Temporal Flow Variations: A Challenge for Water Management in Tanzania

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Abstract

Average river discharges in selected rivers in catchments found in two different climatological zones in Northeast Tanzania were investigated to highlight the changes in distribution of river flows over the years. 10-year (decadal) average daily, weekly and monthly flows were computed for the 1950s through 1990s and 6-year (2000-2005) average flows and assessed to highlight changes in the distribution of flow volumes within the year while trend analysis was used to highlight changes of monthly flows over the years. Results indicated progressive amplification of flow peaking in May, declining and shifted low flows from February to March since the 1970s and progressive declining mean annual flows, although some isolated years of the opposite sign were observed within the decades. Trends indicated predominantly declining dry season flows and augmenting peak wet season flows between the 1950s and 1990s. This situation has strong implications to water resources management in the three river basins (Pangani, Sigi and Umba) in Northeast Tanzania where conflicts related to periodic water scarcity are increasing. It therefore calls for the need of conservation of abundant wet season flows to cater for increasing multi-sectoral water requirements during the dry season while addressing issues of water provision for ecosystem needs.

Key words: River flows, flow seasonality, decadal average flows, multi-year variability, linear trend analysis, water resources management

INTRODUCTION

There have been a number of water related conflicts in various parts of Tanzania including northeast Tanzania. Northeast Tanzania comprises three administrative regions of Tanga, Kilimanjaro and Arusha, which fall within three hydrological basins of Pangani, Umba and Sigi in order of decreasing size.

With a population of over three million inhabitants and number of socio-economic activities, surface and ground water resources have experienced significant pressures. The pressures include direct water abstractions from surface rivers, reservoirs as well as groundwater for various and indirect depletion from changing climate and landcover in which indigenous forests have been cleared for agricultural land. A consequence of such factors acting together is changes of water resources related to enhancement of hydrological extremes of floods and droughts leading ultimately to water unavailability.

Past studies (MNRT, 2005; Valimba, 2005; Valimba, 2007a) have highlighted an indication of increasing frequency, persistency and volumes of river flooding and droughts in various parts of northeast Tanzania. Although the changes have significant implications to water resources management, water allocation and conservation practices, which mainly considers available water volumes at scales rather than daily (weekly, monthly, etc), will be significantly be affected. Therefore, this study intended to investigate changes of seasonal flow regime that might have occurred in relation to changing hydrological extremes in order to complement claims of existing changes and document changes to provide information to guide the decision-making process.

SELECTION OF STUDY CATCHMENTS

The surface water resources of northeast Tanzania are located within the three basins, the large Pangani, medium Umba and small Sigi (Fig 1). The Pangani River basin extends from the northern mountains of Kilimanjaro and Meru through the central Maasai Steppes and Usambara Mountains to Indian Ocean. The surface water resources of Pangani are further subdivided by the *Nyumba ya Mungu* (NyM) Reservoir into two main systems, the upstream and downstream water resources (Fig 1). The upstream system comprises the eastern River Ruvu branch, which drains the eastern Mount Kilimanjaro and eastern and northern North Pare Mountains, and the western River Kikuletwa branch draining the western Mount Kilimanjaro and Mount Meru. The two major upstream rivers flow into the NyM reservoir whose outflow into River Pangani is controlled throughout to the Indian Ocean coast. The downstream reaches of the controlled River Pangani is fed by two major tributaries, Mkomazi and Luengera, which drain the Usambara Mountains found close to the Indian Ocean coastline (Fig 1). The Rivers Umba and Sigi drain the Usambaras to discharge in the Indian Ocean and consequently their catchments extend from these coastal mountains to Indian Ocean coastline.

