JOURNAL OF FLOOD ENGINEERING
Vol. 8 No. 1 (January-June, 2017)

Received: 13th August 2016   Revised: 24th September 2016   Accepted: 10th November 2016

VULNERABILTY ASSESSMENT OF THE SURFACE WATER RESOURCES IN SWAZILAND DUE TO THE IMPACT OF CLIMATE CHANGE AND VARIABILITY

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Abstract: It has been established that climate change in the next 100 years will be due to anthropogenic greenhouse gas emissions. The major effect of the increase of greenhouse gas emissions in the atmosphere is global warming and thus changes in temperature, precipitation and the environment (IPCC, [1]). A calibrated WatBal model was used in assessing the vulnerability of the surface water resources in Swaziland due to climate change. Two scenarios (dry and wet year) were considered given climate change. The WatBal model was used to simulate future stream flows at each of the selected key gauging stations in each catchment (Usuthu, Komati and Mbuluzi) using inputs (precipitation and potential evapotranspiration) from representative GCMs results for Swaziland given climate change. The water stress index for each of the sub-catchments was computed and used in assessing the vulnerability of the water resources in the country given climate change for the dry and wet year scenario. Simulation results show that the Komati at GS30 and the Usuthu at GS7 will face a severe water stress (196.6% and 728.9%, respectively), while the Mbuluzi at GS 32, the Usuthu at GS 16 and GS 19 will face a high water stress (60.9%, 72.8% and 42.2% respectively) given climate change and dry year scenario. However, the Usuthu at GS6 and GS9 will face a moderate water stress (36.0% and 37.2% respectively) given climate change and dry year scenario. The Komati at GS30 and the Usuthu at GS7 will continue to face a severe water stress (86.5% and100.5%, respectively), while the Mbuluzi at GS32, the Usuthu at GS2 and GS19 will face a low water stress (18.2%, 19.56% and 11.63% respectively) and the rest of the sub-catchments (Mbuluzi at GS3, Usuthu at GS5, GS9, GS15 and GS6) will have no water stress given climate change and wet year scenario. Therefore, infrastructure development (groundwater, water storage and distribution facilities *etc.*) is a key adaptation strategy to the expected impacts (floods and droughts) of climate change in the country especially given a dry year scenario.

Keywords: Vulnerability, Climate change, Water stress, Simulation, WatBal model

1. INTRODUCTION

Swaziland which lies between latitude 25° to 27.5° south and between Longitude 30° to 32.5° east enjoys a subtropical climate that is characterised by hot and wet summers and cold and dry winters. Variations in climatic conditions occur within the six physiographic regions (Figure 1) giving rise to three clearly distinguishable climate types (*i.e.* Cwb, Cwa. and Bsh). Highveld and Upper Middleveld are characterized by a Cwb climate. Cwb is a mild humid climate with a dry winter and warm summer with the warmest month below 22°C (Strahler and Strahler, [2]). Lower Middleveld and Lubombo range have a Cwa climate whilst the Western and Eastern Lowveld have a Bsh climate (Murdoch, [3]).

Cwa is a mild humid climate with a dry winter and a hot summer with warmest month over 22°C. Bsh is a semiarid climate which is dry-hot with a mean annual temperature over 18°C (Strahler and Strahler, 1992). Mean annual rainfall ranges from about 1500 millimeters in the Highveld to just >500 millimeters in the Lowveld (Table 1). Highveld temperatures normally exceed 33°C in mid-summer (Dec-Jan). The Lowveld, on the other hand experience a large diurnal temperature range, with maximum temperatures reaching the upper thirties. Semi-arid pockets are found in this region, which is also liable to desertification.

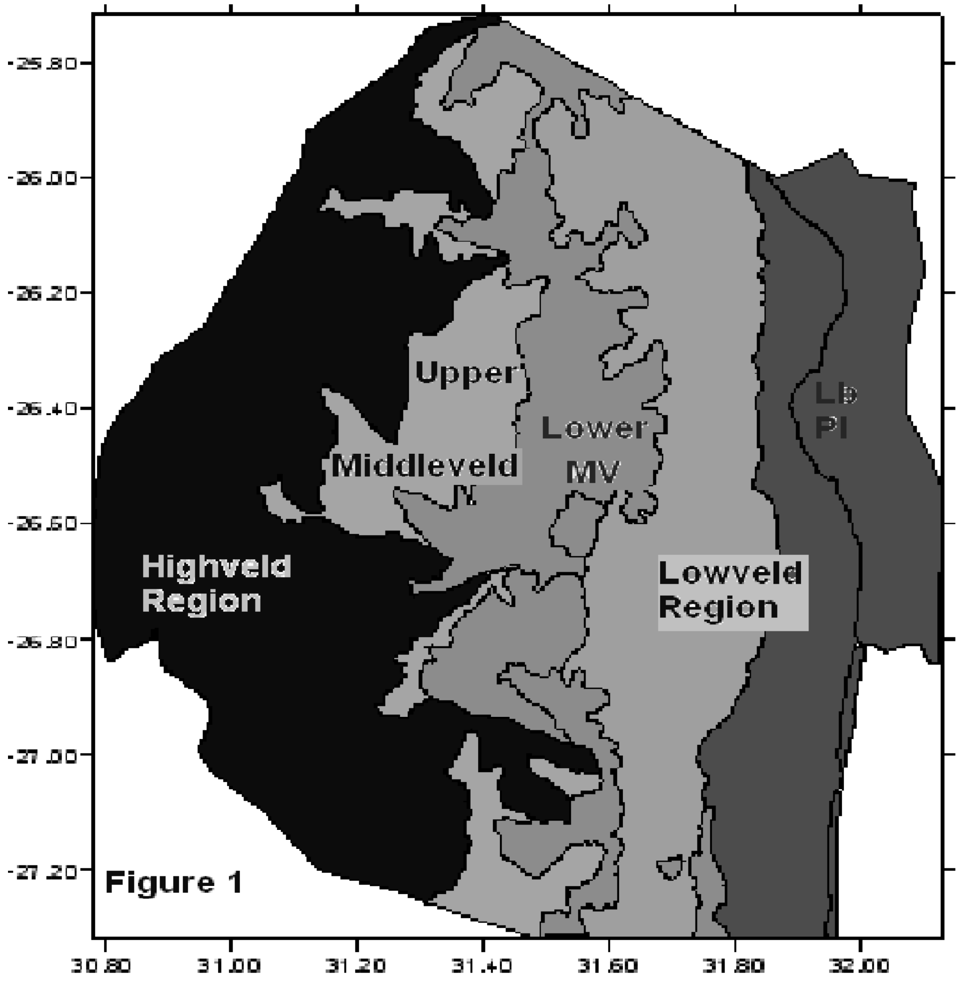

Figure 1: Physiographic regions of Swaziland

Source: National Meteorological Services [4]

Table 1
Average annual rainfall and temperature in each physiographic region

Physiographic Region	*Annual Rainfall (mm)*	*Annual Temperature (°C)*
Highveld	1 500 – 900	17.6 – 16.3
Middleveld	810 – 580	20.5 – 19.3
Lowveld	>500	22.4 - 21.3
Lubombo	710	19.2

Source: National Meteorological Service [4]

The water sources in Swaziland are mainly surface waters (rivers, reservoirs), ground water and atmospheric moisture. There are seven drainage basins in Swaziland and these are: Lomati (1111 km^2), Komati (7371 km^2), Mbuluzi (3100 km^2), Usutu (12903 km^2), Ngwavuma (1305 km^2), Pongola (280 km^2) and Lubombo (125 km^2) (see Figure 2).

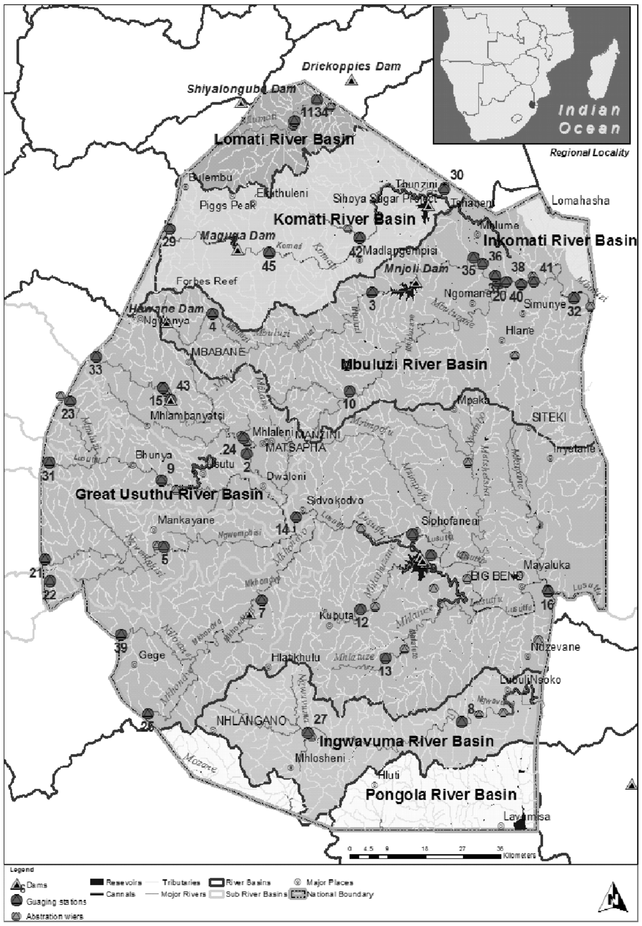

Figure 2: Location of Swaziland's main river basins and corresponding stream flow gauging stations

(*Source:* Ministry of Natural Resources and Energy, Department of Water Affairs [5]

Anthropogenic greenhouse gas warming up has been considered to be the major potential mechanism of climate change over the next few hundred years (IPCC, [1]). A number of gases that occur naturally in the atmosphere in small quantities are known as “greenhouse gases”. Water vapour (H_2O), carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O) trap solar energy in much the same way as do the glass panels of a greenhouse or a closed automobile. However, the earth’s atmosphere has been kept some 30^o Celsius hotter than it would otherwise be, making it possible for humans and other living things to exist on earth because of the natural greenhouse gases effect (IPCC, [1]). This is by the trapping of the outgoing solar energy and thus making the earth 30^oC warmer that it would otherwise be without the natural greenhouse gases.

