EXAMINING THE IMPACT OF CLIMATE CHANGE ON RESERVOIR RELIABILITY

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Abstract. This paper presents results of a study conducted to evaluate the possible impacts of climate change due to doubling of atmospheric carbon dioxide (CO_2) on the reliability of Mazowe reservoir in Zimbabwe. The reservoir supplies most of its water to citrus plantations. Thirty years (1961-1990) of hydrological data (reservoir inflows) and meteorological data were collected from the Zimbabwe National Water Authority (ZINWA) and Department of Meteorological Services respectively. Outputs from the Canadian Climate Centre (CCC) model for the $2CO_2$ temperature and rainfall scenarios were used in the study. The Penman model was used to estimate potential evapotranspiration while reservoir catchment runoff was simulated using the Pitman lumped conceptual model. Research findings revealed that doubling of CO_2 would significantly increase mean annual temperature by 3^oC, potential evapotranspiration (11.8%), rainfall (15%), runoff (36.9%) and reservoir yield (20.4%) at the 10% risk level. Based on the research findings, appropriate mitigation measures should be employed to minimise high rates evaporation from the reservoir. On the other hand, the predicted high reservoir yield requires an increase in water use activities such as extension of irrigated area.

Key words. Climate change, reservoir reliability, model, Mazowe

Introduction

The global warming phenomenon has sparked vigorous research activity with the ultimate aim being to understand the effects of predicted climate change on both natural and managed ecosystems (IPCC, 2007). Research and observations indicate that increases in atmospheric carbon dioxide (CO_2) are raising global and regional temperatures, and producing changes in other climate variables that drive the terrestrial hydrological cycle, most notably precipitation and potential evaporation. At the same time, a warmer world is predicted to result in increased

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water use in domestic, agricultural and industrial sectors (Arnell, 1996; Fowler et al. 2003).

In semi-arid countries, water resources in semi-arid countries are of considerable concern due to high water demand from users, rainfall unreliability, irregularity and high inter-annual variability compounded by unprecedented effects of climate change. Water balance relationships in most river basins are fragile (Kilsby et al. 2007). The most dominant climate drivers for water availability are precipitation, temperature and evaporative demand (Mimikou et al. 2000).. Evaporation is a function of several climate variables (temperature, atmospheric humidity, net surface radiation and wind speed) and non-climatic factors (moisture availability, land-cover and plant physiology). Temperature is particularly important in snow-dominated basins and in coastal areas, the latter due to the impact of temperature on sea level (steric sea-level rise due to thermal expansion of water).

Water resource planning and design has conventionally assumed a stationary mean climate. Climate change invalidates this assumption, and places additional uncertainty on projections of river discharge and water supply, as well as on water demand. Stresses on water resources arising from potential climate change exacerbate water resource management problems over much of the wider southern African region (Buckle, 1996; New 2002; van Oel, 2008).

This article investigates the potential impact of global climate change on yield of Mazowe reservoir in Zimbabwe. Zimbabwe is a water-limited country, with a changing water-management structure and priorities. It is situated in a region with increasing levels of water scarcity and water quality problems, compounded by population growth and issues of social and economic development. During periods of water scarcity, surface water storage reservoirs are increasingly being relied upon to meet demands under increasing water scarcity as a result over-exploitation.

Materials and methods

Study area

Mazowe Dam (17°31'18"S, 30°59'19"E) was built across the Mazowe River in 1918 for irrigating citrus plantations and annual crops like maize, soyabeans and wheat. It lies in agro-ecological region 2 of the country, receives an average rainfall of 864 mm per annum and experiences a mean annual temperature of about 21^0C. The reservoir created by this dam has a full supply capacity of 44.6×10^6 m^3 with a surface area of 540 ha. Average A-pan evaporation rate of dam catchment is the 1630 mm/year (Tererai, 2006). The dam's catchment is 355 km^2. Farmers abstract water from rivers, reservoirs, boreholes as well as weirs thereby affecting amount of water entering downstream dams, including Mazowe dam. Figure 1 shows the location of Mazowe dam and its catchment area.

