# USING REMOTE SENSING DATA TO MODEL GROUNDWATER RECHARGE POTENTIAL IN KANYE REGION, BOTSWANA

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**KEY WORDS:** Remote Sensing, Water Resources, Groundwater Recharge, Arid Areas, Kanye Region, Limpopo Catchment

**ABSTRACT:**

This study focuses on the groundwater recharge potential in the upper Limpopo catchment starting from Kanye region in South Botswana. Existing high resolution remote sensing data were used to estimate the spatial distribution of potential recharge and discharge of aquifers in this semi-arid region. 29 NOAA AVHRR images available for Southern and Central Botswana between 1996 and 2000 were analyzed to produce 29 $K_c$ maps. The comparison of $K_c$ maps in wet and dry seasons shows similar patterns over the upper Limpopo catchment in Kanye region. The conclusion can be drawn that the $K_c$ pattern does not significantly change with time over the region. Therefore the time averaged $K_c$ map can be used together with a map of potential evapotranspiration to calculate actual evapotranspiration for the period 1996-2005. Ten year averages of actual evapotranspiration and precipitation together with the averaged discharge of the catchment to the Limpopo River are then used to calculate a potential recharge/discharge map using the water balance equation. The problem of passing from the potential recharge/discharge map to the actual recharge/discharge map will have to be solved in future research.

## 1. INTRODUCTION

In arid and semi-arid areas, groundwater is often the only water resource, which is available around the year. Groundwater basins are not a resource in itself but long term storage reservoirs. For their sustainable management the recharge is the crucial figure required. Groundwater basins can be viewed as nested systems of recharge and discharge areas, with discharge appearing in the form of springs, streams or evapotranspiration. The understanding of such systems is the prerequisite for their management.

It is difficult to determine the properties of large aquifers, such as transmissivities, storage coefficients and similar parameters, in sufficient resolution. Modelling large aquifers seems an almost hopeless task. But the essential information for water availability is the information on fluxes in and out of the storage. For evaluation of the water balance of an underground reservoir fortunately many types of remote sensing data available nowadays can be employed. The water balance of an underground storage reservoir is determined by precipitation, surface runoff and evapotranspiration and of course anthropogenic abstractions. For all these hydrological components directly or indirectly related remote sensing products are available in relatively high spatial resolution (Brunner et al, 2007).

The main objective of this study is to use the existing remote sensing data to determine the spatial distribution of recharge and discharge of aquifers in semi-arid areas, so that later a hydrological model can be developed to quantify water availability over large geographic domains. The model will then be used to analyze options of sustainable water usage and local water resources management.

Botswana is semi-arid with little net surface runoff from its territory. The mean annual rainfall varies from a maximum of over 650 mm in the extreme north-east area of the Chobe District to a minimum of less than 250 mm in the extreme south-west part of Kgalagadi District. The rainy season is in the southern hemisphere summer, with October and April being transitional months. January and February are generally regarded as the peak rainfall months. Average temperature ranges from 5 to 23 degrees Celsius in July to 18 to 31 degrees Celsius in December or January. A catchment in the vicinity of Kanye will be focused on. Some preliminary modelling work in this region has been done by Wacker and Webersberger in 2003, which could be used in this study to provide the geological and hydrogeological background.

## 2. METHODS

### 2.1 Water Balance

For long-term averaged steady-state conditions, the recharge rate can be calculated from precipitation and evapotranspiration as:

$$\boldsymbol{R = P - ET - Q} \qquad \textbf{\textit{(1)}}$$

where $\boldsymbol{R}$ = recharge rate
$\boldsymbol{P}$ = precipitation rate
$\boldsymbol{ET}$ = actual evapotranspiration rate
$\boldsymbol{Q}$ = surface runoff (all in mm/yr)

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A negative recharge is a discharge (If ***R*** of an area becomes negative, the area is a discharge area.).

