A Risky Climate for Southern African Hydro

ASSESSING HYDROLOGICAL RISKS AND CONSEQUENCES FOR ZAMBEZI RIVER BASIN DAMS

BY DR. RICHARD BEILFUSS

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Front cover photo: *Kariba Dam, with a trickle of Zambezi flowing from it. Photo ©Joseph McKenna (http://www.flickr.com/photos/jpmckenna/)*

Back cover photo: *Villagers cross the Zambezi near the site of the proposed Mphanda Nkuwa Dam, Mozambique. Photo: Lori Pottinger*

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Executive Summary

Africa is highly vulnerable to the impacts of climate change. Numerous climate change models predict that the continent's weather patterns will become more variable, and extreme weather events are expected to be more frequent and severe, with increasing risk to health and life. Within the next 50 years, an estimated 60 to 120 million people in Southern Africa will face water stress.

Across the continent, African leaders are under pressure to grow their national economies, and to raise standards of living for their people, which translate into increased demands for energy. Hydropower is generally being promoted as a source of large-scale energy capacity for the continent. Numerous large dams are being built or under consideration.

However, Sub-Saharan Africa (excluding South Africa) is already 60% dependent on hydropower for its power supply, and many individual countries are much more dependent. The continent has experienced recurring drought in the past quarter century, which has become a leading contributor to power shortages in numerous hydro-dependent countries. Drought-induced power shortages come at a great cost to local economies. Large hydropower schemes also harm the wealth of ecological services provided by river systems that sustain human livelihoods and freshwater biodiversity. These impacts are being compounded by climate change.

Despite these concerns, large dams are being built or proposed typically without analysis of the risks from hydrological variability that are already a hallmark of African weather patterns, much less the medium- and long-term impacts expected from climate change. Likewise, ecosystem services are rarely given much weight in the energy-planning process.

This report presents an evaluation of the hydrological risk of hydro-dependent power systems in the face of climate change, using the Zambezi Basin as a case study. The future of the Zambezi Basin exemplifies the challenges faced by decision-makers weighing potential benefits of hydropower development against the risks of hydrological change. The Zambezi River Basin is the largest in Southern Africa, with a total drainage area of approximately 1.4 million km². The basin currently has approximately 5,000 MW of installed hydropower generation capacity, including the massive Kariba (whose reservoir is, by volume, the largest in the world) and Cahora Bassa dams. An additional 13,000 MW of hydropower potential has been identified. None of these projects, current or proposed, has seriously incorporated considerations of climate change into project design or operation. The report discusses hydrological variability and uncertainty in the Zambezi Basin, the impact of climate change on basin hydrology and hydropower, and the risks for current and future hydropower developments.

The need for incorporating climate change into energy planning is highlighted and recommendations to reduce the risks are proposed.

HYDROLOGICAL VARIABILITY AND HYDROPOWER IN THE ZAMBEZI RIVER BASIN

An understanding of the hydrological variability in the Zambezi River Basin is fundamental to assessing the risks, uncertainties, and consequences of hydro-dependent power systems.

The Zambezi River Basin has one of the most variable climates of any major river basin in the world, with an extreme range of conditions across the catchment and through time. Average annual rainfall varies from more than 1,600 mm per year in some far northern highland areas to less than 550 mm per year in the water-stressed southern portion of the basin.

Runoff is highly variable across the basin, and from year to year. The entire Zambezi River Basin is highly susceptible to extreme droughts (often multi-year droughts) and floods that occur nearly every decade. Droughts have considerable impact on river flows and hydropower production in the basin. For example, during the severe 1991/92 drought, reduced hydropower generation resulted in an estimated US$102 million reduction in GDP, $36 million reduction in export earnings, and the loss of 3,000 jobs. Extreme floods have resulted in considerable loss of life, social disruptions, and extensive economic damage. Hydropower operators and river basin managers face a chronic challenge of balancing trade-offs between maintaining high reservoir levels for maximum power production and ensuring adequate reservoir storage volume for incoming floods.

