Flood analysis and short-term prediction of water stages in river Songwe catchment

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Flood analysis and short-term prediction of water stages in river Songwe catchment

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Abstract. Every year flooding of Songwe River has brought severe problems in the lower part of its catchment located in Kyela District. Floods lead to loss of people's lives, destructions of infrastructures and properties. This study made floods analysis and short-term prediction of water stages. The study used rainfall data of Tenende weather station and water levels data at Kasumulu gauge station for identification of the flood patterns. Floods were grouped into three categories: floods with single peak, floods with several peaks and sprawled floods. The study recommends for the introduction and implementation of flood prediction practices, flood policy, and flood fight education, as well as continuous training of local residents on the best suitable traditional and modern ways of flood management practices and how to mitigate the floods effect.

1. Introduction

Worldwide flood events account for nearly half of the deaths and one-third of all economic losses [1]. Between 1985 and 2005, floods claimed the lives of over 112,000 people, affected more than 354 million people and caused approximately 520 billion Euros (US$690 billion) in financial damages [2]. According to the United Nations Development Programme (UNDP) in 2004, it was estimated that, on average, almost 200 million people in more than 90 countries are exposed to catastrophic flood events every year, average flood damage would be 10 percent higher which could incur the total cost of about $433 million annually [3]. The vulnerability to floods is expected to rise in the last decades due to the overflowing of the riverbanks as well as urbanization which causes overpopulation [4, 5].

Flood-related fatalities in Africa, as well as associated economic losses, have been increased dramatically over the past half-century. In Africa, flood-prone areas are being developed for both industrial and urban settlements. This may have serious consequences in the wake of extreme flood events with continuous pressure from increasing population and economic development. Furthermore, gauging stations on the African rivers are few and poorly managed [6]. The experience indicated that since 1990s, there has been a growing consensus at international level that spending has been focused on relief and other reactive efforts while the management practices initiative for floods are given less priority [7].

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Tanzania is prone to floods and has a long history of flood severity for example, in Morogoro (Dumila/ Dakawa area), Mara regions (Rorya district), Mbeya (Kyela district), Dodoma, and Dar es salaam [8]. Nowadays, only few publications are dedicated to the hydrological predictions in Tanzania [9, 10, 11] for different river basins (Mzimbati and Kilombero River basins) and no one for Songwe River. Likewise, the flood patterns in the Tanzanian rivers remain unknown. Moreover, the number of floods and their severity were intensified over the country in the last decade [12] due to the increased number of the torrential rains. The government is put a number of efforts in addressing disasters in the country through the Government Institutions such as the Prime Minister's Office' Disaster Management Department, the Tanzania Meteorological Agency and the Ministry of Water and Irrigation. Despite that such effort, flood prediction service and flood warning programmes which aimed to know in advance the conditions of water bodies and in a case provide different warnings in order to mitigate the flood effect in Tanzania remain challenging. Annually the floods remain unpredicted and residents unwarned, due to that floods still affect residents and bring damage to property and infrastructure. At the same time, the World Bank Report [13] shows that about 70% of Tanzanians continue to live with less than $2 per day. The poverty reduction has been slow, with approximately 12 million of citizens living in dire poverty while a significant portion of the non-poor population lives just above the poverty line and risks falling into poverty unless proper measures are in place [13].

Songwe River in Mbeya Region has been affected by the floods annually that have been leading to loss of people's lives, livestock and damage of properties [14]. Due to that the study assessed the catchment response on the rainfall and flood patterns.

2. Materials and methods

Data were obtained from the available documents such as books, thesis including both published and un-published reports and articles. Likewise, data from the Lake Nyasa Water Basin Office on water stages and water discharges for Songwe River at Kasumulu gauge stations (1RD1A), were collected for the period 1964-2017. Also were collected daily rainfall data from Tenende weather station for the period 1974-2017 from Lake Nyasa Water Basin Office.