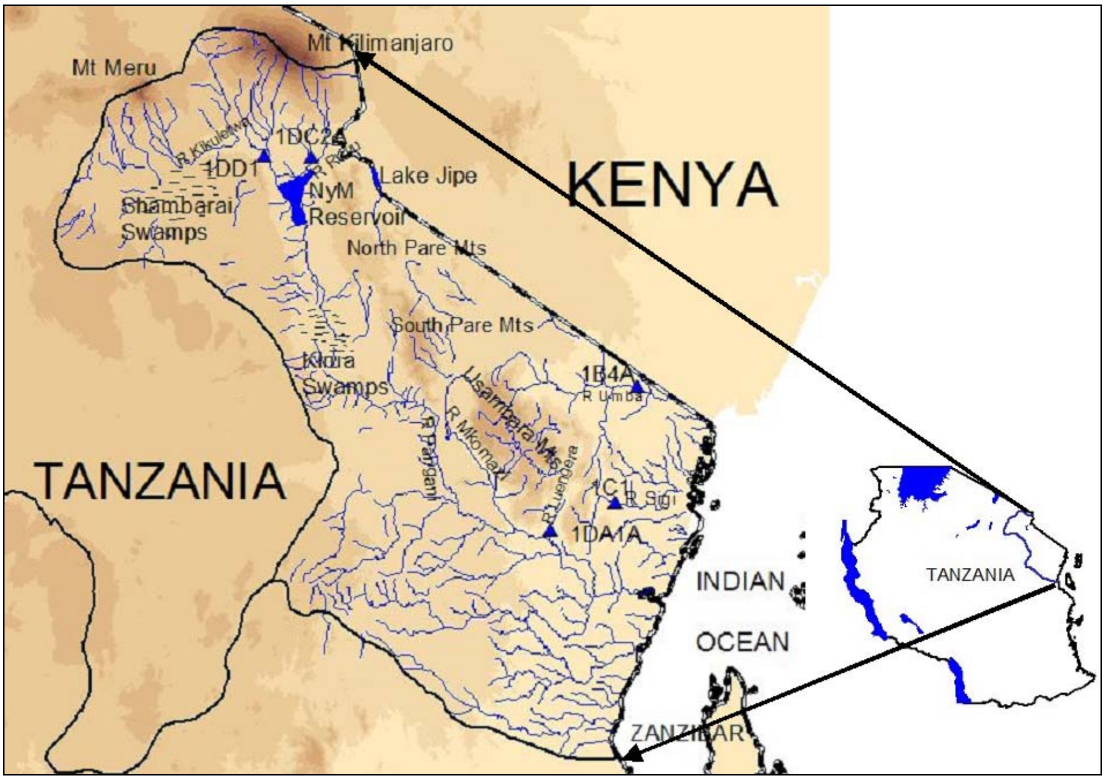

Fig 1: Location of selected catchments for the study.

The climatological analysis (e.g. Valimba, 2005) indicated that northeast Tanzania is divided into two major climatological regions, the inland region comprising the northern Mounts Kilimanjaro and Meru and North Pare Mountains and the coastal region consisting of the Usambara and South Pare Mountains. Consequently, rivers draining mountains in the coastal region (Umba, Sigi, Luengera, Mkomazi and Lower Pangani) exhibit different multi-year pattern of variability from that of rivers draining the northern inland region mountains (Kikuletwa, Ruvu and Upper Pangani).

The selection of catchments for this study considered rivers which are not regulated (naturally or artificially), least effects of water abstractions and the geographical location within the two climatological regions. Need to analyse unregulated rivers screened out all records along the River Pangani from the NyM reservoir to the coastline. The third criterion selected catchments from the upstream and downstream locations of the reservoir. The need for at least one record from each basin retained four stations in the Pangani basin, one in both Umba and Sigi basins. The four retained Pangani catchments were distributed on each upstream branches (one for eastern and western) and major downstream tributaries (Mkomazi and Luengera). The records at the catchment outlets were considered representative of the catchment conditions. However, the second criterion rejected the record of the Mkomazi, where water abstractions are significant (MNRT, 2005). The final selection retained 5 records at the respective flow gauging stations (Fig 1).

DATA AND METHODS

Data

Daily discharge data closest to catchment outlets of the 5 selected catchments were extracted from the database at the Department of Water Resources Engineering of the University of Dar es Salaam. The flow records were of variable length and continuity, spanning the period from the early 1950s through the mid 2000s (Table 1). For comparability analysis, the period 1960s to 1980s is appropriate while the long-term interpretation of the changes considers the 1950s through 2000s for a few records.

Table 1: Inventory of streamflow records and availability of daily data in selected catchments.

Sno.	Code	River	Location	Lat	Long	Area (km^2)	Available record
1	1B4A	Umba	Mwakijembe D/S	-4.5139	38.8917	7130	Feb 1963-Sep 2002
2	1C1	Sigi	Lanconi Estate	-5.0139	38.7997	705	May 1957-Jun 1990
3	1DA1A	Luengera	Korogwe	-5.1333	38.5750	800	Aug 1953-Feb 1995
4	1DC2A	Ruvu	Tanga Road Bridge	-3.5250	37.4667	3368	Jul 1952-Dec 1991
5	1DD1	Kikuletwa	Blw Weruweru conf	-3.5167	37.2833	2849	May 1952-Feb 2005

Average weekly were computed for 52 weeks of hydrological year (1^{st} October-31^{st} September) with the first week starting on 1^{st} October. Monthly flows were computed from average daily flows in which average monthly flows for wet season months (October-May) were determined for months with at least 90% of the daily flows available and no significant rainfall was observed in two days before and during the missing daily flows. For dry season months (June-September) when flows in consecutive days are highly correlated, average monthly flows were determined for months with at least 70% of daily records available. Otherwise, the average monthly values were not determined and considered missing.

