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The assessment of water resources in ungauged catchments in Rwanda

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ABSTRACT

Study region: Rwanda is a landlocked country in Africa with precipitation ranging from 800 mm yr^{-1} in the east to 1500 mm yr^{-1} in high-altitude regions in the north and west.
Study focus: Streamflow estimation is an important task that is required in water resource assessments due to its importance in planning, decision-making and economic development. In this study, streamflow characteristics of ungauged catchments in Rwanda were calculated using a regionalization approach based on climate similarity and stepwise multiple-regression analysis. One climatic homogeneous region was identified and datasets of nine gauged stations and general available catchment characteristics were used to develop non-transformed and log-transformed regression models.
New hydrological insights for the region: Results of this study show that climate, physiography and land cover strongly influence the hydrology of catchments in Rwanda. Using leave-one-out cross-validation, the log-transformed models were found to predict the flow parameters more suitably. These models can be used for estimating the flow parameters in ungauged catchments in Rwanda and the methodology can be applied in any other region, as long as sufficient and good quality streamflow data is available.

1. Introduction

Assessment of water resources is of great value for national socio-economic development and stability of every country. Nevertheless, tools and data needed to carry out such assessments are often limited or lacking, especially in developing countries with limited technical capacity and funding (McNulty et al., 2016). At the core of the social and economic development of Rwanda is the aspiration of the country to become a middle-income country by the year 2020. This is formulated and described in *Rwanda Vision 2020* (MINECOFIN, 2000), and worked out into strategies, plans and actions for accelerated growth. This vision may not be a reality if a country-wide assessment of water resources is lacking.

Availability of water for food production is a major concern since Rwanda has an undulating topography throughout the country (RIWSP, 2012c). Thus, irrigation is practiced at small scales and is typically restricted to valley bottoms where 85–90% of the Rwandan population depends on subsistence farming. However, this may likely change in the future because a number of pilot studies in different parts of the country have been carried out to investigate the potential of rainwater harvesting for hill slope irrigation purposes (GOR, 2007).

In addition, shortages in power production due to a drop in water levels have caused interruption of the Rugezi hydropower plant.

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Hence, as part of the national strategy to substantially increase power production, there is a need to increase the in-country hydropower production (GOR, 2007; MININFRA, 2011). Furthermore, the effects of water-related natural disasters, which are mostly connected with flood and drought conditions, cannot be over-emphasized. In general, more people are affected by droughts than flooding events in Rwanda (WFP, 2009).

In order to achieve *Rwanda Vision 2020*, there is need for a country-wide assessment so as to manage changes in water demand and supply (both surface and groundwater) for agricultural production, hydro-electric power generation, hazard mitigation and disaster preparedness.

Changing climatic conditions over longer periods of time affect water availability and have impact on the spatial and temporal variations of the water fluxes. An integrated water resources management relies on adequate water resources information that is acquired through continuous data collection, in combination with suitable analysis and assessment of the water-related information for water resources planning and development purposes (RIWSP, 2012c). In the case of Rwanda whereby such data or information is limited or lacking, the country would benefit significantly from the water resource assessment capabilities that hydrologic modelling can provide for predicting streamflow especially in ungauged catchments.

Predicting flow variables in ungauged or poorly-gauged catchments is one of the major concerns in hydrological studies, especially in regions with huge spatial variability of the hydrological environment and sparse or lack of data. In many parts of the world, current measurement networks are declining and the impacts of anthropogenic changes and climate amplify this issue. Hence, predictions of poorly gauged or ungauged catchments under these conditions are highly uncertain (Sivapalan et al., 2003).