The natural variability of Zambezi River flows is highly modified by large dams, particularly Kariba and Cahora Bassa dams on the mainstem, as well as Itezhi-Tezhi and Kafue Gorge Upper dams on the Kafue River tributary. Zambezi hydropower dams have profoundly altered the hydrological conditions that are most important for downstream livelihoods and biodiversity, especially the timing, magnitude, duration, and frequency of seasonal flood pulses. More than 11% of the mean annual flow of the Zambezi evaporates from large reservoirs associated with hydropower dams. These water losses increase the risk of shortfalls in power generation, and significantly impact downstream ecosystem functions.

With the dams in place, overbank flood pulses now occur only during major floods in the basin, and are of inadequate volume and duration to sustain healthy functioning floodplain systems that are of global importance, such as Kafue Flats, Mana Pools, and the Zambezi Delta. High flood pulses, when they occur, are often mistimed – they are generated during emergency flood releases or the late dry season in response to required drawdown releases. Dry season flood-recession, essential for river-dependent agriculture, fisheries, and wildlife, is replaced by constant dry-season flows generated from hydropower turbine outflows. The economic impact of the loss of these and other ecosystem services is an important factor in the overall financial risk of hydropower development, especially in a changing climate.

CLIMATE RISKS IN THE ZAMBEZI BASIN

The Intergovernmental Panel on Climate Change (IPCC) has categorized the Zambezi as the river basin exhibiting the "worst" potential effects of climate change among 11 major African basins, due to the resonating effect of increase in temperature and decrease in rainfall. The Zambezi runoff is highly sensitive to variations in climate, as small changes in rainfall produce large changes in runoff. Over the next century, climate change is expected to increase this variability, and the vulnerability of the basin – and its hydropower dams – to these changes.

> Under future climate scenarios, a hydropower dam based on the past century's record of flows is unlikely to deliver the expected services over its lifetime.

The future picture for Southern Africa's climate is increasingly clear, based on observed trends over the past century and increasing confidence in the range of climate change scenarios developed. Overall, the Zambezi will experience drier and more prolonged drought periods, and more extreme floods. The following are key risks predicted for the Zambezi River Basin over the next century:

- The basin is expected to experience a significant warming trend of 0.3–0.6° C.
- Increases in temperatures across the basin will result in an increase in open-water evaporation.
- Multiple studies cited by IPCC estimate that rainfall across the basin will decrease by 10–15%.
- Significant changes in the seasonal pattern of rainfall across the basin are predicted, including delayed onsets, as well as shorter and more intense rainfall events.
- All Zambezi Basin countries will experience a significant reduction in average annual streamflow. Multiple studies estimate that Zambezi runoff will decrease by 26–40% by 2050.

- Increasing water stress is a serious concern in the semi-arid parts of the Zambezi Basin.

HYDROPOWER'S CLIMATE RISKS

These staggering climate change predictions, based on the average (not extreme case) of many climate models, have profound implications for future hydropower in the Zambezi River Basin. Climate change has the potential to affect hydropower operations in at least five important ways:

- Reduced reservoir inflows, due to decreased basin runoff and more frequent and prolonged drought conditions, will reduce overall power output.
- Increased extreme flooding events, due to higher rainfall intensity and more fre-quent cyclones, will increase the risk of worse flood impacts from uncontrolled releases, and risks to dam safety.
- A delayed onset of the rainy season could result in less predictable power pro-duction and more uncertainty and complications in using reservoirs for flood management.
- Increased surface-water evaporation could reduce power production.
- Increased sediment load to reservoirs, resulting from higher rainfall intensity and corresponding erosion, will lead to a decrease in reservoir capacity and greater difficulty in managing floods.

