Edinburgh Research Explorer

Susceptibility of the Batoka Gorge Hydroelectric Scheme to climate change

OPEN ACCESS

Susceptibility of the Batoka Gorge hydroelectric scheme to climate change

Gareth P. Harrison and H. (Bert) W. Whittington

Department of Electronics and Electrical Engineering
University of Edinburgh, Mayfield Road,
Edinburgh EH9 3JL, UK
E-mail address: Gareth.Harrison@ed.ac.uk

Abstract

The continuing and increased use of renewable energy sources, including hydropower, is a key strategy to limit the extent of future climate change. Paradoxically, climate change itself may alter the availability of this natural resource, adversely affecting the financial viability of both existing and potential schemes. Here, a model is described that enables the assessment of the relationship between changes in climate and the viability, technical and financial, of hydro development. The planned Batoka Gorge scheme on the Zambezi River is used as a case study to validate the model and to predict the impact of climate change on river flows, electricity production and scheme financial performance. The model was found to perform well, given the inherent difficulties in the task, although there is concern regarding the ability of the hydrological model to reproduce the historic flow conditions of the upper Zambezi Basin. Simulations with climate change scenarios illustrate the sensitivity of the Batoka Gorge scheme to changes in climate. They suggest significant reductions in river flows, declining power production, reductions in electricity sales revenue and consequently an adverse impact on a range of investment measures.

Keywords: Climate change impacts; River runoff; Hydroelectric power; Batoka Gorge; Zambezi River; Investment

Dedicated to H. (Bert) W. Whittington

On 11 March 2002 and shortly before this work was revised, Professor Bert Whittington was tragically killed in a road accident in Edinburgh. He was aged 56 and leaves his wife Helen and two sons, Barry and Alan. He became the Professor of Electrical Power Engineering at the University of Edinburgh in 1994 and, more recently, acted as consultant to the Scottish Executive and Special Advisor to the UK Parliamentary Select Committee on Energy Policy. It is a tremendous loss to his family, friends and colleagues. He will be remembered as the highly intelligent, witty and talented man that he was and for the inspiration and good humour that he gave to others.

1. Introduction

Despite international efforts, increases in atmospheric concentrations of 'greenhouse' gases look set to rise further given the threefold increase in world energy demand expected over the 21st century (Nakicenovic et al., 1998). By 2100 global mean temperatures are forecast to rise by 1.4– 5.8 8C and will be accompanied by increases in global mean precipitation levels (IPCC, 2001). The impacts of such changes will be significant and far-reaching.

Plans to control the rise in greenhouse gas concentrations have been put forward (UNFCCC, 1998) which aim to cut or stabilise emissions relative to 1990 levels. To achieve the targets, the energy sector will have to change by reducing reliance on fossil fuels, using more renewable energy and practising greater energy efficiency.

A rising demand for electricity, likely increases in fossil-fuel prices and the need for clean emission-free generation sources all appear to be trends in favour of increasing generation from renewable sources, including hydropower. Indeed, hydropower production, currently supplying around 19% of global demand, is anticipated to increase threefold over the next century (Nakicenovic et al., 1998).

However, plans for new hydroelectric stations will have to take account of two major factors. Firstly, the increasing involvement of private capital may not favour hydropower, as private investors generally prefer lower capital-cost, shorter payback options and have an expectation of return on investment higher than that for public investment. Secondly, while precipitation is anticipated to increase on a global level, many parts of the world are anticipated to see significant drying (IPCC, 2001). Studies indicate that declining river flows as a result of changes in climate will lead to declining hydropower production (Harrison and Whittington, 2001). Falling production potential will be detrimental to the economic viability of a scheme, reducing financial return and making investment in hydropower less likely.

2. Hydropower investment appraisal

The diverse nature of hydropower installations and climatic conditions currently restricts examination of the potential impacts of climate change on hydro-electric schemes to individual cases. To assess the impact on investment, it is necessary to consider the problem from the standpoint of potential investors who will be concerned with the impact on a range of investment indicators. To satisfy this need, the authors have devised a methodology, derived from traditional hydropower appraisal, to determine these perform-ance measures.

The techniques of hydropower appraisal are long established with, essentially, historic data on river flow being used as an indicator of future conditions. However, reliance on historic river flows may not be prudent given the prospect of climate change. Some recent project appraisals have attempted to deal with climate change by uniformly altering river flows (Arthur, 1999). Unfortunately, this practice is inadequate as it fails to account for the tendency of catchments to amplify the effects of precipitation changes (Arnell, 1996). This inadequacy is overcome by the changes made to the traditional appraisal process described in the following section.

3. Climate impact analysis tool

To take account of climate change, the traditional reliance on historic river flows was abandoned with the primary data source becoming climatic data. To allow the translation of the climatic variables into estimates of river flow a hydrological model was introduced. This enables the relationship between climate and financial performance to be examined. The revised hydro appraisal process is shown in Fig. 1. It may be seen that other than the hydrology component, the model consists of a reservoir operations model to provide estimates of hydroelectric production from the river flows; an electricity market model to determine sales revenue and a financial model which calculates a range of investment measures.

The complexity of the task necessitated the development of software to facilitate a rapid and accurate exploration of the relationship between climate, hydropower production and financial performance. The software is configured to allow the execution of sensitivity, scenario and risk analyses.

