EXPLORING A WATER BALANCE METHOD ON RECHARGE ESTIMATIONS IN THE KILOMBERO VALLEY, TANZANIA

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Abstract

Simple models that require little input data and are easy to use is the ideal case within hydrology. Basic water balance principles often represent such approaches as the method on rainfall-runoff relationship developed by Sutcliffe et al. in India in 1981. That was tested for the Kilombero Valley in Tanzania in order to estimate the recharge to the soil and sub-surface systems. Measured annual runoff in the streams was compared to the seasonal net rainfall to give the difference as potential recharge. This was done for five separate sub-catchment where the hillslope catchments gave a smaller proportion of the net rainfall to occur as surface runoff compared to the valley-catchments. Due to the difference in hydrologic setting from the original model site in India to the Kilombero Valley (e.g. a wetland and stream type), the soil moisture recharge could not be estimated. Also, corrections are needed to the data preparation process and the state of the original stream flow data is questionable. Thus, the results were interpreted as an indication on how the water resources could be moving in the system. An explaining theory that captured the difference between the landform types is mountain system recharge. That implied that all surplus rainfall generated in the mountains has a potential to eventually recharge the groundwater. The method tested, though its simple general concepts, could not alone give satisfying results for the Kilombero Valley system. However, this study convey the importance of continuous exploration of methods to describe the environment in a simplified way.
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1. Introduction

Within hydrology, data scarcity is a common problem. The lack of sufficient data and appropriate equipment inhibits sustainable decisions and makes water resource management difficult. Considering ongoing global climate change together with a growing population, it is increasingly important to set hydrological frameworks and secure water supply. Africa is the most vulnerable continent and in some parts the agricultural yield could be reduced with as much as 50% by 2020 (IPCC, 2007) under future projections of water scarcity. In Tanzania, about 80% of the employed population is engaged in agriculture (World Bank, 2013). Given that over the last decades there has been a reduction in annual rainfall in east Africa (IPCC, 2007) which effects agricultural yield in Tanzania, it is clear that water resources security and management will continue to directly influence the livelihood of the majority of the people in this African country.

In order to adapt management in a sustainable way, a thorough survey of the existing hydrological system in a region is necessary as a first step such that we can forecast the consequences of management. The Kilombero Valley in central Tanzania has great potential for large scale agriculture (ERB, 2006), but before any planning could start, an evaluation of existing water resources for irrigation is needed. At the same time the valley is already a high risk area for malaria as large irrigated lands are ideal breeding zones for mosquitos (Hetzel, et al., 2008).

A satisfying detailed survey is nonetheless difficult to achieve as data scarcity both in spatial and temporal sense is limited in regions such as the Kilombero Valley. There will always be uncertainties that we cannot model due to natural variability and inherent unpredictability in nature (Montanari & Koutsoyiannis, 2012), however, it is possible through computerized models to understand and represent complex natural systems. Using hydrological models to describe areas as detailed as possible can be troublesome as many models often suffer from over-parameterization of the processes at hand (Rosbjerg & Madsen, 2005). Distributed physical models, for example, are not always the most reliable tools as with more parameters involved the results could be more difficult to validate. Fewer parameters that only treat the fundamental processes (e.g. a parsimonious approach to modeling) could sometimes be a better conceptualization of reality (Rosbjerg & Madsen, 2005).

A recent investigation in the Kilombero Valley by Lyon et al. (2013) used streamflow recession analysis to derive the characteristic drainage timescale that in a simple way describes the storage-discharge relationship in the valley. The method allows the use of limited data by reducing the impact of the temporal variation. Steenhuis et al. (2009) developed a simple sedimentation model for the Ethiopian highlands that was based on physical processes and water balance principles. Their approach managed to capture the trends in the area where saturation processes were dominant over infiltration processes. A commonly used lumped conceptual model is the MIKE BASIN (Bangash, et al., 2012; Ireson, et al., 2006) which has been proven to give good simulations of rainfall-runoff processes under data scarce conditions. Still, most of the existing models (even simplified modeling approaches) are developed for temperate climates and, thus, do not operate well in monsoonal semi-arid conditions (Steenhuis, et al., 2009). Clearly, methods (particularly simplified approaches) for assess water resources must be tested or explored with available data before they can be implemented in to develop management strategies.