3. Results and discussion

3.1 Analysis of the flood patterns

Analysis of the long-term rainfall distribution shows that in all months, the rainfall is above 190 mm. The months of January, April and May receive the maximum rainfalls above 1200 mm. April was detected to have the highest rainfall above 1800 mm. On the other hand, the months of August, September and October received the minimal rainfall compared to other months with the maximum rainfall of only 200 mm. All months received rain throughout the year. From historical perspective, the Songwe River catchment had an average annual sum of rainfall of 2810.3 mm (table 1), while in wettest year the rainfall was 2 times more 4349.0 mm and in driest seasons 2 times less that is 1472.7 mm. Years with rainfall above average are the years which are more vulnerable to flood occurrence. Thus, the years with rainfall above 4000.0 mm were in 1982, 1986, 1989, 1996, 1999 and 2009 associated with high flooding in the lower basin of Songwe River thus resulting to loss of people's lives, washing away the livestock, properties damage, as well as destruction of infrastructures (roads and bridges).

Joint analysis of rainfall at Tenende weather station and water levels at Kasumulu gauge station helps to identify flood patterns. Particularly, the Songwe River catchment experienced uni-modal season of rains, where all precipitations fall in one season (figure 1). Due to that, floods were grouped into three categories (figure 1):

1. Floods with highest peak at the end of wet season (one long wave).
2. Floods with several peaks (several waves).

3. Sprawled floods (one wave without significant peak).

Table 1. Long-term (1974-2016) monthly sums of rainfall at Tenende weather station.

Month	Average rainfall, mm	Max rainfall, mm	Wet years	Min rainfall, mm
January	224.7	1229.8	1986	86.5
February	170.3	356.4	2009, 1994	0.0
March	407.4	737.7	1996, 1983	168.6
April	850.6	1966.6	1996, 1991	284.3
May	502.9	1420.1	1982, 1989	47.7
June	146.7	543.1	1975, 1978	0.0
July	105.8	390.6	1974, 1983	0.0
August	59.8	211.2	1989, 1999	0.0
September	16.5	224.7	2009	0.0
October	26	232.2	2009	0.0
November	134.1	582.9	1988, 1981	0.0
December	165.5	542.7	1988, 1986	0.0
Sum	2810.3	4349.0	1982, 1986, 1989, 1996, 1999, 2009	1472.7

Figure 1a represents the floods with *single picked wave* for three hydrological years (1968-1969, 1978-1979 and 1994-1995). The study revealed that, there was single flood wave with high precipitations which began in November and ended in mid of April. It was also observed that there were months with low precipitations: May, June, July, August, September and October. From the beginning of the wet season, water levels rise slowly and form the peak flow. As rule that category of floods have highest water stages among others floods. After peak flow, the water levels of that flood's type recede slowly until the beginning of dry season (figure 1a).

The floods with *several peaks* (figure 1b) have several waves; as a rule the first wave starts at end of November and reaches recession at the end of December. The second wave starts in January and reaches its recession in March, while the third wave starts in March and ends in May. High precipitations were recorded around December - February, February - March and March - May. The high water levels for the first wave were observed in December in the hydrological year 1965-1966 which was 5.4 m, the highest peak for the second wave was observed in February in the hydrological year 1984-1985 which was 5.7 m, while the highest peak for the third wave was observed in March in the same hydrological year 1984-1985 which was 5.6 m. Also, the highest peak compared to the rest two hydrological years was observed in February in the hydrological year 1984-1985 which was 5.7 m (figure 1b). This means that in the respective hydrological years, three explicit waves of precipitations were recorded.

Figure 1c represents the *sprawled floods* for the hydrological years (1966-1967, 1971-1972 and 1972-1973). Such floods, as rule, have high water levels with several moderate peaks during whole wet season. The peak flow is not significantly different from other peaks. Such floods demonstrate water level rise which starts in November and ends in mid of May. The hydrological year 1972-1973 had the highest water levels compared to the rest hydrological years. The highest floods peaks for this type of flood were in February in the hydrological year 1972-1973 with water level of 4.1 m.

Thereafter, floods were analysed for 52 hydrological years. As well were calculated averages, minimal/earliest and maximal/latest water stages and their dates (table 2).

