Topographic and hydrologic analysis for determining potential of surface water resources for irrigated farming in Tanga region, Tanzania

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Abstract

Topographic and hydrological features of Tanga region were analysed by digital terrain and hydrological modelling in GIS to determine potential of the surface water resources for irrigation. Direct surface runoff (R) and base flow (B) for the critical year with rainfall of 10% non-exceedence were used in the analysis. Potential specific yield (Y) was determined to establish percentage of direct surface runoff that can be stored at reservoir sites.

Nine catchment areas were identified. The Pangani catchment generates the largest R while the Umba catchment generates the smallest R. The Pangani catchment has the highest Y while the Sine Nomine catchment has the lowest Y. In all catchments Y is above 50% of R implying that more than half of the runoff water can be controlled. About 1.8% of the region area is feasible for construction of Type I reservoirs. Type II reservoirs are feasible in 35.2% of the region. Type III reservoirs are feasible for 4.3% of the region. Only about 10% of the catchments have a continuous B for the 10% year. The base flow in most catchments is inadequate for irrigation use. The use of GIS in exploring potential of water resources for irrigation should be strengthened.

Key words: Topography, hydrology, catchments, runoff, reservoirs, irrigation, GIS

Introduction

Tanga region is located between 4°00' and 6 °00' Latitude south and 37 °00' and 39°00' Longitude east in the northeastern part of Tanzania. Landform in the region portrays all forms of variations typical for the tropical zones. This large variation in landforms has had a significant influence on climate in the region.

The coastal plain and Usambara mountains have a bimodal rainfall pattern with reliable onset dates and good distribution. Rainfall decreases eastward, with the short rains becoming more unreliable. In the southwestern part of the region, particularly Handeni district, the short rains are more unreliable for agricultural activities. The western part of the Usambaras is leeward and therefore receives lower rainfall than the eastern side.

During recent decades, precipitation trends in the region have become unpredictable. A shift in the onset date of the rains has become a common phenomenon. Presently rainfall distribution is also poor. This trend has affected rainfed agriculture and food security in the region. Therefore alternative sources of water need to be explored if sustainable agricultural production and food security is to be restored.

There are perennial rivers and streams in the region. Most of them originate from the Usambara mountains. Flowing water from these rivers has been serving as sources of water for hydropower generation, industrial use and domestic water supply. Despite of this large number of rivers and streams, exploitation of the flowing water for irrigated agriculture has remained low. Efforts to establish large-scale irrigation ventures in the region are constrained by a number of uncertainties. Discharge from rivers and streams is unreliable and is closely related to the amount of rainfall received. On one hand major rivers in the region are tagged with water-use by-laws governing use of the flowing water. Secondly, water use requirements of most of the land utilisation types have not been worked out, thus hindering accurate determination of the amount of flowing water that can be allowed to flow to agricultural systems. Thirdly, policies governing the utilisation of surface water resources other than stream and river flow have not been established.

There is high potential for development of rainwater harvesting systems in the region. The collected water could serve as a good source of supplementary irrigation water to compensate for rainfall inadequacy. However, this potential has not been utilised. This work is a methodological study aimed at enhancing use of GIS as a tool for assessment, planning and utilisation of surface water resources in the context of sustainable soil and water management.

Objectives

- Inventory of catchment areas and drainage networks
- Determination of surface water production of the catchment areas
- Elaboration of potential water sources for irrigation development in the region

Materials and methods

The study is based on topographic analysis of contours spaced at a vertical interval of 20m. Topography and hydrology are combined to facilitate calculation of catchment areas, suitable sites for dam construction and calculation of possible reservoir volumes with assistance of hydrologic analysis extensions available in ArcView GIS (ESRI, 1992-1999).

Catchment areas

The drainage network and topography served as baseline information for establishment of catchment areas in the region. The contours and drainage lines were digitised in PC ArcInfo and subsequent analyses performed in ArcView GIS (ESRI, 1992-1999). This involved digital terrain modelling of the surface features and eventually delineation of catchment areas.

