base model, the combination of temperature, crop coefficient and humidity in the estimation of ET would influence results by providing a much better spatial and temporal perspective.

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