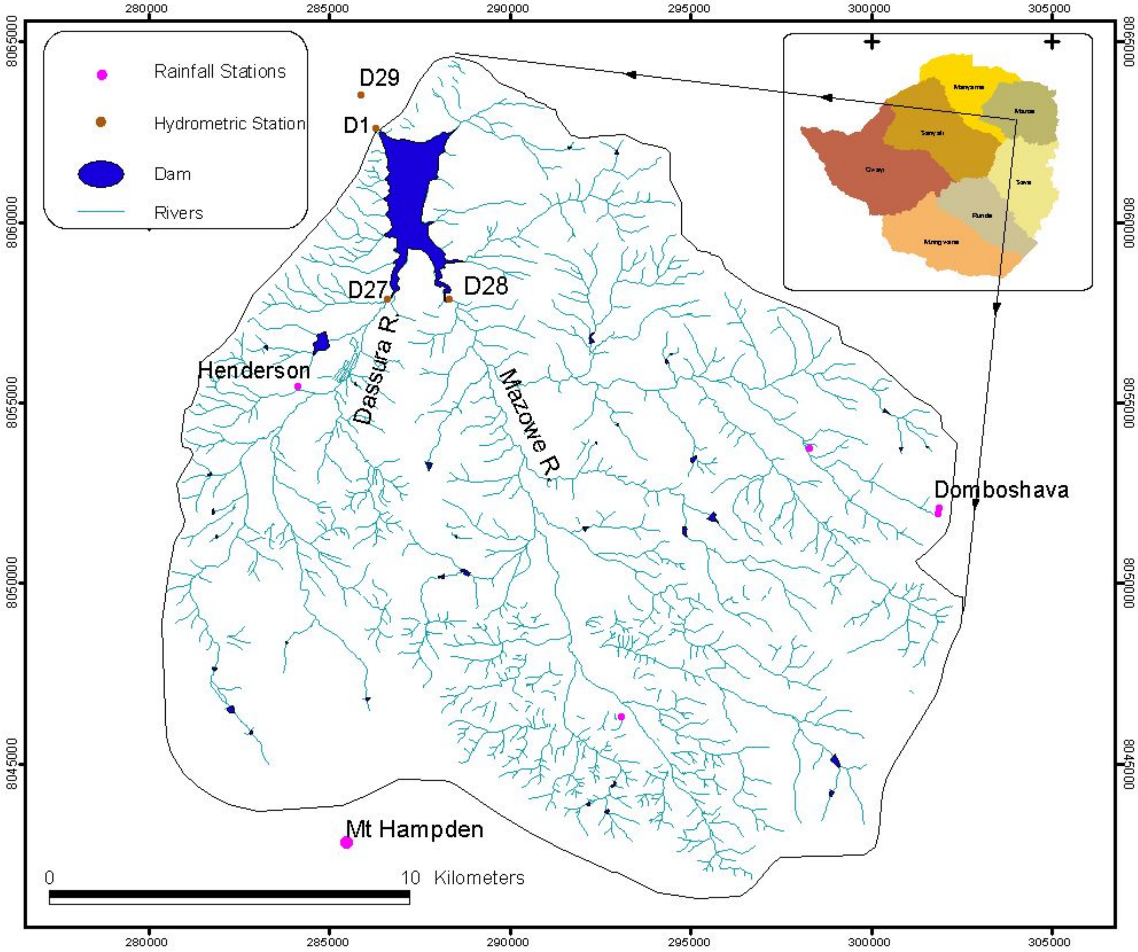

Figure 1. The Mazowe dam and its catchment

Data

Climate and river flow data spanning 30 years (1961-1990) to represent the baseline ($1CO_2$) were obtained from Department of Meteorological Services and Zimbabwe National Water Authority (ZINWA) respectively. Meteorological data from the 5 stations were used to estimate mean areal values.