The replacement of missing monthly values used two approaches, flow routing and rainfall-runoff modeling. Flow routing at daily time step was used for catchments where upstream daily records were available for the periods when daily flows are missing at the study stations. Routing models were calibrated between an upstream and a downstream station and used to estimate missing daily flows in the downstream record using recorded flows upstream. Daily flows were then used to compute average monthly flows. For the case when no upstream flows are available, rainfall-runoff modeling was used. Single reservoir models calibrated at the monthly time step were preferred to systems models (Simple Linear Model – SLM and Linear Pertubation Model – LPM) at the daily time step since this minimizes the errors associated with estimation of daily flows. No attempts were made to extend flow records beyond their periods of available observations.

Methods

Seasonal flow regime

Long term average daily, weekly and monthly flows, computed using the entire record length, were used to establish average intra-annual patterns of flow variations that describe the seasonal flow regimes in northeast Tanzania.

Decadal analysis

This method aims at a comparative analysis of decadal (10-year) averages to highlight the direction of change of flows between 1950s and 2000s. The method involves computation of decadal average (1950-59, 1960-69, etc) flows for each day, week and month for each of the selected records. The decadal average flows were therefore used to investigate the changes of flow regime in northeast Tanzania.

Trend analysis

Despite the usefulness of decadal averages on highlighting the nature of changes, they are often affected by cyclic pattern to sometimes fail to clearly provide the nature of changes. Linear trends were therefore used to statistically characterize the direction of change of average flows. Of interest to this study were the high flows in April and May and low flows in February and March. The indices investigated were i) average monthly discharges, ii) minimum monthly discharges in February and March, iii) monthly frequency of flows below the drought flow index (Q70, Valimba, 2007a) in February and March, iv) maximum monthly discharges in April and May and v) monthly frequency of flows above flood flow index (Q5) in April and May. Slopes of linear trends for each series of selected indices were determined using the non-parametric Man-Kendall procedure as used in Hirsch *et al*. (1993) and Valimba (2005). The procedure reduces the effects of outliers and was considered appropriate for the study.

RESULTS

Flow Seasonality

Average flows indicate spatially variable patterns of seasonal flow variations with the predominance of bimodal flow regime with distinct peaks in November and May (Fig 2) following the short and long rains respectively. The early rains in mid to late October contribute to flow increase to first peaking in November/December and recession follows the end of the short rains in northeast Tanzania. Progressive reduction of flows is observed to intermediate low flows in February (Fig 2) and subsequent flow increase is observed following the onset of the main rainy season, the long rains in March.

