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Eco-hydrology of the Pangani River downstream of Nyumba ya Mungu reservoir, Tanzania

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ABSTRACT

Eco-hydrological studies are highly emphasized worldwide at the moment especially where hydraulic structures such as dams are concerned, mainly focusing on benefiting both humans and existing ecosystem for the present and future generations. The study at Pangani basin was aimed at assessing the sufficiency and the amount of flow reaching the downstream area of the Pangani River for maintenance of ecosystem. Fish species were considered as the indicators for ecosystem health.

Flow duration curves (FDC) and hydrographs were developed by using the collected historical daily flow data and used for assessing the flow variation before and after Nyumba ya Mungu (NYM) dam construction. The results showed that there is no seasonality and that for most part of the year the flow is within 20–40 m^3/s. From the comparison it was found that there is 42.7% decrease in Q_5, 2.1% decrease in Q_{95}, 38.9% increase in Q_{75}, 23.4% increase in Q_{50} and decrease of percentage exceedence of 50 m^3/s by 61.5%. Physical habitat simulation model (PHABSIM) was used for hydraulic simulation incorporating geometric and flow data collected in the field. From the simulations minimum flow for habitat protection is about 15 m^3/s and for flood formation flows should be greater than 50 m^3/s. Thus the required reservoir outflow for sustainable water resources management at the NYM should follow the above specifications.

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1. Introduction

Eco-hydrology defines new approaches to freshwater protection, restoration and management, thus one increases opportunities for ecosystems maintenance. Eco-hydrological studies on river systems have two main purposes: first, they are used to develop an understanding of the relationship between the various parts of a river ecosystem (channel, wetlands and floodplains, banks, groundwater, estuary; and their plants and animals (the biota)) and flow; and secondly, they are used to advise management on how flows can be manipulated for offstream purposes whilst holding changes to the river within acceptable limits (King, 2007). Recently there is an increasing number of countries such as South Africa which have engaged in eco-hydrological studies successfully within Africa, but in Tanzania it is still a new concept being applied recently in some rivers. In the Pangani basin as a result of the Nyumba ya Mungu (NYM) dam construction in mid 60s a number of researchers such as (MoW, 1996; PBWO/IUCN, 2007) have commented on the effects to the aquatic ecosystem as well as the environment downstream. Hence the rising need for this eco-hydrological study which is done by determining flow variation assessments before and after the dam construction, and also hydrological and hydraulic features of Kirua swamp area, in order to know the sufficiency of the controlled releases for maintenance of ecosystem in comparison to when the flow was natural.

2. Description of the study area and methodology

2.1. The study area

The Kirua swamps are located between Latitudes of 4°07′–4°34′S and Longitudes 37°26′–37°44′E within the Pangani basin just downstream of NYM dam. The dam is one of the most important man-made regulating reservoirs on the river, which started operation in 1968 incorporating a power plant with a capacity of producing 8 MW and ever since the flow downstream has been controlled. The swamps were estimated at 90,000 ha by Ivo-Norplan (1997) and it is said to have decreased to 36,500 ha (IUCN 2, 2006). Downstream of the dam there is a gauging station 1D8C serving the inflow into the swamp area. Fig. 1 shows the study area within the Pangani basin, the gauging stations and the layout sketch of site selected.

2.2. Methodology

In addressing issues of Eco-hydrology so far there is no recommended specific method but a number of them and each having one thing more or less than the other, with varying demand for