Human activities, however, are now raising the concentrations of these gases in the atmosphere and thus increasing their ability to trap energy. The global greenhouse gas emissions due to anthropogenic activities have increased since pre-industrial times with an increase of about 70% between 1970 and 2004 (IPCC, [6]). Human-made carbon dioxide which, is the most important contributor to the enhanced greenhouse gases effect, comes mainly from the use of coal, oil, and natural gas. It is also released by the destruction of forests and other natural sinks and reservoirs that absorb carbon dioxide from the air.

The IPCC [6] also reports that the atmospheric concentrations of CO_2 (397ppm) and CH_4 (1774ppb) in year 2005 exceed by far the natural range over the last 650,000 years. Fossil fuel use is the major contributor of global CO_2, followed with land-use change. It has been established that the climate change in the next 100 years will be due to anthropogenic activities (IPCC, [7]). It has also been reported that 1995-2006 are the warmest years (with anomaly ranging from 0.28 to 0.52^oC) in the history of instrumentation (since 1850) and the global surface temperature rise is due to the greenhouse gases effect (IPCC, [6]).

It has been reported (IPCC, [1]) that nine of the planet’s 10 warmest years have occurred since 2000 and worldwide surface temperatures continue to rise in 2013, according to satellite and meteorological data. Since 1880, when atmospheric concentrations of CO_2 were 285 parts per million (ppm), the average global temperature has risen 1.7 degrees Celsius (°C); atmospheric CO_2 concentrations crossed a milestone of 400 ppm in 2013. “Long-term trends in surface temperatures are unusual and 2013 adds to the evidence for on-going climate change,” IPCC, [8]).

The major effect of the increase of anthropogenic greenhouse gas emissions in the atmosphere is global warming and thus changes in precipitation and the environment. The frequency of extreme events such as floods and droughts are expected to increase given climate change (IPCC1, [1]). Africa and with large cities such as Banjul, Lagos, Alexandria, Dar es Salaam, Cape Town, Maputo *etc.* could be in a verge of being submerged (Elasha *et al.*, [9]). It is estimated that 70 million people will be at risk from coastal flooding by 2080 (Bloomfield, [10]).

2. METHODOLOGY

Two scenarios have been considered in the vulnerability analysis, a dry- and a wet scenario (the dry and wet scenario were based on the drier and wetter years that have been experienced in the sub-catchments based on historic records). The observed stream flows and precipitation data were grouped into dry and wet scenarios. The dry year scenario here is all drier years with a return period of ten years and above. Similarly a wet year scenario is all wet years with a return period of ten and above. That is if a gauging station has a record length of 30 years three drier and three wet years were selected in developing the dry and wet year scenarios for the catchment. The assessment was conducted utilizing rainfall runoff modelling for each of the stream flow gauging stations using an appropriate rainfall runoff model for each scenario.

For rainfall runoff modelling the WatBal model was selected for use in this study. WatBal (Yates and Strzepek, [11]) is a lumped conceptual integrated rainfall runoff model. The inputs required for water balance modelling when using a monthly time step are: the mean monthly precipitation for the basin, the mean monthly river discharges in the closing profile of the basin and the mean monthly potential evapotranspiration (*PET*). If the *PET* data is not available, the model uses either the Thornthwaite or the Priestly-Tailor method. Observed and predicted potential evapotranspiration data was used in this study.

The water balance is written as a differential equation involving input and output, where storage is lumped as a single conceptualized bucket with the components of discharge and infiltration being dependent on the relative storage which is expressed as follows:

$$S_{max}\,[dz(t)/dt] = P(t)(1 - \beta) - R_s(z,Pe,t) - R_{ss}(z,t) - R_b - E_v(z,PET,t)$$

Where, $S_{\max}$ is maximum catchment storage capacity (mm), z ($0 \leq z \geq 1$) – the relative value of the water storage in the catchment compared to $S_{\max}$, P is the precipitation (mm/month), β is the direct runoff coefficient ($0 \leq \beta \leq$), R_s is the surface runoff described in terms of storage and precipitation over time t, R_{ss} is the subsurface runoff (mm/month), R_b is the baseflow (mm/month), E_v is actual evaporation (mm/month) which is a function of potential evapotranspiration (*PET*), relative catchment storage state z and time t, t is the time (month). The model contains five variables which are: direct runoff, surface runoff, subsurface runoff, maximum catchment water holding capacity and base flows.

The model computes total runoff as the sum of the four components:

$$R_t = R_s + R_{ss} + R_b + R_d$$

The direct runoff R_d (the runoff from impermeable surface and open water surface) is given as:

$$R_d = \beta \mathrm{XPn}$$

Where Pn is the effective precipitation, β is the direct runoff coefficient, and is not part of the optimization routine and must be predicted by the user (in a trial and error process during model calibration). The value of R_d is calculated directly from effective precipitation, and is not dependent on relative catchment storage state z. Surface runoff R_s, is given by:

$$R_s(z, P, t) = z^{\varepsilon}(Pn - R_b) \text{ for } Pn > R_b$$
$$= 0 \text{ for } Pn < R_b$$

Where, ε is the calibrated surface runoff coefficient. Sub-surface runoff R_{ss} is a function of the relative storage state z and the calibrated coefficient α:

$$R_{ss} = \alpha z^{\gamma}$$

Where, γ is a parameter which must be predefined by the user with values in the range of $0< \gamma \leq 2$.

WatBal accounts for changes in the soil moisture by taking into account precipitation, runoff, actual evapotranspiration while using potential evapotranspiration to derive the extraction of water from the soil strata. It has been established that, any estimate of climate change impacts on water resources depends on the ability of the model to relate changes in actual evapotranspiration to predict changes in the runoff in the stream. WatBal has been found appropriate for the evaluation of the impact of climate change on water resources because it meets the above criteria. Secondly it requires less input parameters compared to other hydrologic models. For more details of the WatBal model see Yates and Strzepek [11]. There are two stages in the application of a rainfall runoff model and that is model calibration and application.

The model was calibrated using the observed stream flows, observed precipitation, potential evapotranspiration and other relevant information at each of the gauging stations. Table 2a and 2b shows the model optimal parameters during calibration for eight sub-catchments. It can be seen from Table 2a and 2b that the correlation coefficient between

Table 2a

Optimal model parameters during calibration in the sub-catchments for dry and wet year scenario

Model parameters	*Komati at GS 30*		*Mbuluzi at GS 3*		*Mbuluzi at GS 32*		*Usuthu at GS 2*	
	Wet year	*Dry year*	*Wet year*	*Dry year*	*Wet year*	*Dry year*	*Wet year*	*Dry Year*
Surface runoff coefficient, epsilon	44.544	15.875	40.675	0.9628	12.349	86.5	14.42	10.738
Groundwater coefficient, alpha	0.566	0.006	6.216	1	0.0014	0.073	3.05	1.193
Maximum basin holding capacity S_{max}	164	100	350	650	260	60	380	90
Base flow R_b	0.01	0.015	0.365	0.12	0.045	0.015	0.3	0.002
Direct runoff coefficient (DRC)	0.015	0.01	0.155	0.07	0.05	0.015	0.005	0.002
Sub-surface runoff coefficient (SSRC)	2	2	2	2	2	2	2	2
Initial storage, Z_i	0.4	0.28	0.1	0.2	0.25	0.1	0.25	0.29
Correlation coefficient	0.854	0.837	0.923	0.880	0.911	0.900	0.983	0.973

observed and simulated stream flow ranges from 0.854 to 0. 977 for the wet year scenario, and from 0.837 to 0.992 for dry year scenario, respectively.

The General Circulation Models that were used in the forecasting of temperature, rainfall and PET are: CCCMA; CGCM; CNRM CM3; CSIRO Mk3.0; GFDL CM2.0; GFDL CM2.1; IPSL CM4; MICROC 3.2; MIUB ECHO-G; MPI ECHAM5; MRI CGCM 2.3.2a; HadCM3 and HadGEMI. The above 12 GCMs were objectively selected on the basis of the realism with which they represent the observed 20th Century seasonal cycle of African precipitation (South, East, Northeast and West) (Shongwe *et al.*, [12]). A similar calibration was carried out using output precipitation and derived PET from 12 objectively combined GCM simulations. The GCMs are combined using a Bayesian weighting procedure which assigns unequal weights to each GCM output depending on its bias with respect to observed (1961–2000) precipitation and on the extent to which it is an outlier from the rest in the future (2061–2100) climate. Details of the Bayesian weighting method can be found in Tebaldi *et al*. [13].

The calibrated rainfall runoff model (WatBal model) was used to generate stream flows given precipitation and potential evapotranspiration generated by GCMs and downscaled for Swaziland for each of the scenarios.