Surface water resources

The basic data for the assessment of the surface water resources were the monthly and annual totals of the direct surface runoff (R) and the base flow (B) for the critical year considered to be that with a rainfall of 10% non-exceedence (the 10% year) for each catchment area. Long term discharge rates of the rivers and streams available in AHT (1976) and recent updates were analysed for each catchment area to determine annual discharge rates. Major components of the surface water are runoff, storage, potential specific yield and base flow.

Runoff

The monthly values of R were obtained from the analysis of the distribution of the effective rainfall contributing to runoff for a group of stations considered to be representative of the climatic region in which the sub-catchment area was located. The annual total represents the cumulative runoff from the various hydrological units comprising the sub-catchment area based on the rainfall records from the representative station for the 10% year.

Potential reservoir storage

Potential storage was considered to be the amount of useable surface water per sub-catchment area on the assumption that it would be possible to store a percentage of the direct surface runoff at selected reservoir sites. The storage potential of each catchment area was determined by topographic analysis of standard 1:50,000 scale topographic maps. The relationship between storage volume and water surface area to depth was based on the assumption that the land profile can be approximated by a second-degree parabola both in the longitudinal and traversal directions of the valley.

At a particular site where a contour intersected the stream the distance Ly across the valley and the distance Lx along the streambed between the first and the second contour intersection points were measured. The following mathematical relations were used.

$V = 2/3\ Hd2/S_xS_y$ and $As = 4/3\ Hd/S_xS_y$

in which V = the storage volume, H = the contour interval, d = the water depth, S_x = the longitudinal valley slope, S_y = the cross-sectional valley slope and A_s= the water surface area. Simplifying, $V = Kd^2$ and $A_s = 2Kd$. Figure 1 presents the slope elements considered in determination of storage volume.

Longitudinal Cross-sectional Plan
Figure 1. Slope elements and reservoir plan

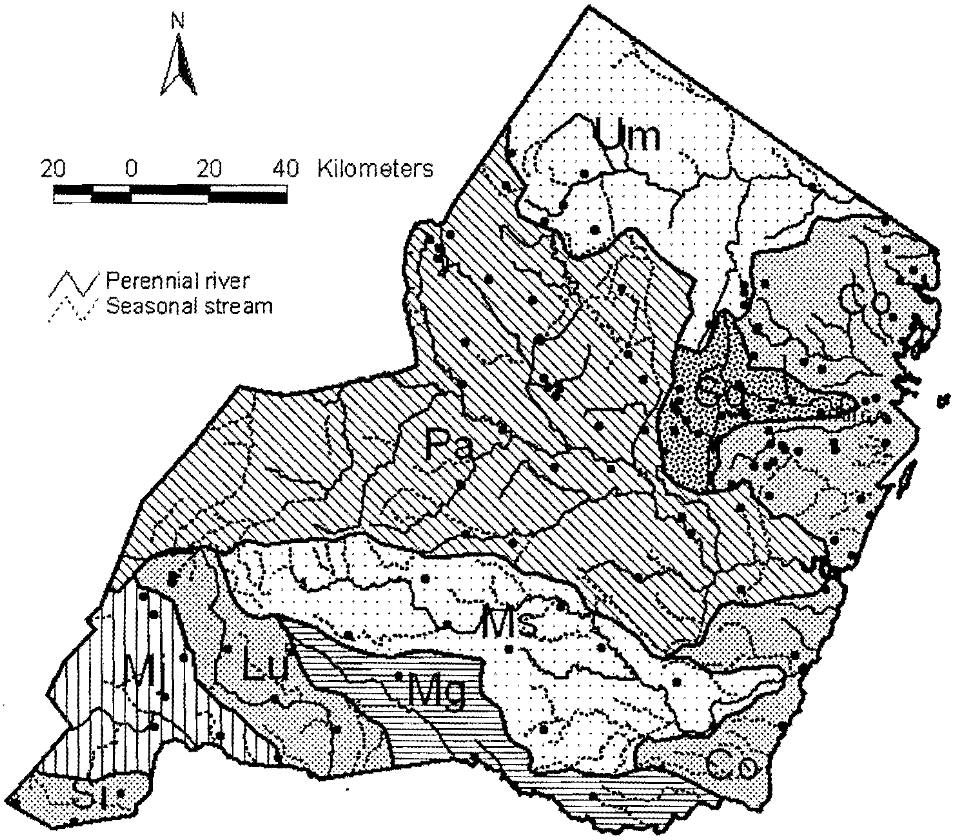
Potential specific yield
The potential specific yield (Y) was determined assuming that all the surface runoff water can be stored at reservoir sites, considering the storage potentiality factor of the catchment, losses due to evaporation and seepage.