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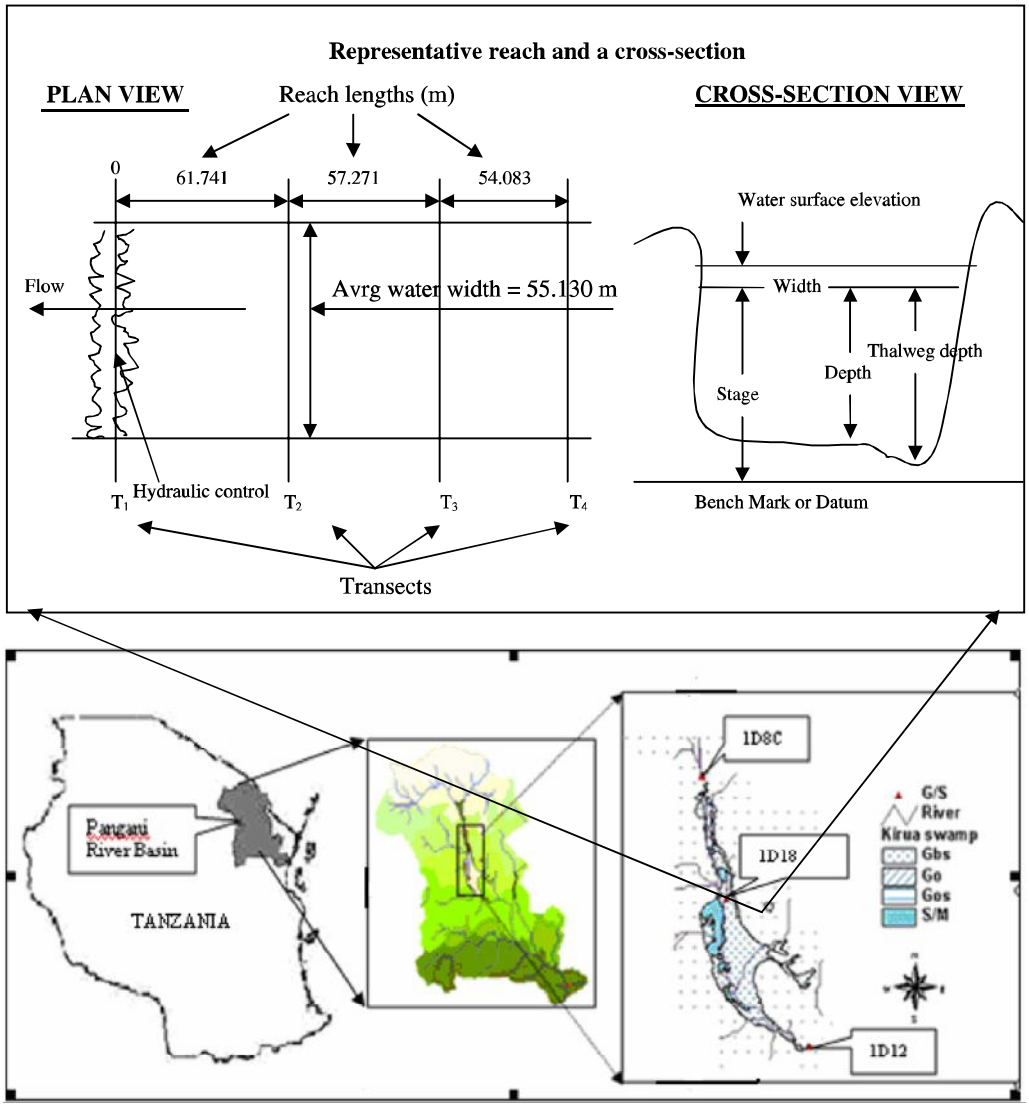


Fig. 1. Map of Kirua swamp system. G/S = Gauging Station; Gbs = Bushed grassland seasonally inundated; Go = Open Grassland; Gos = Open Grassland seasonally inundated; S/M = Permanent Swamp/Marsh. (Source: Modified from Moges, 2003).

data and time. These methods as stated by King et al. (2000) can be categorized into hydrological methodologies, hydraulic methodologies, habitat simulation methodologies and holistic methodologies.

The criteria for selection of methodologies were to capture the trend of flow variations with time; relate hydraulic parameters at present to ecology; limited field data; rapidness and effectiveness; and inexpensive. Thus in this study we settled for hydrological and hydraulic methodologies, with fish as species of ecological importance.