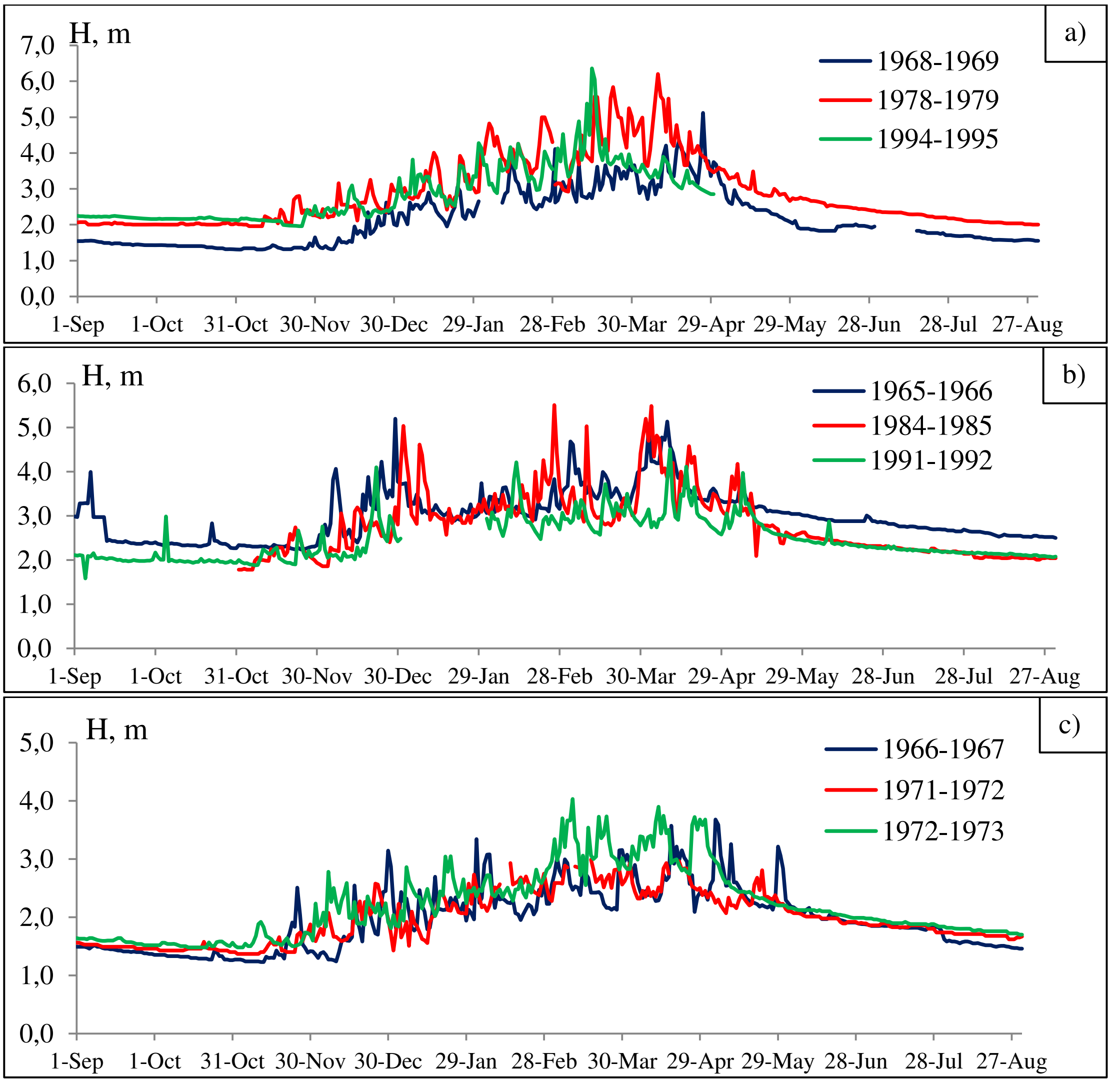

Figure 1. Flood categories (a) floods with highest peak at the end of wet season; (b) floods with several peaks; (c) sprawled floods.

