SENSITIVITY OF HYDROPOWER PERFORMANCE TO CLIMATE CHANGE

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Abstract: One solution to reduce the extent of climate change is to replace fossil-fuelled electricity generation with renewable sources including hydropower. However, simultaneous changes in climate may alter the available hydropower resource, threatening the financial viability of schemes. To illustrate the potential problem, a sensitivity analysis is presented that considers the impact of altered precipitation and temperature on river flows, energy production and financial performance measures of a planned hydro scheme in Sub-Saharan Africa. The behaviour of the river basin was found to amplify changes in precipitation and, while the design and planned operational strategy of the station tended to moderate the impact, the overall financial impact remained significant. Comparison with (non-climate) project parameters indicated that financial performance, not surprisingly, depends strongly on discount rate and electricity sales price and that, importantly, it showed a similar sensitivity to precipitation change and rising temperature. Critical changes in climate were identified in order to indicate the severity of climate change that could be tolerated before the project becomes financially non-viable.

Key Words

Hydroelectric power generation, Climatic changes, Sensitivity analysis, River flow, Investments

1. Introduction

When environmental pressures are added to likely increases in fossil-fuel prices, increased electricity generation from renewable sources, including hydropower, appears to be attractive. Accordingly, global hydropower production, which at present meets around one-fifth of global demand, is anticipated to increase by three times by 2100 [1]. Despite this, new hydroelectric development will occur in a troubled environment. Firstly, the increasing involvement of private capital, resulting from electricity supply liberalisation, might work against hydropower. This is likely, as private investment generally prefers lower capital-cost, shorter payback options and expects higher investment returns than the public sector. Secondly, while precipitation is anticipated to increase on a global level, many parts of the world are anticipated to see significant drying [2]. A wide range of studies have found that river flows (e.g. [3], [4]) and consequently hydropower production (e.g. [5], [6]) are sensitive to changes in precipitation and temperature. Declining hydroelectric production potential will be detrimental to the economic viability of schemes, reducing financial returns, raising unit prices and, ultimately, making investment in hydropower less likely [7].

Harrison and Whittington [8] extended the scope of water resource related climate impact studies by examining the impact of General Circulation Model (GCM) -derived climate change scenarios on the financial performance of a proposed hydro scheme. In common with other scenario analyses, the analysis was limited in that it provided information from a limited range of possibilities only. Furthermore, the process of translating GCM scenarios into a form suitable for hydrological studies is complex and time consuming and, therefore, could be considered as excessive for preliminary investigations. The present study removes these limitations by analysing the sensitivity of station revenue streams and financial performance to changes in precipitation and temperature in a manner that is akin to standard sensitivity studies as used in capital investment analysis.

2. Case Study Scheme

The scheme modelled is the 1600 MW Batoka Gorge project proposed for the Zambezi River, upstream of Lake Kariba on the Zambia-Zimbabwe border (Fig. 1). The 1993 feasibility study [9] proposed a gravity arch dam with the scheme to operate as run-of-river and produce in the region of 9,100 GWh per year. The scheme was modelled using software developed by Harrison and Whittington [8], which consists of a series of serially-connected components (hydrological, reservoir, market and financial models) that allow the projection of river flow, energy production and financial performance based on scenarios of climate (Fig. 2). Key aspects of the software are briefly described below with more detail available in [8].

The model is driven by monthly climatic data covering the period from 1961 to 1990 extracted from the global time-series dataset developed by New et al. [10] and spatially averaged for the area of the river basin above Victoria Falls. The resulting monthly precipitation and potential evapotranspiration are shown in Fig. 3, along with the monthly discharge over the Falls.

The hydrological model employed is a simple lumped parameter model based on that of Yates [11]. Following calibration, the model was found to reproduce seasonal low flows well but its performance with high flows was poor. These tended to be low and early and were attributed to the simple nature of the model and the lack of explicit modelling of the seasonal swamp systems that heavily influence river flows in the Zambezi [8].

The reservoir model operates in a similar manner to the industry standard HEC-5 [12] by attempting to meet monthly energy production targets whilst ensuring that flow, energy and storage restrictions are met. Evaporation and spillage are accounted for and all electricity production attracts a specified sales price.

Overall, it was found that the software model provided a satisfactory simulation of the Batoka scheme for the purposes of preliminary study and in illustrating the analytical concept [8].

3. Sensitivity Analysis

Sensitivity analysis is a key component of project appraisal. As future values for project parameters are difficult to predict, there will always be a degree of uncertainty surrounding the expected project results. In order to identify critical variables, project parameters (e.g. construction cost) are varied and their impact on project returns and the investment decision is examined. Here, sensitivity analysis has been extended to include climatic variables.