2.2.1. Hydrological methodologies

There are numerous methodologies that rely primarily or solely on hydrological data for deriving environmental flow recommendations, requiring only historical flow records. Also they are highly appropriate at the reconnaissance level of water resource development and for planning purposes, providing routine, yet low resolution estimates of quantities of water to be set aside for environmental maintenance. Such methods include Tennant method (or Montana method) according to Tennant in King et al. (2000) and flow duration curve analysis (FDCA).

Flow duration curves display the relationship between discharge and the percentage of time that it is exceeded. Where historical flow records are analysed over specific durations in FDCA, according to Gordon et al. in King et al. (2000), FDCs are used to derive specific flow percentiles (percentage exceedance values) associated with required suitable river conditions, often in combination with professional judgement, to produce environmental flow recommendations. Most recent methodologies based primarily on hydrological indices, also incorporate biological criteria in some instances (King et al., 2000).

Weaknesses of hydrological methodologies are: from ecological perspective is that it does not adequately address the dynamic and variable nature of the hydrological regime and also due to lack of ecological information as input, professional judgement is essential when these methodologies are employed.

The collected historical flow data were daily series from 1957 to 1994 for 1D8C. The data were then split into two groups representing natural and modified flow regime i.e. 1957–1967 and 1969–1993, respectively with highest flow of 255 m^3/s and lowest 2 m^3/s. Thus the FDC and hydrographs were developed for comparison between natural and modified regime (controlled releases).

2.2.2. Hydraulic methodologies

Hydraulic rating methodologies can be considered as an advance over purely hydrology based ones because they incorporate

ecologically based information on the instream and physical habitat of the biota. The most commonly used hydraulic methodology is the wetted perimeter method as stated by Tharme in King et al. (2000). In this study the derived relationship between changes in wetted perimeter and changes in flow values will be utilized in minimum flow recommendation. These methodologies enable a fairly rapid, though simple, assessment of flows for maintenance of such habitat areas for requirements such as fish spawning and passage. Also they are sufficiently flexible for application to many aquatic species and activities, and are low to moderately resource intensive. For high efficiency in derivation of hydraulic parameters, a model is applied as explained in the sections below.

Weaknesses of hydraulic methodologies are: they rely on the assumption that a single hydraulic variable or group of variables can adequately represent the flow requirements of target species for a particular activity and cannot be used easily for other out of channel components of the riverine eco-system such as riparian vegetation (King et al., 2000).

2.2.3. Hydraulic models

There are a number of reliable hydraulic models which have been established and utilized successfully worldwide, but in this case PHABSIM fitted well the criteria for method selection. The PHABSIM model is a habitat hydraulic model, part of a broad conceptual and analytical framework for addressing stream flow management issues. It mainly predicts physical microhabitat changes associated with flow alterations such as reduction of stream flow. In carrying out hydraulic simulations it assumes that the shape of the channel does not substantially change with discharge over the range of flows being simulated.

Water surface profile program (WSP) was used to predict longitudinal profiles of the water surface elevation changes over a range of simulated discharges. This program utilizes MANSQ program (whose main equation is Manning's) in supplying initial water surface elevation. Also velocity simulation and average depth parameters simulation are carried out. The governing equations are continuity, energy and manning's whereby continuity is useful for flow balance calculation; energy equation is for calculation of total energy of stream at given cross section and it accounts for net effects of energy loss between adjacent locations within stream reach; and manning equation defines energy slope at each location.

In PHABSIM, inputs are geometric and flow data as shown in Tables 1 and 2, as obtained from field work carried out in the month of April. All measurements were done with respect to the established Temporary Benchmark (TBM), at left bank of cross section 1 whose elevation was set at 100 m. Four cross sections were established with critical hydraulic control in the first cross section as shown in Fig. 1, which also shows the reach lengths between transect 1 and 2 as 61.741 m, transect 2 and 3 as 57.271 m and between transect 3 and 4 as 54.083 m, thus the total length of study reach is 173.095 m. The average measured width of water surface in the study reach is 55.13 m. The reach lengths once measured were used for calculation of slope which is required in the hydraulic simulations. The criteria for the site selection were channel straightness, hydraulic control presence and absence of flow interference among others as specified by King et al. (2000).

