JOURNAL OF
ENVIRONMENTAL HYDROLOGY

The Electronic Journal of the International Association for Environmental Hydrology
On the World Wide Web at http://www.hydroweb.com

VOLUME 15 2007

DEVELOPMENT OF REGIONAL EQUATIONS FOR ESTIMATION OF LOW FLOW REGIMES OF SMALL CATCHMENTS ON PEMBA ISLAND, ZANZIBAR

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This paper describes the application of a multiple regression technique to the development of regional equations for the estimation of low flow regimes for ungauged catchments. The major goal was to establish the level of low flow indices in ungauged catchments found on Pemba Island where favorable features for developing small scale hydropower projects exist. The approach adopted made use of various combinations of physical catchment characteristics data for small gauged catchments covering an area ranging from 20 to 100 km^2 *similar to the two catchments found in Pemba. The derived regression models allowed an estimate of the low flow regimes for the catchments of interest. The accuracy of the calculated low flow indices determined from the developed regional models for each of the eight small catchments was verified using a statistical analysis technique that yielded the highest coefficients of determination* (R^2) *corresponding to the lowest values of the standard error (Se). These results indicate that low flow regimes can be modeled with reasonably good results using regional equations developed here.*

INTRODUCTION

Zanzibar which is comprised of Unguja and Pemba Islands forms part of the United Republic of Tanzania, and the two islands are situated some 30 km from the mainland coast of East Africa. The island of Pemba has a total surface area of about 988 km^2, according to the Hydrological Map of Zanzibar (1987), and is traversed by an elevated landscape forming a divide resulting in the formation of steep sloping lands to the west and moderate slopes to the eastern side of the island. The river basins receive an average annual rainfall of 1700 mm. During storms, excess precipitation drains from the sandy plateau and is channeled into the major streams. Most of the streams are to be found in the northeastern part of the island. Recent studies conducted on the island gave an indication of the existence of favorable features in two river basins, the Piki and Chamanagwe, that could be exploited for developing small scale hydropower projects.

Before the development of any small scale hydropower scheme can be implemented, an essential step is to determine whether a sufficient and reliable amount of water is available to make the scheme economically viable. As a standard practice gauging stations should be set up and the discharge observed for at least two dry seasons. However, for planning purposes this period is too large, and since on the island of Pemba there are no gauged rivers, it is desirable to apply regional hydrological models to provide a rapid estimate of the temporal variability of the river flows at the potential sites (Garren, 1992). This paper describes the application of a multiple regression technique used for the development of regional equations for the estimation of low flow regimes in ungauged catchments found on the Island of Pemba.

The technique and analysis adopted are standard, and the flow equation models derived using multiple regression techniques are for the 10-day mean annual minimum, 90 percentile flow, and base flow index. Their optimum values were obtained using physical catchment characteristics such as area, site elevation and length of the main stream. The low flow index values obtained using the developed regional equations have been verified by making a comparison between them and the assembled indices for eight catchments located in the Indian Ocean drainage basin, which have been calculated using the low flow estimation software which forms part of the HYMAS (Hydrological Modeling Application Software) package (Smakhtin et al., 1995). The results in this study are of considerable use in obtaining low flow data at ungauged sites, as well as making assessments of the hydropower potential in the river basins of interest.

DERIVATION OF REGRESSION MODELS

Selection of physical catchment characteristics

Small scale hydropower projects are normally run-of-the-river schemes with no storage of water. In order to be able to establish whether there will be sufficient discharge available, as a normal practice flow duration curves are used to determine the dependable flows (Midgley, et al., 1994). However, for the case of the two ungauged river basins on Pemba Island, stream discharge data was not available at the identified sites upon which a reliable flow estimate could be made. Application of a regional model describing the relationships between physical catchment properties and their hydrological response characteristics is desirable and allows one to understand and predict sufficiently well the flow regimes of the ungauged catchments within that region.

In order to develop flow estimation models, a sample of data of the key physical catchment characteristics (PCC) of the river basins must be obtained. For this study, the key physical catchment characteristics used were gathered from a sample of eight small catchments having an area ranging from 20 to 100 km2, similar to the area of the basins being studied. The PCC are usually obtained using topographical maps (preferably of the scale 1:50,000), geological maps and meteorological data. The channel slope index (CTI) based on the “S1085” is determined between a point 10% and 85% of the total length of the main channel length (L). The area of each catchment (*AREA*) is obtained using a planimeter, while the site altitude (HTSN) for each catchment is determined from topographical maps (preferably of the scale 1:125,000). The assembled values of the physical characteristics of the small catchments used in the analysis are given in Table 1.