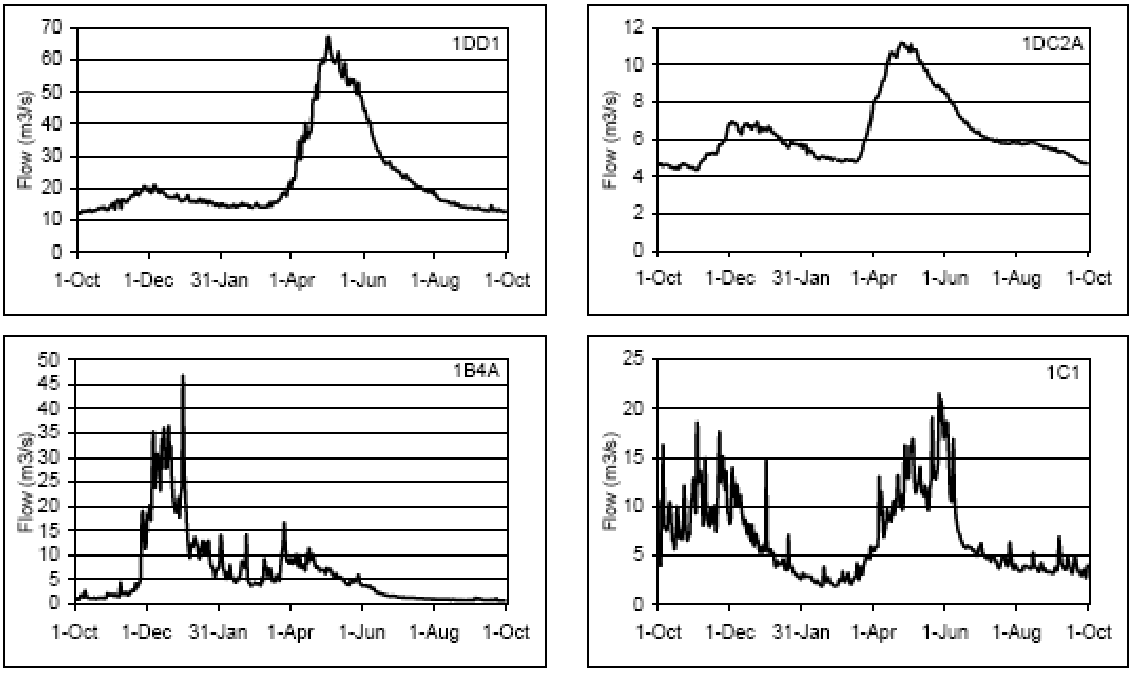

Fig 2: Flow seasonality in northeast Tanzania rivers indicated by average daily flows.

High rainfalls during the long rains in northern catchments (upstream of NyM reservoir – 1DD1, 1DC2A) contribute to highest flows in April and May (Fig 2) while high rainfalls during the short rains in catchments on northern part of Usambaras and Pare result in the highest flows in December in Umba catchment (1B4A). Rivers such as the Sigi, which drain the northern and eastern parts of the Usambara receives high rainfalls during both the short and long rains and consequently have well defined bimodal flow regime with almost comparable peaks in the two seasons (1C1, Fig 2).

The second flow recession occurs since late May after the end of the long rains throughout the dry season (late May-mid October) to low flows in late September to mid October. Whilst rivers with the highest peak during the long rains and/or short rains (1DD1, 1C1) experience the lowest flows in February, those with the peak during the short rains (1B4A) experience lowest flows in October (Fig 2).

Changing Flow Regime

High and medium flows

Results indicated increasing high flow peak in April/May, irregular changes of medium flow peak in November/December and there is relatively no indication of shifting peaks (Fig 3). Throughout the upper and coastal catchments in the three basins, flow peaks occurring in May have consistently increased from lower peaks in the 1950s to the highest peak in the 1980s (Fig 3) and correspond to percentage increase in the range 4-33% (Table 2). Similarly, average April flows have increased 4-143% of their 1950s averages. Unlike the consistent May flow increase, the highest April flow increased was experienced in the 1960s and, despite being higher than the 1950s, April flows have consistently decreased in the subsequent decades (Table 2). Despite the lack of consistency in medium November/December flow changes in

May-peaked catchments, there is a slight indication of increasing December peak in the catchment draining the eastern Mt Kilimanjaro (1DC2A) (Fig 3). However, the consistent increase of December peak is evident in the catchment of 1B4A with peak flows in December (Fig 3).

Table 2 Changes of average monthly flows in selected catchments in northeast Tanzania relative to the 1950s averages.

	1DD1			1DC2A			1C1		
Month	1960s	1970s	1980s	1960s	1970s	1980s	1960s	1970s	1980s
Oct	58.9	76.5	148.9	17.3	7.7	6.9	54.1	24.4	61.9
Nov	160.6	80.5	132.2	42.7	21.3	18.0	138.4	0.6	46.1
Dec	96.3	49.5	117.0	67.5	33.8	55.2	*-41.7*	*-53.0*	*-36.2*
Jan	94.4	80.6	102.9	58.6	29.7	16.0	*-33.1*	15.1	*-31.7*
Feb	39.7	67.7	69.2	5.1	18.7	*-15.8*	*-24.3*	*-40.8*	*-52.5*
Mar	83.9	90.1	102.8	34.5	17.1	*-17.8*	*-33.8*	*-70.0*	*-73.6*
Apr	90.1	121.6	60.1	143.3	71.7	40.6	7.9	4.7	*-4.6*
May	9.2	16.9	22.5	30.0	13.1	32.4	4.7	9.1	24.2
Jun	29.5	47.6	48.4	8.6	0.6	*-0.5*	31.7	0.7	*-18.4*
Jul	47.8	74.1	76.1	*-2.3*	*-12.1*	*-8.8*	*-12.6*	*-22.4*	*-2.8*
Aug	39.3	87.9	102.5	*-3.9*	*-15.7*	*-5.9*	*-52.4*	*-63.2*	*-37.5*
Sep	9.5	38.5	61.6	*-2.3*	*-13.8*	*-11.3*	*-24.0*	*-34.3*	*-13.8*