Ecological data collected were from literature and from the surrounding field, riparian vegetations and fish. Fish such as the *Barbus* spp. and *Synodontis* spp. were collected at the time.

Table 1
Summary of geometric data

Transect name	Reach length (m)	Thalweg (m)	WSL (m)	Water depth (m)
T_1	0	97.482	98.748	1.266
T_2	61.741	97.323	98.774	1.451
T_3	119.012	97.035	98.794	1.759
T_4	173.095	97.332	98.799	1.467

Table 2
Summary of River flow data

Transect or cross section name	Measured hydraulic flow parameters				
	Total width of Water surface, W (m)	Total area, A (m^2)	Total discharge, Q (m^3/s)	Mean velocity, Vm (m/s)	Water surface level, WSL (m)
T_1	60.70	–	–	–	98.748
T_2	67.15	33.655	15.4	0.487	98.774
T_3	46.20	41.956	14.0	0.320	98.794
T_4	46.47	37.328	13.5	0.339	98.799

3. Results and discussion

3.1. Hydrological results

3.1.1. Flow variation assessment

Flow duration curves drawn for the natural and controlled releases are as shown in Fig. 2. It can be seen that there is a sharp drop between 0% and 10% for the controlled releases. Quantitatively there is a 42.7% decrease in Q_5, 2.1% decrease in Q_{95}, 38.9% increase in Q_{75}, 23.4% increase in Q_{50} and 1.4% decrease in Q_{25}. Also from the hydrographs developed in Fig. 3 (incorporating the obtained percentiles) it can be seen that before dam construction there was a natural flow variability i.e. season to season, year to year, and afterwards that isn't the case. The Q_5 have decreased from 90 m^3/s to 50 m^3/s which represents higher flows and for most of the time after dam construction due to the controlled releases flow is between 20 m^3/s to 40 m^3/s that is in between Q_{25} and Q_{75}.

3.1.2. Impact on ecology based on hydrological findings

Reduction in high flows occurrence has great negative impacts on fish in terms of productivity. Higher flows in the case of Kirua flood the banks leading to swamp and floodplain formation, and flooding once in a while is necessary for fish spawning, feeding, growth of young fish species and washing away of nutrients from floodplains into the river, thus increasing reproduction and fish population. The increase of duration of low flow periods in the river places enormous stress on people within the area undermining their capacity to grow crops, as well as taking a toll on freshwater species and habitats. The flow variations from season to season, year to year (low flows, high flows, medium flows), are useful in maintaining the biodiversity and resilience of the system thus making it more able to cope with human disturbance. Moreover the majority of *Chiloglanis* spp. which was collected in the study area are said to be riffle dwelling species and are dependent on perennial flow during all stages of their life cycle. Such requirements provide important pointers as to the magnitude, distribution and constancy of low flows needed during dry season.

3.2. Hydraulic results

3.2.1. Hydraulic simulation findings

The hydraulic model was calibrated using the obtained natural flow percentiles 5%, 50%, 75%, 95% and then it was verified using discharge values 5, 25 and 50 m^3/s whose effect is known as stated in literature (MoW, 1996d; Ivo-Norplan, 1997). Whereas flow above 50 m^3/s is said to cause flooding of the whole area, 25 m^3/s is known to cause flooding of some areas only and at 5 m^3/s most parts are dry. For application return period floods (2, 5, 10, 20, 25, 50 and 100 years) were established by one of the recommended (Mkhandi, 1997; Babak et al., 1993) flood frequency analysis