In line with standard practice for hydropower studies and recognising the limitations of available climatic data, the technique uses a monthly time step. Whilst this may reduce accuracy, it allows the use of simple representations for several components in the model, a priority, given the preliminary nature of the study.
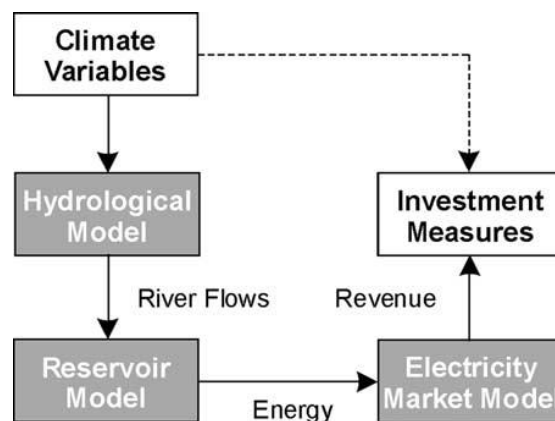

Fig. 1. Adapting the financial appraisal process to take account of climate change.

3.1. Hydrological model

For this application, a relatively simple water balance model was adopted and incorporated into the software to provide a basic accounting procedure for water flows within the catchment. The 'WatBal' model was presented by Yates (1996) although the structure used in this application is closer to the version used by Bowling and Strzepek (1997), in that there is no capability for direct runoff. The WatBal model has been widely reported, used in a variety of catchments with different climate types and sizes, and has compared favourably with other models. The simple lumped-parameter model represents the catchment as a single storage 'bucket' (shown schematically in Fig. 2) and the mass balance is represented as a differential equation (Bowling and Strzepek, 1997)

$$S_{MAX} \frac{dz}{dt} = P_{EFF}(t) - R_S(z,t) - R_{SS}(z,t) - R_B$$
$$- AET(PET,z,t) \qquad (1)$$

where S_{MAX} is the maximum soil moisture storage, z the relative soil moisture storage level, P_{EFF} the effective precipitation, R_S the surface runoff, R_{SS} the sub-surface runoff, R_B the baseflow, and PET and AET are potential and actual evapotranspiration, respectively. All values are in mm/day except S_{MAX} (mm) and z (taking values between 0 and 1). The inputs to the model are effective precipitation and a variety of climatic variables that enable PET to be calculated. The individual components of Eq. (1) are presented below

$$AET(PET,z,t) = PET(t)\frac{5z - 2z^2}{3} \qquad (2)$$

$$R_S = z^{\varepsilon}(P_{EFF} - R_B) \text{ for } P_{EFF} > R_B, \text{ else zero} \qquad (3)$$

$$R_{SS} = \alpha z^2 \qquad (4)$$

where ε is the surface runoff exponent and α the sub-surface runoff coefficient (mm/day). The total runoff in each period R_T (mm/day) is the sum of R_S, R_{SS} and R_B.
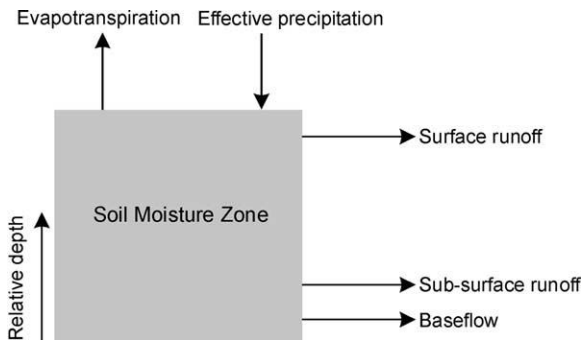

Fig. 2. Conceptual structure of the 'WatBal' hydrological model.

3.1.1. Potential evapotranspiration

To calculate AET, Eq. (2) requires a measure of the potential rate. The method chosen for this application is the Priestley – Taylor reference crop measure, which provides good estimates with lower data requirements than more complex techniques (Shuttleworth, 1993). It is given by

$$PET = \beta \frac{\Delta}{\Delta + \gamma}(R_n - G) \qquad (5)$$

where R_n is the net radiation exchange for the surface (mm/day), D the gradient of the saturated water vapour pressure curve and g the psychrometric constant (kPa/8C). These values may be calculated using mean monthly temperature, vapour pressure and cloud cover data. The coefficient b depends on the climate type and may be taken as 1.26 or 1.74 in humid or arid climates, respectively (Shuttleworth, 1993). For estimates over a reasonably large area the soil heat flux (G) is effectively zero and can be ignored (Yates, 1996).

3.1.2. Model solution and calibration

The complexity of the differential equation (Eq. (1)) necessitated a numerical solution and the Runge – Kutta method (Mathews, 1987) was found to be effective. Three parameters (a, 1 and S_{MAX}) require calibration to reproduce historic river flow patterns. Heuristic methods (Yates, 1996) and proprietary genetic algorithms (GAs) (Bowling and Strzepek, 1997) have been employed to calibrate various forms of the WatBal model. Here, a variation of the simple GA presented by Michaelwicz (1996) was chosen to maximise the correlation between observed and simulated flows.