The Batoka scheme's climate sensitivity was assessed by altering historic precipitation and temperature levels by similar amounts to those indicated by GCMs. The changes in precipitation ranged from +20% to –20% and temperature is raised by up to 4°C. The changes are applied equally in all months across each year in the analysis. The authors accept that this approach does not represent the state-of-the-art, however, they believe that its use is justified for preliminary studies and as an indictor for more detailed study as it is inherently simple, rapid and allows many more scenarios to be examined.

Standard sensitivity analysis assumes that the variables being altered are independent of each other. With climate change, temperature and precipitation cannot be considered to be independent (particularly at the temporal and spatial scales used in this study) as the rise in temperature leads to the change in precipitation. Therefore, instances with changes in only one of the two variables may not be credible scenarios. For completeness, however, the study includes such scenarios, although it should be noted that some combinations of temperature and precipitation may not be feasible. The most extreme conditions considered here are temperature increases of 4°C together with changes in precipitation of +20% or –20%. To avoid repetition, these combinations are referred to as 'wet' and 'dry' conditions, respectively. Except where indicated explicitly, all other project parameters remained unaltered. The results are presented in the following sections and summarised in Section 3.5.

3.1 Hydrological Sensitivity

Fig. 4 shows the predicted change in annual runoff from the Upper Zambezi as temperature and precipitation levels are altered over the range described above. The results are in agreement with the conclusions drawn by Arnell [13], that firstly, runoff changes tend to be greater than the precipitation change causing them and, secondly, that runoff is more sensitive to changes in precipitation than changes in temperature. As would be expected, runoff is related positively to precipitation change and negatively to temperature and, furthermore, runoff is relatively more sensitive to precipitation increases (as indicated by the closer proximity of the contours in the right of Fig. 4). The scale of the amplification of changes in precipitation is significant: for example, a 20% increase in rainfall raises annual runoff by just over 46%. In contrast, changes in runoff due to temperature change are limited to 2% per °C change. The combined effect of a 20% increase in precipitation together with a 4°C rise in temperature (i.e. wet conditions) is to increase river flows by just over 35%, while dry conditions deliver a 39% decrease.

As Fig. 5 shows, the annual figures mask differences between changes in high flows (January-July) and low flows (August-December). For example, under wet conditions there is an almost 40% rise in high flows but only a 16% rise in low flows. The greater increase in wet season flows is caused by the inability of already wet soils to absorb more water. The changes for the extreme conditions are summarised in Table 1.

Changing precipitation levels (and, to a lesser extent, temperature) tend to alter the variance of river flows in addition to altering the mean flows [13]. The results are in agreement with this, with the standard deviation of monthly flows changing proportionately more than mean flows. Under wet conditions, the variability of monthly flows, as measured by the coefficient of variation (CV), rises by almost 13%. For the opposite change in precipitation, CV decreases by 11%.

Overall, the results of simulations indicate that river flows are sensitive to changes in climate and in particular to precipitation change, with several effects apparent, ranging from changes in the seasonal balance of flows to changes in flow variability.

3.2 Energy Production Sensitivity

Energy production is constrained by the capacity of the turbines as well as the available storage. Turbine capacity restricts the station's ability to take advantage of increased flows and can result in the spillage of significant portions of the increase. With a limited capability to carry over water to later periods, production is more sensitive to reduced flows in responding to precipitation changes and temperature rise (as indicated by the contour separation in Fig. 6). Precipitation changes of +20% and –20% lead to respective annual production changes of +14% and –20%. Temperature changes appear to be much less important, altering output by just over 1% per °C change (half that in runoff). Wet conditions produce a 10% increase in production, while dry conditions lead to a 25% decrease in production

The performance of the station can be gauged not only by the quantity of energy that is produced but also by the success of the operating rules in making best use of the available resource and capital. The volume and incidence of spillage provides a good proxy for the resource use while the station load factor provides an indication of the use of capital. These measures are given in Table 2. They show that under wet conditions, there is a significant rise in the incidence and quantity of spillage and an increase in station load factor. There are opposite and proportionately greater changes under dry conditions.

Such changes in performance are related to the seasonal changes in production, shown in Fig. 7. Although volumetrically greater changes in output occur during the high flow period, changing climate impacts proportionately more on low flows. Under wet conditions, production is raised by 7% and 18% for high and low flow periods, respectively, while dry conditions see output decrease by 23% and 30% on the same basis.

Fig. 7 also shows significant changes in the minimum production level, an important consideration in determining whether the electricity system is capable of meeting demand. The mean minimum monthly production level is a reasonably proxy for the firm power level of the plant, and under dry conditions this declines from 440 MW to 323 MW (a 27% change).