Penman model

The Penman model was used to estimate potential evapotranspiration of the catchment and evaporation from Mazowe dam. Potential evapotranspiration of the dam catchment and open water or reservoir evaporation E_o is estimated from (Shaw, 1983).

$$E_o = \Delta/\gamma\, H + E_a/(\Delta/\gamma + 1) \qquad \text{Eqn. 1}$$

where:

γ -hydrometric constant (=0.27mmHg/temperature)

Δ -change in vapour pressure with time

H-is the available heat estimated from;

$$H = (1-r)R(0.24\cos L) + 0.52 n/N) - T^4(0.56 - 0.08 e_d^{1/2})(0.10 + 0.9 n/N) \qquad \text{Eqn. 2}$$

where:

r is albebo (r=0.05 for water and r=0.3 for vegetation).

n-average sunshine duration per month

e_d-saturation vapour pressure at dew point

N-average possible maximum sunshine duration

T^4-black body radiation

L-latitude of the area

R-total monthly radiation

E_a-aerodynamic term estimated from mean wind speed (μ) and vapor pressure deficit (e_a-e_d) as;

$$u = 0.35(0.5 + \mu/100)\,(e_a - e_d) \qquad \text{Eqn. 3}$$

Pitman Model

The Pitman rainfall-runoff model was used to simulate the catchment runoff. Input data comprise monthly precipitation and potential evapotranspiration. Precipitation data were obtained from the Department of Meteorological Services while potential evapotranspiration data were obtained as output from the Penman model. Figure 2 shows the model structure (Gorgens, 1983).

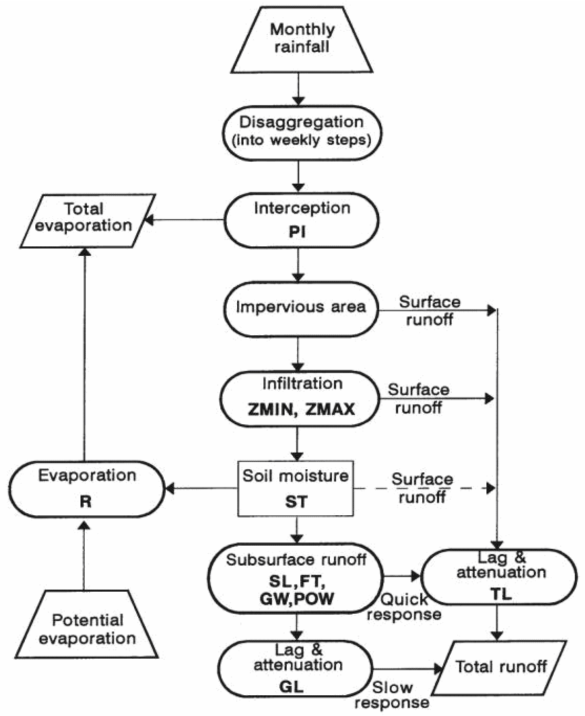

Figure 2. Pitman model flow chart.

The calibration of the model was done using the Rosenbrock automatic parameter optimization routine attached to the model. Thus parameter values are automatically changed using a trial-and error technique until the model reproduces a goodness of fit between the predicted and observed values. Calibration involved changing catchment maximum absorption rate (ZMAX) which regulate the volume of surface runoff, the minimum catchment absorption rate (ZMIN) which determines the depth of monthly rainfall required to initiate surface runoff, the maximum soil capacity (ST) which determines the catchment ability to regulate runoff for a given precipitation and runoff from soil moisture at full capacity (FT) which controls the rate of runoff from soil moisture for ant given moisture state (Gorgens, 1983). Table 1 shows the parameter values used in the Pitman model.

Table1. Pitman model parameters

Parameter		Value	Units	Description
Monthly Time Series	P		mm/month	Monthly rainfall
	PE		mm/month	Monthly total evaporation
Non-temporal Parameters	POW	3	-	Power of soil moisture-runoff equations
	SL	0.0	mm	Soil moisture storage below which no runoff occurs (~wilting point)
	ST	769.8	mm	Maximum soil moisture capacity (~porosity/saturation)
	FT	2.2	mm/month	Runoff from soil when soil moisture is at full capacity
	GW	4	mm/month	Maximum groundwater runoff
	AI	5	%	Impervious portion of the catchment
	ZMIN	70.6	mm/month	Minimum catchment absorption rate
	ZMAX	573.7	mm/month	Maximum catchment absorption rate
	PI	20	mm	Interception storage
	TL	0.25	months	Lag of surface runoff
	GL	1.4	months	Lag of runoff from soil moisture