In this current study, another method to describe the general rainfall-runoff regime is explored. This method was developed by Sutcliffe et al. (1981) for predominantly monsoonal conditions in India. It was developed for a specific site, but the concepts behind draw on mass balance principles that in a general way could potentially be applied to other sites. The outcome of the Sutcliffe et al. (1981) method gives an estimate on soil moisture recharge and groundwater recharge at the catchment scale. Due to the little amount of required data and simple principles
involved, the same method could therefore be tested for the Kilombero Valley of central Tanzania. This kind of exploratory modeling is important in the effort to gain new insight in established theories of interacting processes (Rosbjerg & Madsen, 2005). If the method of Sutcliffe et al. (1981) can be successfully applied in the Kilombero Valley to get an estimation of the groundwater recharge and soil moisture recharge, it could be used as a simple tool for local decision makers to give a first indication on how the water resources are distributed.

2. Site Description and Datasets

The Kilombero Valley lies within the greater Rufiji River Basin that drains into the Indian Ocean south of Dar es Salam. The Rufiji River Basin holds about 3 million people and in the Kilombero Valley Ifakara is the main city with the many small villages throughout (ERB, 2006). In 2006 about 38 000 hectare in the valley was irrigated and the total potential is about 330 000 ha of irrigable land (of a total area of about 34 000 km²). The main crops are rice, maize, bananas and sugarcane (ERB, 2006). The regional climate is semi-arid with a unimodal rainfall regime. Average annual rainfall lies at 1400 mm and mean annual temperature at 21°C, where it is cooler and wetter in the mountains compared to the warmer and drier valley (REMP, 2003).

The main Kilombero Valley catchment is divided into five separate sub-catchments considered in this study: 1KB4, 1KB8, 1KB10, 1KB14 and 1KB15A (Fig. 1). Station 1KB17 represents the whole basin as its position is the most downstream in the valley. It is also important to mention that 1KB8 and 1KB10 are both within 1KB4 (nested catchment) and are therefore included in the analysis of 1KB4. Characteristic data for each sub-catchment is presented in Table 1. The main features of the valley is the Kilombero Valley Floodplain (also called Kibasila swamp). In 2002 this valley region became a Ramsar Site covering 8000 km² that generate about two thirds of the Rufiji River flow (RIS, 2002). The annual flooding raises the water levels between November to April with most of the peak flows occurring in March-April. These fluctuations are vital for wildlife migration, fish production and soil fertility (RIS, 2002).

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Area (km²)</th>
<th>Mean Elevation (m a.s.l)</th>
<th>Landform characteristic*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1KB4</td>
<td>18048</td>
<td>1204</td>
<td>92</td>
</tr>
<tr>
<td>1KB8</td>
<td>2531</td>
<td>1370</td>
<td>99</td>
</tr>
<tr>
<td>1KB10</td>
<td>8577</td>
<td>1029</td>
<td>92</td>
</tr>
<tr>
<td>1KB14</td>
<td>580</td>
<td>905</td>
<td>100</td>
</tr>
<tr>
<td>1KB15A</td>
<td>337</td>
<td>1306</td>
<td>100</td>
</tr>
<tr>
<td>1KB17</td>
<td>34230</td>
<td>885</td>
<td>78</td>
</tr>
</tbody>
</table>

* Source: Lyon, et al., 2013.