The variability of production is also altered by the changes in flows. With the upper limit on production fixed by turbine capacity, the increased production resulting from increased flow during the low flow period reduces the range of production values and consequently the standard deviation. Under wet conditions the proportionately larger increase in mean production lowers CV by 11%. Dry conditions see the opposite effect with CV increasing by 23%.

Overall, energy production was found to be sensitive to changes in precipitation with seasonal production and production variability related proportionally to the precipitation level. Such changes imply a major impact on the scheme's financial performance.

3.3 Revenue and Financial Sensitivity

In the present study, a flat rate (US$30/MWh, in real 1993 $US) is paid for all station output, which reflects the less developed nature of the Zimbabwean electricity market in which the station is assumed to operate [9]. In these circumstances, changes in income directly follow the pattern of production and the changes affect financial performance similarly. Fig. 8 shows the forecast variation of net present value (NPV) with changes in precipitation and temperature. It shows a positive relationship with precipitation and a negative, albeit less pronounced, one with temperature. Once again, the contour separation in Fig. 8 indicates the greater vulnerability to reduced precipitation. Accumulated changes in annual revenue means that NPV is very sensitive to changes in rainfall: NPV is reduced by over 250% under dry conditions, while it doubles under wet conditions.

Other financial measures reflect the changes in NPV, albeit with smaller percentage changes. Under wet conditions, internal rate of return (IRR) increases from 11% to almost 12%, while the discounted payback period (at 10% discount rate) reduces by just over 19%. With dry conditions, IRR falls to 8.25% and discounted payback extends to over thirty years, beyond the assumed project lifetime. Production costs, which are 1.52 ¢/kWh under current conditions (again at a 10% discount rate), are lowered to 1.39 ¢/kWh or raised to 2.01 ¢/kWh under wet and dry conditions, respectively.

The present analytical technique is useful in identifying the severity of climate change required to render the project economically non-viable. Investment appraisal rules state that a project should only be accepted if it returns a positive NPV at the discount rate used (normally the investor's minimum acceptable rate of return). Here, a 10% real discount rate is used and the non-viability of the project can be identified where NPV is negative or where NPV falls by at least 100%. One of the contours in Fig. 8 represents the combinations of precipitation and temperature changes that lead to a 100% drop in project value. Hence, all combinations to the left of this line render the project non-economic, whilst those to the right are acceptable. With no temperature rise, the project would remain viable with uniform decreases in precipitation of just over 11%. However, as temperature rises the tolerable reduction falls such that, for a temperature rise of 4°C, a decrease of just over 6% is required to remove profitability. For this geographic region, some GCMs project reductions in precipitation and temperature rise in excess of the critical combinations identified here. Accordingly, they have been found to lead to the project becoming economically non-viable [8].

3.4 Climate Sensitivity in Context

In order to set the climate change results in context, the impact of changes in risk factors that are traditionally known to affect hydroelectric projects were examined. This allowed a comparison of the sensitivity of the project to climate change relative to other project parameters. Evidence [14] indicates that large engineering projects, particularly those involving dams, are prone to cost and schedule over-runs. In addition to extending the period where there is no revenue associated with project, in the intervening period the price of electricity may change or, indeed, the generating station may default on an electricity supply contract. The following key project parameters were selected for testing: civil engineering costs, on the basis that they represent the main capital cost, with inaccurate estimation having a significant impact on project returns; build period, which impacts on the amount of loan interest capitalised; and electricity sales prices. The effect of varying discount rate is also considered as it is critical to project worth. Each parameter was altered, in turn, by ±20% of its original value and the simulation re-run under historic climate conditions.

The NPV results from these simulations are shown in Fig. 9 and are compared with the results obtained under wet (20% precipitation) and dry (–20% precipitation) conditions. In terms of project parameters, NPV is most sensitive to changes in discount rate with increases reducing the present worth of future sales income. Next most sensitive is electricity sales price, followed by project civil costs and build period. As would be expected, decreases in sales price or rising project cost and build period lead to a reduced financial performance. Importantly, the sensitivity to precipitation (and temperature) is of a similar magnitude to both the discount rate and sales price. This adds credibility to the view that investors should be concerned about the effects of this (apparently) uncontrollable risk factor.

3.5 Results Summary

Table 3 summarises the effect of applying the wet and dry climatic conditions on several major indicators for the Batoka Gorge project. Simulation results from conditions representing current climatic conditions are presented for the purposes of comparison.