In semi-arid regions actual ET and precipitation are uncertain figures of similar magnitude. Therefore no reliable information concerning absolute values of recharge can be obtained by the surface water balance. Still, the resulting difference-map (P–ET) can be used for the identification of distinct zones of potential for recharge or discharge if such zones show up in a systematic fashion.

## 2.2 Precipitation

Precipitation can be estimated from cloud temperature and height derived from various satellites. An example of the application of such algorithms is the estimation of precipitation over southern Africa, provided by Famine Early Warning Systems Network (FEWS NET) in 8 km resolution since 1995. It utilizes Meteosat V satellite data, Global Telecommunication System (GTS) rain gauge reports, and microwave data from SSM/I and AMSU for the computation of estimates of accumulated rainfall. Rainfall Estimates (RFE) are produced by NOAA/CPC (Climate Prediction Center) and the data for the whole of Botswana are available for download (http://www.cpc.noaa.gov/products/fews/data.html). In this study we used the precipitation data between 1996 and 2005.

## 2.3 Evapotranspiration

Actual evapotranspiration $ET_{act}$ can be calculated as the product of a potential evapotranspiration $ET_0$ and a crop coefficient $K_c$:

$$\boldsymbol{ET_{act}\,(x, y, t) = K_c(x, y, t)\; ET_0(t)}$$

The potential $ET_0$ is the ET rate for a crop with a defined height as well as a defined surface roughness and bulk stomatal resistance. The potential ET in this study was calculated using the FAO Penman–Monteith equation with the data available from local meteorological stations in South and Central Botswana on a daily basis for the period of ten years from 1996 to 2005.

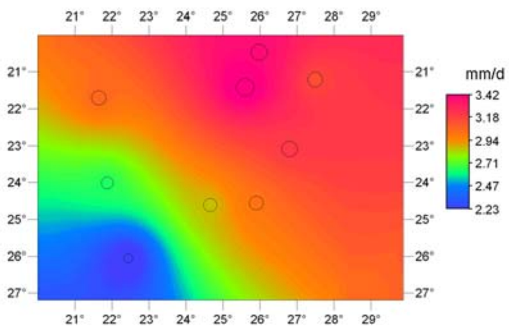



Figure 1: Potential ET calculated from meteorological station data with moving average interpolation on 09/07/1998.

It was shown in previous studies that the crop coefficient pattern over a region is usually relatively constant, although the values change from month to month. Such patterns can be used to estimate a more realistic spatial distribution of recharge/discharge than what would be obtained under the assumption of homogeneity over the whole region (Brunner et al. 2004).

The crop coefficient of a specific day can be estimated from the ratio of actual evapotranspiration of the day $ET_{24}$ and the potential ET of the same day. NOAA AVHRR (1.1km resolution) images and a simplified surface energy balance algorithm described by Roerink et al. (2000) were adopted to calculate $ET_{24}$ whenever a clear image without clouds could be obtained. An example map is shown below:

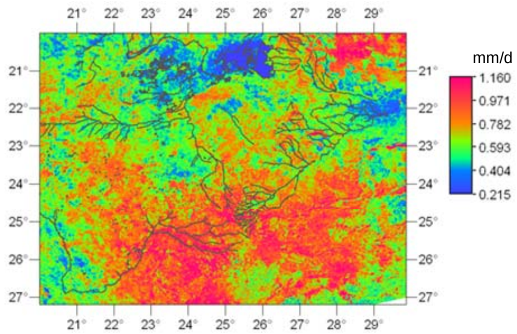



Figure 2: Actual $ET_{24}$ map calculated from NOAA 14 AVHRR image on 09/07/1998.

Together with the $ET_0$ map, a $K_c$ map can be calculated for the day (09/07/1998) as shown in Figure 3.