Table 2b

Optimal model parameters during calibration in the sub-catchments for dry and wet year scenario

Model parameters	*Usuthu at GS 5*		*Usuthu at GS 6*		*Usuthu at GS9*		*Usuthu at GS 16*	
	Wet year	*Dry year*	*Wet year*	*Dry year*	*Wet year*	*Dry year*	*Wet year*	*Dry Year*
Surface runoff coefficient, epsilon	58.84	12.664	8.413	10.638	10.984	35.734	14.3	20.909
Groundwater coefficient, alpha	0.223	0.015	0.769	0.368	0.058	0.157	0.147	0.376
Maximum basin holding capacity S_{max}	95	290	175	95	84	90	85	83
Base flow R_b	0.099	0.029	0.002	0.001	0.029	0.019	0.045	0.039
Direct runoff coefficient (DRC)	0.007	0.005	0.002	0.001	0.005	0.005	0.005	0.005
Sub-surface runoff coefficient (SSRC)	2	2	2	2	2	2	2	2
Initial storage, Z_i	0.25	0.25	0.21	0.26	0.257	0.25	0.25	0.25
Correlation coefficient	0.964	0.962	0.962	0.965	0.977	0.944	0.976	0.992

The projected domestic water use in the sub catchments was computed after projecting the current population to 2050. The mathematical equations that are used for population projection are as reported by Shryock *et al*. [14]. The following equation was used in the population projection for its simplicity in application.

$$P_t = P_o \rho^{rt}$$

Where r is the population growth rate, t is the number of years, and ρ is the base of the natural system of logarithms and P_o is the current population. The water stress index by Milano *et al*. [15] has been used to assess the water availability in the sub catchments of the major river basins (Komati, Mbuluzi and Usuthu) in the country.

2.1. Selection of sub-catchments for vulnerability assessment

The following sub-catchments were selected for vulnerability assessment of surface water resources in Swaziland are: Komati River at GS30, Mbuluzi River at GS32, Lusushwana River at GS2, Great Usuthu at GS9, Ngwempisi River at GS5, Mkhondvo River at GS7, Usuthu River at GS6 and Usuthu River at GS16. Figure 2 shows the location of the selected gauging stations in the three major catchments (Komati, Mbuluzi and Usuthu).

3. RESULTS AND DISCUSSION

3.1. Simulation of future flows

The calibrated WatBal model was used to simulate the future flows in the Komati, Mbuluzi and Usuthu catchments. The inputs into the calibrated WatBal model are: future precipitation, future potential evapotranspiration and observed stream flows for the dry and wet year scenario. The observed precipitation and potential evapotranspiration are adjusted using the median of the average GCMs projections in 2050 for the A2 climate scenario to make the future precipitation and potential evapotranspiration (IPCC, [6]).

Table 3 shows the observed and future runoff for the Komati River at GS30 for dry and wet year scenarios (the hydrological year starts in October and ends in September). It can be seen from Table 3 that the future annual runoff is going to be less than the observed by 8.8% (9.02 Mm^3) and 6.6% (53.91 Mm^3) for the dry and wet year scenario, respectively. This means that there will be less, flows in the Komati River basin at GS30 in both dry and wet year scenarios given A2 climate change scenario.

Table 4 shows the observed and future runoff for the Mbuluzi River at GS3 for dry and wet year scenarios. It can be seen from Table 4 that the future annual runoff is going to be less than the observed by 5.9 (6.13 Mm^3) and 1.5 (6.55 Mm^3) per cent for the dry and wet year scenario, respectively. This means that there will be less runoff in the Mbuluzi River basin at GS3 in both dry and wet year scenarios given A2 climate change scenario. Although the magnitude of the annual runoff decrease is similar but it will be more severe in the dry year scenario by 5.9 per cent while only 1.5 per cent in the wet year scenario.

Table 5 shows the observed and future runoff for the Mbuluzi River at GS32 for dry and wet year scenarios. It can be seen from Table 5 that the future annual runoff is going to be less than the observed by 3.3 (2.11 Mm^3) and 2.9 (11.07 Mm^3) per cent for the dry and wet year scenario, respectively. This means that there will be less runoff in the Mbuluzi River basin at GS32 in both dry and wet year scenarios given A2 climate change scenario.

Table 3
Observed, future monthly runoff and flow changes for the Komati River at GS30 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Percentage change*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Percentage change*
Oct	8.04	7.36	-8.46	21.02	18.63	-11.37
Nov	7.78	9.80	+25.96	46.25	40.75	-11.89
Dec	13.12	10.59	-19.28	141.95	79.62	-43.91
Jan	12.32	14.27	+15.83	192.45	157.17	-18.33
Feb	12.10	11.43	-5.54	92.71	128.24	+38.32
Mar	11.78	9.89	-16.04	66.75	107.00	+60.30
Apr	7.26	8.24	+13.50	99.11	77.50	-21.80
May	4.55	6.44	+41.54	60.23	57.76	-4.10
Jun	6.74	5.34	-20.77	42.16	37.41	-11.27
Jul	6.16	5.29	-14.12	23.70	24.62	+3.88
Aug	5.89	5.06	-14.09	13.62	15.19	+11.53
Sep	7.00	5.12	-26.86	11.21	13.3614	+19.19
Total	102.74	93.72	-8.78	811.16	757.25	-6.65

Although the magnitude of the annual runoff decrease is similar in terms of percentage but the magnitude of the change is high in the wet year scenario compared to the dry year scenario. The implication here is that there will be less water to store in the catchment given climate change and this will have a negative impact on irrigated agriculture.

Table 4
Observed, future monthly runoff and flow changes for the Mbuluzi River at GS3 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	7.59	3.51	-53.75	12.16	20.21	+66.20
Nov	7.96	5.03	-36.81	16.01	30.10	+88.01
Dec	9.43	9.21	-2.33	40.15	41.86	+4.26
Jan	12.55	14.08	+12.19	45.81	58.94	+28.66
Feb	11.55	13.64	+18.10	68.27	67.56	-1.04
Mar	12.65	13.72	+8.46	73.35	55.89	-23.80
Apr	11.89	11.00	-7.49	43.16	34.77	-19.44
May	10.50	9.32	-11.24	35.74	23.83	-33.32
Jun	7.67	7.43	-3.13	21.20	22.57	+6.46
Jul	6.07	6.49	+6.92	17.05	12.55	-26.39
Aug	6.64	5.61	-15.51	14.15	10.73	-24.17
Sep	5.77	4.67	-19.06	11.31	13.21	+16.80
Total	110.26	103.71	-5.94	398.36	392.23	-1.54

Table 5
Observed, future monthly runoff and flow changes for the Mbuluzi River at GS32 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Percentage change*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Percentage change*
Oct	5.40	3.74	-30.74	11.26	14.51	+28.86
Nov	5.81	5.48	-5.68	19.74	18.02	-8.71
Dec	10.04	9.77	-2.69	53.76	22.45	-58.24
Jan	10.52	10.95	+4.09	33.67	53.48	+58.84
Feb	7.81	7.65	-2.05	132.23	116.80	-11.67
Mar	4.41	5.83	+32.20	50.90	64.15	+26.03
Apr	5.15	4.06	-21.17	22.10	25.75	+16.52
May	5.02	3.21	-36.06	14.86	14.45	-2.76
Jun	2.59	2.56	-1.16	12.16	10.83	-10.94
Jul	2.50	2.59	+3.60	11.53	10.66	-7.55
Aug	2.48	2.65	+6.85	9.34	10.29	+10.17
Sep	1.53	2.65	+73.20	12.76	11.81	-7.45
Total	63.25	61.14	-3.34	384.28	373.21	-2.88

Table 6 shows the observed and future runoff for the Usuthu River at GS15 for dry and wet year scenarios. It can be seen from Table 6 that the future annual runoff is going to be less than the observed by 6.2 (2.94 Mm^3) and 4.9 (10.83 Mm^3) per cent for the dry and wet year scenario, respectively. This means that there will be less runoff in the Usuthu River basin at GS15 in both dry and wet year scenarios given A2 climate change scenario.

Table 6
Observed, future monthly runoff and flow changes for the Usuthu River at GS15 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	3.63	2.77	-23.7%	6.90	6.39	-7.4%
Nov	5.17	4.88	-5.6%	11.70	12.50	6.8%
Dec	5.85	5.87	0.3%	23.30	22.51	-3.4%
Jan	7.91	7.67	-3.0%	29.38	28.06	-4.5%
Feb	4.20	5.30	26.2%	36.00	36.33	0.9%
Mar	4.32	4.41	2.1%	34.11	30.14	-11.6%
Apr	4.67	4.44	-4.9%	19.13	21.75	13.7%
May	3.74	3.21	-14.2%	21.14	19.92	-5.8%
Jun	2.52	1.81	-28.2%	13.49	14.47	7.3%
Jul	2.01	1.37	-31.8%	10.40	7.98	-23.3%
Aug	1.90	1.19	-37.4%	8.16	5.06	-38.0%
Sep	1.33	1.36	2.3%	6.58	4.36	-33.7%
Total	47.23	44.29	-6.2%	220.30	209.47	-8.2%

Although the magnitude of the annual runoff decrease is high in terms of percentage for the dry year scenario but the magnitude of the change is high in the wet year scenario compared to the dry year scenario. The implication here is that there will be less water flowing into the Lupohlo dam given climate change with wet year scenario and this will have a negative impact on the hydropower generation and also for urban water supply and irrigated agriculture downstream.

Table 7 shows the observed and future runoff for the Usuthu River at GS2 for dry and wet year scenarios. It can be seen from Table 7 that the future annual runoff is going to be less than the observed by 12.3 (17.14 Mm^3) and 12.3 (98.2 Mm^3) per cent for the dry and wet year scenario, respectively. This means that there will be less runoff in the Usuthu River basin at GS2 in both dry and wet year scenarios given A2 climate change scenario.