3.2. Reservoir model

The reservoir model determines the energy production based on the applied operating rules and the incident inflow series. The routine operates iteratively to capture the inter-relationships between aspects of hydropower operation (e.g. hydraulic head or evaporation), and accounts for spillage and evaporation, which are both important when considering future climate effects. The routine, based on that used by the HEC-5 package (USACE, 1990), assesses the feasibility of meeting energy targets while taking account of the end storage levels and flow or energy limits. Production is simulated on a monthly basis, but the routine can use greater temporal detail where required, e.g. in deregulated markets where energy prices can vary hourly. In a similar manner to Simonovic and Srinivasan (1993), each month can be sub-divided such that sub-periods (e.g. an hour) represent the aggregated conditions during that period throughout the month. The rate of energy production is considered to be constant over each sub-period while inflow and evaporation rates are constant over the month.

3.3. Electricity market model

The electricity market model uses the energy production estimates from the reservoir model to determine revenue in each period. Using the monthly sub-division used in the reservoir component, the model can simulate a variety of different market systems. This is achieved by specifying the type of purchase contract for the station's output that details the electricity sales price for given sub-periods. A possible limitation on model validity is the simplifying assumption that the electricity network absorbs all energy produced, but the authors do not consider this to be a major impediment for preliminary investigations.

3.4. Financial model

This component provides measures of the financial performance of the project based on the revenue earned together with user-entered data such as project costs, inflation and interest rates and the financing structure. The financial analysis routines are based on standard economic appraisal methods (e.g. Au and Au, 1983 and others), and determine a range of measures that include net present value (NPV), internal rate of return (IRR), discounted payback, and unit energy cost.
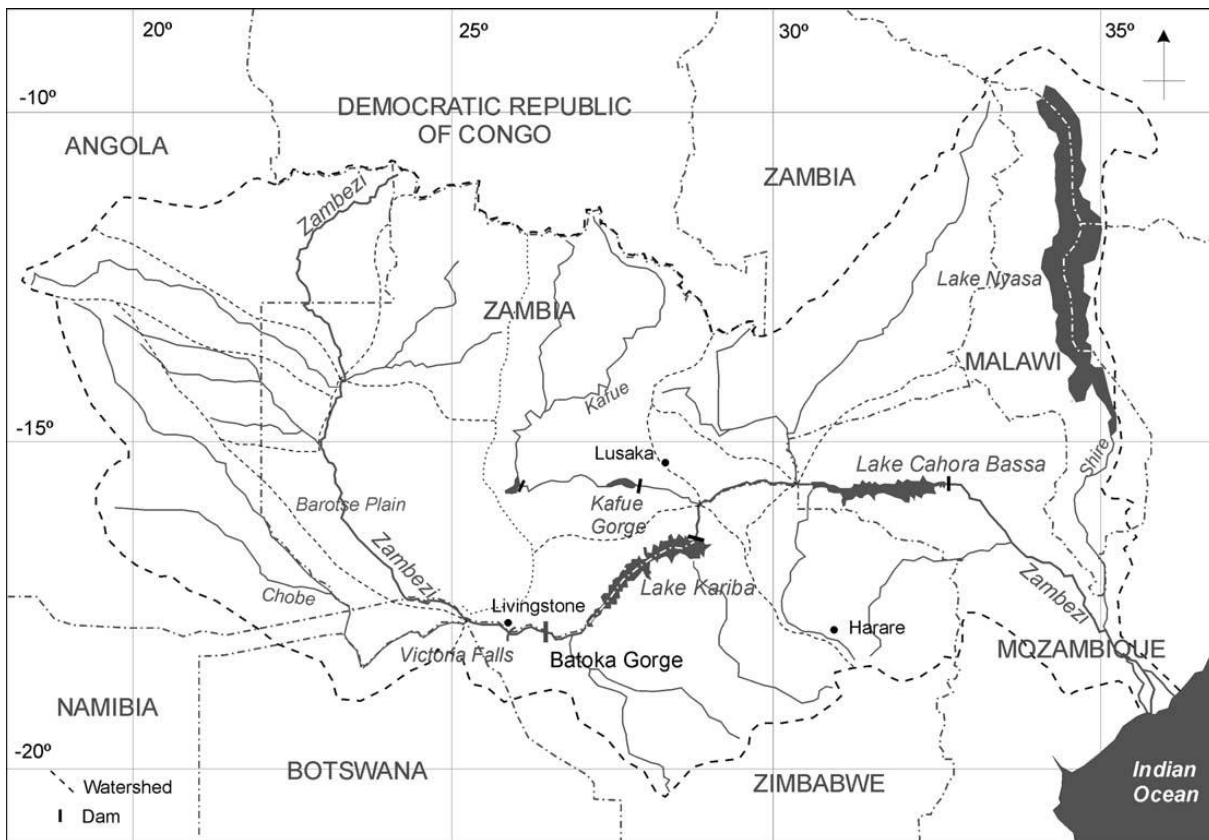

Fig. 3. The Zambezi River Basin and the location of the proposed Batoka Gorge scheme.