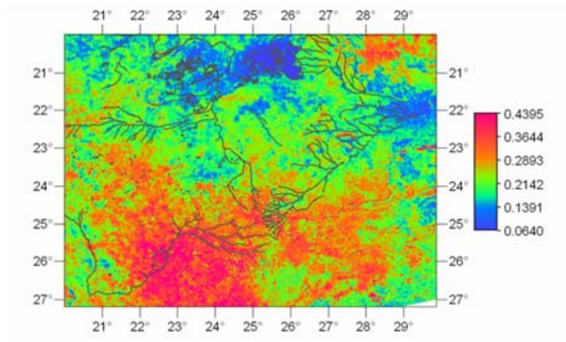



Figure 3: $K_c$ map calculated from $ET_{24}$ map and $ET_0$ map for 09/07/1998.

29 such images can be obtained from the NOAA 14 satellite between 1996 and 2000. These images were analyzed to obtain an averaged $K_c$ pattern over the five year period (from 1996 to 2000), which is assumed to provide a reasonable estimate for the studied period 1996 to 2005.

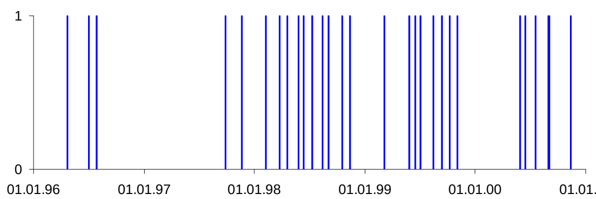



Figure 4: The dates of available cloud-free NOAA 14 AVHRR images from 1996 to 2000 applicable for $K_c$ calculation.

### 2.4 Runoff Network Calculation

Although surface runoff in arid or semi-arid region is small compared to both rainfall and evapotranspiration separately, it could play an important role in determining the actual recharge in the region, as the difference of annual rainfall and evapotranspiration is small. Since it is impossible to estimate the surface runoff of every pixel of the region, we make use of flow measurements on the Limpopo River in calculating the water balance over the whole catchment. Seleka Farm gauging station was chosen as the outlet point of the catchment studied. The DEM map from the Shuttle radar topography mission (SRTM) data (90m resolution) was used to generate the catchment area and drainage network of the Limpopo River above the gauging station at Seleka Farm.

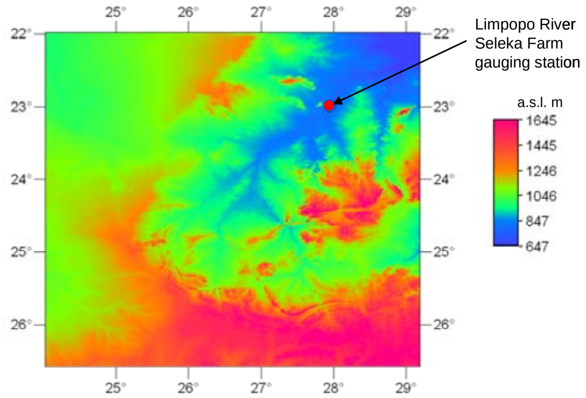



Figure 5: DEM map of Kanye region with location of the gauging station Seleka Farm on the Limpopo River.

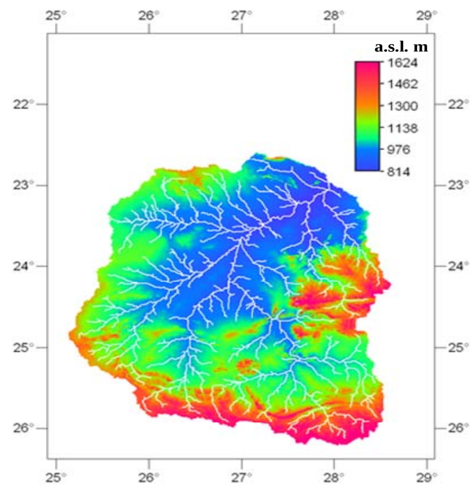



Figure 6: Catchment above Seleka Farm gauging station and drainage network.