Although the magnitude of the annual runoff decrease is the same in terms of percentage for both scenarios but the magnitude of the change is high in the wet year scenario compared to the dry year scenario. The implication here is that there will be less water to store in the catchment given climate change with wet year scenario and this will have a negative impact on the hydropower generation (at Edwaleni and Magudula power plants) and also for urban water supply and irrigated agriculture downstream.

Table 8 shows the observed and future runoff for the Usuthu River at GS9 for dry and wet year scenarios. It can be seen from Table 8 that the future annual runoff is going to be less than the observed by 12.0 (12.03 Mm^3) and 4.8 (28.49 Mm^3) per cent for the dry and wet year scenario, respectively.

Table 7
Observed, future monthly runoff and flow changes for the Usuthu River at GS2 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	12.93	10.21	-21.0%	17.97	33.82	88.2%
Nov	17.49	16.22	-7.3%	28.26	58.91	108.5%
Dec	17.62	16.54	-6.1%	78.50	92.94	18.4%
Jan	20.52	20.43	-0.4%	88.11	101.03	14.7%
Feb	14.22	17.07	20.0%	161.18	143.63	-10.9%
Mar	12.97	13.10	1.0%	130.18	106.45	-18.2%
Apr	10.54	10.68	1.3%	93.55	46.60	-50.2%
May	8.95	6.74	-24.7%	73.32	50.36	-31.3%
Jun	7.81	3.84	-50.8%	41.60	27.45	-34.0%
Jul	5.36	3.03	-43.5%	32.94	12.16	-63.1%
Aug	5.66	2.25	-60.2%	27.54	11.37	-58.7%
Sep	4.73	1.56	-67.0%	22.39	12.60	-43.3%
Total	138.80	121.66	-12.66%	795.54	697.34	-12.3%

This means that there will be less runoff in the Usuthu River basin at GS9 in both dry and wet year scenarios given A2 climate change scenario. Although the magnitude of the annual runoff decrease is high in terms of percentage for the dry year scenario but the magnitude of the change is high in the wet year scenario by 42 per cent. The implication here is that there will be less water to store in the catchment given climate change with wet year scenario and also less water in the dry year scenario and this will have a negative impact on water availability to different water uses downstream.

Table 8
Observed, future monthly runoff and flow changes for the Usuthu River at GS9 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	5.69	5.65	-0.7	20.05	3.66	-81.75
Nov	10.43	12.06	+15.63	79.48	43.03	-45.86
Dec	13.22	13.21	-0.07	87.24	110.37	+26.51
Jan	22.21	21.11	-4.95	100.38	211.43	+110.63
Feb	9.22	11.56	+25.38	89.33	97.81	+9.49
Mar	15.06	9.64	-35.99	61.56	39.39	-36.01
Apr	6.09	4.75	-22.00	55.37	26.78	-51.63
May	4.64	2.83	-39.00	36.54	22.94	-37.22
Jun	3.65	1.93	-47.12	24.30	7.00	-71.19
Jul	3.33	1.58	-52.55	21.32	3.91	-81.66
Aug	4.05	2.33	42.47	15.12	2.83	-81.28
Sep	2.70	1.61	-40.37	9.52	2.57	73.00
Total	100.29	88.26	-11.99	600.22	571.73	-4.75

Table 9 shows the observed and future runoff for the Usuthu River at GS5 for dry and wet year scenarios. It can be seen from Table 9 that the future annual runoff is going to be more than the observed by 5.3 (3.13 Mm^3) per cent for the dry year scenario but a decrease of 1.4 (7.97 Mm^3) per cent for the wet year scenario.

This means that there will be more runoff in the Usuthu River basin at GS5 in the dry year scenario but less runoff in the wet year scenario given A2 climate change scenario. Although the magnitude of the annual runoff increase is high in terms of percentage for the dry year scenario but the magnitude of the change (decrease) is high in the wet year scenario. The implication here is that there will be less water to store and abstract in the catchment given climate change with the wet year scenario.

Table 10 shows the observed and future runoff for the Usuthu River at GS7 for dry and wet year scenarios. It can be seen from Table 10 that the future annual runoff is going to be less than the observed by 20.6 % (20.2 Mm^3) and 14.5 % (113.41 Mm^3) for the dry and wet

Table 9
Observed, future monthly runoff and flow changes for the Usuthu River at GS5 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	5.30	4.51	-14.91	12.66	18.64	+47.24
Nov	7.92	8.05	+1.64	49.72	32.87	+33.89
Dec	7.47	9.32	+24.77	136.99	112.72	-17.72
Jan	10.31	7.81	-24.25	98.14	118.73	+20.98
Feb	5.80	5.61	-3.28	78.63	85.88	+9.22
Mar	6.15	5.41	-12.03	56.26	53.80	-4.37
Apr	4.08	4.56	+11.76	37.73	33.35	-11.61
May	2.54	3.71	+46.06	29.06	33.46	+15.14
Jun	2.26	3.20	+41.59	19.04	26.37	+38.50
Jul	2.38	3.11	+30.67	14.73	19.64	+33.33
Aug	2.38	3.31	+39.08	12.08	15.43	+27.73
Sep	1.97	3.10	+57.36	10.95	13.09	+19.54
Total	58.56	61.69	+5.34	556.01	563.98	+1.43

year scenario, respectively. This means that there will be less runoff in the Usuthu River basin at GS7 in both dry and wet year scenarios given A2 climate change scenario.

Although the magnitude of the annual runoff decrease is high in terms of percentage for the dry year scenario but the magnitude of the change is high in the wet year scenario by 17.8 %. The implication here is that there will be less water to store and abstract in the catchment given climate change with wet year scenario and also less water in the dry year scenario and this will have a negative impact on water availability to different water uses downstream.

Table 11 shows the observed and future runoff for the Usuthu River at GS6 for dry and wet year scenarios. It can be seen from Table 11 that the future annual runoff is going to be less than the observed by 12.3 (61.35 Mm^3) and 11.6 (314.51 Mm^3) per cent for the dry and wet year scenario, respectively.

This means that there will be less runoff in the Usuthu River basin at GS6 in both dry and wet year scenarios given A2 climate change scenario. Although the magnitude of the annual runoff decrease is more or less the same in terms of percentage for both scenarios but the magnitude of the change is high in the wet year scenario by 19.5 per cent. The implication here is that there will be less water to store in the catchment given climate change in both scenarios and this will have a negative impact on water availability to the different water uses downstream.

Table 10

Observed, future monthly runoff and flow changes for the Usuthu River at GS7 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	6.52	5.96	-8.59	30.22	26.88	-11.05
Nov	12.75	8.71	-31.69	76.06	35.05	-53.92
Dec	12.68	9.11	-28.15	169.85	159.60	-6.03
Jan	15.39	9.78	-36.45	117.24	115.05	-1.87
Feb	11.45	7.52	-34.32	122.03	126.17	+3.39
Mar	8.41	7.65	-9.04	89.42	48.70	-45.54
Apr	6.57	6.20	-5.63	59.72	30.69	-48.61
May	4.77	5.17	+8.39	42.62	32.84	-22.95
Jun	4.79	4.35	-9.19	25.38	27.21	+7.21
Jul	6.59	4.27	-35.20	20.12	23.39	+16.25
Aug	4.31	4.61	+6.96	16.15	22.38	+38.58
Sep	3.67	4.35	+18.53	14.44	21.88	+51.52
Total	97.90	77.70	-20.63	783.25	669.84	-14.48

Table 11

Observed, future monthly runoff and flow changes for the Usuthu River at GS6 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	36.757	24.1384	-34.33	83.81	45.16	-46.12
Nov	72.291	82.13586	+13.62	187.85	171.43	-8.74
Dec	75.004	65.01794	-13.31	454.88	314.19	-30.93
Jan	75.317	75.91916	+0.80	434.88	487.83	+12.18
Feb	51.843	61.5391	+18.70	476.99	424.44	-11.02
Mar	50.890	54.89539	+7.87	360.16	388.55	+7.88
Apr	37.057	39.56085	+6.76	223.75	271.27	+21.24
May	28.471	17.90913	-37.10	176.09	161.96	-8.02
Jun	24.977	7.15863	-71.34	109.95	74.22	-32.50
Jul	15.295	3.89329	-74.55	85.43	33.09	-61.27
Aug	17.734	3.114632	-82.44	67.32	15.57	-76.87
Sep	14.016	3.01416	-78.49	56.95	15.82	-72.22
Total	499.651	438.2965	-12.28	2718.06	2403.55	-11.57

Table 12 shows the observed and future runoff for the Mhlatuzane River at G19 for dry and wet year scenarios. It can be seen from Table 12 that the future annual runoff is going to be less than the observed by 6.8 (1.4 Mm^3) and 10.8 (9.45 Mm^3) per cent for the dry and wet year scenario, respectively.

The magnitude of the change is high in the wet year scenario by 14.8 per cent. The implication here is that there will be less water in the catchment thus less runoff into Lubovane dam given climate change in both scenarios and this will have a negative impact on water availability to the different water uses downstream.