4. Batoka Gorge hydroelectric scheme

4.1. Background

The Zambezi River is the fourth longest in Africa, drains an area of over 1,350,000 km^2 and is shared by eight nations (Fig. 3). The basin has a tropical climate with annual rainfall ranging from 1400 mm in the north to 700 mm in the south (Salewicz, 1996). The basin, particularly the upper section above Victoria Falls, is very complex hydrologically due to the intermittent streams and the influence of the Barotse Plain and Chobe swamps (Balek, 1977). The seasonal swamp systems play a major role in regulating floodwaters and act to trap sediment and allow significant evaporative loss (Reibsame et al., 1995). Despite this, flow over Victoria Falls averages 1237 m^3/s and with the contribution of numerous tributaries rises to 3500 m^3/s at the delta (Masundire and Matiza, 1993).

Such large river flow provides the Zambezi with significant hydroelectric potential, most of which is situated downstream from Victoria Falls. Facilities currently in operation are the 108 MW run-of-river (RoR) scheme at the Falls, the 1266 MW Kariba Dam and the 2075 MW Cahora Bassa. Together with the schemes on tributary rivers, total installed capacity in the Basin is 4684 MW producing approximately 33,000 GWh/year. The section of the river between the Falls and Cahora Bassa is also the focus for several new-build schemes which include the 1600 MW Batoka Gorge project. Overall, the new-build schemes and upgrades of existing facilities could create an extra 13,000 MW of capacity (Tapfuma, 1993).

The Batoka Gorge project was chosen for initial testing and validation of the software and techniques. It is planned for the Zambezi River upstream of Lake Kariba on the Zambia – Zimbabwe border (Fig. 3). The 1993 feasibility study (BJVC, 1993) proposed a 181 m gravity arch dam with 1680 Mm^3 of storage. The relatively small storage (compared to Lake Kariba) means that the plant is intended to operate as a RoR allowing more effective use of the storage in Lake Kariba and maximising firm power delivery on a system level. Annual energy production is expected to be approximately 9100 GWh.

The lack of a major impoundment in the upper basin makes Batoka Gorge a good candidate for climate impact assessment. Despite this, most investigations into future water resources on the Zambezi have focussed on Kariba (Salewicz, 1996), due to its central role in regional electricity production. Reibsame et al. (1995) featured the Batoka scheme in addition to Kariba. With Kariba situated downstream and Batoka operated as RoR, Kariba has limited influence on the operation of Batoka. Therefore, as in this study, it is reasonable to consider Batoka in isolation without consideration of conjunctive operation with Kariba. In any event, before using the model in a climate impact study it was important to ensure that its performance under current climate was acceptable.

4.2. Climate data

The hydrological model requires a series of monthly values of climatic variables that represent the basin upstream of the Victoria Falls. These were extracted from the global time-series dataset developed by New et al. (2000) and available from the Climatic Research Unit at the University of East Anglia. The data provides coverage for the Earth on a 0.5⁸ latitude/longitude grid for the years 1901– 1996. In this case, precipitation and other data necessary to calculate the Priestley – Taylor PET was used for the period from 1961 to 1990. With the software, in its present form, requiring that the basin be modelled as a single catchment, each variable was spatially aggregated to provide a single average value for the upper Zambezi Basin. Comparisons with other sources (BJVC, 1993; Reibsame et al., 1995) indicated that there was good agreement.

4.3. Hydrological model calibration

The hydrological model was calibrated using historic river flow data measured at Victoria Falls, which provided sufficient data for split sample testing (using 15 years each for calibration and validation periods). Following the practice of Yates (1996) and others the baseflow value was set to the 95% exceedance flow, calculated to be 0.04 mm/day.

This resulted in a high correlation between observed and simulated river flows ($R^2 \sim 0.80$) and a good representation of low flows. However, the values of flood flow were unacceptably low and manual adjustment was necessary to improve the accuracy of seasonal variation. The resulting parameters were $\alpha = 2.5$, $\varepsilon = 3.5$ and $S_{MAX} = 40$ mm. Although the correlation measure was significantly reduced (Table 1), there was an improved volumetric and visual fit. Although unfortunate, previous research has stressed the importance of seasonal representation over mathematical fit (Arnell, 1996; Bowling and Strzepek, 1997).

The comparison between simulated and observed mean monthly flows is shown in Fig. 4. The closeness of the fit during low flows can be seen, along with poorer representation of high flows where peak flows are lower in volume and earlier in timing. Yates (1997) noted similar difficulties in modelling the Zambezi. This may be due to the fact that it is difficult for a lumped parameter model with relatively few parameters to simulate significant seasonal variation in flow, particularly given the large area of the upper Zambezi Basin. An alternative explanation is the omission, from the model, of the significant seasonal storage provided by the Barotse and Chobe seasonal swamps. The temporary storage of early

high flows in the swamps would tend to reduce flows in January and February and concentrate the flood in April and May. This, to some extent, explains the discrepancy.
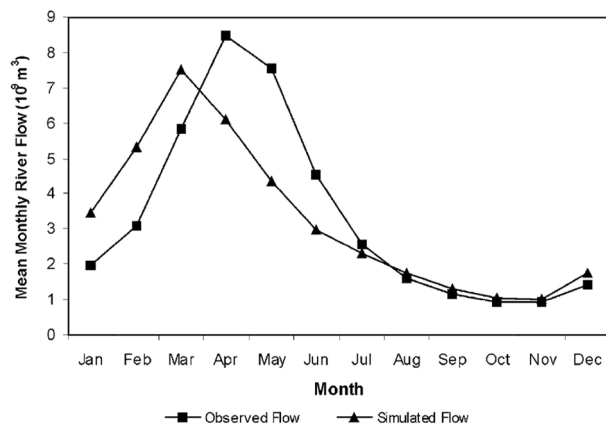

Fig. 4. Comparison of monthly observed and simulated flows.