Low flow indices determination

For studies involving small catchments, there are no strict guidelines currently established as to what low flow characteristics to use. The average annual flow is a basic value used to characterize streams, but average flow is of limited use as an indicator of the resource potential, since this flow is not available for a substantial amount of time. The most commonly used primary low flow index, is the flow that can be expected to exist for a high percentage of time, and which is equaled or exceeded 90 percentage of time (Q90), and this is usually expressed as a proportion of the long-term mean flow (ADF) in m^3/s (Nelms et al., 1998).

Table 1. Values of physical catchments characteristics for testing regional equations.

Gauge Station Code:	**AREA (km^2)**	**L (km)**	**HTSN (m)**	**CTI_{1085}**
1DB18	38	12.9	1540	72.13
1DB22	23.3	8.1	1650	39.70
1GA2	86.6	16.4	540	123.43
1HA8	32.5	10.9	580	120.43
1HA9A	21.6	9.9	530	115.48
1KB23	42.4	11.6	230	72.29
1KB24	38.8	11.6	610	157.71
3B8	99.9	22.49	1360	12.45

The secondary low flow indices that have been considered to specify a dependable flow as a measure of resource potential include the flow value estimated for the 10-day mean annual minimum flow MAM(10) expressed in m^3/s. The second is the baseflow index (BFI), representing the general baseflow response of a catchment frequently used to study the effects of catchment geology on low flows. It is usually estimated as the volume of baseflow divided by the volume of total streamflow, normally calculated by digital filtering from continuous daily streamflow data as described in Beven (2001) and Smakhtin et al. (1995). A list of the selected low flow indices that represent the hydrological response characteristics (HRC) of the catchments considered, including their definitions is presented in Table 2.

The corresponding assembled parameter values of the low flow indices for all eight catchments are presented in Table 3. These values are used to verify the accuracy of the results that have been obtained using the developed regional equations.

Flow estimation model derivation

If each model parameter can be estimated from physical catchment characteristics, it is possible to predict streamflow for ungauged catchments. The regional model equations to be determined must therefore depict the relationship between the low flow indices and the physical catchment characteristics. The approach adopted in developing the regional equations made use of

Table 2. A definition of the low flow indices.

Parameter	Description
ADF	The mean daily flow in m^3/s
Q90	The daily flow equaled or exceeded 90% of the time standardized by the ADF
MAM(10)	The 10 day mean annual minimum flow standardized by the ADF
BFI	The base flow index

a multiple regression technique that included statistical analysis for the purpose of obtaining a best fit of flow parameters. Depending on the type of the low flow indices being considered, the multiple regression analysis could be performed using the following general form of the equation (Mwakila, 2002).

$$Y(k) = \beta_o + \beta_1 X_1(k) + \beta_2 X_2(k) + \ldots\ldots + \beta_p X_p(k) + S_e(k) \tag{1}$$

where *Y(k)* represents the low flow indices, $X_1(k), X_2(k), \ldots X_p(k)$ are the physical catchment characteristics (PCC) in the kth model simulation parameter values; $\beta_o, \beta_1, \beta_2, \ldots \beta_p$ are the partial regression coefficients obtained by minimizing the regression error, *Se*. R^2 is the coefficient of determination, and *p* is the number of the PCC used in the regression model.

To derive the predictive equations for estimating low flow indices using Equation 1, various combinations of physical catchment characteristics were examined to obtain the best fit of the partial regression coefficients. The approach made application of statistical analysis procedures that yielded the highest values of the coefficients of determination R^2 corresponding to the lowest values of the standard error *Se*. This paper presents only the best (in terms of statistical criteria) models derived for the estimation of the flow that is equaled or exceeded 90 percent of the time Q90, the 10-day mean annual minimum flow MAM(10), and the baseflow index BFI (Kachigan, 1986).

RESULTS AND DISCUSSION

Regression model results

The regional equations for estimating low flows in ungauged catchments were developed using multiple regression analysis that incorporated physical catchment characteristics of the eight small basins assembled in Table 1. Statistical analysis that was conducted to show how the selected physical catchment characteristics affect the accuracy of the regression models revealed the best combination of the physical catchment characteristics in the regression model for Q90. These were the catchment area (AREA), the main channel length (L), and the site altitude (HTSN) since

Table 3. Calculated values of low flow indices for eight small catchments.