Table 12
Observed, future monthly runoff and flow changes for the Usuthu River at GS19 for dry and wet year scenarios

	Dry year scenario			*Wet year scenario*		
Month	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	1.78	1.39	-21.91	3.302	3.18	-3.69
Nov	5.06	4.97	-1.78	4.301	5.68	+32.06
Dec	3.26	3.41	+4.60	10.668	11.20	+4.99
Jan	3.08	3.18	+3.25	12.039	12.52	+4.00
Feb	0.76	1.40	+84.21	12.751	12.93	+1.40
Mar	1.61	1.16	-27.95	15.513	13.78	-11.17
Apr	1.74	1.09	-37.36	11.694	8.92	-23.72
May	0.77	0.70	-9.09	4.663	4.60	-1.35
Jun	0.62	0.47	-24.19	5.687	2.16	-62.02
Jul	0.60	0.49	-18.33	3.466	1.99	-42.59
Aug	0.59	0.54	-8.47	2.760	1.34	-51.45
Sep	0.80	0.49	-38.75	1.869	0.87	-53.45
Total	20.68	19.28	6.77	88.714	79.17	-10.76

Table 13 shows the observed and future runoff for the Usuthu River at G16 for dry and wet year scenarios. It can be seen from Table 13 that the future annual runoff is going to be less than the observed by 7.4 (45.63 Mm^3) per cent for the dry year scenario. However, there will be an increase of the future annual runoff by 4.4 (60.81 Mm^3) per cent for the wet year scenario.

Since GS16 is at the border with South Africa, the implications here are that there will be less water leaving the country in the dry year scenario but more water leaving in the wet year scenario. The frequency of floods is expected to increase especially in the wet year scenario.

3.1. Annual runoff changes

Table 14 presents the observed, simulated (future) annual runoff and runoff changes in the sub-catchments for the dry and wet year scenarios. The information in Table 14 has been obtained from Tables 3 to 13. This is mainly due climate change and variability since as a result of these phenomena the amount of precipitation will vary with some areas receiving more while others none or less. It can be observed in Table 14 that there is a decrease in the annual runoff volumes across all the sub-catchments except for Usuthu River at GS5 (which indicates an increase of 5.3%) during the dry year scenario. The annual runoff decrease

Table 13
Observed future monthly runoff and flow changes for the Usuthu River at GS16 for dry and wet year scenarios

Month	*Dry year scenario*			*Wet year scenario*		
	Observed runoff (Mm^3)	*Future runoff (Mm^3)*	*Flow changes (%)*	*Observed runoff (Mm^3)*	*Future runoff (Mm^3)*	*Flow changes (%)*
Oct	11.63	32.03	+175.41	54.63	57.96	+6.10
Nov	62.27	43.30	-30.46	221.49	165.33	-25.36
Dec	56.96	68.13	+19.61	235.91	242.03	+2.59
Jan	62.56	79.32	+26.79	329.43	356.43	+8.20
Feb	150.08	126.75	-15.55	145.25	203.45	+40.07
Mar	93.93	65.08	-30.71	125.32	102.71	-18.04
Apr	37.98	34.44	-9.32	83.58	95.46	+14.21
May	20.51	27.97	+36.37	44.23	101.18	+128.76
Jun	32.56	24.11	-25.95	49.74	48.71	-2.07
Jul	27.21	24.41	-10.29	44.54	29.49	-33.79
Aug	23.93	24.41	+2.01	36.79	25.42	-30.91
Sep	40.09	24.11	-39.86	26.48	30.02	+13.37
Total	619.70	574.07	-7.36	1397.39	1458.20	+4.35

ranges from 1.4 to 61.35 Mm^3. Table 14 also shows that there will be a decrease in annual runoff for the wet year scenario in all the sub-catchments except for Usuthu River at GS16 which indicates an increase of 4.4%. The annual runoff decrease ranges from 6.55 to 314.51 Mm^3. The decrease in the annual runoff in both scenarios suggests that there will be less water in the sub-catchments given climate change. Therefore, there is a need to implement climate change adaptation strategies in the country.

Table 14
Observed, future annual runoff (Mm^3) and runoff changes (%) for dry and wet year scenarios in the respective sub-catchments.

River	*Gauging Station*	*Dry year scenario*			*Wet year scenario*		
		Observed (Mm^3)	*Runoff (Mm^3)*	*% change*	*Observed (Mm^3)*	*Runoff (Mm^3)*	*% Change*
Komati	GS 30	102.74	93.72	-8.78	811.16	757.25	-6.65
Mbuluzi	GS 3	110.26	103.71	-5.94	398.36	392.23	-1.54
buluzi	GS 32	63.25	61.14	-3.34	384.28	373.21	-2.88
Usuthu	GS15	47.23	44.29	-6.2%	220.30	209.47	-8.2%
Usuthu	GS 2	138.80	121.66	-12.66%	795.54	697.34	-12.3%
Usuthu	GS 9	100.29	88.26	-11.99	600.22	571.73	-4.75
Usuthu	GS 5	58.56	61.69	+5.34	556.01	563.98	+1.43
Usuthu	GS 7	97.90	77.70	-20.63	783.25	669.84	-14.48
Usuthu	GS 6	499.651	438.2965	-12.28	2718.06	2403.55	-11.57
Usuthu	GS 19	20.68	19.28	6.77	88.714	79.17	-10.76
Usuthu	GS 16	619.70	574.07	-7.36	1397.39	1458.20	+4.35

Figures 3 and 4 were created by assigning the projected changes in runoff per gauging station to the upper catchments for the dry year and wet year scenarios, respectively (Table 14).

It should be noted that a gauging station may incorporate all sub-catchments up-stream runoff yet its projected runoff change be assigned selectively and different to the upper sub catchments. Take for instance GS16 in Figures 3 and Figure 4 which measures flows for all rivers in the Great Usuthu Basin. The change in runoff is projected to decrease by 7.4% and increase by greater than 4% for the dry and wet scenario, respectively while the projected change at GS6 is projected to decrease by more than 10% on both scenarios. The runoff flow changes for GS6 were assigned to the upper catchment while the catchments between GS6 and GS16 were assigned GS16 values as shown in Figures 3 to 4.

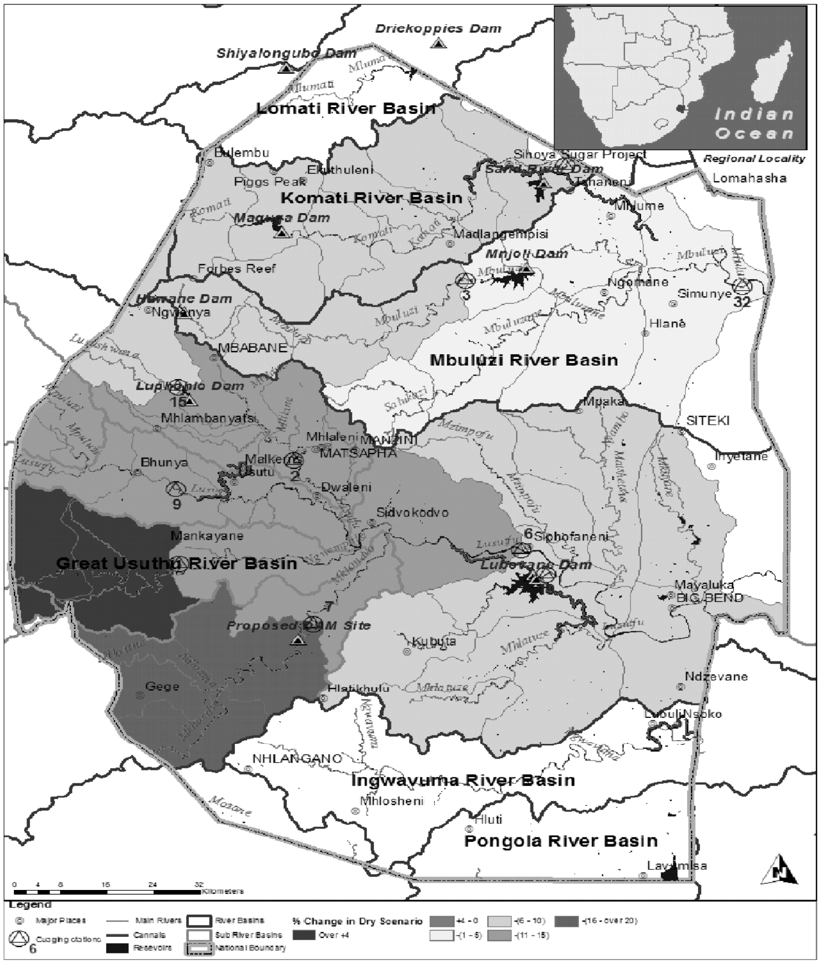

Figure 3: Annual runoff changes in the sub-catchments for dry year scenario

Source: Ministry of Natural Resources and Energy, Department of Water Affairs [5]