Table 1
Model performance over calibration and validation periods

	Calibration period (1961–1975)	Validation period (1976–1990)
Correlation coefficient (R^2)	0.61	0.49
Mean absolute error (mm/month)	1.00	0.98

Table 2
Comparison of runoff elasticity

Study	Elasticity	
	Precipitation	Temperature (°C)
Calculated values	2.02	-0.42
Reibsame et al. (1995)	1.88	-1.68

Table 3
Climate change scenarios for the 2080s (relative to 1961–1990 mean)

	HadCM2	HadCM2-S	ECHAM4
Precipitation change (%)	-12.5	-17.6	-1.6
Temperature change (°C)	+5.3	+4.4	+5.0

A further issue surrounds the combination of model parameters that were deemed optimal. Yates (1996) warns that different parameter sets can produce similar flow patterns, e.g. large values of S_{MAX} and α or smaller values of both. While this might not be a problem at the calibration level, it can result in very different climate sensitivity, particularly with smaller

soil storage values tending to overestimate sensitivity. A comparison was made with Reibsame et al. (1995), to test this possibility. The 'elasticity' measure, applied to climate studies by Schaake (1990), provides a convenient measure of sensitivity and is used by Reibsame et al. (1995) to compare several river basins including the Zambezi. Elasticity, in this sense, is defined as the ratio of percentage change in runoff to percentage change in a climate variable (with sensitivity implied by a magnitude greater than 1). To calculate these ratios, uniform changes were made to precipitation levels (±10%) and temperatures (±2°C).

Table 2 compares the results with the values from Reibsame et al. (1995). The precipitation elasticity measures are quite close (within 7%), although the value calculated here is higher. The temperature elasticity measure is very low by comparison and suggests that the catchment is insensitive to changes in temperature. The relative insensitivity could reflect the failure to account for the major evaporative losses from the seasonal swamps or differences between the PET methods used. In this case, the PET sensitivity is limited to 1.4%/°C, which is lower than the 3 – 4%/°C values suggested by Budyko (1982) and others. However, as Reibsame et al. (1995) do not specify their method, it is difficult to comment further other than to say that major over-estimation of sensitivity is unlikely, given the apparent insensitivity to temperature change.

4.4. Overall model performance

Additional information was necessary for simulating the operation and financial performance of the Batoka scheme and much of it was extracted from the feasibility study. The reservoir model required data ranging from turbine capacities to monthly energy targets. With no information regarding the energy targets, it was decided to follow the approach of Reibsame et al. (1995) and set equal monthly energy targets of 757 GWh. With only limited reservoir storage and the planned RoR operation, it was considered likely that alternative strategies would not deliver significant differences in production and hence would not have a major impact on the scheme's climate vulnerability. With the scheme intended to mainly supply the Zimbabwean state-owned electricity system, the feasibility study assumed that power would be purchased at $30/MWh (in real 1993 US$), and hence the software's sub-period system would not be required. Capital and variable costs, discount rates, and other financially relevant data were also found in the feasibility study.

The feasibility study data (BJVC, 1993) also provided a benchmark by which the overall model performance could be gauged. Although power production is over-estimated by around 3%, the seasonal variation follows river flows well (i.e. acting as RoR). However, the scheme's financial performance is slightly underestimated, with the IRR

within a half a percentage-point, NPV within 20% and the unit cost within 4%.

The authors accept that, in its present form, the hydrological model fails, adequately, to represent the complex hydrology of the upper Zambezi, and that this precludes reliance on the results of climate studies as a reasonable indicator of future conditions. It is anticipated that better performance could be gained by the use of sub-catchments as well as by explicitly accounting for the swamps. However, given the preliminary nature of this work, the model was regarded as acceptable for use in illustrating a climate change analysis of the performance of the Batoka Gorge project.

5. Climate change impacts on Batoka Gorge

5.1. General circulation model (GCM) data

Three climate change scenarios (all available from the IPCC Data Distribution Centre) were used in this study. Two are from the results of the HadCM2 GCM developed by the Hadley Centre at the UK Meteorological Office (Mitchell et al., 1995). They differ in that one, HadCM2-S, incorporates the effects of aerosols that have the tendency to cool the atmosphere. The third scenario is from the ECHAM4 GCM developed by the Max Planck Institute fur Meteorologie (Roeckner et al., 1996). All sets of data represent conditions projected for the 2080s and consist of the changes in precipitation and temperature relative to the results of control runs that represent current conditions. The data was spatially averaged for the upper basin, and the projected changes are shown in Table 3.

The operation of the Batoka Gorge scheme was examined over the 30 years between 1961 and 1990 for climate conditions predicted by the three GCM scenarios. The results are presented in the following sections and summarised in Section 5.5.