Once the catchment area is determined, the flow at the river outlet can be used to estimate the overall runoff from the catchment region. The available local flow measurements at Seleka Farm gauging station were analyzed and compared to monthly rainfall on the catchment (Figure 7). It is shown in Figure 8 that the annual accumulated rainfall over the catchment is highly correlated with the annual flow. A fitting curve can be used to estimate the flow rate at Seleka Farm station for the years when no flow measurements are available. By doing this a ten-year averaged surface run-off from the catchment area could be estimated and used for water balance computations of the whole catchment.

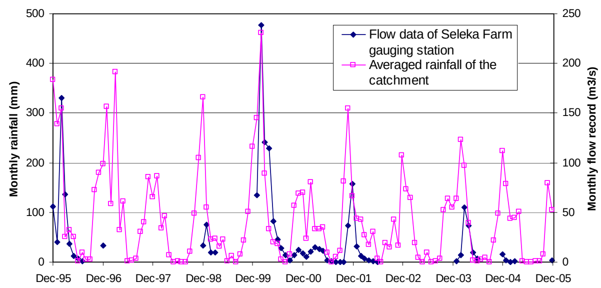



Figure 7: Flow data from Seleka Farm gauging station plotted against monthly rainfall in the catchment.

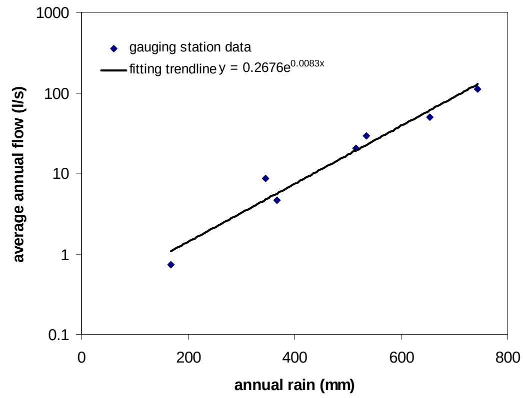
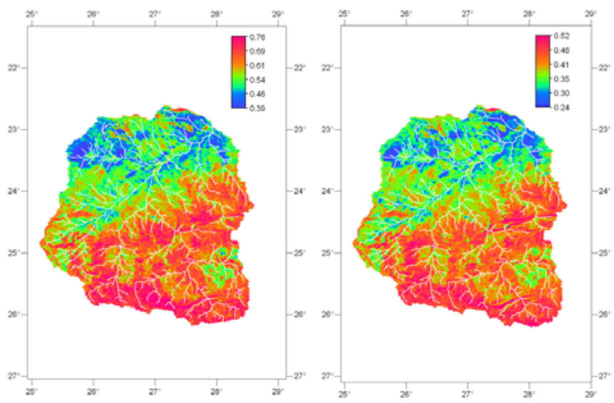



Figure 8: Annual flow from Seleka Farm gauging station plotted against annual accumulated rainfall.

## 3. RESULTS AND DISCUSSIONS

The crop coefficient of the catchment was calculated in both wet and dry season using available AVHRR images. The comparison is shown in Figure 9. It is obvious that the patterns of $K_c$ in wet and dry seasons look very similar although the mean value is higher in the wet season.



(a) Wet season (b) Dry season

Figure 9: Five-year-average $K_c$ map of the catchment in wet season and dry season.

A cross correlation of the two $K_c$ maps in Figure 10 confirms the similarity in the patterns. This means the spatial $K_c$ variation pattern is consistent within the five years between 1996 and 2000, when the images were sampled.

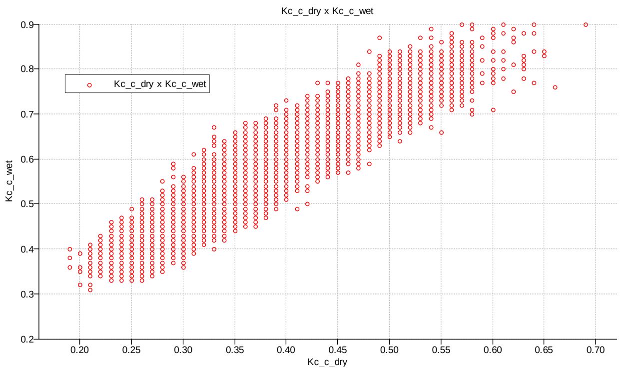



Figure 10: Cross correlation of the $K_c$ maps in wet and dry seasons

It is therefore reasonable to assume that this $K_c$ pattern can also be used as an averaged spatial $K_c$ pattern for the study period 1996 to 2005. However, the actual value of $K_c$ changes each month due to the different stages of vegetation growth through the year. This variation is shown for the spatially averaged $K_c$ values of the catchment for the available years in Figure 11.