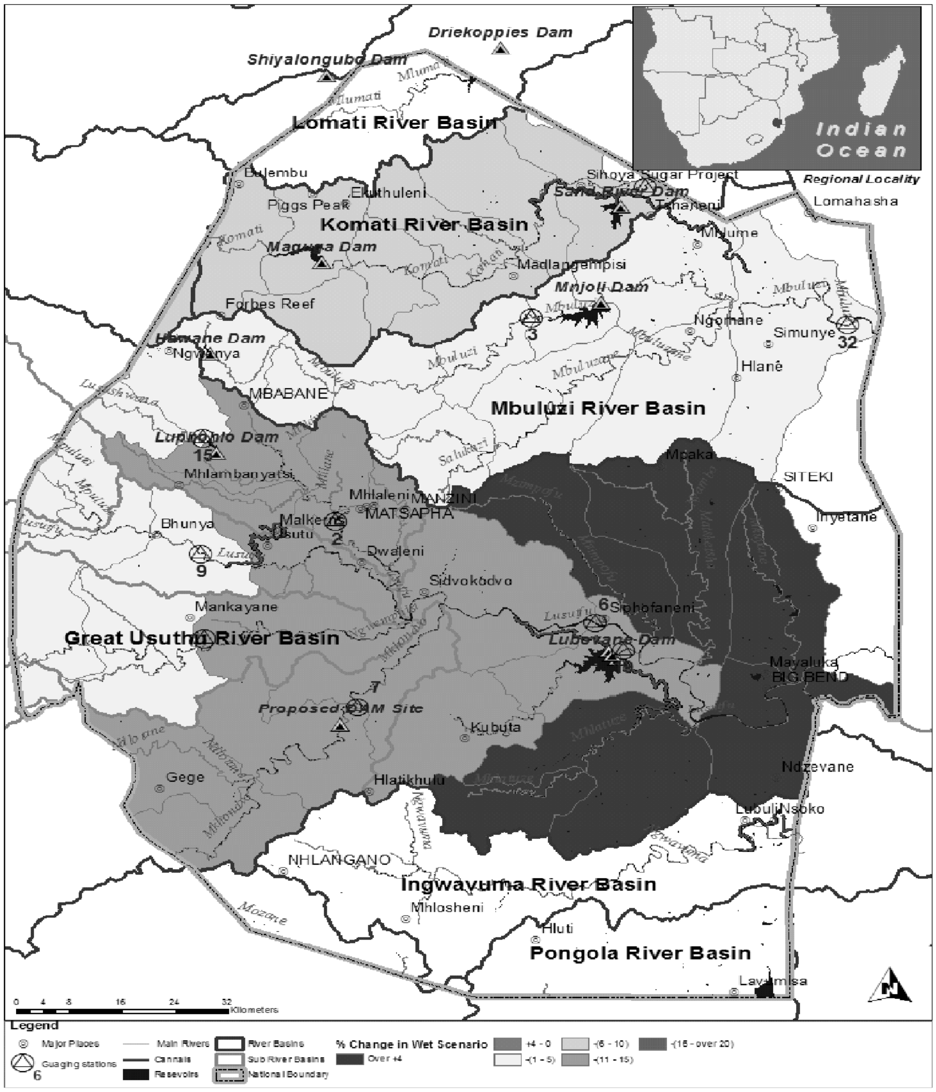

Figure 4: Projected percentage annual runoff changes in the sub-catchments for wet year scenario

Source: Ministry of Natural Resources and Energy, Department of Water Affairs [5]

3.2. Water use projections

The first assumption is that the current stream flow measurements at the sub-catchment outlets were done after the water use for domestic and livestock upstream have been abstracted. Therefore, the future water use for domestic and livestock will be that to be consumed by the extra population (human beings and livestock) and water user industry and irrigation in each sub-catchment. This water use was added to the projected water abstractions in each sub-catchment. The total annual water use was divided by the future annual water availability (which is the sum of the simulated future water and the current water abstractions) in order to obtain the water stress index for each sub-catchment. This was done on an annual basis

3.3. Projected water use for livestock

Livestock in Swaziland is dominated by cattle, goats and chickens, with cattle alone posing the biggest water demand based on their numbers and unit consumption rate (100 litres per day). Based on the increase in the conversion of grazing land to commercial and subsistence crop production cattle numbers have remained steady and are projected to decline (PRIMA report, [16]). Therefore the current numbers of cattle have been kept constant for the period to 2050. It has also been assumed that the current water measurements were taken after the livestock have taken their share of water. Therefore, no water projections to 2050 for livestock in all the sub-catchments were undertaken.

3.4. Projected domestic rural water use in the sub-catchments

The projected domestic water use in the sub-catchments is computed after projecting the predicted population to 2050. It is reported that, 77% of the population live in rural areas (CSO, [17]) and have an assumed water use per capita per day of 30 litres (information from DWA). Table 15 shows the current, projected population and projected domestic water demand in the sub-catchments.

Table 15
Current, projected population and projected domestic water demand in the sub-catchments

Name of catchment	*Current population*	*Population in 2050*	*Population difference*	*Domestic water use (Mm^3/a)*
Komati at GS30	93319	140044	46725	0.5116
Mbuluzi at GS3	29267	43924	14657	0.1605
Mbuluzi at GS32	119338	179102	59764	0.6544
Usuthu at GS2	263686	395688	132002	1.4454
Usuthu at GS5	14337	21519	7182	0.0786
Usuthu at GS7	16094	24156	8062	0.0883
Usuthu at GS9	11893	17850	5957	0.0652
Usuthu at GS15	2577	3868	1291	0.0141
Usuthu at GS6	55712	83619	27907	0.3056
Usuthu at GS19	2333	3502	1169	0.0128
Usuthu at GS16	72760	109206	36446	0.3991

3.5. Projected water demand for irrigation and urban areas

The information on the projected water use for irrigation and domestic use in urban areas in the sub-catchments has been obtained from the PRIMA report [16] for GS30, GS2 and GS7. Table 17 shows the projected water demand in the sub-catchments.

The annual domestic urban water use is 1.7 per cent of the total water use. The current water abstractions records in the sub-catchments do not separate irrigation water use and domestic urban and industrial water use. Therefore, a factor of 0.02 has been used to separate the current urban and industrial water use in the sub-catchments. Then a factor of 0.05 has been used to project the urban and industrial water use to 2050 to obtain the values in column 3 in Table 16.

The projected water use in Lusushwana River at GS2 is 9.6 Mm^3 per annum in the PRIMA report [16] which translates to a growth rate of 7.3 per cent. Therefore, a growth rate of 10 per cent has been assumed to project the irrigation water demand in the sub-catchments. Therefore, the current water abstractions were multiplied by 0.1 to obtain the projected irrigation water demand in the sub-catchments to obtain the values in the second column.

Table 16
Projected annual water use (Mm^3) in the sub-catchments

Name of catchment	*Irrigation water use (Mm^3/a)*	*Urban domestic and industrial water use (Mm^3/a)*	*Rural domestic water demand (Mm^3/a)*	*Total projected water demand (Mm^3/a)*
Komati at GS30	590.0	8.694	0.5116	599.21
Mbuluzi at GS3	0.7	0.147	0.1605	1.01
Mbuluzi at GS32	7.0	1.512	0.6544	9.17
Usuthu at GS2	9.6	19.58	1.4454	30.63
Usuthu at GS5	0.7	0.147	0.0786	0.93
Usuthu at GS7	673	0.357	0.0883	673.45
Usuthu at GS9	4.383	0.924	0.0652	5.37
Usuthu at GS15	0.178	0.042	0.0141	0.23
Usuthu at GS6	20.65	4.3365	0.3056	25.29
Usuthu at GS19	6.0	0.0735	0.0128	6.09
Usuthu at GS16	155.0	14.826	0.3991	170.23

3.6. Future water availability in the catchments

The future runoff has been simulated using the WatBal model given the future precipitation, potential evapotranspiration and the observed stream flows as inputs. The current water abstractions for domestic (urban, rural and livestock), industrial and irrigation use in the catchments has been projected to year 2050. The water stress index has been used to assess the water availability in the sub-catchments of the major river basins (Komati, Mbuluzi and Usuthu) in the country. The water stress index (Milano *et al.*, [15]) is expressed as follows:

$$WSI = \frac{Annual\ water\ withdrawal}{Annual\ water\ available}$$

If WSI > 80%, the sub-catchment faces severe water stress

If 40% < WSI < 80%, the sub-catchment faces high water stress

If 20% < WSI < 40%, the sub-catchment faces moderate water stress

If 10% <WSI < 20%, the sub-catchment faces low water stress

If WSI < 10%, the sub-catchment faces no water stress

Table 17 presents the future annual runoff, current annual water abstractions, projected annual water abstractions, total future annual water abstractions and the water stress index for each sub-catchment for the dry year scenario.

It can be observed in Table 17 that Komati catchment at GS30 and Usuthu catchment at GS7 will face severe water stress under climate change (dry year scenario). Sub-catchments Mbuluzi at GS32, Usuthu at GS2 and Usuthu at GS16 will face high water stress given climate change (dry year scenario). Sub-catchments Usuthu at GS6 and Usuthu at GS19 will face moderate water stress given climate change (dry year scenario). Sub-catchment Usuthu at GS15 will face low water stress while sub-catchments Mbuluzi at GS3, and Usuthu at GS5 will have no water stress given climate change (dry year scenario).

However, it should be pointed out here that water storage facilities are proposed in the Komati River basin (reconnaissance and pre-feasibility for Silingane dam have been completed (PRIMA report, [16]) and therefore, this will moderate the water stress indicated in this catchment. The feasibility study for Ethemba dam along Mkhondvo River is complete and therefore once implemented it will moderate the water stress in Usuthu River at GS7.

What can be concluded here is that all the sub-catchments except sub-catchment Mbuluzi at GS3 and Usuthu at GS5 will be vulnerable given climate change in the dry year scenario. The out flows of the major catchments that is Komati at GS30, Mbuluzi at GS32 and Usuthu at GS16 are projected to be low given climate change. Therefore, this will have an effect on the sharing of the water resources of these rivers with South Africa and Mozambique as noted by Matondo *et al.* [18].