5.2. Projected hydrological conditions

All three scenarios imply decreases in annual rainfall relative to the 1960 – 1991 mean, ranging from 1.6% for ECHAM4 to 17.6% for the aerosol-inclusive HadCM2-S. Significant changes in seasonal rainfall occur for all scenarios with both HadCM2 and HadCM2-S scenarios suggesting greater falls during the wet season (defined here as January – July) of 15 and 19.2%, respectively. ECHAM4 projects a greater decrease in the dry season (August – December). Temperature is projected to rise by up to 5.3 °C although the inclusion of aerosols is seen to result in a lower rise (as indicated by HadCM2-S). Seasonal temperature increases are fairly constant through-out the year for all scenarios although HadCM2 implies slightly greater wet season warming.

Simulations indicate that for all scenarios annual flow levels at Victoria Falls reduce between 10 and 35.5%. In each case the resultant flow change is

greater than the precipitation change, confirming the amplifying effect of the hydrology. The resulting river flows are shown in Fig. 5 (with changes summarised in Section 5.5). As Table 4 shows, ECHAM4 produces the least change although, in line with the rainfall change, the reduction is greater in the dry season (12.1%). HadCM2-S shows the greatest reductions all round but with a slightly greater decrease in wet season flows (36.1%).
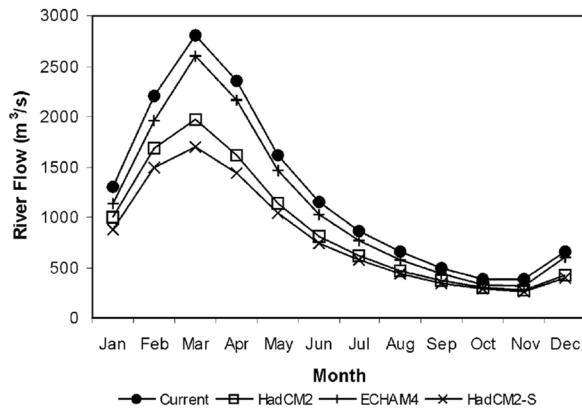

Fig. 5. Monthly mean river flows under current and GCM scenarios.

Table 4
Seasonal changes in runoff under GCM scenarios

GCM scenario	Runoff change (%)		
	Annual	Wet season (Jan–July)	Dry season (Aug–Dec)
ECHAM4	-10.0	-9.5	-12.1
HadCM2	-28.3	-28.2	-28.9
HadCM2-S	-35.5	-36.1	-32.6

5.3. Electricity production at Batoka Gorge

The GCM scenarios indicate sizeable reductions in annual electricity production between 6.1 and 21.4% (see Section 5.5). The changes are less severe than the river flow changes which suggests that the station is, to some extent, able to maintain production levels despite reductions in flow.

Under current climatic conditions a significant fraction of annual flows are spilled from the reservoir during the wet season. As Table 5 shows, both the volume and the incidence of spillage reduce under conditions of climate change by two-thirds and a half, respectively. In fact, they reduce to a greater extent than both energy production and (by association) station load factor.

These factors are reflected in the change in seasonal production. For each scenario, dry season production declines by up to twice as much as the annual decrease, with smaller reductions in wet season generation. This

can be seen in Fig. 6 which shows the percentage of maximum energy production achieved, on average, each month. For example, under the HadCM2-S climate scenario, dry season and wet season production decrease by 32 and 18%, respectively. The changes in dry season production have implications for system firm energy levels as, under the same conditions, the mean minimum monthly output falls by 30% to 307 MW.

Declining production has a direct and adverse effect on the revenue stream, with mean monthly sales falling from $16.9 million to between $13.1 and $15.9 million (in 1993 US$, see Section 5.5). Other than altering mean values, the climate-change scenarios result in more variation in production levels and consequently the revenue stream also becomes more variable. With the normalised standard deviation for revenue rising by between 10 and 27%, this may indicate potential for short-term cash flow problems.
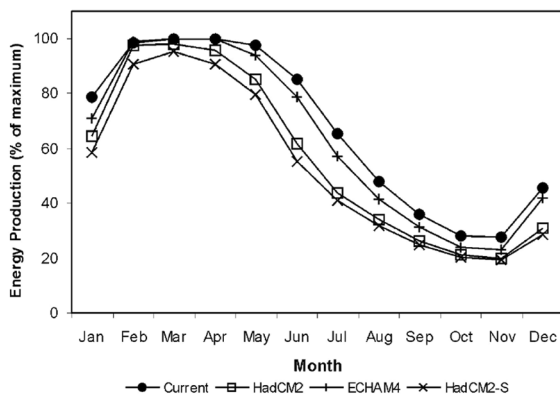

Fig. 6. Monthly mean energy production under current and GCM scenarios.

5.4. Financial viability of scheme

Reductions in electricity sales of the magnitude suggested in the preceding section have a major impact on the financial viability of the scheme. The impact on NPV is significant, as Fig. 7 shows. Here, the scenarios reduce NPV from $98 million by between $60.8 million and $214.8 million, with both Hadley scenarios indicating negative values. IRR also falls, from 11% to between 8.65 and 10.35%, while unit costs rise from US¢1.52/kWh to US¢1.62 – 1.92/ kWh (again the changes may be found in Section 5.5).