	R	0.5	-	Evaporation-soil moisture storage relationship

Reservoir yield analysis

The reservoir yield analysis Program from the Zimbabwe National Water Authority (ZINWA) was used to simulate changes in the reservoir yields at 10% risk level for different temperature and rainfall scenarios. A 10% risk risk level implies that the reservoir will have a probability of failure of 0.1. The 10% risk level or reliability level of 90% is the design criteria of Zimbabwean dams supplying water for agriculture or irrigation purposes. Dams supplying domestic water are designed for 96% reliability. The Yield Program's input data consist of dam catchment area (355 km^2), mean annual runoff, mean annual rainfall, coefficient of variation of rainfall and runoff, open water evaporation, drawoff (1 500 m^3), upstream storage(0), catchment area and reservoir full volume (39 357 000 m^3). The model was applied to Mazowe reservoir because it satisfied the condition of storage ratio (ratio of full supply capacity to the product of mean annual runoff and catchment area) of being greater than 0.5.

The Canada Climate Centre (CCC) model (lat. x long: 3.75^0 x 3.75^0) was selected because it simulated the baseline precipitation rates over the Mazowe dam catchment with a small error margin. The outputs from the model consisted of the 1CO2 and 2CO2 runs for precipitation and surface air temperature.

Results and discussion

Temperature changes

Figure 3 shows the mean monthly temperatures for the 1CO2 and 2CO2 conditions. Doubling of 2CO2 will increase mean annual temperature by 16.3% from the baseline condition. Thus, on average the monthly temperature will increase by 3^0C for the doubling of carbon dioxide. The average monthly temperature for the baseline condition of 18.38 ^{0}C is significantly (p=0.000) lower than 21.17 ^{0}C to be experienced under the 2CO2 scenario.

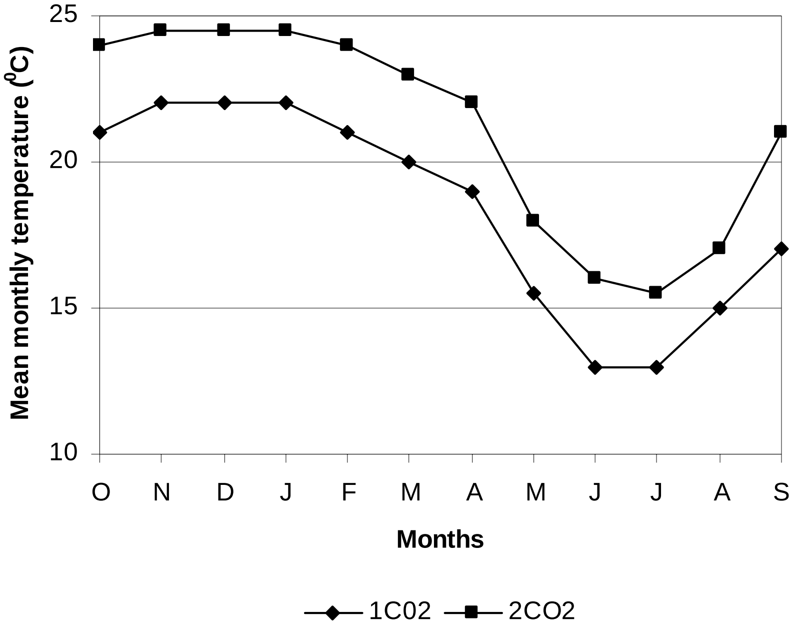

Figure 3. Temperature changes for the 1CO2 and 2CO2 scenarios.

Runoff changes

Figure 4 shows that with the doubling of carbon dioxide (2CO2) the mean monthly runoff in the catchment or reservoir inflows will increase by 36.9% from the baseline conditions. The baseline mean runoff value of 2.45 x 10^6m^3 is significantly (p=0.007) lower than 8.21 x 10^6m^3 for the 2CO2 condition.