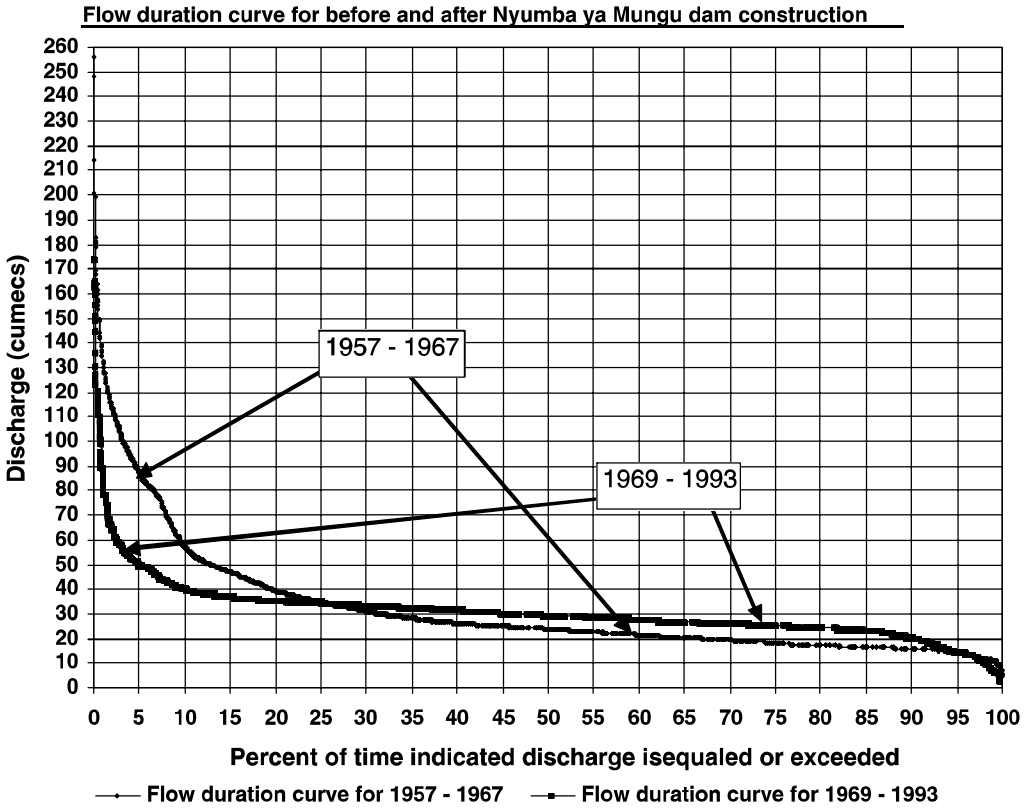


Fig. 2. Flow variations by flow duration curves.