Numerous studies have indicated that hydropower economics are sensitive to changes in precipitation and runoff. Most hydropower projects are designed on the basis of recent climate history and the assumption that future hydrological patterns will follow historic patterns. However, this notion that hydrological systems will remain "stationary" in the future (and thereby predictable for the design and operation of hydropower schemes) is no longer valid. Under future climate scenarios, a hydropower station based on the past century's record of flows is unlikely to deliver the expected services over its lifetime. It is likely to be over-designed relative to expected future water balances and droughts, and under-designed relative to extreme inflow events. Extreme flooding events, a natural feature of the Zambezi River system, have become more costly downstream since the construction of large dams, and will be exacerbated by climate change. The financial and social impact of a major dam failure in the Zambezi River Basin would be nothing short of catastrophic.

The design and operation of the Batoka Gorge and Mphanda Nkuwa dams now under consideration for the Zambezi illuminate these concerns. Both dams are based on historical hydrological records and have not been evaluated for the risks associated with reduced mean annual flows and more extreme flood and drought cycles.

ECOSYSTEM SERVICES UNDERVALUED

The wealth of ecological services provided by river systems that sustain life on earth are rarely given much weight in the energy planning process. The current course of dam building in Africa is not being evaluated with respect to the impact of dam-induced hydrological

changes on the ability of rural populations to adapt to new flow regimes, much less on their ability to adapt to climate change's impacts more generally. Ecosystem services are of critical importance for adaptation to climate change. The Millennium Ecosystem Assessment concluded that efforts to reduce rural poverty and eradicate hunger are critically dependent on ecosystem services, particularly in Sub-Saharan Africa. Continued dependence on hydropower systems will exacerbate the economic impact of reduced ecosystem services already associated with river development.

The value of the ecosystem services threatened by hydropower development in the Zambezi River system is astonishing. A recent economic valuation study estimates that the annual total value of river-dependent ecosystem services in the Zambezi Delta is between US$930 million and $1.6 billion. Agriculture, fisheries, livestock, tourism, and domestic water supply are all affected. Cumulatively, the economic value of water for downstream ecosystem services exceeds the value of water for strict hydropower production – even without valuation of biodiversity and cultural uses of the river system.

RECOMMENDATIONS

Reducing the economic risks of climate change in hydro-dependent systems must address current as well as planned infrastructure. The report recommends the following:

■ **Assess hydropower in the context of comprehensive basin-wide planning:** Planners need to carefully consider dams in the context of how climate change will shape water supply, and how future river flows must meet competing demands for power, conservation, and water for domestic use, agriculture, industry, and other services. Community- and ecosystem-based adaptation approaches that integrate the use of biodiversity and ecosystem services into an overall strategy aimed at empowering people to adapt to climate change must be central to any comprehensive planning efforts.

■ **Incorporate climate change scenarios into dam design:** The major implication of climate change for dams and reservoirs is that the future is uncertain, and can no longer be assumed to mirror the past. Until reliable data series are available for the design and operation of new hydropower dams, projects should be approached with extreme caution. Climatic uncertainty must be incorporated into dam design, to avoid the hazards of over- or under-designed infrastructure and financial risk.

■ **Diversify the regional power pool to reduce hydropower dependency:** Creating a diverse energy supply is critical for climate-change adaptation in water-stressed regions. The Southern African Power Pool (SAPP) provides an excellent framework for diversifying power production and reducing dependency on hydropower. In practice, however, SAPP has emphasized large-scale coal and hydropower development to feed the regional grid, without serious consideration of climate change

impacts and risks. SAPP can play a key leadership role in adapting the regional power grid to the realities of climate variability and water scarcity through promotion of decentralized energy technologies, energy efficiency standards, demand-side management, and feed-in tariffs to support renewable technologies.

■ **Improve existing hydropower capacity rather than investing in new infrastructure:** Existing hydropower structures should be rehabilitated, refurbished, renovated, or upgraded prior to the construction of new hydropower facilities. Adding new or more efficient turbines is almost always much lower impact than building new dams.