Catchment Code:	ADF m^3/s	Q90 (as %MF)	MAM(10) m^3/s	BFI
1DB18	0.62	35.70	0.25	0.83
1DB22	0.24	41.80	0.07	0.84
1GA2	0.61	3.30	0.01	0.47
1HA8	0.83	9.60	0.05	0.53
1HA9A	0.98	21.30	0.17	0.56
1KB23	0.99	0.10	0.13	0.70
1KB24	0.69	18.90	0.12	0.70
3B8	0.52	0.20	0.01	0.35

they yielded the highest value of the coefficient of determination R^2 and the lowest values of the standard error Se (Kachigan, 1986).

In the case of the predictive model for MAM(10), the combination of the catchment area (AREA) and the site altitude (HTSN) yielded the best regression model, while the best regional equation for estimating base flow index, BFI, was derived using a combination of physical catchment characteristics: (AREA), (L), and (HTSN). This analysis did however, result in nonlinear regression models. The computed values for Q90, MAM(10), and BFI for all eight small catchments when compared with their corresponding values assembled in Table 3 were found to be in a close agreement. The resulting best regression models developed from the analysis with their corresponding values of the coefficient of determination and the standard error are presented in Table 4.

The results indicate that the regression models developed can yield representative flow estimation values for small ungauged catchments which are more hydrologically homogeneous (Midgley et al., 1994), and hence, low flow regimes can be modeled with reasonable accuracy.

Application of regional equations

The derived regional equations were applied to estimate the values of low flow regimes for the Chamanangwe and Piki rivers on Pemba Island. To do this, the values of the physical catchment characteristics for the two basins given in Table 5, were determined using topographical maps. The basin locations are shown in Figure 1.

Calculations for the low flow regimes: Q90, MAM(10), and BFI for the two catchments using the developed regional equations listed in Table 4, yielded some indicative low flow values that are presented in Table 6.

These results show that the Q90 flow values in the 2 catchments, are estimated to reach 20.20% and 50.5% of the mean flow for Chamanangwe and Piki rivers respectively. The 10-day mean annual minima MAM(10) have also been estimated to reach 0.05 m^3/s for Chamanangwe river, and 0.067 m^3/s for the Piki river, while the baseflow index for the two catchments was found to be around 0.46 for the Chamanangwe and 0.92 for the Piki. These values should however, be considered to be rather indicative

CONCLUSIONS

Regression models have been developed for the purpose of estimating low flow regimes for ungauged catchments on the Island of Pemba. The relationships are derived by examining various combinations of physical catchment characteristics gathered from eight other catchments. The

Table 4. Models for estimating low flow regimes in ungauged catchments.

Low-flow index	**Regression model**	R^2	***Se***
Q90 (as % of MF)	$11.6-0.264AREA+0.083HTSN+82.5L^{-0.82}$	0.64	9.70
MAM (10) m^3/s	$AREA^{-0.3}-1.13HTSN^{-0.26}$	0.40	0.90
BFI	$0.758-0.0067AREA+0.00238HTSN^{-0.25}+0.293L^{0.13}$	0.65	0.15

Table 5. Measured physical characteristics of two catchments in Pemba.

Name of river catchment	**AREA** (km^2)	**L** (km)	**HTSN** (m)
Chamanangwe	16.6	9.6	10.0
Piki	10.8	2.3	11.0