4. Discussion

Overall, the climate-finance system modelled in the case study is more sensitive to precipitation change than temperature change. The contribution to the overall sensitivity from individual components of the system can be examined using the elasticity measure, familiar in economics and used in several hydrological studies [6], [15]. Elasticity (ϕ) is defined as the percentage change in one quantity (e.g. runoff, Q) due to a percentage change in another (e.g. precipitation, P), i.e., $\Delta Q/Q = \phi \ (\Delta P/P)$. An elasticity of magnitude greater than unity indicates that changes are amplified. The elasticity of several aspects of the Batoka system to temperature and precipitation changes have been estimated and are shown in Table 4. The value for annual river flows confirms the tendency of the river basin to amplify applied rainfall changes. The lower elasticity (less than unity) of both energy production and internal rate of return indicate that the design and operation of the hydro station and its financial structure tend to damp changes. The annual river flow elasticity for precipitation compares well with the results of [6], although the temperature elasticity does not. While direct comparison was not possible, the discrepancy may be due to differences in PET estimation or, as suggested earlier, the failure to explicitly model the seasonal swamp systems that add to the hydrological complexity of the Zambezi [8].

This sensitivity analysis shows that the output and financial performance of the Batoka scheme are at risk from reductions in the level of precipitation and rising temperatures. Although this analysis cannot substitute for full risk analysis, it is useful in identifying how outcomes will change if project parameters (in this case precipitation and temperature) differ from their expected values, and in finding the degree of climate change that can be tolerated for the scheme to remain economic.

The scenarios are applied uniformly in space and time and cannot, therefore, be regarded as fully realistic. They should be regarded as worst case, although the approach could be improved by gradually imposing changes in climate over the lifetime of the project.

5. Conclusion

Potential climate change points to the continuing and increased use of renewable sources including hydropower. However, deregulation means increasing private investment in the electricity industry and a potentially difficult financial prospect for hydro. This may be exacerbated by the impact of climate change on the resource. Using a case study, a sensitivity analysis was performed to examine how important aspects of the study scheme, including river flows, energy production and financial performance, may be at risk from changes in precipitation and temperature. Overall, the scheme was found to be sensitive to climate change and, in particular, to changes in precipitation. The river basin was found to amplify changes in precipitation, although the operation of the hydro station and its financial structure tended to limit the extent of the impact on financial performance. Comparison with (non-climate) project parameters indicated that the sensitivity of financial performance to climate change is of a similar magnitude to variations in electricity sales price and discount rate, both significant issues with most projects. Critical changes in climate were identified in order to indicate the severity of climate change that could be tolerated before the project becomes financially non-viable.

6. Dedication

On the 11th March 2002, Professor Bert Whittington was tragically killed in a road accident in Edinburgh. He was aged 56 and is survived by his wife and two sons. Bert became 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 Trade and Industry. His loss is felt tremendously by his family, friends and colleagues and he will be remembered for his intelligence, wit and talent as well as his ability to entertain and inspire others.

7. Acknowledgements

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Biographies

Dr Gareth Harrison is a Post-Doctoral Research Fellow in the Institute for Energy Systems at the University of Edinburgh. He holds Bachelors and PhD degrees from the University awarded in 1997 and 2001, respectively. His doctoral research examined the impact of climatic change on the economics of hydroelectric schemes. He is currently researching the integration of distributed renewable energy generation within distribution networks. Dr Harrison is a member of both the Institute of Electrical and Electronic Engineers and the Institution of Electrical Engineers.

The late *Professor Bert Whittington* was Professor of Electrical Power Engineering at the University of Edinburgh. A former professional footballer, he received BSc and PhD degrees from Strathclyde University before joining the Central Electricity Generating Board. He returned to academia in 1973 as a lecturer at the University of Edinburgh and was made Professor in 1994. His research interests were extremely wide ranging from high voltage systems to energy policy. Professor Whittington was retained as a consultant to a large variety of organisations, notably the European Union and, more recently with the Scottish Executive and as a Special Advisor to the UK Parliamentary Select Committee on Trade and Industry. He held Fellowships with the Institution of Electrical Engineers, the Royal Society of Arts and the Royal Society of Edinburgh.

Dr Robin Wallace is head of the Institute for Energy Systems and a Senior Lecturer in the School of Engineering and Electronics at the University of Edinburgh from where he holds a BSc and PhD. Until 1984 he worked in the Project Engineering Group at Parsons Peebles Motors and Generators where he became Assistant Chief Project Engineer working primarily on hydropower plants. He moved to university and joined the University of Edinburgh in 1986. His research interests include renewable distributed generation and computational intelligence applications within power engineering. A consultant on small hydropower and distributed generation issues, Dr Wallace is a Chartered Engineer and a Member of the Institution of Electrical Engineers.