The rules of investment appraisal state that a scheme will be considered viable if the NPV is positive at the chosen discount rate (here, 10% in real terms). Under the ECHAM4 scenario the NPV remains positive and would still be considered as a viable investment. However, both Hadley scenarios lead to negative NPV implying that the scheme would be regarded as non-viable and, on the basis of financial performance alone, would not proceed.

5.5. Results summary

The results of 30-year long simulations using the three climate scenarios are summarised in Table 6, together with the simulation of current climate for comparison. Overall, the climate change scenarios examined here result in river flows, production and financial performance that are significantly different than that from historic climate conditions. Such climate changes would adversely affect the performance of the Batoka Gorge scheme, both in terms of its productive capability and its financial return.

With the prospect of climate change it is no longer prudent for decision-makers to rely on historic river flow data when considering potential hydroelectric schemes. The results of this and similar studies could and, perhaps should, be used by decision-makers to determine the future of hydroelectric schemes. However, the climate change scenarios used in this study are only a few of the multitude of scenarios that suggest temperature changes in the range suggested by the IPCC, and importantly, the full range of scenarios includes many that project increased precipitation. Given this, it will be difficult to determine the most likely scenario of change. Although a weighted average across many scenarios could provide a single value for expected economic return, at present it is not possible to do this objectively, as the probability of any given climate change scenario is very uncertain. However, as investment decision-making often relies on subjective estimates, this does not explicitly rule out the use of climate scenarios for this purpose.
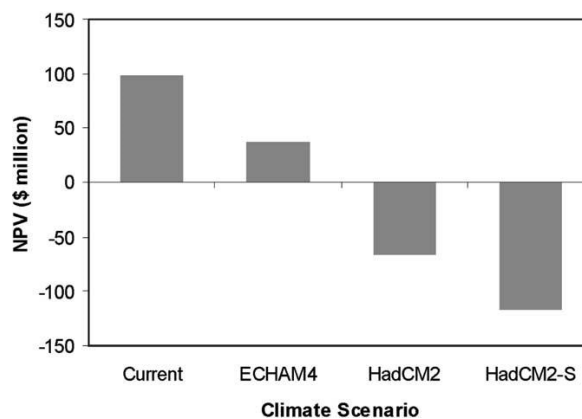

Fig. 7. Project NPV with current and GCM scenarios for the 2080s

Table 5
Hydroelectric station performance measures for GCM scenarios

Measure	Current 1960–1991	HadCM2 2080s	HadCM2-S 2080s	ECHAM4 2080s
Target production met (%)	103.1	86.1	81.0	99.8
Station load factor (%)	66.8	55.8	52.5	62.7
Spill incidence (% of months)	37.0	24.0	18.0	32.0
Spill volume (% of inflow)	28.2	14.5	9.2	24.6

Table 6
Summary of climate impacts for GCM scenarios

Measure	Current 1960–1991	HadCM2 2080s	HadCM2-S 2080s	ECHAM4 2080s
Mean monthly precipitation (mm)	74.60	65.40	61.41	73.48
Mean monthly temperature (8C)	21.90	27.30	26.33	26.96
Mean monthly river flow (£ 10^9 m^3)	3.21	2.31	2.07	2.89
Mean monthly production (GWh)	780.30	652.30	613.38	732.59
Mean monthly sales (in 1993 US$M)	16.90	13.90	13.10	15.87
NPV[a] ($M at 10%)	98.00	266.00	2116.73	37.23
IRR (%)	11.00	9.25	8.65	10.35
Unit cost[a] (US¢/kWh)	1.52	1.80	1.92	1.62

[a] 10% discount rate applied.

6. Conclusions

The continuing and increased use of renewable energy sources, including hydropower, is a key strategy to limit the extent of future climate change. However, the trend towards deregulation in the electricity industry will involve increasing amounts of private investment which may not favour hydropower projects. More importantly, the very fact that climate is changing may alter the availability of this natural resource. The impact of such changes in terms of their effect on the financial viability of schemes will be of particular interest to investors.

To quantify the relationship between changing climate and scheme financial viability, a model was developed. Based on the traditional hydro appraisal process, the technique avoids the reliance on historic river flow patterns by linking climatic variables with river flows through the use of a hydrological model.

The use and performance of the prototype software was examined through the use of the planned Batoka Gorge scheme as a case study. The model was found to perform well, given the inherent difficulties in the task, although there is concern regarding the ability of the hydrological model to reproduce the historic flow conditions of the upper Zambezi Basin. Simulations with GCM scenarios depicting current and potential future climates were compared and illustrate the sensitivity of the case study scheme to changes in climate. Under the future climatic conditions examined there would be significant reductions in river flows, declining power production, reductions in electricity sales revenue and consequently an adverse impact on a range of investment measures; indeed, in several cases the scheme would be non-economic.

While the authors do not claim that their analysis, in its current form, presents an exact prediction of future conditions, they believe that the results of this study indicate a potentially serious issue for hydroelectric projects. Further, they believe that a refined version of the methodology should be applied in other regions of the world, since hydroelectric exploitation and climate change are both global issues.

Acknowledgments

References

Arnell, N., 1996. Global Warming, River Flows and Water Resources, Wiley, Chichester.

Arthur, J., 1999. Private communication.

Au, T., Au, T.P., 1983. Engineering Economics for Capital Investment Analysis, Allyn and Bacon, Boston.