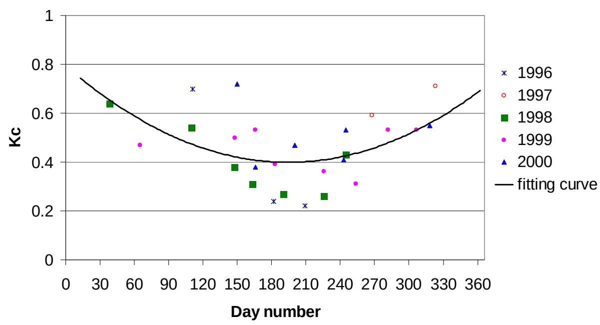



Figure 11: Spatially averaged $K_c$ values of the catchment plotted against day number of the year.

Analyzing the available spatial means of $K_c$ yields an annual mean value of $K_c$ over the catchment area of 0.48. This value together with the pattern map can then be used to produce the averaged annual $K_c$ map over the study period, which is shown in Figure 12.

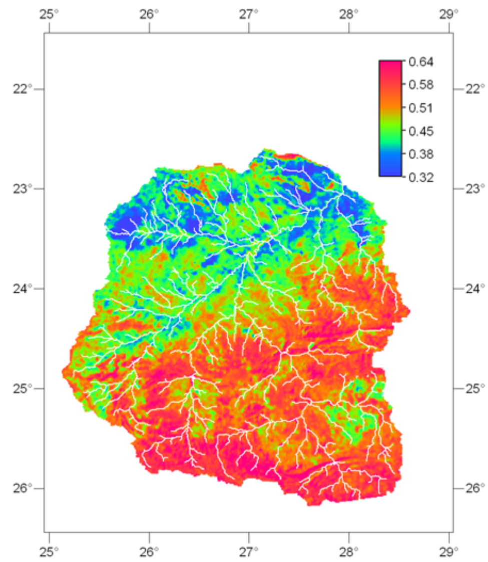



Figure 12: Averaged annual $K_c$ map

As $ET_{24}$ can only be calculated from NOAA AVHRR images for clear sunny days, using the resulting crop coefficient values to estimate the crop coefficient over the whole year will result in an over-estimation of ET, due to the neglect of cloud cover effects. The recharge map calculated from the overestimated $K_c$ tends to underestimate recharge of the region. Therefore the $K_c$ map needs to be calibrated with the water balance equation.

For the period 1996 to 2005, the overall groundwater storage of the catchment remained more or less the same, as can be seen from the practically constant piezometer heads observed over this period. Thus it is reasonable to assume that after correction for the outflow, recharge and discharge in the region cancel out to zero. The overall water balance of the catchment over the 10 year period reads:

$$\boldsymbol{ET = P - Q} \qquad (2)$$

The resulting ET value was used to correct the mean $K_c$ of the catchment. The corrected $K_c$ map is shown in Figure 13. It has the same pattern but a lower $K_c$ range. This indicates that using only sunny day images without cloud cover effect resulted in an overestimation of ET.