Tables

Table 1: Seasonal changes in runoff under wet and dry conditions

Precipitation and Temperature Change	Runoff Change (%) Annual	High flows	Low flows
dP = +20% ; dT = +4°C	+35.3	+39.5	+15.6
dP = –20% ; dT = +4°C	–39.3	–40.7	–32.6

Table 2: Hydroelectric station performance measures

Measure	Current climate	Precipitation and Temperature Change dP = +20% ; dT = +4°C	dP = –20% ; dT = +4°C
Station load factor (%)	67	73	50
Spill incidence (% of months)	37	46	11
Spill volume (% of inflow)	28	43	6

Table 3: Summary of simulations of current and future wet and dry conditions ([†]10% discount rate applied)

Measure	Current Climate	Precipitation and Temperature Change	
		dP =+20% ; dT = +4°C	dP = –20%; dT = +4°C
Mean monthly precipitation (mm)	74.60	89.57	59.71
Mean monthly temperature (°C)	21.90	25.94	25.94
Mean monthly PET (mm)	169.39	177.89	177.89
Mean monthly river flow (10^9 m^3)	3.21	4.38	1.97
Mean monthly production (GWh)	780.34	857.03	586.34
Mean monthly sales (in 1993 US$M)	16.90	18.56	12.70
Net present value[†] ($M)	98.07	197.75	–149.47
Internal rate of return (%)	11.00	11.95	8.25
Unit energy cost[†] (US¢/kWh)	1.52	1.39	2.01
Discounted payback[†] (Years)	20.46	16.58	>30.00

Table 4: System elasticities of precipitation and temperature

Measure	Precipitation	Temperature
Annual river flow	2.02	–0.42
Energy production	0.77	–0.24
Internal rate of return	0.70	–0.20

Figures

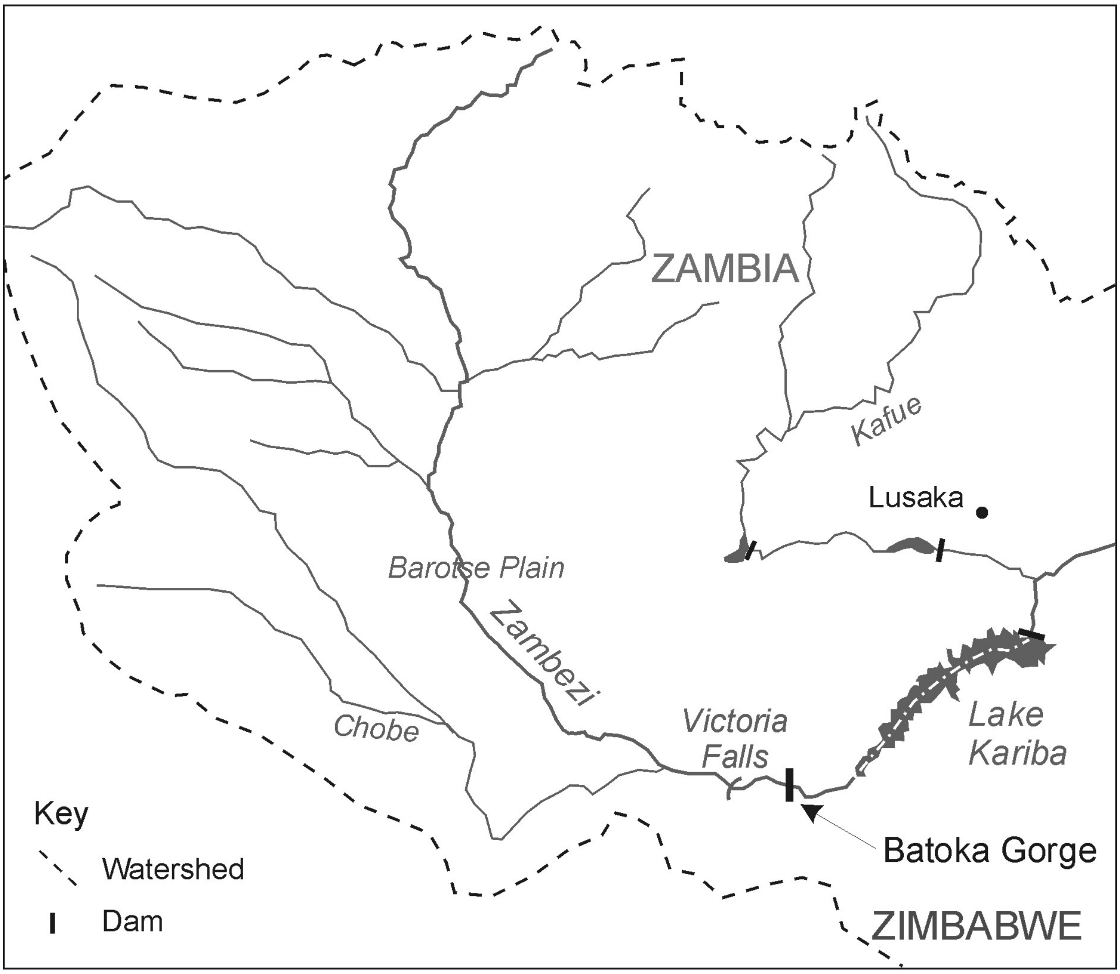

Figure 1: The Upper Zambezi Basin and the location of the proposed Batoka Gorge Scheme