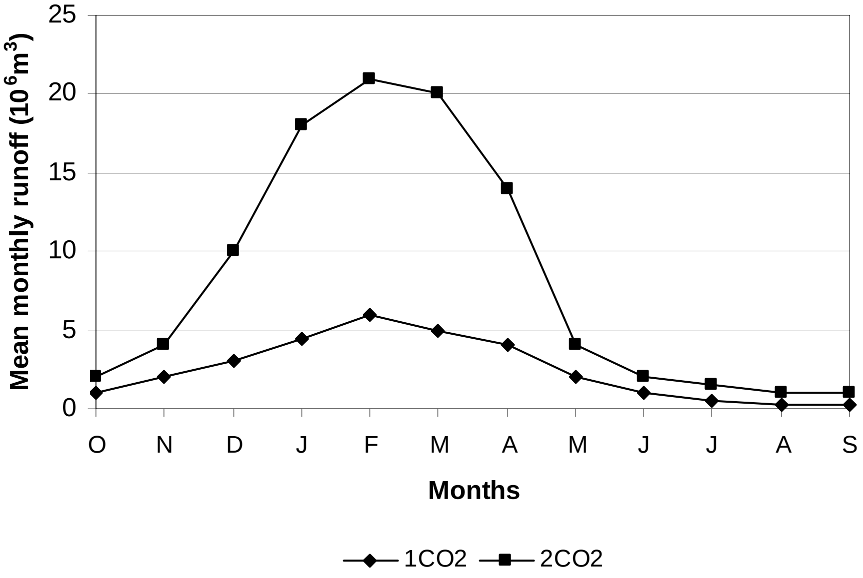

Figure 4. Mean monthly runoff for the 1CO2 and 2CO2 conditions

Precipitation changes

The average areal precipitation is projected to increase by 15% with the doubling of carbon dioxide. Comparising the means between the 1CO2 of 72.08 mm and 2CO2 (85.5 mm) conditions, it is observed that the differences are significant (p=0.013).

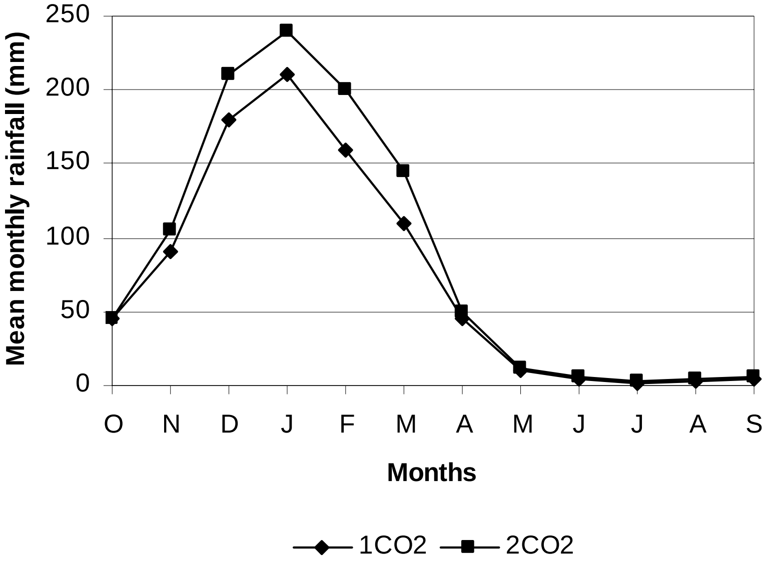

Figure 5. 1CO2 and 2CO2 areal precipitation changes

Changes in potential evapotranspiration

Figure 6 shows the monthly potential evapotranspiration for the 1CO2 and 2CO2 conditions. The Penman model outputs indicate that the average monthly potential evapotranspiration in the catchment will increase by 11.8% from the baseline value of 107.75 mm. The difference between potential evapotranspiration during the 1CO2 and 2CO2 scenarios is significant (p=0.000).