The floodplain itself holds a mixture of swamps, lakes, rivers, riverine forest and grassland and further out to the edges it is dominated by the miombo woodland (RIS, 2002). In most areas the soil moisture remains relatively high (near saturation) up till 3-6 months after the rainy season (RIS, 2002), but in other parts the soil drains immediately after the end of the rainy season (Kangalawe & Liwega, 2005). Common soil types are acrisols and lixisols which are clay-rich in the subsoil (FAO, 2007). Northwest of the floodplain are the Udzungwa Mountains (up to 2580 m) while in the southeast rise the Mahenge Highlands (up to 1520 m).

The sub-catchments of 1KB15A and 1KB14 are both situated along the hillside of the Udzungwa Mountains. Vegetation in this region is of mainly evergreen tropical forest with high species diversity (Lovett, 1996). The area has a general slope of 15-30% and the soils are rich in nutrients and productive for farming (MAFC, 2006). Nitisol is the dominant soil type at the hillsides (Lyon, et al., 2013) that is typically deep and well-drained (FAO, 2007). However, much of the area is protected by various smaller reserves and the Udzungwa Mountain National
Water Balance for Estimation of Groundwater Recharge, Kilombero Valley, TZ

Sub-catchment 1KB4 has a land cover consisting of mostly shrubs and woody vegetation, but also areas of grassland and rainfed herbaceous crops to the northwest (FAO, 2003). According to Ministry of Agriculture, Food and Cooperatives (MAFC) (2006), the dominant soil type is acrisol with low fertility and common crusting-processes (hardening of top soil in the drying phase (Perrolf & Sandraström, 1995)). In 1KB8, landslides are common which makes larger and safe infrastructure unusual (Marwa & Kimaro, 2005). The exception is the construction of a hydro power plant in year 2000 along the Kihansi River (1KB8) with an effect of 180 MW (Marwa & Kimaro, 2005). There are no investigations on how the power plant has affected the downstream hydrology.

Figure 1. Map showing sub-catchment positions and elevation of the Kilombero Valley. Location of measuring stations show the different scales of representation.

Park (1KB14) such that there is not any opportunity for agricultural practices (Kangalawe & Liwega, 2005).
Three datasets were needed to perform the water balance within this study: precipitation, temperature and surface runoff. The period of available data gave 21 consecutive years (1960-1981). Both temperature data and precipitation data were originally taken from the Food and Agriculture Organization (FAO), the Institute for Resource Assessment at the University of Dar es Salaam and the Rufiji Basin Water Office. The data were gathered and processed by Lyon et al. (2013) before the analysis carried out in this study. As no temperature stations exist inside the catchment, data were used from four of the closest stations, all within a range of about 200 km (Figure 1). These records gave monthly mean temperatures for the whole basin, representing an average elevation of 1105 m above sea level. The precipitation data considered were collected from 57 stations within the catchment, where about 16 of these generated the monthly means presented in Lyon et al. (2013). These means were determined through Inverse Distance Weighting and produced values for each of the sub-catchments in the basin. The runoff dataset was provided by the Tanzanian Ministry of Water and was also treated (i.e. gaps filled with various interpolation methods) by Yawson et al. (2005). Most missing values were found in 1KB4 (38%), and 1KB8, 1KB10 and 1KB17 had all about 24% missing values (Yawson, et al., 2005). The annual averages of temperature, precipitation and runoff are presented in Table 2. The values are based on hydrological years, starting in October to the following November (e.g. the annual value for 1960 begin in October 1960 and end in November 1961).