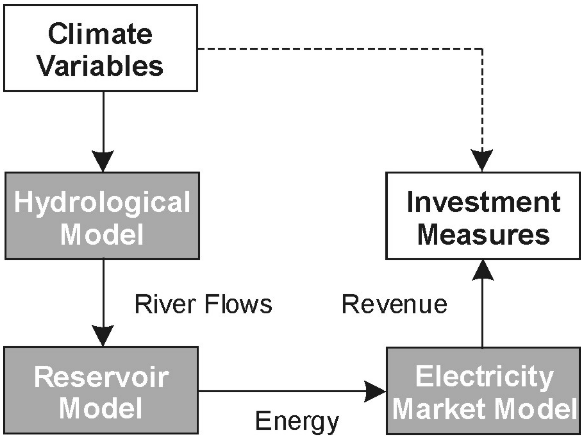

Figure 2: Schematic of software technique

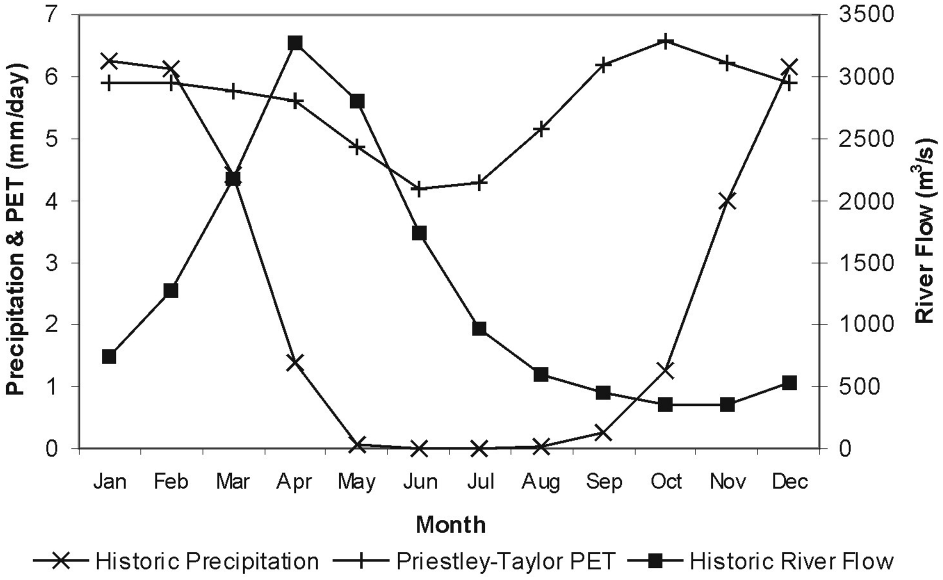

Figure 3: Historic mean monthly precipitation, PET and discharge for Upper Zambezi

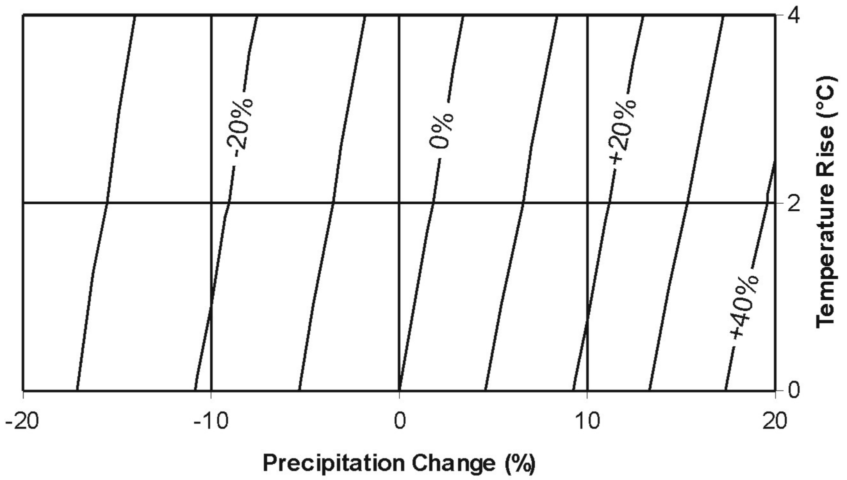

Figure 4: Variation of annual river flows with uniform changes in precipitation and temperature