Table 2 shows that, on average, floods start on 24thNovember and end on 21st May for the recorded 52 hydrological years. Peak flow, on average, was observed on 29th March and maximal water level equal 5.00 m. The end of floods on average was to be observed on 21st May. This gives the average duration of flood regime in Songwe River to be about 178 days. Water level rise between minimal water levels before the beginning of the wet season and the peak flow was about 3.20 m (table 2). Analysis of the earliest dates shows that in the historical perspective for the past 52 years, the flood usually started on 2nd November, with the peak flow on 29th December and end of flood on 27th April. Shortest duration of the flood regime was about 147 days. Lowest water level before the flood was 1.23 m and it rose minimally by 1.66 m and formed the maximal water level equal 2.99 m. Particularly, such peak flow was detected on 1971-1972 hydrological year (table 2). Highest water level was recorded as 7.55 m in 2015-2016 hydrological year. Generally, floods have about 4 peaks annually, but in some years, the number of peaks increased significantly and could reach 6, while in other years flood could have only 1 explicit peak.

Table 2. Summary of the parameters for Songwe River floods for 1965-2016.

Hydrological year	H_{dry}, m	Date of flood beginning	Maximal water stage		Date of flood end	Duration of flood, days	Increment of water stage, m
			Date	H max, m			
Average	1.91	24-Nov	29-Mar	5.00	21-May	178	3.09
Year	1991-92; 1992-93	1987-88; 1988-89	1985-86; 1996-97; 2007-08;	2011-12	1975-76; 1984-85;	1981-82	1974-75
Minimal or earliest	1.23	2-Nov	29-Dec	2.99	27-Apr	147	1.66
Year	1967-68	1984-85	1965-66	1971-72	1987-88	1965-66	1971-72
Maximal or latest	3.11	15-Dec	8-May	7.55	7-Jun	208	4.96
Year	2014-15	1965-66	1989-90	2015-16	1973-74	1973-74	2013-14

3.2 Prediction of water stages through multiple regression

For prediction of the daily water levels at Kasumulu gauge station in Songwe River, data of one gauge station at Kasumulu (1RD1A) and daily sums of rainfall for Tenende weather station were used. The water level in two days before prediction (H_{n-2}) corresponds to the certain level of water accumulation within the river bed. The changes of the water level in a day before prediction (ΔH_{n-1}) corresponded to the present tendency within a particular catchment as reaction on the presence or absence of rainfall. Rainfall was used in a day before the prediction (X_{n-1}) in order to compare the reaction of received rainfall and water level increase. Formula for such type of correlation is as follows:

$$H(n) = a_0 + a_1 H(n-2) + a_2 \Delta H(n-1) + a_3 X(n-1) \quad (1)$$

where H (n) – is the water level at Kasumulu gauge station, cm; H (n-2) – is the water level at Kasumulu gauge station two days before prediction, cm; ΔH (n-1) – is the change of water level at Kasumulu gauge station one day before prediction, cm; a_0, a_1, a_2 – are coefficients calculated by the Ordinary Least Squares (OLS); X – is the daily rainfall at Tenende weather station, mm; n – is the date of prediction delivery.

Due to the fact that rainfall in some days had a value equal to"0" the multiple regression analysis was done for two types of equations:

1. For days with rainfall more than "0" – days potential for water stages rise.
2. For days with rainfall equal "0" – days which have static water flow due to the present amount of water within catchment.

Prediction of water levels with rainfall more than "0"

Received coefficient of multiple regression is 0.87 which is high and shows suitability of the established regression (2) for short-term forecast delivery. The equation for prediction of the water levels at Kasumulu gauge station for days with rainfall more than "0" is as follows:

$$H(n) = 52{,}97 + 0{,}83 \cdot H(n-2) + 0{,}64 \cdot \Delta H(n-1) + 0{,}13 \cdot X(n-1) \quad (2)$$

where H (n) – is water level at Kasumulu gauge station, cm; H (n-2) – is water level at Kasumulu gauge station two days before prediction, cm; ΔH (n-1) – is change of water level at Kasumulu gauge station one day before prediction, cm; X – is daily rainfall at Tenende weather station, mm; n – is date of prediction delivery.