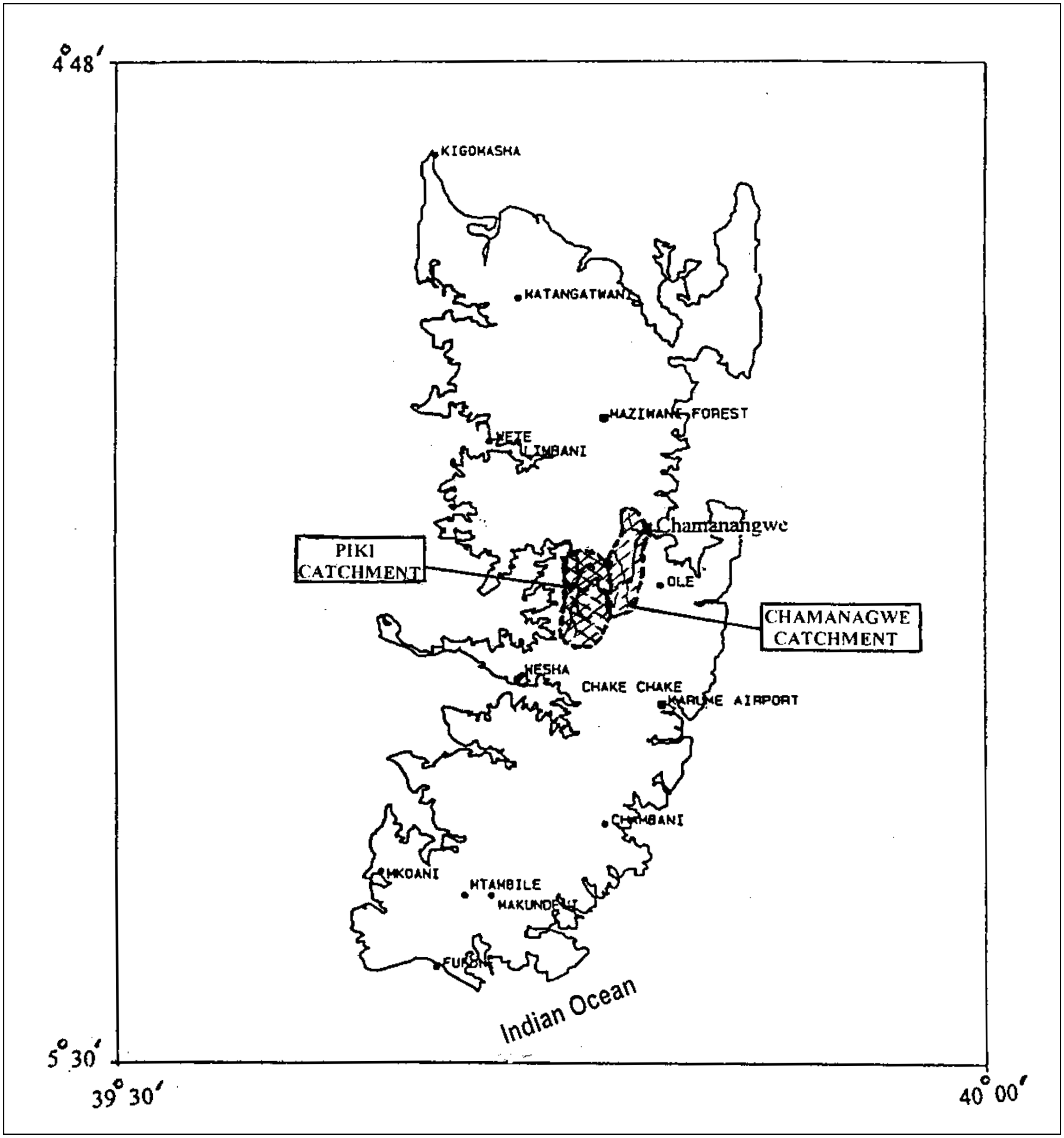

Figure 1. Pemba Island catchments and rainfall stations.

size of the small catchments selected was in the range similar to the two catchments found in Pemba. Both the primary and secondary low flow models have been derived by performing a stepwise regression analysis technique (Smakhtin et al., 1997) in accordance with their statistical significance. Verification of the results obtained for low flow indices using the developed regional equations gave a close agreement with the low flow values calculated for each of the selected eight catchments.

The results suggest that the regression models obtained may be particularly appropriate for use at ungauged sites (Mimikou and Gordios, 1989). Hence, the presented technique allows flow duration data to be estimated without the actual observed flow at a site, as has been demonstrated

Table 6. Estimated low flow indices for two catchments.

Name of river catchment	**Q90** (as %MF)	**MAM(10)** (m^3/s)	**BFI**
Chamanangwe	20.2	0.050	0.46
Piki	50.5	0.067	0.92

for the case of the two ungauged river basins found in Pemba Island. The limitations with this study can however, be attributed to the small sample of gauged catchments used in deriving the models, and lack of the actual streamflow data for river basins in Pemba to compare with at the time of the study. As such, a separate research effort is needed to improve the regression model accuracy on the basis of observed data. If the outcome of such study is positive, it would enhance the value of the results obtained in this study.

ACKNOWLEDGMENTS

The financial support of the Tanzania Commission for Science and Technology and the University of Dar es Salaam, is greatly appreciated. The contributions offered by Prof. G.R John and Dr. B.A. Majaja is also acknowledged for their useful critical review of the paper.

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