The consistent increase of average May flows in consecutive decades and decreasing average April flows were contributed by a combination of persistent high flows and high peak flows in May (Fig 4). Wide flow peaks at 1DC2A and 1C1, for example, experienced since the 1970s replacing narrow flow peak in the 1950s and 1960s are illustrative of the contributing causes. A linear trend analysis of May flow maxima indicated both decreasing and increasing flow maxima (Fig 5). The persistent high May flows (Fig 4) could be the sole contributor to increasing average May flows in the upper catchments of Pangani basin (1DD1, 1DC2A) since May flow maxima have either decreased between 1950s and 2000s (1DD1) or not changed (1DC2A) (Fig 5). In contrast, by both persistent high December flows (Fig 4) and increasing December flow maxima (Fig 5) could be attributing to increasing average December flows in the coastal catchments (1B4A).

The pattern of decadal April flow changes could be attributed to high rainfalls in the 1960s through the early 1970s (Valimba, 2005) which might have contributed to substantial groundwater recharge that sustained April flows higher through the 1980s decade of reduced rainfall than in the 1950s. The consistent increase of average May flows in consecutive decades, decreasing average April flows and increasing end of April and May rainfall amounts related to long rains (March-May rains) shifting (Camberlin *et al.*, 2003; Valimba, 2006) strongly suggest their contribution towards substantial flow peaking in May. Unlike in other eastern coastal basins of Tanzania such as Wami River basin where flow peak has shifted from April to May (Valimba, 2007b), there is no shifting in northeast Tanzania.