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Temperature (°C)</th>
<th>Potential evapotranspiration (mm)</th>
<th>Precipitation (mm)</th>
<th>Observed runoff (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1KB4</td>
<td>21.3</td>
<td>1031</td>
<td>1052</td>
<td>348</td>
</tr>
<tr>
<td>1KB8</td>
<td>21.3</td>
<td>1031</td>
<td>1220</td>
<td>500</td>
</tr>
<tr>
<td>1KB10</td>
<td>21.3</td>
<td>1031</td>
<td>971</td>
<td>801</td>
</tr>
<tr>
<td>1KB14</td>
<td>21.3</td>
<td>1031</td>
<td>1287</td>
<td>320</td>
</tr>
<tr>
<td>1KB15A</td>
<td>21.3</td>
<td>1031</td>
<td>900</td>
<td>1906</td>
</tr>
<tr>
<td>1KB17</td>
<td>21.3</td>
<td>1031</td>
<td>1105</td>
<td>500</td>
</tr>
</tbody>
</table>

### 3. Method

#### 3.1 Theory

The method of Sutcliffe et al. (1981) was developed for a monsoonal climate with distinct wet and dry seasons. The annual cycle of Kilombero Valley is presented in Figure 2 which also shows a clear seasonality in monthly rainfall and potential evapotranspiration. Between December and April the valley experiences a water surplus due to excess of rainfall over evaporation. In May to October the evaporation exceeds the precipitation and result in water deficits. By this division of the year into a water limited period (dry season of water deficit) and energy limited period (wet season of water surplus), Sutcliffe et al. (1981) only required the potential evapotranspiration in their further calculations. During this annual fluctuation of water availability, water in the soil layer will go from field capacity to wilting point within a year and in that way, according to Sutcliffe et al. (1981), could give the seasonal soil moisture storage. In the wet season of excess water, the complete recharge of the soil moisture zone (or root zone) would then be a first charge on the net rainfall, the surplus water from rainfall over evaporation. Sutcliffe et al. (1981) also assumed that this seasonal recharge would be constant from year to year in a long time steady state system. This is also under the presumption that the considered unit is uniform in its surface characteristics and that there is no major change in land use as the unit is only represented by one value.
The rest of the net rainfall in the wet season would be distributed between surface runoff and infiltration into the ground as potential groundwater recharge (Sutcliffe et al., 1981). This partitioning of water was further assumed by Sutcliffe et al. (1981) to generally be proportional, i.e. from every rainfall event the same proportion of surface runoff would go to groundwater recharge year after year. They also mention that part of this groundwater recharge could return to the rivers as baseflow or dry season component of the river discharge, and is not possible to trace if considering total amounts on an annual basis. To incorporate the seasonality of the net rainfall and its fluctuation of the soil moisture storage the analysis has to consider yearly totals. In this way the ‘groundwater recharge’ set by Sutcliffe et al. (1981) would therefore in this study only be treated as the maximum potential amount that could recharge the groundwater.

To yield estimates on the soil moisture recharge and the potential groundwater recharge the components of the runoff needs to be investigated. From the arguments above, a simple water balance to describe the physical characteristics would be as presented in Equation 1 and 2 if assuming no change in storage over a long time in a steady state system.

\[ P - PET = P_{Net} \]  
\[ P_{Net} = R + Gw \]  

Precipitation (P) subtracted by potential evapotranspiration (PET) yields the surplus net rainfall (\( P_{Net} \)) that in turn is further partitioned between the surface runoff (R) and potential groundwater recharge (Gw). By comparing the seasonal surplus of water with observed annual totals of measured runoff in the streams, it should reveal a proportion of water that is “missing” in the stream discharge which could be the groundwater recharge. Producing the seasonal net rainfall would then be based on monthly records (n) where only the positive rainfall excess values were added to the annual sum as in Equation 3:

\[ P_{Net} = \sum_{n=1}^{12} \max(0, P_n - PET_n) \]
According to Sutcliffe et al. (1981), the seasonal net rainfall representing the annual total of water input to the system would then for each of the sub-catchments be plotted against the annual average measured runoff (derived from monthly discharge records divided over their respective catchment areas to eliminate the difference in size) as in Figure 3a. In the diagram (Figure 3a), following the method of Sutcliffe et al. (1981), the intercept on the horizontal axis (the net rainfall axis) tells how much it needs to rain before any runoff occurs (i.e., the amount of water to “get the system going” in the beginning of the wet season). The deviation of the function from a 45°-reference line (slope = 1) would then tell the proportion of that infiltrated into the ground or the potential ground water recharge (i.e., the amount of extra water added to the system not seen in the rivers annually).