Mathematically, Y = RESA, in which R = annual specific direct surface runoff, E = a reduction factor to take account of the losses due to evaporation and seepage, S = the storage potentiality factor of the catchment and A = the area of the catchment (km^2).

Base flow
Base flow was taken to be the minimum dependable monthly base flow for the catchment during the 10% year. This represents that part of the rainfall that after infiltrating into the ground flows towards the stream from underground storage, reappearing at the surface after a considerable time lag. This was considered to be identical with the lowest average daily measured flow in every month. It represents that part of the river water resource of the region that may be tapped directly without the need for artificial storage. Base flow was determined from records available at various hydrological stations in the region.

Results

Catchment areas
Catchment areas generated from topographic and hydrological analysis in Tanga region are presented in Figure 2. Nine major catchment areas were identified. The Pangani river catchment with a total area of 9694 km^2 is the largest while the Sine Nomine is the smallest catchment area in the region. This large number of catchment areas and rivers in the region is attributed to high precipitation and the predominance of mountainous and hilly topography in the region.



Code	Name	Extent (km2)
Co	Coastal region	3070
Mj	Mjonga river	2022
Mg	Mligaji river	1840
Lu	Lukigura river	1485
Ms	Msangasi river	3750
Sg	Sigi river	987
Um	Umba river	3625
Pa	Pangani river	9694
Si	Sine Nomine	326

Figure 2. Catchment areas in Tanga region

Surface water production

Runoff (R)

Table 1 presents surface water production in the region for each catchment area. The Pangani river catchment generates the largest R in the region. This is attributed to prevailing high rainfall in the major part and the high topographical variations of the catchment. The topographic variations characterised by long slopes provide a large surface area for runoff to collect. The Msangasi river and Coastal catchments have reasonably high runoff values but these are far lower than that of the Pangani river catchment. The Sine Nomine and Umba river catchments produce the lowest runoff in the region.

Table 1. Surface water production in Tanga region

Catchment area	Area	R	Y	B	Y/R
	Km^2	$10^3m^3/km^2/year$			%
Coast	3070	123	75	13	61
Lukigura	1485	131	74	7	56
Mjonga	2022	113	58	5	51
Mligaji	1840	66	34	8	52
Msangasi	3750	162	92	11	57
Pangani	9694	657	363	100	55
Sigi	987	140	77	60	55
Sine	326	97	58	2	60
Umba	3625	27	14	6	50

Potential specific yield (Y)

The Pangani river catchment has the highest Y while the Sine Nomine catchment has the lowest Y. The results indicate that Y is directly proportional to R. The observed trend reveal also that Y is above 50% of R in all catchment areas. This imply that more than half of the runoff water can be controlled and utilised for various production activities in the region.

Base flow (B)

Long-term stream flow records exist for only three rivers namely the Sigi, the Umba and the Lwengera from which the estimate of B was made. Extension of the results to other catchment areas was made on the fundamental assumption that B is directly proportional to rainfall and inversely proportional to evaporation. Calculations of the minimum dependable monthly flow for the 10% year show that only about 10% of the sub-catchment areas have a continuous B.

Trends of R, Y and B

Figure 3 compares R, Y and B for the catchment areas in the region. The figure reveals that R and Y are the largest potential surface water resources in the region. Whereas R is the largest surface water resource, Y is about 50% of R for all catchment areas. The base flow is the lowest surface water resource and amounts to less than 50% of R for all catchment areas.