■ **Prioritize investments that increase climate resilience:** Climate models warn about the impact of changing rainfall and runoff patterns on grain yields, water availability, and the survival of species. Yet large hydropower dams threaten to decrease, rather than enhance, climate resilience – especially for the rural poor – by prioritizing power generation over water supply, eliminating natural flood pulses which support food production, and increasing evaporative water loss. Investments should aim to enhance climate resilience by helping poor and vulnerable communities prepare for, withstand, and recover from the negative effects of climate change.

■ **Implement environmental flows for climate adaptation:** Environmental flows are an important policy and management tool for restoring river systems. Environmental flows will be critical to help communities living downstream of dams to adapt to a changing climate, and should be incorporated into existing hydropower operations, as well as future dam design. Environmental flows have a vital role in maintaining and restoring key ecosystem services, especially for the Kafue Flats, Mana Pools, and the Zambezi Delta "Wetlands of International Importance." Collaborative e-flow efforts among water authorities, dam operators, power companies, NGOs, and regional universities should be supported.

■ **Ensure that monitoring and evaluation systems support adaptive management:** These systems are essential to any strategy to adapt hydropower to climate change. They should help society understand clearly whether current water management practices are delivering on their promised outcomes, and enable decision-makers to apply any lessons learned to improve present and future management.

■ **Rethink flood management strategies:** Many hydropower projects are justified on the basis of providing flood control in addition to energy generation. However, allowing for flood storage means the reservoir must be drawn down to provide flood capture space at the very time that this water is most needed to supply energy. Alternative operating scenarios for existing dams and better approaches to flood management should be adopted, including the use of natural or enhanced floodplain storage in the river

basin in conjunction with run-of-river operation of large hydropower dams.

■ **Allocate hydropower revenues to compensate for dam impacts:** The regulation of rivers for strict hydropower generation is associated with adverse impacts to river systems and the ecosystem services they provide. New financial mechanisms are needed to reallocate revenue from hydropower sales to directly compensate affected downstream water users for losses caused by dam operations to agriculture, grazing, and fisheries. At a basin level, hydropower revenue could be used to reduce pressures on river systems, including removal of exotic invasive species and negative impacts from land-use changes such as clear-cutting riparian forests, which directly threaten the viability of hydropower schemes.

■ **Ensure best social and environmental practices:** Dams in the Zambezi Basin are being planned under a variety of standards, with very little public input, and with very little if any attention to the broad social and environmental impacts that these projects may bring. Given the importance of well-functioning river systems to climate adaptation efforts in Africa, standards must be improved and become mandatory to minimize these risks and properly evaluate all alternatives.

■ **Develop strong institutional capacity for water resources management:** This may be the single most important factor in the successful adaptation of existing hydropower systems to cope with climate change, as many of the above recommendations would be impossible to implement with strengthened institutional capacity. Significant technical, financial, and social capacity is required across the spectrum of agencies dealing with water management. Those responsible for hydropower management at all levels must be trained in new modes of dam operation and equipped with models and tools for implementation.

The ecological goods and services provided by river basins, which are key to enabling societies to adapt to climate change, are under grave threat from climate change as well as existing and planned hydropower development schemes. Successful adaptation in a highly vulnerable region such as the Zambezi River Basin requires a major shift in thinking, planning and designing water investments for the future. Many major hydropower developers, utilities and lenders acknowledge these concerns, but continue to recommend large-scale investments in hydropower development, at the expense of alternative energy systems that would pose less of a climate risk, and be better suited to adaptation needs. An alternative pathway, focused on climate-smart investments that explicitly factor in financial risk and the ecological functions and the values of river systems, is urgently needed. It is hoped that this report will assist basin countries to make informed decisions on incorporating hydrologic variability and adaptation strategies into long-term planning and investment decisions for the Zambezi River Basin and beyond.