The average annual values of groundwater recharge were calculated from an average year of seasonal net rainfall, which also corresponds to the mean annual runoff. The samples from India in Figure 3b give an example of the expected outcome.

3.2 Potential Evaporation

The most common approach for estimating evapotranspiration is the Penman-Monteith Equation which represents the evapotranspiration from a vegetated surface (Dingman, 2008). However, the lack of sufficient data available for Kilombero Valley required another simpler approach. The potential evapotranspiration can be obtained at a monthly time step from the Standard Thornthwaite method (Thornthwaite, 1948) which only uses the parameters temperature and average daylight. The Standard Thornthwaite method starts by calculating an annual heat index \( I \) from the sum of all the monthly indices, \( i \):

\[
i = \left( \frac{T}{5} \right)^{1.514}
\]

where \( T \) is the monthly mean temperature. The annual heat index is then given by:

\[
I = \sum_{n=1}^{12} i_n
\]

where \( n \) is the number of months. The potential evapotranspiration is then calculated with the following relationship:

\[
PET' = C \cdot \left( \frac{10T}{I} \right)^{\alpha}
\]

Figure 3. (A) The conceptual theory behind the method and (B) an example with observations from India (taken from Sutcliffe et al., 1981).
where $C$ is a constant (16) and $a$ is function of $I$:

$$a = 67.5 \cdot 10^{-8} I^3 - 77.1 \cdot 10^{-6} I^2 - 0.0179 I + 0.492$$

Last, $PET'$ needs to be calibrated for the specific month by weighing with the average hours of daylight ($d$) and the number of days in the respective month ($N$):

$$PET = \frac{PET'}{12} \cdot \frac{N}{30}$$

The Standard Thornthwaite method was developed for a temperate climate, but is still widely used over the world (Xu & Singh, 2001). Usually these calculations yield underestimations of the evapotranspiration and should be calibrated from Penman-Monteith calculations for more detailed results (as done by REMP (2003)). However, this was not possible in this current study where the Standard Thornthwaite method was used to estimate monthly potential evapotranspiration values for Kilombero Valley.

4. Result

The application of the method of Sutcliffe et al. (1981) for each sub-catchment is presented in Figures 4, 5 and 6 with the blue dotted line as the 45°-reference line and the black solid line as the trend line to runoff versus net rainfall. Sutcliffe et al. (1981) assumed the 45°-reference line begins where the fitted trend line crossed the horizontal axis (in Figure 3). Conceptually, this implies that there is no flow in the river until it rains a certain amount (i.e., there is an inherent soil moisture recharge to be met before runoff occurs). In the Kilombero Valley there is always water in the river courses which pushes the trend line to cross the horizontal axis on the negative side (Figure 4). By then placing the 45°-reference line at the intersection of the vertical axis then corresponds instead to the level of baseflow (flow unaffected by rainfall events) in the river and how much the flow rises with incoming seasonal runoff. This means that the soil moisture recharge appears to be non-existent in the valley or not possible to capture through this method.

![Figure 4](image-url)
Figure 5. Results for sub-catchments 1KB10 and 1KB17 giving function slopes of about 0.5.
Water Balance for Estimation of Groundwater Recharge, Kilombero Valley, TZ

The annual mean potential groundwater recharge estimated from the method of Sutcliffe et al. (1981) for a year of average precipitation is presented in Table 3. The results show the highest estimated groundwater recharge to sub-catchment 1KB14 and the lowest to 1KB10. The mean squared error has a range of about 0.02 and 0.5 with sub-catchment 1KB15A as the lowest and 1KB10 as the highest. Most of the sub-catchments, including the main Kilombero Valley (1KB17), indicated annual baseflow levels between 100-300 mm/year where 1KB10 showed up to 610 mm/year. The exception is sub-catchment 1KB15A with an estimated value of 2004 mm/year.