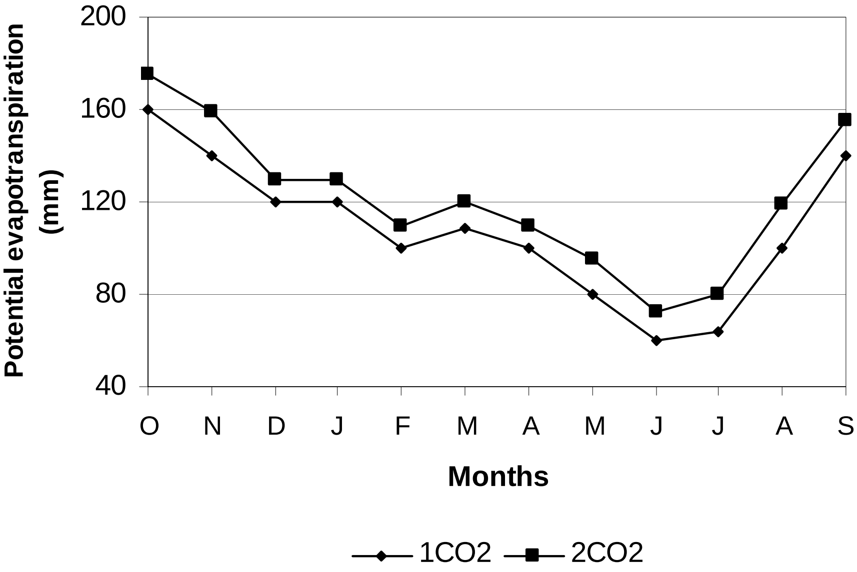

Figure 6. Potentail evapotranspiration rates for the 1CO2 and 2CO2 conditions

Changes in annual reservoir yield

With the doubling of carbon dioxide, the mean annual reservoir yield will increase by 20.4% from the 1961-1990 baseline average. The increase in reservoir yield will have a positive effect on irrigated agriculture because water will be available.

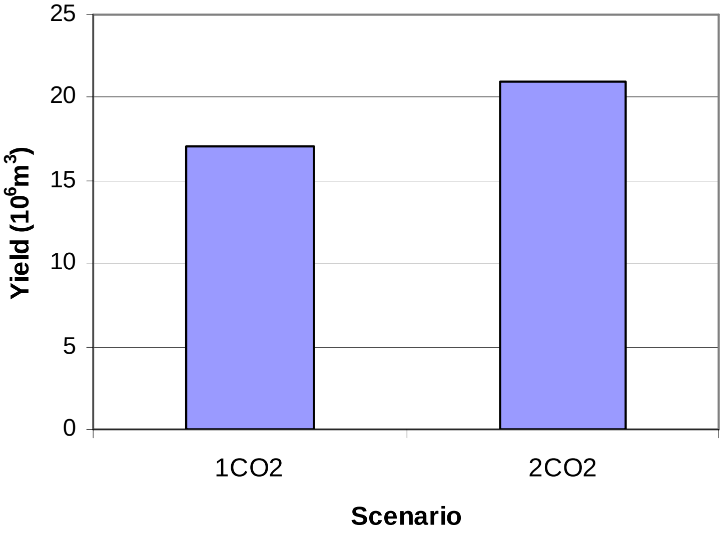

Figure 6. Annual reservoir yields for the 1CO2 and 2CO2 scenarios.

Conclusions

A study of the possible impacts of climate change due to the equivalent doubling of atmospheric carbon dioxide on the reliability of Mazowe dam at 10% risk level showed an increase in mean annual reservoir yield of about 20.4% from the 1961 to 1990 annual average. This rise in yield will be a result of the 15% and 36.9% increase in rainfall and runoff respectively. The mean annual temperature is likely to increase by 3^{0}C resulting in a 11% rise in potential evapotranspiration. Research findings show that the doubling of carbon dioxide will significantly ($p<0.05$) the average values of hydrological parameters considered. The Canadian Climate Centre model outputs of the 2CO2 temperature and rainfall scenarios were used in this study.

Based on the research findings, area under irrigation will need to be expanded to utilise high reservoir yields. However, appropriate mitigation measures against high evaporation rates need to be employed.

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