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Part 1: Introduction

CLIMATE CHANGE IN AFRICA

In the coming decades, billions of people, particularly those in developing countries, will face shortages of water and food and greater risks to health and life as a result of climate change. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007a) dispelled many uncertainties about climate change. Warming of the climate system is now unequivocal, and mostly due to man-made emissions of greenhouse gases. Over the past century, atmospheric concentrations of carbon dioxide increased from a pre-industrial value of 278 parts per million to 379 parts per million in 2005, and the average global temperature rose by 0.74° C – the largest and fastest warming trend discerned in the history of the Earth. An increasing rate of warming has taken place particularly over the past 25 years. The IPCC Report's detailed projections for the 21st century show that global warming will continue to accelerate. The best estimates indicate that the Earth could warm by 3° C by 2100. Even if countries reduce their greenhouse gas emissions, the Earth will continue to warm. Predictions by 2100 range from a minimum of 1.8° C to as much as 4° C rise in global average temperatures, resulting in serious effects; these include reduced crop yields in tropical areas leading to increased risk of hunger, spread of climate sensitive diseases such as malaria, and an increased risk of extinction of 20–30% of plant and animal species (IPCC 2007b).

Africa is already a continent under pressure from climate stresses and is highly vulnerable to the impacts of climate change. Many areas in Africa are recognized as having climates that are among the most variable in the world on seasonal and decadal time scales. Serious floods and droughts can occur in the same area within months of each other. These events can lead to famine and widespread disruption of socio-economic well-being. An estimated one-third of African people already live in drought-prone areas and 220 million are exposed to drought each year. Many factors contribute to and compound the impacts of current climate variability in Africa. These include poverty, weak institutions, limited infrastructure, lack of technology and information, low levels of primary education and health care, poor access to resources, and armed conflicts. The overexploitation of land and water resources, increases in population, desertification and land degradation pose additional threats (UNDP 2006).

Climate change forecasts for Africa predict that the continent's weather patterns will become more variable, and extreme weather events are expected to be more frequent and severe, with increasing risk to health and life (McMichael *et al.* 2006). This includes increasing risk of drought and flooding in new areas (Few *et al.* 2004), and inundation due to sea-level rise in the continent's coastal areas (Nicholls 2004). Within the next 50 years, the number of people facing water stress will increase dramatically (Arnell 2004).

Climate change will be an added stress to already threatened species and ecosystems in Africa, and is likely to trigger species migration and habitat reduction on an unprecedented scale. Up to 50% of Africa's total biodiversity presently is at risk due to land-use conversion for settlement and agriculture, deforestation, pollution, poaching, civil war, population growth, and the introduction of exotic species (Boko *et al.* 2007). Freshwater ecosystems, especially river systems, have experienced rapid degradation due to the past century of water resources development, and are particularly vulnerable to the added effects of climate change (Palmer *et al.* 2008; Pittock *et al.* 2008; Vorosmarty *et al.* 2010).

HYDROPOWER DEVELOPMENT, RIVER SYSTEMS, AND CLIMATE CHANGE

Across the continent, African leaders face an enormous and growing demand for energy, and the added challenge of establishing sustainable energy systems in the face of climate change. Numerous large dams are being built or proposed to meet Africa's long-term power supply needs. Development planners argue that large hydropower dams are a least-cost, indigenous power supply, and note that less than 10% of the region's hydropower potential has been developed. Hydropower is increasingly promoted as a source of energy with low emissions of greenhouse gases, with a production capacity at a scale necessary to meet pressing energy demands with current technology (Pittock 2010).

However, Sub-Saharan Africa (excluding South Africa) is already 60% dependent on hydropower for its power supply, and many individual countries are much more dependent. Recurring drought is commonly acknowledged as a leading contributor to power shortages

in numerous hydro-dependent countries. Drought-induced power shortages come at great economic cost to local economies, and add to the perception that African economies are risky places to do business. Kenya, for example, experienced a 25% reduction in hydropower capacity during the 2000 drought, resulting in an estimated 1.5% reduction in GDP valued at $442 million (Stiftung 2010). Expanding the role of large hydropower in Africa's energy sector would increase dependence of African power grids on rainfall.