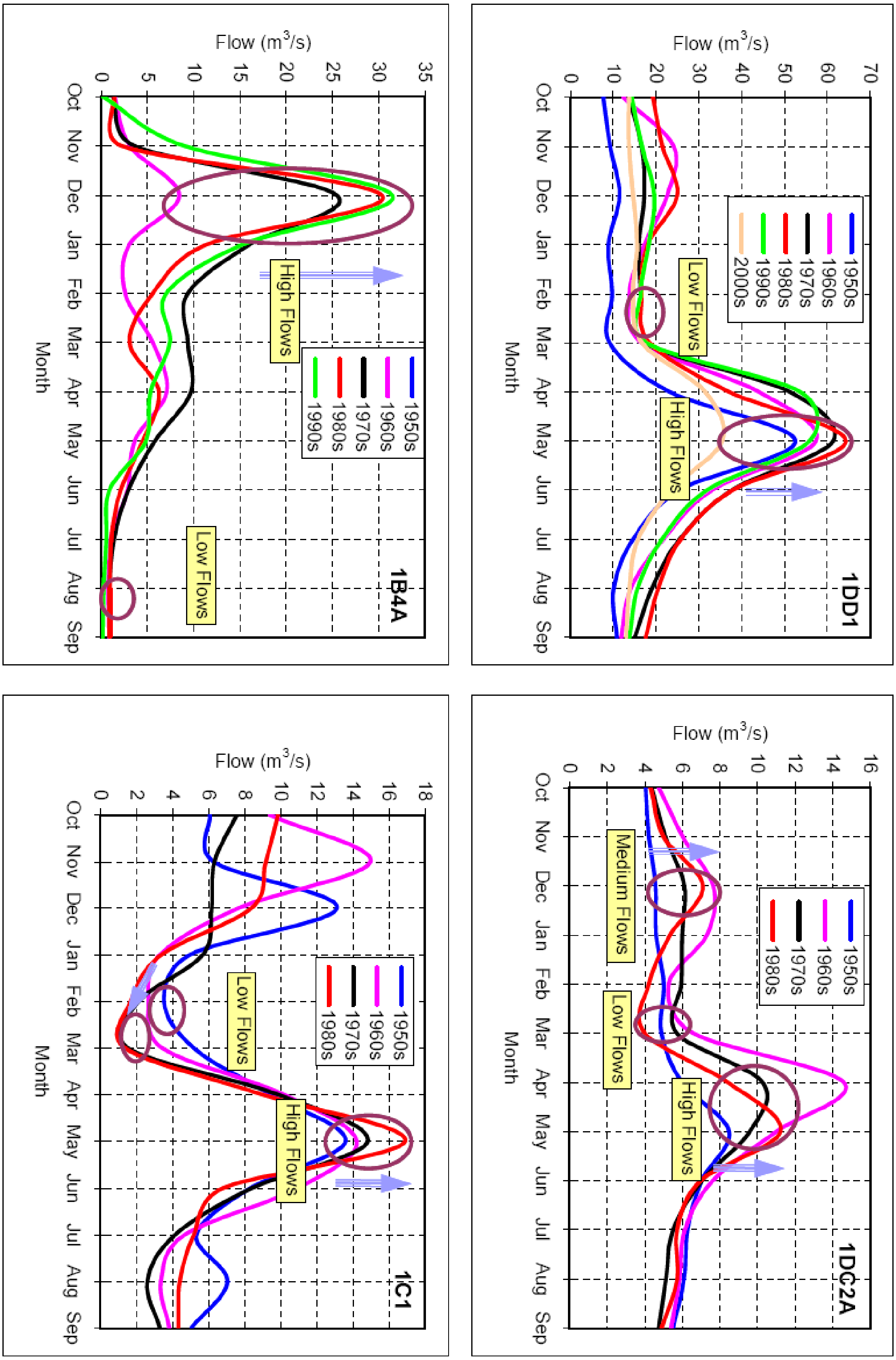

Fig 3: Changing monthly flow seasonality in selected catchments in northeast Tanzania. Allows show the nature of change (increase: up; decrease: down).