Balek, J., 1977. Hydrology and Water Resources in Tropical Africa, Elsevier, Amsterdam.

Batoka Joint Venture Consultants (BJVC), 1993. Batoka Gorge hydroelectric scheme feasibility study final report. Zambezi River Authority, Lusaka, Zambia.

Bowling, O.P., Strzepek, K.M., 1997. Examining the impacts of land-use change on hydrologic resources. Interim Report 97-31. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Budyko, M.I., 1982. The Earth's Climate: Past and Future, Academic Press, New York.

Harrison, G.P., Whittington, H.W., 2001. Impact of climatic change on hydropower investment. In: Proceedings of the Fourth International Conference, Hydropower '01, Bergen, Norway. A.A. Balkema, Rotterdam, pp. 257–261.

Intergovernmental Panel on Climate Change (IPCC), 2001. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Xiaosu, D. (Eds.), Climate Change 2001: The Scientific Basis, Cambridge University Press, Cambridge, 944 pp.

Masundire, H.M., Matiza, T., 1995. Some environmental aspects of developments in the Zambezi Basin ecosystem. In: Matiza, T., Crafter, S., Dale, P. (Eds.), Water Resources Use in the Zambezi Basin. Proceedings of a Workshop Held at Kasane, Botswana, 28 April–2 May 1993. The World Conservation Union (IUCN).

Mathews, J.H., 1987. Numerical Methods for Computer Science, Engineering, and Mathematics, Prentice-Hall, Englewood Cliffs, NJ, pp. 395–444.

Michaelwicz, Z., 1996. Genetic algorithms þ data structures ¼ evolution programs, Springer, London.

Mitchell, J.F.B., Johns, T.C., Gregory, J.M., Tett, S., 1995. Climate response to increasing levels of greenhouse gases and sulphate aerosols. Nature 376, 501–550.

Nakicenovic, N., Grubler, A., McDonald, A. (Eds.), 1998. Global Energy Perspectives, Cambridge University Press, Cambridge.

New, M.G., Hulme, M., Jones, P.D., 2000. Representing twentieth century space-time climate variability. II. Development of 1901 – 1996 monthly grids of terrestrial surface climate. J. Climate 13, 2217–2238.

Reibsame, W.E., Strzepek, K.M., Wescoat, J.L. Jr., Perritt, R., Gaile, G.L., Jacobs, J., Leichenko, R., Magadza, C., Phien, H., Urbiztondo, B.J., Restrepo, P., Rose, W.R., Saleh, M., Ti, L.H., Tucci, C., Yates, D., 1995. Complex river basins. In: Strzepek, K.M., Smith, J.B. (Eds.), As Climate Changes: International Impacts and Implications, Cambridge University Press, Cambridge, pp. 57– 91.

Roeckner, E., Arpe, K., Bengtsson, L., Christophe, M., Claussen, M., Dumenil, L., Esch, M., Giorgetta, M., Schlese, U., Schulzweida, U., 1996. The atmospheric general circulation model ECHAM4: model description and simulation of present day climate. Report No. 218. Max Planck Institute for Meteorology, Hamburg, Germany, 90 pp.

Salewicz, K.A., 1996. Impact of climate change on the Lake Kariba hydropower scheme. In: Kaczmarek, Z., Strzepek, K.M., Somlyody, L., Priazhinskaya, V. (Eds.), Water Resources Management in the Face of Climatic/Hydrologic Uncertainties, Kluwer Academic Publishers, Rotterdam, pp. 300–321.

Schaake, J.C., 1990. From climate to flow. In: Waggoner, P.E., (Ed.), Climate Change and US Water Resources, Wiley, New York, pp. 177–206.

Shuttleworth, W.J., 1993. Evaporation. In: Maidment, D.R., (Ed.), Handbook of Hydrology, McGraw-Hill, London, pp. 4.1–4.53.

Simonovic, S.P., Srinivasan, R., 1993. Explicit stochastic approach for planning the operation of reservoirs for hydropower production. In: Kundzewicz, Z.W., Rosbjerg, D., Simonovic, S.P., Takeuchi, K. (Eds.), Extreme Hydro-logical Events: Precipitation, Floods and Droughts, IAHS Press, Wallingford. pp. 349 – 359.

Tapfuma, V., 1995. The Batoka Gorge Hydroelectric Project: design and potential environmental impacts. In: Matiza, T., Crafter, S., Dale, P. (Eds.), Water Resources Use in the Zambezi Basin. Proceedings of a Workshop Held at Kasane, Botswana, 28 April– 2 May 1993, pp. 57–68. The World Conservation Union (IUCN).

United Nations Framework Convention on Climate Change (UNFCCC), 1998. Kyoto Protocol to the United Nations Framework Convention on Climate Change, UNFCCC, Bonn, Germany.

US Army Corps of Engineers (USACE), 1990. HEC-5 Simulation of Flood Control and Conservation Systems, Users Manual, Hydrologic Engineering Center, Davis, USA.

Yates, D.N., 1996. WatBal: an integrated water balance model for climate impact assessment of river basin runoff. Water Res. Dev. (2), 121–139.

Yates, D.N., 1997. Approaches to continental scale runoff for integrated assessment models. J. Hydrol. 201, 289–310.