Information from gauged catchments is usually transferred to the ungauged catchments using regionalization processes (Blöschl and Sivapalan, 1995). Studies on regionalization in hydrology have progressed continuously as a result of the need for streamflow predictions in ungauged catchments. Thus, understanding hydrological processes, their associated uncertainties and the development of models with increasing predictive power have become vital. In literature, a number of definitions of regionalization could be found, but the definition stated by Blöschl and Sivapalan (1995) is often used. They stated that "*regionalization is the process of transferring information from comparable catchments to the catchment of interest*". Since the objective of this study was to develop models to predict flow parameters in ungauged catchments in Rwanda, a regionalization approach was used. Some studies estimate parameters of streamflow statistics, usually flow quantiles, while others estimate parameters of rainfall-runoff models for simulating continuous streamflow or estimate continuous streamflow without using a model (Hrachowitz et al., 2013; He et al., 2011). There are many methods used for parameter regionalization (Merz and Blöschl, 2004).

The spatial proximity method assumes that catchment characteristics and climate vary smoothly in space. Thus spatial proximity, which is usually defined based on the distances between the catchment centroids or catchment outlets, between the catchments may be an appropriate measure of similarity when selecting the donor catchment (Li et al., 2009; Randrianasolo et al., 2011). A donor catchment is a catchment that is most similar in terms of its physiographic attributes to the catchment of interest (Parajka et al., 2005). In order to account for nested catchments, geostatistical distances can be used (Skoien et al., 2006; Skoien and Blöschl, 2007).

Similarity of catchment characteristics and climate, as an alternative method, selects the donor catchment(s) based on the similarity of the catchment characteristics and climate in the catchments. Similarity is calculated by the root mean square difference of all the characteristics in a pair of catchments (Blöschl et al., 2013). In order to make the characteristics comparable, they are usually standardized. Kokkonen et al. (2003) transferred the entire set of parameters from the catchment which has the most similar elevation to that of the catchment outlet while McIntyre et al. (2004) defined the most similar catchment on the basis of the catchment area, standardized annual mean precipitation and base-flow index. While some studies (Parajka et al., 2005; Zhang and Chiew, 2009) used a large number of catchment characteristics, others (e.g. Oudin et al., 2010) used fewer, yet more relevant catchment characteristics.

The model averaging method uses a weighted combination of the parameter sets from more than one donor catchment, where the catchments are chosen either based on spatial proximity, catchment characteristics or both (Seibert and Beven, 2009). Each catchment can either be assigned to its own group of donor catchments or, alternatively, the region can be divided into groups of catchments (Burn and Boorman, 1993).

Parameter regression is the most widely used method for rainfall-runoff model regionalization (McIntyre et al., 2004). This method relates the model parameters explanatorily to physiographic characteristics in the gauged catchments through empirical equations which can then be used to predict the model parameters in the ungauged catchments (Merz and Blöschl, 2004; Mazvimavi et al., 2004, 2005; Wagener and Wheater, 2006; Young, 2006; Parajka et al., 2013). To investigate the value of seasonality indices for regionalizing low flows, Laaha and Blöschl (2006, 2007) used stepwise-multiple regressions based on physical catchment characteristics and seasonality indices to make regionalization models. Using cross-validation, they assessed the value of different models that incorporate seasonality by different approaches in order to predict low flows in ungauged catchments. They compared the models for the 95% quantile of specific discharges and also examined the specific low flow discharges of the summer and winter periods (q_{95s}, q_{95w}). Their results showed that grouping the study area into different regions and separate regressions in each region provides the best model performance. According to Laaha and Blöschl (2006, 2007), a global regression model yields the lowest performance and a global regression model that uses regional calibration coefficients only performs slightly better. They recommended that separate regression models in each of the regions are to be chosen over a global model in order to represent differences in the way catchment characteristics are related to low flows.

In order to make reliable predictions in ungauged basins, it is preferable that the equations which relate the model parameters and the catchment characteristics should be hydrologically reasonable. According to Sefton and Howarth (1998), this is not always possible because the explanation of the regression equations is often not straightforward by reason of unrepresentative catchment characteristics and issues related to the selection of model parameters (Blöschl, 2005). As pointed out by Kokkonen et al. (2003), high