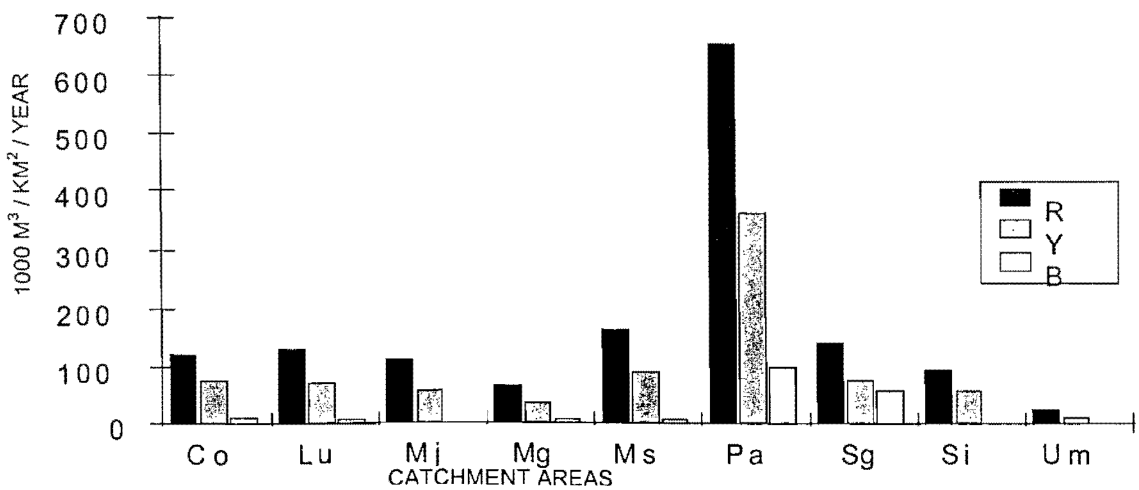


Figure 3. Trends of R, Y and B in Tanga region

Storage reservoirs

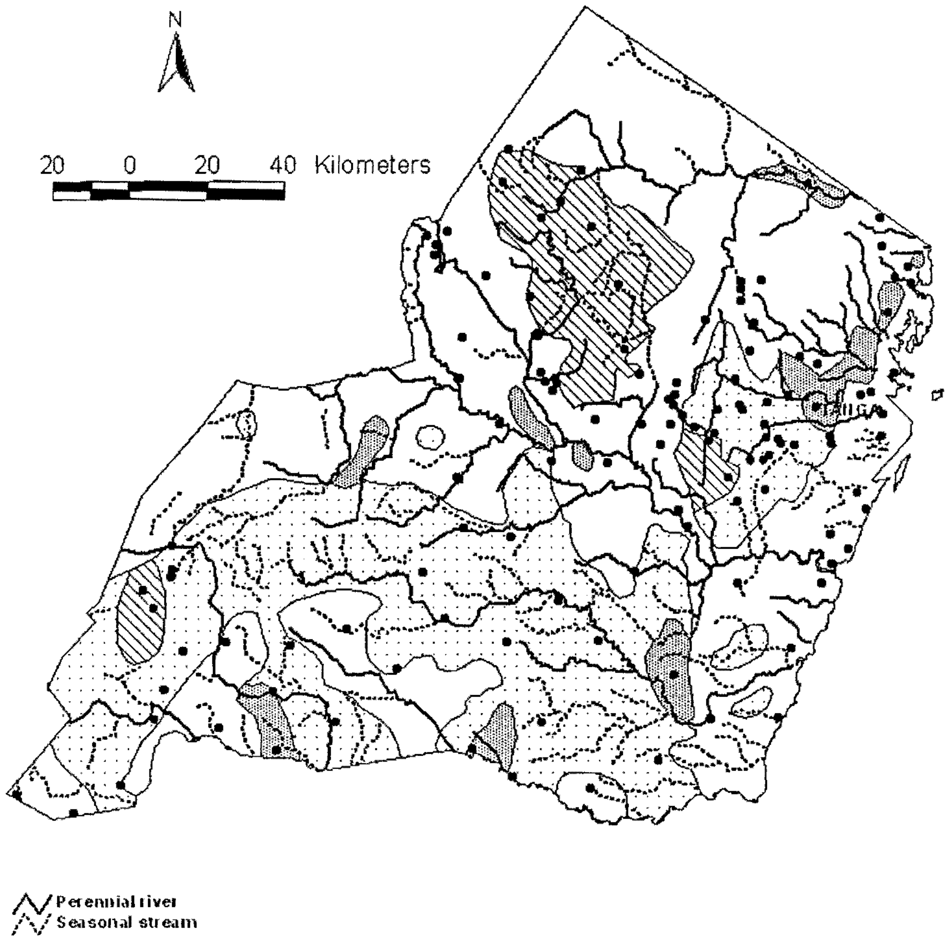
As determined by storage characteristics and topographical configuration of the different areas, three reservoir types were elaborated for the region. The storage reservoirs are defined on the basis of volume, surface area and depth. Characteristics of the three reservoir types, including also the range of volumes and surface areas for water depths of 5m and 10m are presented in Table 2.