Prediction of water levels with rainfall equal "0"
Coefficient of multiple regression is 0.90 which is high and shows suitability of the established regression (3) for short-term forecast delivery. Thus, coefficient of 0.90 indicates strong relation in between selected variables and water levels at Kasumulu gauge station for days without rainfall. The equation for prediction of the water levels at Kasumulu gauge station for days with rainfall less than "0" is as follows:

$$H(n) = 36,23 + 0,86 \cdot H(n-2) + 0,75 \cdot \Delta H(n-1) \quad (3)$$

where H (n) – is the water level at Kasumulu gauge station, cm; H (n-2) – is the water level at Kasumulu gauge station two days before prediction, cm; ΔH (n-1) – is the change of water level at Kasumulu gauge station one day before prediction, mm; n – is the date of prediction delivery.

Multiple regression quality evaluation
Thus, figure 2 indicates the predicted and observed water stages in 2014-2015 hydrological years with the same forecast observed in days of minimal water flow. Hence multiple regression formulas through equations 2 and 3 provide good results in comparison with the observed data.

The evaluation of the quality of the established equations 2 and 3 was based on permissible error and percentage of the successful forecasts [15]. The results for equations 2 and 3 show that more than 91% and 96% of all predictions were successful. Thus, it is recommended to use the equations 2 and 3 in delivery of forecasts of water stages in Songwe River with lead time 1 day.

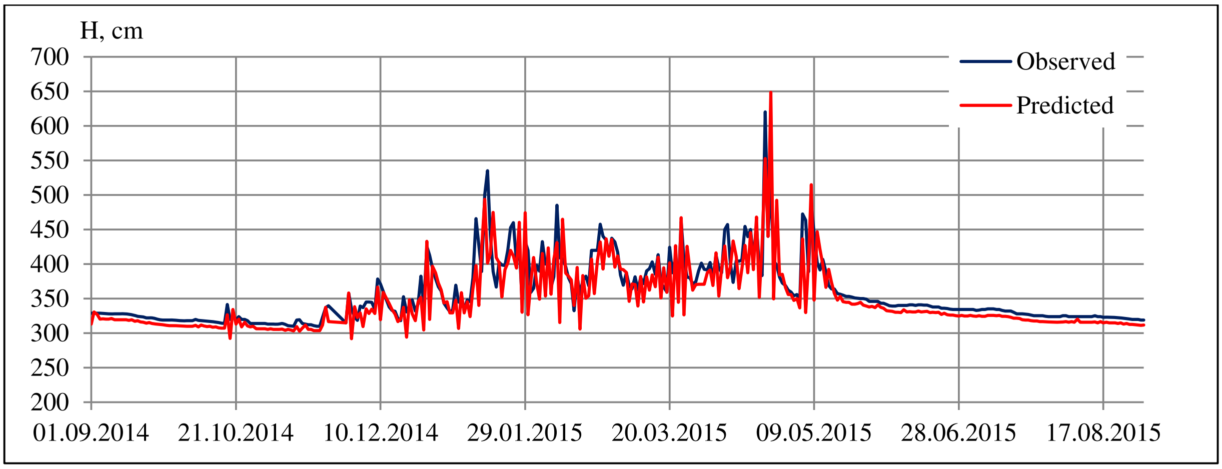

Figure 2. Predicted and observed water stages in 2014-2015 hydrological year for Songwe River at Kasumulu gauge station.

4. Conclusion

Songwe River catchment experienced unimodal season of rains, where all precipitations fall in one season. Floods were grouped into three categories: floods with single peak; floods with several peaks and sprawled floods. Generally, floods have about 4 peaks annually, but in some years could reach 6, while in other years flood could have only 1 explicit peak.

For prediction of the daily water levels at Kasumulu gauge station in Songwe River data of one gauge station at Kasumulu (1RD1A) and daily sums of rainfall for Tenende weather station were used. These data were analysed through two multiple regressions separately for days with rainfall and without it. The

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evaluations of the quality of the established equations for days with rainfall showed that 91-96% of all predictions were successful. That gives an opportunity to use equation in delivery of forecasts of water levels in Songwe River with lead time 1 day.

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