Table 3. Mean annual net rainfall and groundwater recharge values.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Mean annual groundwater recharge (mm)</th>
<th>Fraction of mean annual precipitation (%)</th>
<th>Mean annual net rainfall (mm)</th>
<th>Slope of the function (%)</th>
<th>Intersect horizontal axis (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1KB4</td>
<td>275</td>
<td>26</td>
<td>409</td>
<td>33</td>
<td>-654</td>
</tr>
<tr>
<td>1KB8</td>
<td>371</td>
<td>30</td>
<td>535</td>
<td>31</td>
<td>-1099</td>
</tr>
<tr>
<td>1KB10</td>
<td>167</td>
<td>17</td>
<td>358</td>
<td>53</td>
<td>-1145</td>
</tr>
<tr>
<td>1KB14</td>
<td>417</td>
<td>32</td>
<td>600</td>
<td>31</td>
<td>-445</td>
</tr>
<tr>
<td>1KB15A</td>
<td>318</td>
<td>42</td>
<td>283</td>
<td>-35</td>
<td>5784</td>
</tr>
<tr>
<td>1KB17</td>
<td>237</td>
<td>21</td>
<td>444</td>
<td>47</td>
<td>-629</td>
</tr>
</tbody>
</table>

Figure 6. Results for sub-catchments 1KB14 and 1KB15A giving function slopes of about 0.3 and -0.3 respectively. Note that diagram 1KB15A begins at an observed runoff of 1000 mm/year and not at 0.
5. Discussion

5.1 Data quality

Before an interpretation or meta-analysis of the results can proceed, consideration must be given to the data quality and its potential impact on the results. The results of this study demonstrated that sub-catchment 1KB15A clearly has inconsistent values. The runoff values were extremely high without any similar elevated precipitation values. As these values were divided over their respective catchment area, there might be some error in catchment delineation. Still, the same results have been published by Yawson (2005), which made the quality of the original data more questionable than the processing itself. For this reason 1KB15A was disregarded from the further meta-analysis and discussion of the results, however, it does demonstrate the highly variable quality of the data for this region.

Also, the result for 1KB14 also showed different values compared to the other sub-catchments. From the precipitation dataset there was a clear division between the years 1961-72 to the rest of the years in that there was about double the amount of annual precipitation (analysis not shown). The division was clearly seen by two clusters which are both close to the horizontal axis (Figure 6, 1KB14). Since 21 years represents a relatively short dataset, it was difficult to see tendencies in the data. For example, in 1967 it rained throughout the dry season as well which produced extremely high net rainfall (the sample furthest to the right in Figure 6, 1KB14). The expected consequence would be higher runoff values for the same year, but the runoff observed was still comparable with that within an average year. If removing extreme or unrealistic values from such a short dataset, it would highly affect the gradient and mean values. Therefore, 1KB14 is still regarded as a valid result in the further meta-analysis, but regarded as the least stable result.

Another important aspect about the runoff data was that having fixed measuring stations within a wetland region makes it almost impossible to catch all flowing water in the complex river system. This was especially true for stations 1KB4 and 1KB10 where the flow was believed to be underestimated. Still, station 1KB10 showed relatively high baseflow levels to abruptly become much lower at the station 1KB4 which lay right after (Figure 1). This change in streamflow and position of stations 1KB4 and 1KB10 together with the varying quality of the data of 1KB15A and 1KB14 seems to make the runoff data as a general the most unstable parameter in the analysis. The missing values reported by Yawson (2005) in the runoff dataset were not large enough to imply any major changes to the outcome. If better quality of the runoff data were available it would strengthen the results to make them more robust but might also contribute to a different outcome and interpretation of the Kilombero Valley.