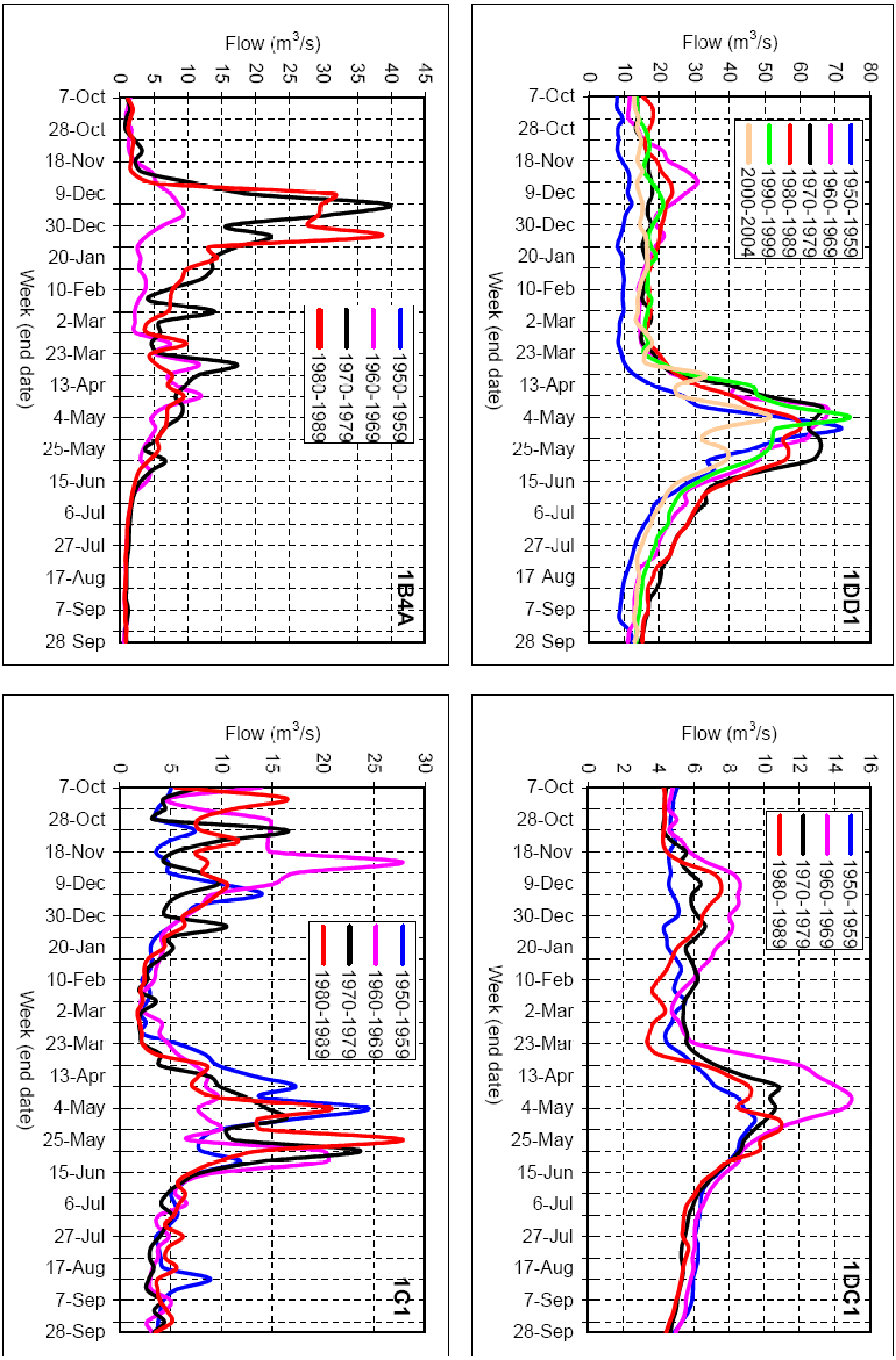

Fig 4: Changing weekly flow seasonality in selected catchments in northeast Tanzania.

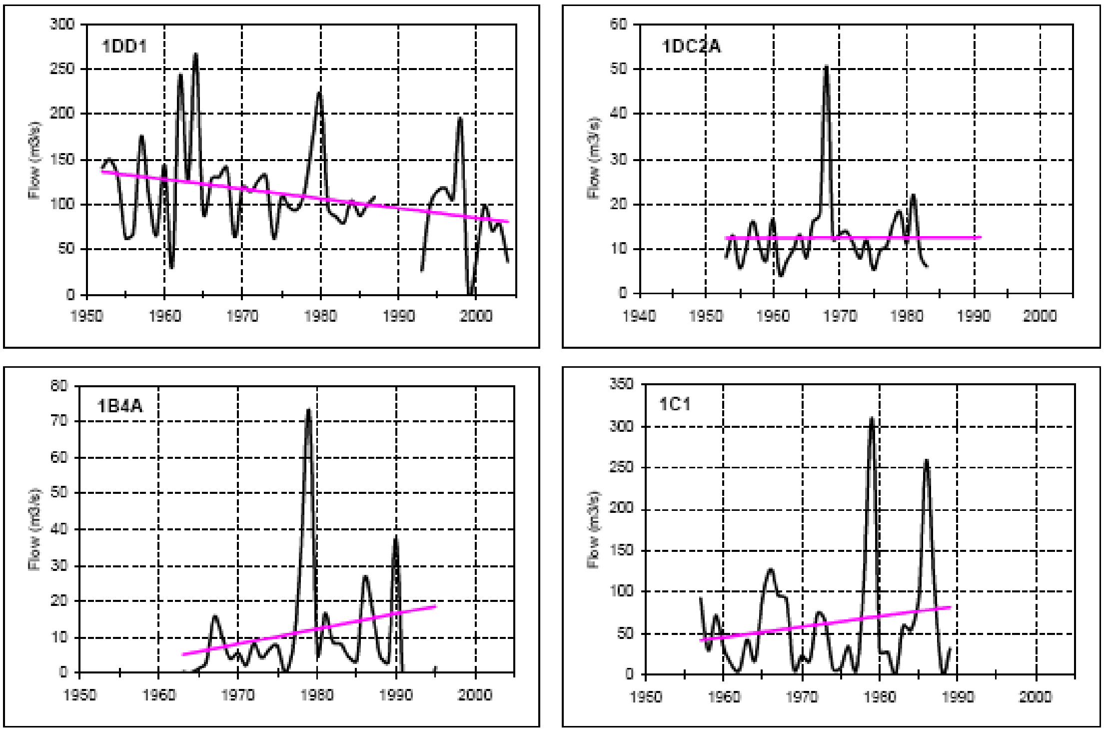

Fig 5: Multi-year variability of maximum May flows in selected catchments in northeast Tanzania.

Low flows

Except for the catchment of 1B4A with lowest flows in September/October where no changes were identified, lowest flows occurring in February and March in other catchments have either show no consistent changes (1DD1, 1DC2A) or consistently changed (1C1) (Fig 3). The percentage changes, however, indicated a consistent increase of 40-70% (February) and 80-102% (March) low flows at 1DD1 while low flow at 1C1 have consistently decreased by 24-53% (February) and 34-74% (March) (Table 2). Unlike the March low flow augmentation at 1DD1, the low flow reduction at 1C1 has been accompanied by shifting occurrence from February to March (Fig 3).