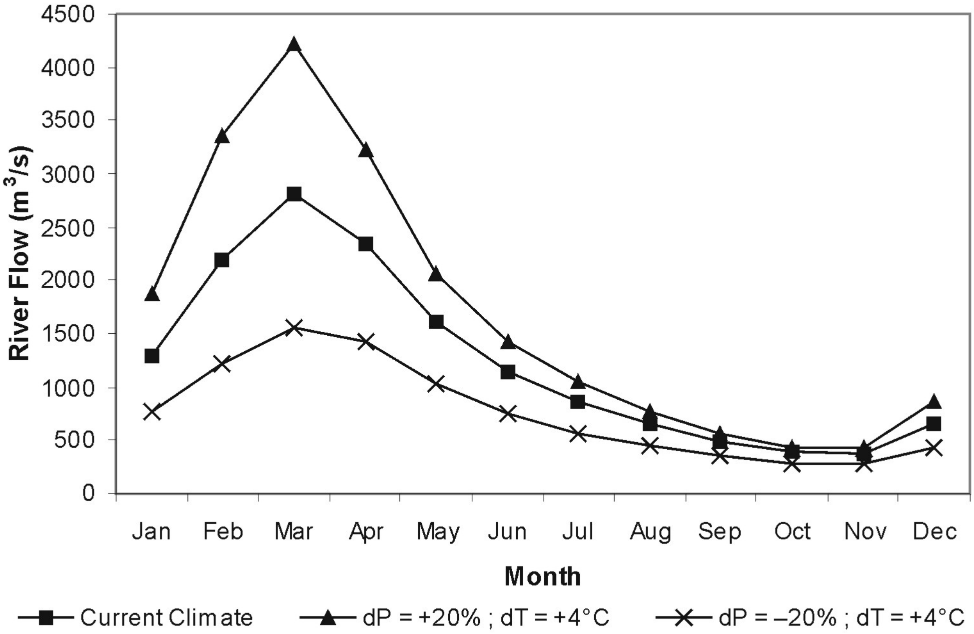

Figure 5: Seasonal variation of river flows with uniform changes in precipitation and temperature

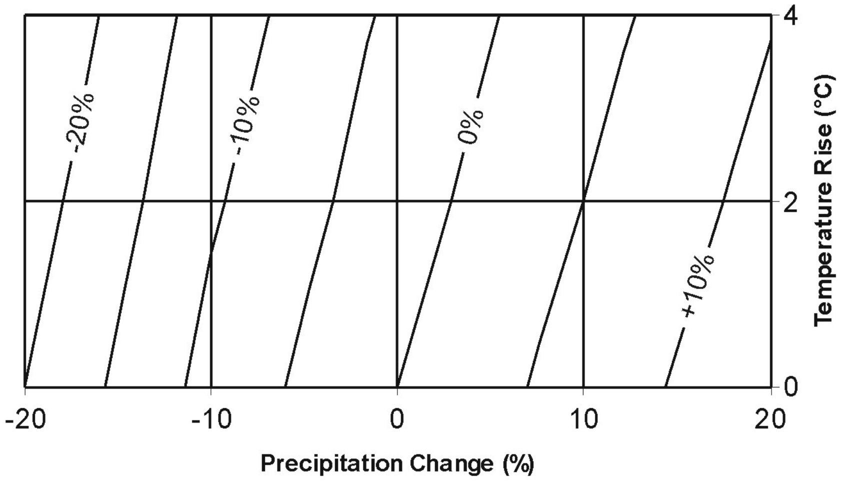

Figure 6: Variation of annual production with uniform changes in precipitation and temperature