Table 2. Characteristics of potential reservoir types in Tanga region

Reservoir type	S_x	S_y	K	Volume (V) 10^3 m^3		Water surface area (As) 10^3 m^2	
				5m	10m	5m	10m
I	0.02	0.1	5000	125	500	25	50
II	0.01	0.08	12700	318	1270	64	127
III	0.005	0.06	23000	575	2300	115	230

Feasibility of storage reservoirs

Figure 4 presents the feasibility of storage reservoirs in the region. The major part of the Usambara mountains and small parts east of Muheza and Handeni districts occupying 485.08 km^2 (1.81%) are feasible for construction of Type I reservoirs. Type II reservoirs are suitable for areas occupying 9422.88 km^2 (35.16%). Areas occupying 1149.72 km^2 (4.29%) are feasible for Type III reservoirs. The rest of the area in the region covering 15742.32 km^2 (58.74%) is not feasible for construction of storage reservoirs.



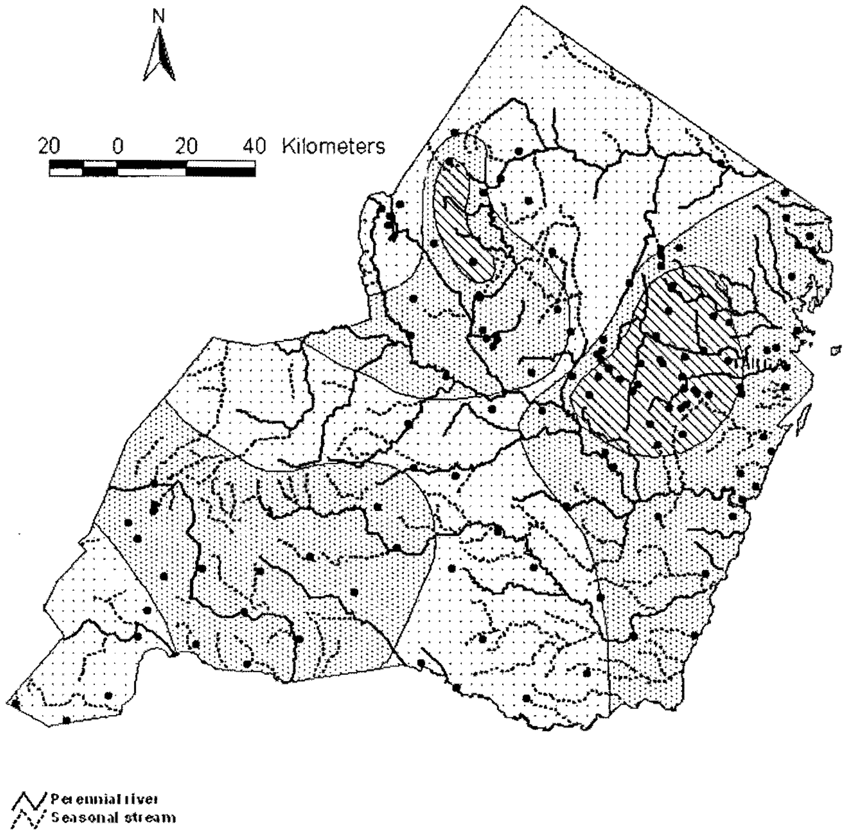
Reservoir	Extent (sq.km)	Proportion(%)
Flat valley slope (Type III)	1149.72	4.29
Moderate steep valley slope (Type II)	9422.88	35.16
Not feasible	15742.32	58.74
Steep valley slope (Type I)	485.08	1.81