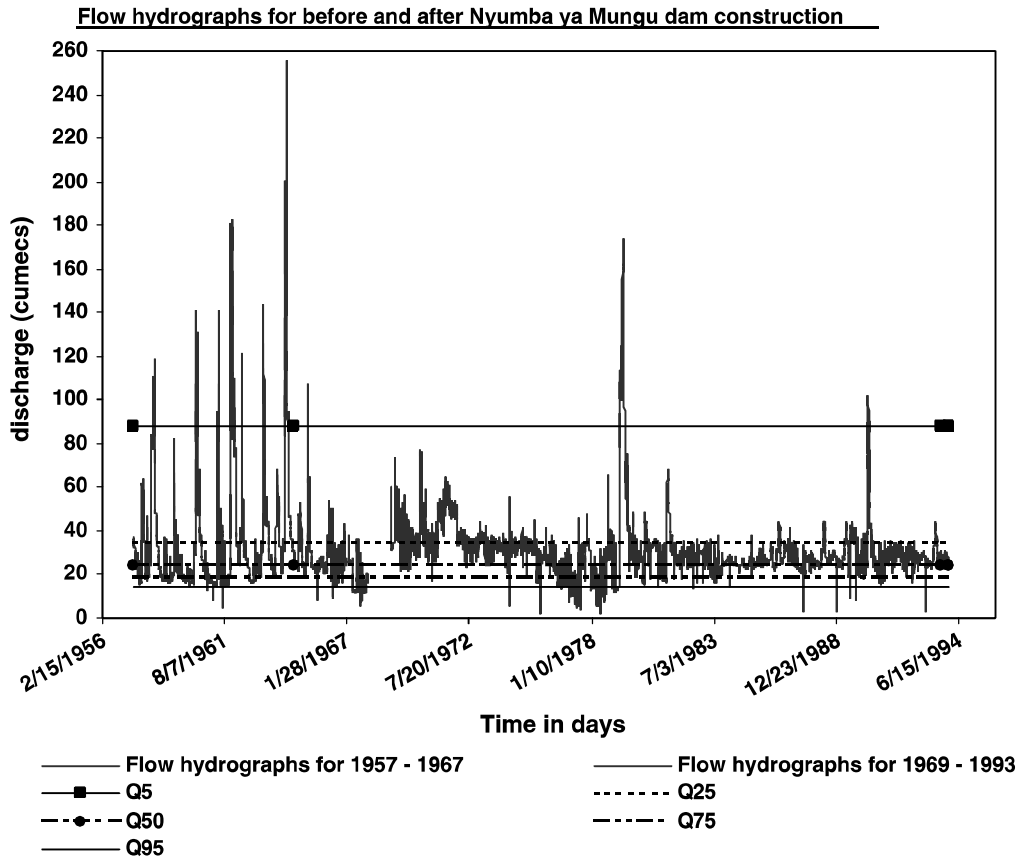


Fig. 3. Flow variations by flow hydrographs.

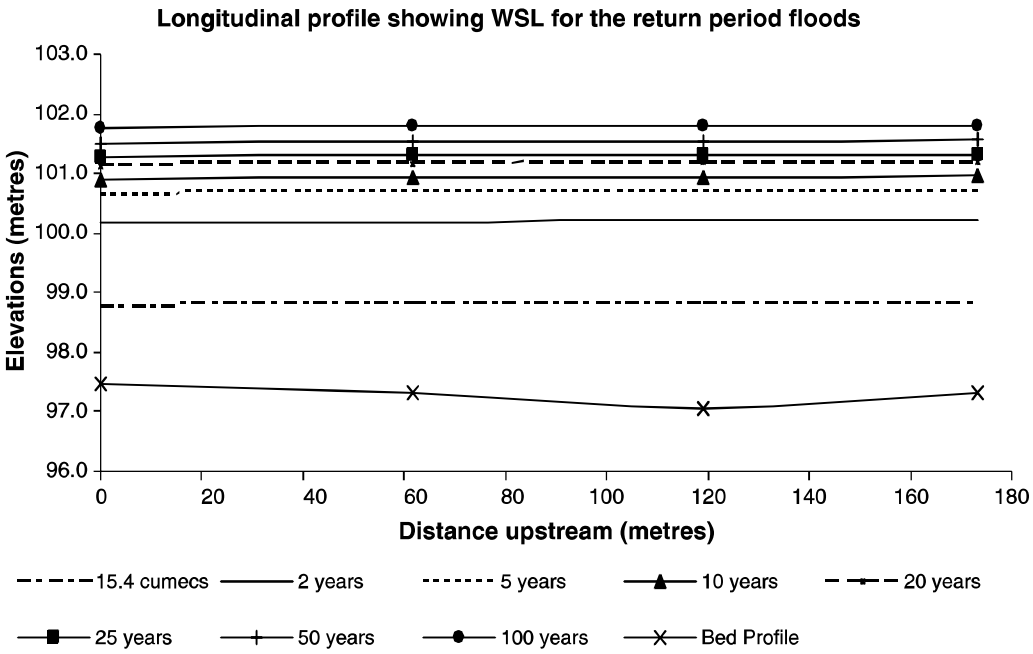


Fig. 4. Longitudinal profile for the return period floods.

approach namely Log Pearson type III, the resulting profiles are as shown in Fig. 4. Fig. 4 shows the longitudinal bed profile overtopped thus the area is completely flooded, and also water surface levels (WSL) attained under measured flow of 15.4 cumecs during field work is shown.