Table 17

Simulated future annual runoff, current annual water abstractions, projected annual water abstractions, total future water abstractions and water stress index in respective sub-catchments (Dry year Scenario)

Sub-catchment name	*Future annual runoff (Mm^3)*	*Current annual water abstractions (Mm^3)*	*Projected annual water abstractions (Mm^3)*	*Total future water abstractions (Mm^3)*	*Water stress index (%)*
Komati at GS30	93.72	414.00	599.21	1013.21	199.6
Mbuluzi at GS3	103.71	7.00	1.01	8.01	7.
Mbuluzi at GS32	61.14	71.90	9.17	81.07	60.9
Usuthu at GS2	121.66	131.47	30.63	162.1	64.0
Usuthu at GS5	61.69	7.00	0.93	7.93	11.5
Usuthu at GS7	77.70	17.03	673.45	690.48	728.9
Usuthu at GS9	88.26	43.83	5.37	49.2	37.2
Usuthu at GS15	44.29	1.78	0.23	2.01	4.4
Usuthu at GS6	438.3	206.54	25.29	231.83	36.0
Usuthu at GS19	19.28	3.53	6.09	9.62	42.2
Usuthu at GS16	574.07	912.53	170.23	1082.76	72.8

Table 18 presents the future annual runoff, current annual water abstractions, projected annual water abstractions, total future annual water abstractions and the water stress index for each sub-catchment for the wet year scenario. It can be seen from Table 18 that sub-catchments Komati at GS30 and Usuthu at GS7 will experience severe water stress while Usuthu at GS16 will experience high water stress given climate change (wet year scenario). Sub-catchments Mbuluzi at GS32, Usuthu at GS2 and Usuthu at GS19 will experience low water stress while sub-catchments Mbuluzi at GS3, Usuthu at GS5, Usuthu at GS6, Usuthu at GS9 and Usuthu at GS15 will experience no water stress given climate change (wet year scenario).

The major catchments that is Komati, Usuthu and Mbuluzi will experience severe, moderate and low water stress, respectively given climate change (wet year scenario). The projected out flows of Komati and Mbuluzi are going to be low given climate change except for the Usuthu where there is an increase in the projected runoff. Therefore, the sharing of water resources in Komati and Mbuluzi with South Africa and Mozambique will be affected given climate change (wet year scenario).

Table 18
Simulated future annual runoff, current annual water abstractions, projected annual water abstractions, total future water abstractions and water stress index in respective sub-catchments (Wet year Scenario)

Sub catchment name	*Future annual runoff (Mm^3)*	*Current water abstractions (Mm^3)*	*Projected annual water abstractions (Mm3)*	*Total future water abstractions (Mm3)*	*Water stress index (%)*
Komati at GS30	757.25	414.00	599.21	1013.21	86.5
Mbuluzi at GS3	392.23	7.00	1.01	8.01	2.00
Mbuluzi at GS32	373.21	71.90	9.17	81.07	18.21
Usuthu at GS2	697.34	131.47	30.63	162.1	19.56
Usuthu at GS5	563.98	7.00	0.93	7.93	1.55
Usuthu at GS7	669.84	17.03	673.45	690.48	100.5
Usuthu at GS9	571.73	43.83	5.37	49.2	7.99
Usuthu at GS15	209.47	1.78	0.23	2.01	0.95
Usuthu at GS6	2403.55	206.54	25.29	231.83	8.88
Usuthu at GS19	79.17	3.53	6.09	9.62	11.63
Usuthu at GS16	1458.20	912.53	170.23	1082.76	45.67

Figure 5 was created by assigning the projected water stress index per gauging station to the upper catchments for the dry year scenarios shown in Table 18. The projected water stress index was assigned selectively and different in lower and upper sub catchments. This was based on assigning the projected water stress index for respective gauging station to the upper sub catchments. The difference between sub catchments in the same basin are due to water demands against availability in the various sections of the basin river. The assumption made is that the upper catchment water abstractions will be based on the water availability as measured from the selected gauging stations shown in the Map. GS7 which is in the middle of the Mkhondo River Basin indicates a projected severe water stress index. Just after the gauging station, the remainder of the river basin, with flows only measured at GS6, indicates that the water stress index is high. The combined catchments between (GS2, GS5, GS9, GS7) and GS6 have moderate and low water stress index. This

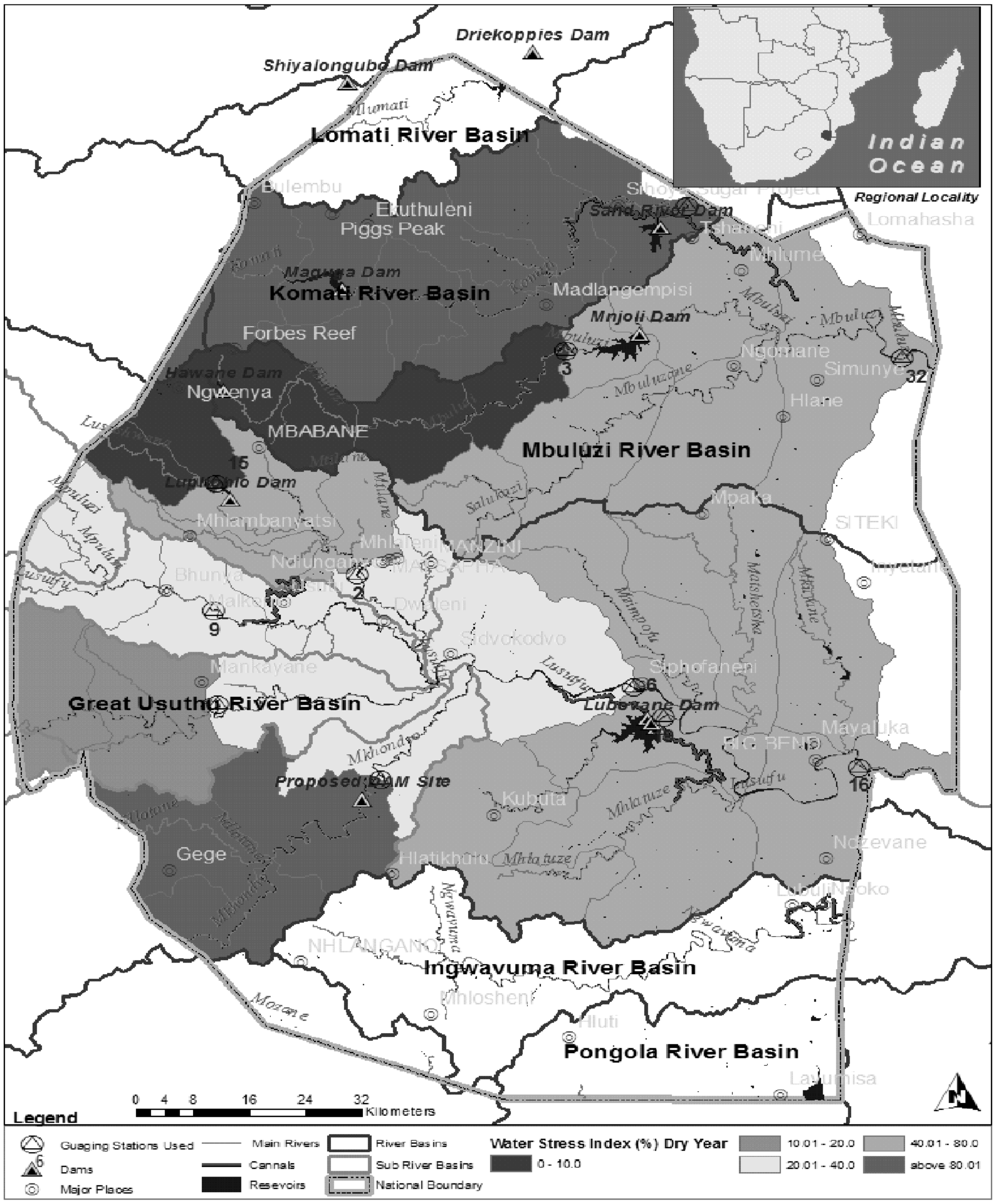

Figure 5: Map of future water stress index in respective sub-catchments under dry year scenario

Source: Ministry of Natural Resources and Energy, Department of Water Affairs [5]

it is not to conclude that water is available in any stretch of the river sub catchment equally. Abstraction allocation should take into consideration not only the sub catchments within a gauging station but the lower end needs such as highly water stressed GS16 sub catchment allocations.

Figure 6 was created by assigning the projected water stress index per gauging station to catchments for the wet year scenarios shown in Table 18. The projected water stress index was assigned selectively and different in lower and upper sub catchments. Upper sub catchments were assigned projected water stress index for respective gauging station although their effect contribute to the index of the lower sub-catchments. The difference between sub catchments in the same basin are due to water demands against availability in the various sections of the river basin. The assumption made is that the upper catchment water abstractions are based on the water availability as measured from the selected gauging stations shown in the Map. To illustrate this effect, GS7 which is in the middle of the Mkhondo River Basin indicates a severe water stress index. The lower end, with flows only measured at GS6, indicates that there is no water stress. The combined catchments between (GS2, GS5, GS9, GS7) and GS6 have no water stress.

This it is not to conclude that water is available at any stretch of the river sub catchment individually. Abstractions need to be taken into consideration not only the upper sub catchments but the downstream as well such as highly water stressed GS16 sub catchment allocations.

It can be observed from the above analysis that only two sub-catchments (Mbuluzi at GS3and Usuthu at GS15) and 5 sub-catchments (Mbuluzi at GS3, Usuthu at GS5, GS9, GS15 and GS6) will have no water stress under dry and wet year scenario respectively. Therefore, the country will have more area with water stress given dry year scenario while it will have a less area with water stress given wet year scenario.