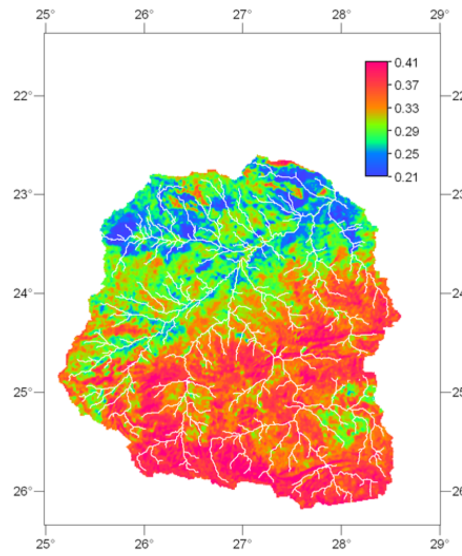



Figure 13: Corrected annual $K_c$ map

As discussed above, the potential ET of Southern and Central Botswana can be calculated from local meteorological station data on a daily basis for the study period from 1996 to 2005. An averaged annual $ET_0$ map of the catchment area can thus be derived, which is shown in Figure 14.

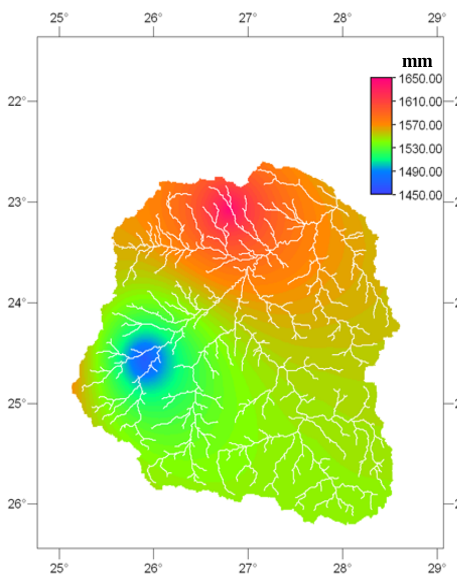



Figure 14: Annual potential ET of the catchment, averaged over the period from 1996 to 2005.

The averaged annual ET map calculated from $ET_0$ and $K_c$ maps is shown in Figure 15. The $ET_0$ map shows a modest variation of the annual potential ET over the catchment from 1450 mm to 1650 mm, while the actual ET values change more dramatically from as low as 350 mm to 750 mm. The contribution of annual $ET_0$ to the spatial variation of annual ET seems therefore less significant than that of the spatial $K_c$ variation.

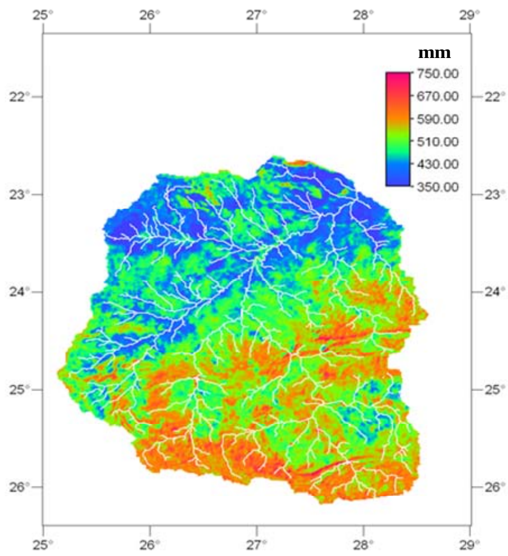



Figure 15: Annual ET map

The annual precipitation map of the catchment from RFE data (8km resolution) is plotted in Figure 16. It is obvious that the southern part of the catchment benefits from more rain than the northern part. This also explains why the vegetation density in the southern part is higher compared to the northern part, which is characterised by higher $K_c$ values. However, higher vegetation density means that more water can be discharged through evapotranspiration. Therefore more precipitation in a region does not directly result in more groundwater recharge. It is useful to show the difference between annual rainfall and ET in a map to find out the possible recharge and discharge areas.