3.2.2. Impact on ecology based on hydraulic findings

From the hydraulic simulations the response of hydraulic parameters such as wetted perimeter, wetted width, hydraulic depth, hydraulic radius, average velocity and cross sectional area with respect to flow changes is significant. These parameters are important in analyzing the habitat of fish species. Most of these parameters increase as discharge increases. Also variations of stage with discharge is as shown in the stage discharge graph in one of the cross sections in Fig. 5, whereby it can be seen that at the highest stage flow is also highest and vice versa. Also in the figure it shows that for flow to be above 50 m^3/s the stage should be greater than 99.35 m, thus given the stage values flow values can be determined from these graphs.

The effect of very low flows such as less than 5 m^3/s, which has been occurring after dam construction, can also be seen, whereby the channel wetted area and width are greatly reduced. Flow variations whether high, medium or low impact on hydraulic parameters very significantly. It implies among many other hydraulic parameters, the greater the wetted perimeter the higher the diversity of fish species and quantity. Fish of many species move into inundated forest at high water to breed and feed and back to low water channels as level falls. Some fish mainly young remain in pools and as the level falls those fish, which can tolerate deoxygenated conditions, remain in swamps. Some fish such as Cyprinids Garra and Labeo, Catfishes Chiloglanis are adapted to fast moving water (Lowe, 1987). When the flow increases, the index of safe wading conditions at a cross section decreases.

Results from cross section 1 (place of critical hydraulic control) exhibit sensitivity of width, depth and velocity to flow changes and being shallowest would indicate critical water level needed to protect all habitats. Once a minimum level of flow is estimated other habitats such as pools and runs are satisfactorily protected.

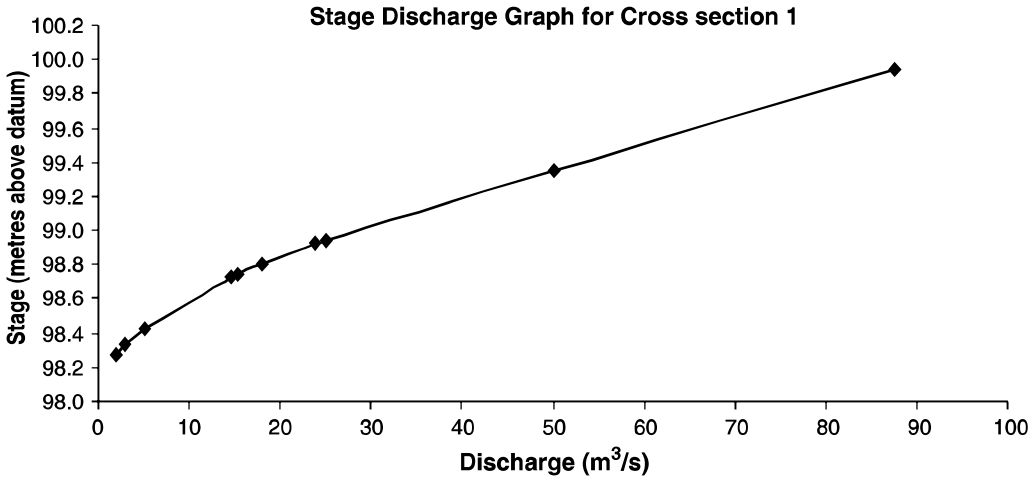


Fig. 5. Stage (elevation in metres above datum) discharge curve for cross section 1.

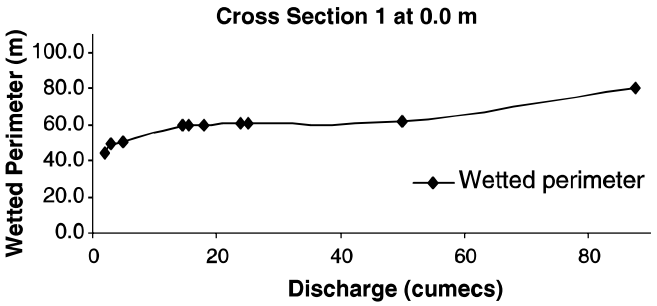


Fig. 6. Wetted perimeter variation with discharge.