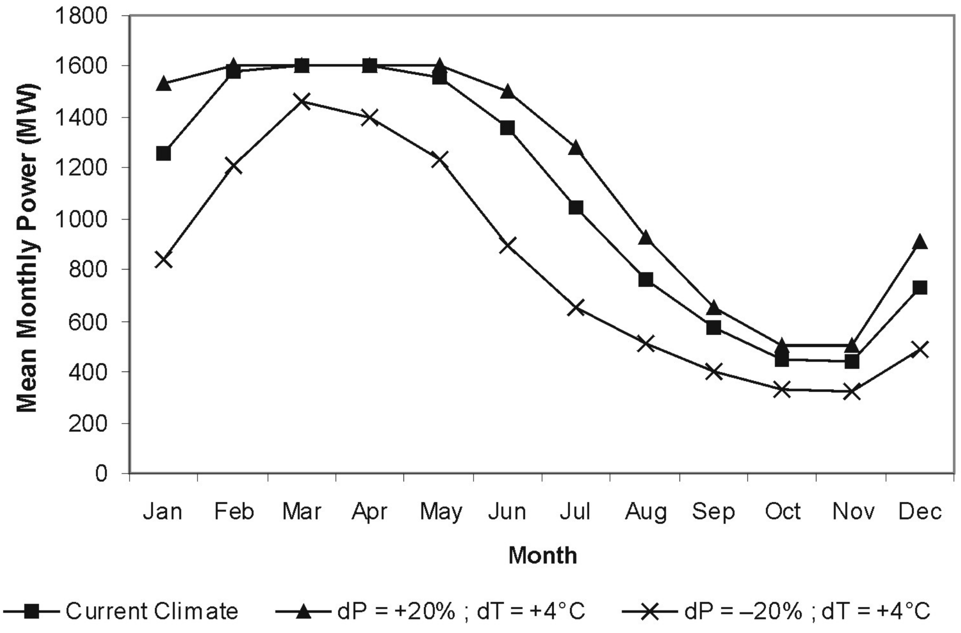

Figure 7: Seasonal variation in production levels with uniform changes in precipitation and temperature

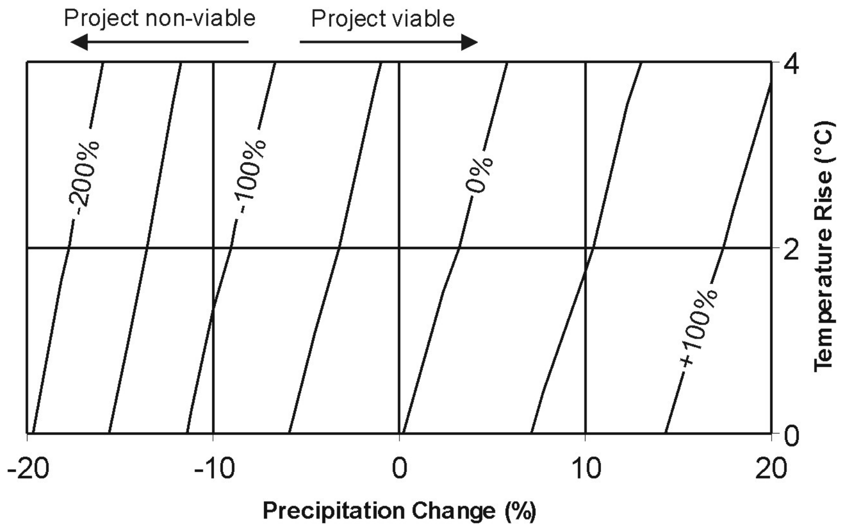

Figure 8: Variation of project NPV with uniform changes in precipitation and temperature

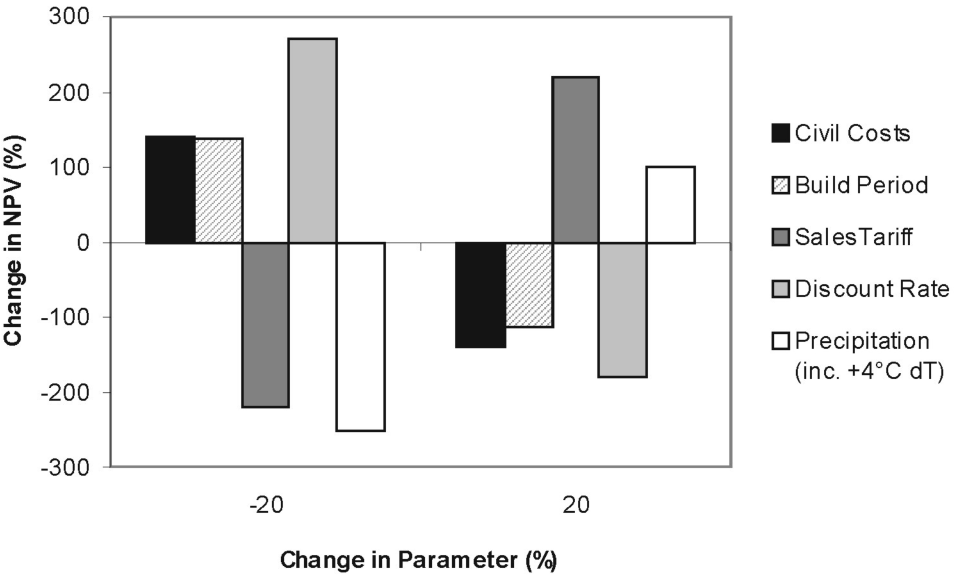

Figure 9: Variation of project NPV with climate and project parameter changes