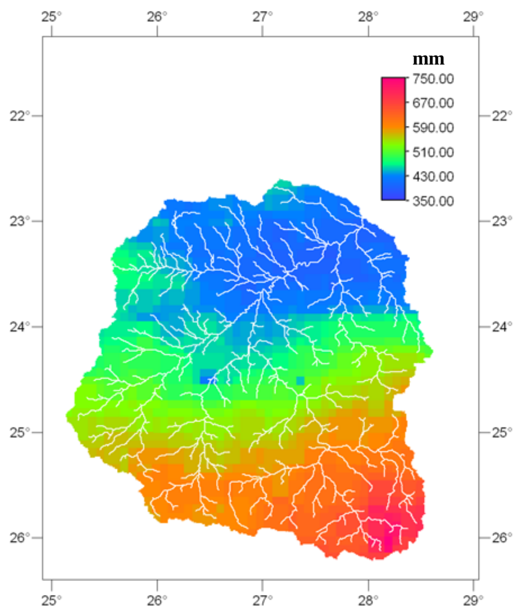



Figure 16: Annual precipitation of the catchment averaged over 10 years from 1996 to 2005.

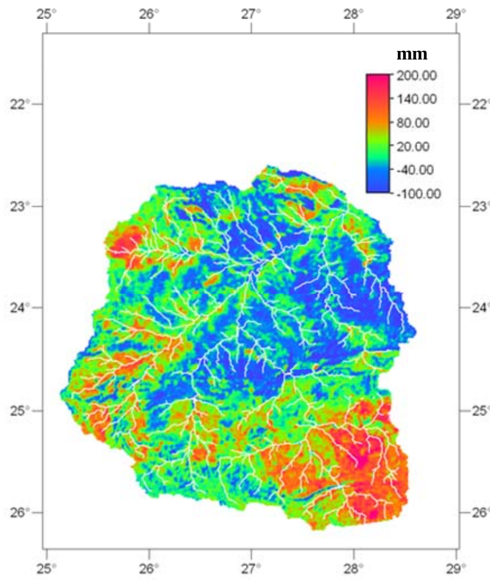



Figure 17: Averaged annual Precipitation-ET map

The difference between annual rainfall and annual ET is positive in the upstream ends of the drainage network, becomes negative further downstream and then turns positive again along the major channels. It seems that precipitation excess in the upstream is transported (either in the subsurface or on the surface) to regions with high vegetation density, where it is consumed together with the local precipitation, leading to a total evapotranspiration larger than the local precipitation (precipitation deficit). The river channels themselves seem to supply water to their surroundings as their balance is positive. The precipitation excess cannot be set equal to recharge to the aquifer. A partial redistribution of recharge by runoff occurs before water actually seeps to the groundwater reservoir. Rainfall may thus not become effective for recharge in its location of origin.

Although surface runoff is much smaller than precipitation and evapotranspiration in the overall recharge estimation for the catchment, the amount could be significant in precipitation re-distribution.

## 4. CONCLUSIONS

The $K_c$ pattern in the studied catchment remains the same over the year although the mean value changes with the season. Using AVHRR images of clear sunny days to calculate $K_c$ maps over the year without considering cloud cover effects will result in over-estimating annual ET values. This in turn leads to underestimation of precipitation excess, which is the origin of groundwater recharge.

Precipitation redistribution, be it on the surface or in the subsurface, influences the vegetation distribution, which is reflected in the $K_c$ pattern.

The Precipitation – Evapotranspiration map shows clearly areas of surplus and deficit. These are not yet the recharge and discharge areas of groundwater. Superimposed to the flow in the subsurface there may be substantial redistribution of precipitation by surface runoff. It is hoped that in the future the surface flow part can be separated out from the total flow between excess and deficit areas, thus yielding the actual recharge and discharge fluxes, which are required. The piezometric heads in the catchment are known to follow the topography. Therefore both subsurface and surface fluxes would be parallel, following the gradient of the DEM. In a first approximation, it could be assumed that the subsurface flux is a constant proportion of the total flux. An independent method of recharge estimation such as the chloride method or other environmental tracer methods would have to be used to determine the proportionality constant. Further refinement would involve the integration of soil infiltration properties, the distribution of confining layers of the aquifer, which exclude recharge, and others.

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