It implies that the most obvious physical dimension that can be changed by altered flow regimes is the wetted perimeter of the channel (Acreman and Dunbar, 2004). Hence by maximizing wetted perimeter for this part of the river, enough fish food and habitat will be available to support a healthy aquatic community in the river as a whole. So a minimum stream flow required for habitat protection is the one where increases in stream flow no longer produce large increases in wetted perimeter. (http://www.mass.gov/dfwele/river/programs/rifls/lf_7q10.htm). Fig. 6 shows the variation of wetted perimeter in cross section 1 as referred above, whereby it can be seen from 15 m^3/s the variation of wetted perimeter is insignificant compared to flow changes. But from above 45 m^3/s and below 15 m^3/s the wetted perimeter variation is significant with respect to flow changes.

4. Conclusions and recommendations

4.1. Conclusions

From the combination of the findings of this study, i.e. from the hydrological, hydraulic and ecological part the following can be concluded:

- After the dam construction, seasonal flow variation ceased. There is persistence of flow ranging from 20 to 40 m^3/s.
- From the hydraulic simulations for maintenance of ecosystem within Kirua swamp the minimum stream flow required is about 15 m^3/s, and for flood development reservoir outflow should be greater than 50 m^3/s i.e. approximately for two months each year.
- The proposed reservoir outflow i.e. spillage, release and bypass, should be greater than 50 m^3/s for higher flows and minimum flow of about 15 m^3/s. Also should be linked to current climate within the catchment so that releases mimic wet and dry years. Even though it may be difficult to achieve required flood levels by releasing valuable stored water to supplement a natural downstream flood all the elements of flow regimes i.e. floods, medium and low flows are important to ecosystem.

4.2. Recommendations

- In future the researcher could have various sites in order to represent different flow regimes of Kirua swamp.
- Moreover in fieldwork the researcher for better simulation results could extend the cross sections to include the floodplains
- Also researchers could work on more than one ecological species present on a site and not only fish.
- Future research to access database for fish species and could go further to do habitat simulation with the used PHABSIM model as it accommodates such analysis.

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References

Acreman, M., Dunbar, J.M., 2004. Defining environmental river flow requirements review. Hydrology and Earth System Sciences 8 (5), 861–876.
Babak, N., Fang, X.Y., Vijay, P.S., 1993. Comparative evaluation of frequency distributions for Louisiana extreme rainfall. Journal of the American Water Resources Association 29 (2), 211–219.
IUCN 2, 2006. Socio-economic baseline assessment: the role of river systems in households livelihood, Pangani River basin flow assessment initiative, Pangani Basin Water Office, IUCN Water and Nature Initiative, First Draft Report.
Ivo-Norplan, 1997. Pangani River Training Project Feasibility study, PBWO – TANESCO, Pangani Falls Redevelopment, IVO International and NORPLAN A/S.
King, J., 2007. Hydrological data needs for the study and management of river ecosystems. <http://www.cig.ensmp.fr/~iahs/maastricht/s1/KING.htm> (accessed July 2007).
King, J.M, Tharme, R.E., De Villiers, 2000. Environmental flow assessments for Rivers: Manual for the Building Block Methodology, Water Research Commission Report No.: TT 131/00, Freshwater Research Unit University of Capetown, South Africa.
Lowe, R.H., 1987. Ecological Studies in Tropical Fish Communities. Cambridge University Press.
Mkhandi, S.H., 1997. Evaluation of Procedures and Development of Statistical Models for Determining Frequency of Floods with Special Reference to Southern Africa. Dar es Salaam University Press, Dar es Salaam.
Moges, S.A., 2003. Development and application of hydrological decision support tools Pangani River basin in Tanzania. Dar es Salaam University Press, Dar es Salaam.
MoW., 1996. River basin management component report D: sensitive Ecosystem (wetlands), River basin management and small holder irrigation improvement project, Ministry of Water and Livestock keeping.
PBWO/IUCN, 2007. Pangani River System-State of the Basin Report-2007, PBWO, Moshi, Tanzania and IUCN Eastern Africa Regional Program, Nairobi, Kenya.