Figure 4. Feasibility of storage reservoirs in Tanga region

Discussion

Drought hazards

Figure 5 presents drought hazards in Tanga region. It is evident that only 3% of the region experience a low drought hazard. Most of the region area (70%) has a moderate drought hazard. A considerably large land area in the region (27%) has a high drought hazard. This implies that rainfed agriculture for 97% of the region area is in most years uncertain due to drought hazards. Alternative sources of supplementary irrigation water need to be explored for optimisation of crop performance.



Drought	Coverage (sq.km)	Proportion (%)
High	7068	27
Low	948	3
Moderate	18784	70

Figure 5. Drought hazards in Tanga region

Runoff and rainfall
Table 3 presents monthly values of runoff as percentage of the total annual runoff in the region. The table shows that the bulk of the runoff occurs in the main wet season lasting about three months of March, April and May. These months contribute over 50% of runoff. During the driest months there is virtually no runoff. This implies that crops growing in the field during the dry season are subject to drought due to evapotranspirative deficits. Optimum crop performance can be achieved with supplementary irrigation for most of the arable land in the region.

The potential specific yield (Y) is above 50% of R in the region. This implies that there is high potential for utilising runoff water for irrigating crops. Agricultural development policies and in particular the irrigation policy for Tanga region should consider the possibility of utilising runoff water for irrigation. The runoff water can be collected and concentrated in storage reservoirs in many parts of the region. For effective utilisation of this large amount of water, storage reservoirs need to be constructed.

Table 3. Monthly direct surface runoff as percentage of annual total

Region	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Southern and western areas	1	0	0	1	5	6	9	9	11	18	25	15
					42%						58%	
Usambara Mountains	4	3	3	4	7	9	8	4	2	11	23	22
					44						56	
Dry northern areas	1	1	0	0	3	6	20	14	1	21	22	5
					47						53	
Coastal areas	5	3	3	4	6	11	5	2	2	9	23	27
					41%						59%	

Base flow and irrigation

The base flow in most of the catchment areas is inadequate to provide water for agricultural uses. The contribution of B is only evident in the Pangani and Sigi river catchments. However, the Pangani river which could have supported irrigation to some extent, is governed by the Pangani River Ordinance of 1961. According to the ordinance no authority charged with the duty of controlling or regulating the water of the Pangani river is permitted to reduce the flow at the Great Pangani Falls to less than 12.7m^3/s or, when the natural flow there exceeds 12.7 m^3/s, to not less than 19.9 m^3/s 12km upstream of Hale. Therefore irrigated agriculture in the region can only be developed with dependency on other sources of water such as runoff.

Conclusions

- This study analysed topography and hydrology characteristics of Tanga region to determine surface water resources with potential use for irrigation.
- Nine catchment areas exist in the region, with Pangani being the largest and Sine Nomine the smallest.
- Runoff is the largest surface water resource, most of which is generated by the Pangani, Msangasi, Sigi and Lukigura catchments.
- Potential specific yield is higher than 50% for the entire region indicating that runoff has high potential for supporting irrigated agriculture.
- Topographically about 40% of the region area has potential for storing runoff water in storage reservoirs.
- The base flow of most rivers in the region is inadequate for supporting irrigated agriculture.
- The Digital Terrain Model and hydrological analysis in GIS environment are suitable tools for calculation of catchment areas, simulation of dam construction and calculation of reservoir volumes.
- Notwithstanding findings of this study, more work is required to determine water balance for potential land utilisation types and soil characterisation to establish management requirements for sustainable production.

References

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