The changes of average monthly flows could be attributed by similar changes of low flow frequency rather than volume as indicated by relatively smooth flow hydrographs during the low flow period (Fig 4). That is, flows are either persistently below or above a reference (1950s) low flow magnitude. However, time series analysis of February/March flow magnitudes indicated augmenting flow minima at 1DD1 and 1B4A and slightly declining flow minima at 1DC2A and 1C1 (Fig 6). Whilst the positive trends towards low flow augmentation might be advantageous for basin water resources planning, the declining low flows might substantially increase the current stress and water-scarcity conflicts in the region.

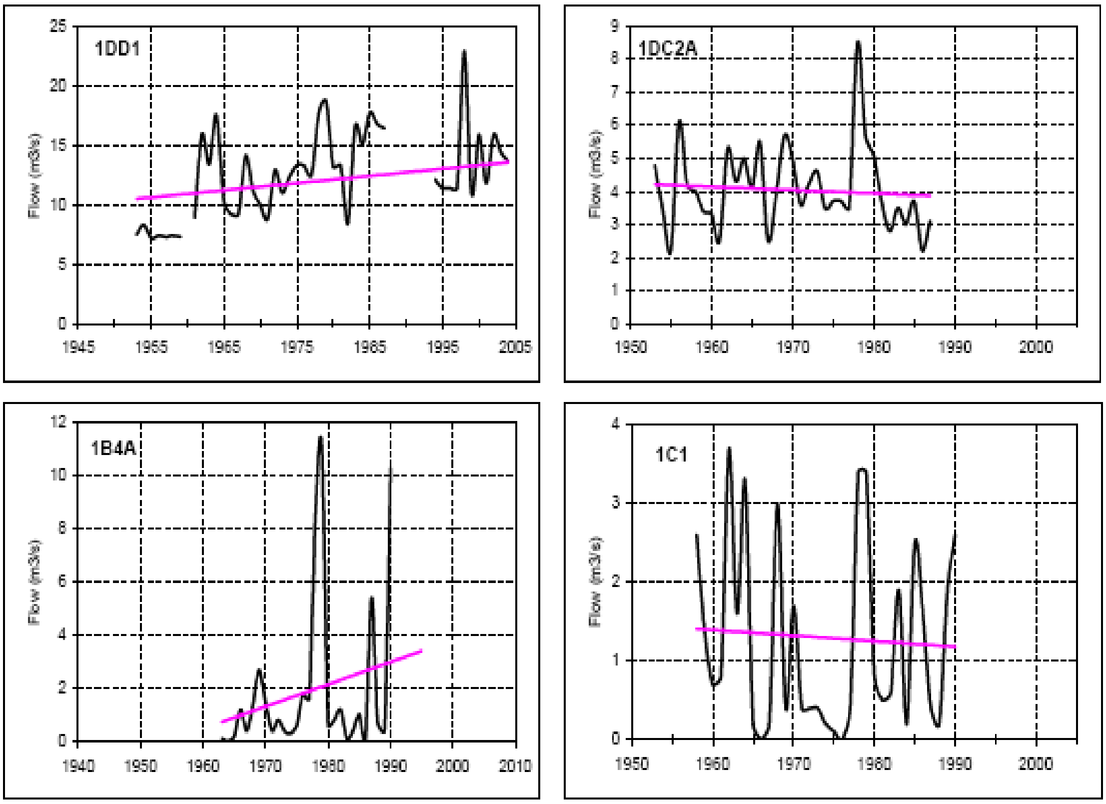

Fig 6: Multi-year variability of minimum March flows in selected catchments in northeast Tanzania.

CONCLUSIONS

This study has indicated the spatially variable patterns of seasonal flow variations in northeast Tanzania with flow peaking in April/May in most parts of northeast Tanzania and in December in rivers draining the northern part of the eastern arc mountains. Over the decades of available flow observations (1952-2005), the study has identified significant changes in high and low flows in the region. The changes of high flows were related to augmenting flow peaks in May while changes of low flows corresponded to flow reduction and/or shifting occurrence from February to March. High flow augmentation corresponded mainly to increasing persistent high flows although in some catchments peak flow increase played additional role. Similarly, low flow reduction or increases were mainly affected by persistently low flows while reduction of flow minima contribute to the situation in some catchments. The major implication of this observation is on the management of the scarce water resources in northeast Tanzania, which is currently under increasing stress for use in various socio-economic activities. It is proposed among the many relevant measures that increasing water flows during the high flow period should be stored to augment and stabilize low flows during the dry season to ensure adequate water supplies to communities.

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