Further, as temperature data was an average over the whole basin and not developed for each of the specific sub-catchments, this could lead to both over- and underestimations of temperature. The reference elevation for the mean temperature was calculated for 1105 m above sea level, when the actual average elevation of the main Kilombero Valley is 885 m. As it is generally warmer at lower elevations, the mean temperature should be higher and thus also the evapotranspiration in the region. Concerning the precipitation data, most of the gaging stations (as shown in Figure 1) are along the mountain side. As it potentially rains more in the mountains due to orographic influences the dataset could represent an overestimation. As there were no hydroelectric in the area during 1960-81, this would have no influence on the result. Thus, if a proper quantification of all the uncertainties could calibrate the datasets to a more correct representation, it might result in even more factors that could affect the outcome. It is not believed that these corrections for over- and underestimations would change the general outcome of the results (except the runoff data). In this way the results can be seen as an exaggeration to a much more complex reality and thus facilitate observation and analysis of the most dominant processes.
5.2 Interpretation

In order for the method of Sutcliffe et al. (1981) to work, the streams need to mirror the changes in precipitation and not have any other source of water input. If the rivers in the Indian catchment are only supplied by the seasonal precipitation from the wet season, they would be defined as so called ephemeral streams that would disappear during dry season (Dingman, 2008). In the Kilombero Valley a continuous flow all months of the year indicates that there are other sources of water that sustain the river even when there is no rainfall during the dry season. The main source of this baseflow is usually assumed to be from groundwater (Dingman, 2008). Thus, even if there is a certain recharge amount for the soil moisture zone it cannot be seen by investigating streams that never dry up completely, like in this study of the Kilombero Valley.

However, the difference between seasonal rainfall and observed runoff still reveals that not all of the net rainfall is likely to become surface runoff. Within the Kilombero Valley there is a wide variety of ecological and climatological features. In the mountains, evergreen forests bring increased faunal activity to the soil which further increases the permeability of the already fast draining nitisols. The results of the corresponding catchments 1KB8 and 1KB14 showed a slightly larger divergence from the reference line, which could imply larger groundwater recharge values according to the theory behind Sutcliffe et al. (1981). Some part of the divergence could also be explained by the water consuming vegetation (de Vries & Simmers, 2002). The opposite features are seen in the lower lying floodplain. The less permeable soils (acrisols and lixisols) are combined to sparse vegetation with lower retention capacities. These factors might contribute to a general reduced infiltration and apply foremost to 1KB10 and a large part of 1KB17 as a nested watershed. However, the great wetland might increase infiltration to the groundwater but at the same time with the surrounding water-consuming farming (e.g. rice) also evaporate a large proportion of the incoming water. These catchments have less hill characteristics relative to the other catchments and showed smaller deviations to the reference line (and thus showing a higher proportion of net rainfall in the rivers). The exception is 1KB4 that has the same hill characteristic as 1KB10 (92%) but a slope of the function of 0.3 which is closer to more mountainous catchments. Even if the number of catchments were small and data within was questionable, there was a difference in estimated groundwater recharge if following the interpretation of Sutcliffe et al. (1981). It rains more in the mountains which should yield more groundwater recharge, but the fractions of rainfall in Table 3 showed no direct correlation. It seemed more realistic that a combination of surface conditions with the landform features influenced the recharge.

The capacity of water to infiltrate the soil is depending on a variety of factors. For example, a study from the semi-arid zones in western Africa (Perrolf & Sandraström, 1995) concluded that intensity of surface sealing, soil faunal activity and vegetation cover were critical for infiltration. Surface sealing is created when a rainstorm- or irrigation event degrade a thin layer in the soil structure and highly decreases its permeability (Perrolf & Sandraström, 1995). Soil faunal activity creates macropores (voids larger than 75µm) that with cracks and fissures at the surface improves percolation downwards. Especially in semi-arid areas where the potential evapotranspiration often is greater than precipitation, these surface conditions becomes important (de Vries & Simmers, 2002). High-intensity rainfall events and ability to accumulate water in depressions and streams both increase the infiltration and recharge possibilities. However, de Vries & Simmers (2002) points out that vegetation brings higher retention storage and subsequently withdraw water the following dry season, all decreasing the amount of potential groundwater recharge.