3.7. Impact on floods

Stream flow observations are assumed to be random values where the value of one observation of the process is not correlated with the values of adjacent observations, and the statistical properties of all observations are the same. When there is no correlation between adjacent observations, the output of a hydrologic system is treated as stochastic, space independent, and time independent. This type of treatment is appropriate for observations of extreme hydrologic events (floods, droughts etc.). A random variable X is a variable described by a probability distribution. There are several statistical distribution functions in the literature such as extreme value type1, extreme value type2, extreme value type3 etc. (Linsely *et al.*, [19]). A probability distribution is a function representing the probability of occurrence of a random variable. By fitting a distribution to a set of hydrologic data, a great deal of probabilistic information in the sample can be summarized in the function and its associated parameters. A computer programme EASRFIT5.5 professional has been used in fitting the appropriate probability distribution to the extreme stream flow

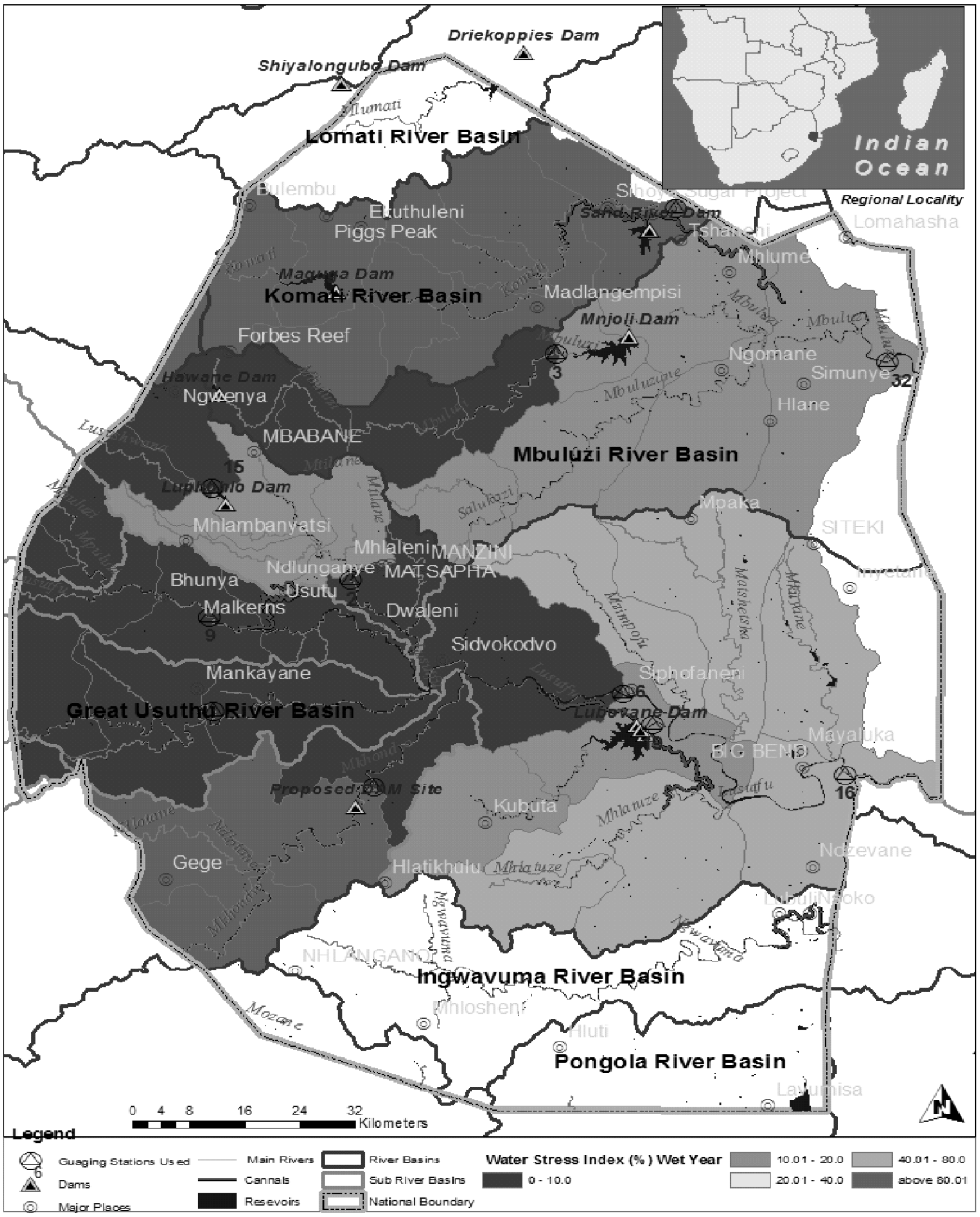

Figure 6: Map of future water stress index in respective sub-catchments in wet year scenario

Source: Ministry of Natural Resources and Energy, Department of Water Affairs [5]

values at selected gauging stations in the major catchment in Swaziland. This computer programme uses three goodness of fit tests (Kolmogorov Smirnov, Anderson Darling and Chi Squared) and the distribution with the best statistic and highest rank was selected. Table 19 presents the return period and the corresponding flood magnitudes at selected subcatchments in Swaziland. It can be seen from Table 19 that flood magnitudes vary according to the catchment area but also with physiographic regions. However, the Lusushwana River at GS15 has moderate flood magnitudes compared to Mhlatuzana River at GS19 and Lomati River at GS34 which both have high flood magnitudes even though they have similar sizes. The Komati River at GS29 experiences high flood magnitudes compared to GS30 at exit to South Africa. This could be due to the fact that the Komati River is highly regulated between these two gauging stations. Highest, flood magnitudes in the country, occurs at GS6 and this is due to the size of the catchment which originates from South Africa which also traverses the three physiographic regions of Swaziland namely: Highveld, Middleveld and Lowveld.

Table 19
Type of probability distribution that best fit extreme values, Return period and Corresponding, flood magnitudes (m^3/s) at respective sub catchments in Swaziland

Sub-catchment name	*Area (km^2)*	*Type of statistic distribution*	*T10 m^3/s*	*T20 m^3/s*	*T50 m^3/s*	*T100 m^3/s*
Lusushwana River at GS15	581	Gen, Extreme Value	108	138	184	227
Great Usuthu at GS9	2681	Gen. Extreme value	373	531	829	1150
Ngwempisis River at GS5	3232	Log-Pearson 3	276	323	387	433
Mkhondo River at GS7	3628	Gamma (3P)	431	520	652	744
Usuthu River at GS6	12559	Log-Pearson	1723	2292	3076	3690
Mhlatuzana River at GS19	526	Gen. Extreme Value	502	679	971	1248
Komati River at GS29	5484	Pearson6	1016	1947	4500	8413
Komati River at GS30	7423	Gen. Extreme Value	257	348	498	639
Mbuluzi River at GS3	722	Log-Gamma	327	504	844	1207
Mbuluzi River at GS32	2944	Lognormal (3P)	747	1338	2586	4018
Ngwavuma River at GS 8	1305	Pearson5	487	744	1264	1866
Lomati River at GS34	740	Log-Pearson type3	357	604	1134	1767

It has been reported that floods and droughts have become more frequent and intense in Southern Europe and western Africa but have become less frequent and intense in North America and northwestern Australia (IPCC, [8]). Globally, studies project an increase of flood hazards (Hirabayashi *et al.*, [20] and Hirabayashi *et al.*, [21]). It is therefore, expected that the frequency of floods will increase in the river basins in Swaziland given climate change especially for the wet year scenario.

4. SUMMARY AND CONCLUSIONS

It has been established that climate change in the next 100 years will be due to anthropogenic greenhouse gas emissions. The major effect of the increase of greenhouse gas emissions in the atmosphere is global warming and thus changes in temperature, precipitation and the environment. This is also expected to cause an increase in the frequency of floods and droughts. The simulations from the WatBal model generally depicts that Swaziland just like almost all countries (Nyong, [22]) is not spared from the impacts of climate change and variability. More importantly, water resources will be over-stretched in the event of a decline in precipitation since population projection indicates that it will continue to increase. Therefore, the major river basin catchments of Swaziland in particular Komati and Usuthu will experience a severe and a moderate water stress given climate change (wet and year scenario). Notably, though the WatBal model simulations indicates that the Mbuluzi catchment will experience a low water stress given climate change (wet year scenario). Despite the projections of the model that Mbuluzi catchment will be less water stressed given climate change, considering that this is a trans-boundary river just like Komati, riparian rights between Swaziland, South Africa, and Mozambique will be affected. The decrease in the surface water resources in Swaziland due to climate change has also been reported by Matondo and Msibi [23] and Matondo *et al*. [18].

The current reservoir storage volume per capita is about 700 cubic meters. Developed countries have a mean water storage volume per capita of about 2700 cubic meters (Matondo, [24]). Therefore, the reservoir storage volume per capita for Swaziland is only 26% of developed countries. In conclusion, Swaziland as a country, in an effort to mitigate for climate change must invest more on rainwater harvesting through construction of dams, earth dams and also roof top rainwater harvesting. This will alleviate the severity of the impacts of climate change on human beings, livestock, and industry considering that both human and livestock numbers are projected to continue increasing. Therefore, although some dams have been already constructed in Swaziland and also between Swaziland and South Africa, namely Lubovane, Maguga, and Driekoppies, there is still a room for improvement in this endeavor. The water storage facilities will also alleviate the impact of floods in the country given climate change. It is however, recommended that Environmental Impact Assessments (EIA) and corresponding Comprehensive mitigation Plans (CMP) will be undertaken prior to the development of the water storage facilities in order to reduce the expected adverse impacts associated with such structures [25].

Acknowledgements

Financial support for this work was obtained from UNDP Swaziland Office. Therefore, this support is highly appreciated. The data used in the study was provided by the Department of Meteorology, Ministry of Works and the Water Resources Branch, Ministry of Natural Resources and Energy. The authors would like also like to acknowledge the help of Dr. E. Shongwe and Mr. P. Simelane for meteorology and stream flow data quality processing. The help of Mr. Bheki Ginindza in the processing of the Maps/ Figures is also highly appreciated.

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