A theory that could explain the features of the Kilombero Valley and (at least in part) the responses explored within the methodology of Sutcliffe et al. (1981) presented here is mountain-front recharge. That process is based on surface water originating from mountains in dry regions that will infiltrate the ground at the base of the mountains before reaching the basin floor (Wilson & Guan, 2004). This is usually the main groundwater recharge component in dry areas.
(Wilson & Guan, 2004). As mentioned earlier, stations 1KB4 and 1KB10 both lay within the wetland. According to the mountain-front theory (Wilson & Guan, 2004), this water is already less than what could have been produced uphill due to continuous infiltration along the mountain front. On the other hand, catchments further up with stations at the hill side should show more flowing surface water (discharge), which all eventually would infiltrate to form recharge. In this sense, all the discharge produced in the mountain could go to groundwater recharge. The amount of that recharge estimated by this method of course would then be influenced by the position of the station. This is with the simplification that all diffuse and indirect recharge is neglected.

A good review over different methods to measure recharge from the mountain system is presented by Ajami et al. (2011). They also highlight the importance of detailed information on the site’s geological structure as recharge through the mountain bedrock (mountain block recharge) is one of the major contributors to groundwater recharge. The recession analysis by Lyon et al. (2013) also indicated a difference in storage between upland hillslopes and valley wetlands due to different effective hydraulic conductivity. It was therefore more reasonable to call the mountain system recharge to be the dominating feature of the recharge in the Kilombero Valley than the saturation of the soil moisture zone from Sutcliffe et al. (1981). Sutcliffe et al. (1981) mention that their method can only estimate the groundwater recharge in principle, as their deviation from the 45°-reference line was small compared to the scatter of the data (Figure 3b). Sub-catchment 1KB4 and 1KB10 showed the best fit to the trend line and the deviation was clearer than presented by Sutcliffe et al. (1981). Even if all observed runoff would infiltrate at the mountain front, this deviation, in principle, could tell the average proportion of net rainfall that could recharge the groundwater. The catchments at the hillslopes showed that about 30% of the seasonal net rainfall could be reflected in the rivers as runoff (from an average slope of 0.3) and that in the valley that same proportion was about 50% (from 0.5 in slope). Sutcliffe et al. (1981) recommended further studies to see where the possibly infiltrated water could continue. Because this deviation from the 45°-reference line might show water that will later discharge in the streams as baseflow or percolate downwards to deep sub-systems. To better understand that partitioning, Sutcliffe et al. (1981) suggest flow recession analysis to investigate the time variable of the storage in the catchment.

6. Conclusion

The method of Sutcliffe et al. (1981) proved rather unsuccessful in the Kilombero Valley. The different flow regime placed the estimated soil moisture recharge to be negative and thereby not possible to interpret by this method. For the potential groundwater recharge there was a small difference between the sub-catchments at the hillslopes and the ones with more valley features. However, the method applied only attempted to give an estimate of the recharge balance which turned out to be better explained by the theory on mountain system recharge. If considering the mountain-front recharge and the amount of streamflow that would infiltrate and recharge the groundwater, it is only the remaining surface water that discharges into the wetland. The proportion of that possible recharge to the groundwater would be affected by the position of the measuring station and would be better estimated by flow recession analysis. With further studies of also the geology, the mountain block recharge could add to a more complete understanding of the system’s hydrology. Deeper knowledge is required on rainfall-runoff processes in semi-arid mountainous areas before simplified models could be used with higher certainty. If the data is not available, the theory has to compensate to be able to approach the desired hydrological survey.

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7. References


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