Also at stake (but rarely given much weight in the energy-planning process) is the wealth of ecological services provided by river systems that sustain life on earth. Freshwater ecosystems and species are among the most highly threatened in the world. Hydropower dams block fish migrations, inundate upstream habitats, and displace human communities. Downstream, the modification of water flow regimes caused by dams is one of the primary causes of the degradation of freshwater ecosystems worldwide (Richter *et al.* 1997). Harrison, Opperman, and Richter (2007), in questioning the sustainability of large-dam hydropower, note "the basic life histories of freshwater organisms – how, where and when they reproduce and grow – have evolved in response to natural flow variations such as seasonal high flows and natural drought periods…when these natural flows are highly altered, populations of freshwater species can plummet or even be driven to extinction." Hydropower dams store floodwaters for later use, reducing daily flow rates in the high-flow season, including eliminating small floods. They also augment natural low flows in the dry season, when stored water is released for power generation. In some instances, dam releases can cause unnatural high flows at the wrong time of year, washing away riverbank crops or sandbar nests of birds and reptiles. Extreme fluctuations in flow resulting from peak-power production also stress fish and aquatic ecosystems. In addition to changes in the flow regime, dams can heavily modify water temperatures and the downstream transport of sediment, further affecting river ecosystems. All of these environmental impacts can have serious implications for downstream plant and animal communities, as well as human communities dependent upon the goods and services provided by properly functioning river ecosystems.

Climate change further exacerbates these challenges. The IPCC technical group on climate change and water (Bates *et al.* 2008) raised concern that climate change will affect the functional operation of existing water infrastructure, including hydropower, and water management practices. Large hydropower projects are highly vulnerable to future changes in precipitation and stream flow. A recent World Bank Energy Sector Management Assistant Program (ESMAP) report (Ebinger and Vergara 2011) states that "heavy reliance on hydropower creates significant vulnerability to climate

Zambezi waters are critical to sustainable economic growth and poverty reduction in the region. The current course of dam building in Africa is not being evaluated with respect to the impact of dam-induced hydrological changes on the ability of rural populations to adapt to climate change.

change and is a feature that many low- and middle-income countries have in common." The report summarizes the impacts on the hydropower sector as "reduced firm energy, increased variability, and increased uncertainty." It warns that "long-lifespan infrastructure, such as hydropower plants, is generally less adaptable to changes in actual facilities whereas short-lifespan infrastructure can be replaced in the long term as the climate changes." And in order to "increase the flexibility of the system and its resilience to more variable climatic conditions," the report recommends "an adaptation response may require a policy decision to diversify away from hydropower."

African energy planning is occurring without the benefit of proper analysis of the risks to large dams' viability from hydrological variability that is already a hallmark of African weather patterns, much less the medium- and long-term impacts posed by climate change. With regard to climate change, two risks are routinely overlooked in energy planning at both the sectoral and project levels. First, historical hydrological patterns (on which hydropower operation and project viability are routinely based) are becoming unreliable for predicting future hydrological patterns. Second, the current course of dam building in Africa is not being evaluated with respect to the impact of dam-induced hydrological changes on the ability of rural populations to adapt to climate change.

How can the risks of hydrological uncertainty on African energy portfolios be assessed and integrated into sectoral and project-level decision-making? What policy changes should governments adopt to address the risks of hydropower dependency in national and regional power sectors, in light of such hydrological uncertainty? This report examines risk and uncertainty related to hydropower development and climate change in Southern Africa, focusing on the Zambezi River Basin as a case study.

THE ZAMBEZI RIVER BASIN

More than a decade ago, the IPCC (2001) categorized the Zambezi as the river basin exhibiting the "worst" potential effects of climate change among eleven major African basins, due to the resonating effect of increase in temperature and decrease in rainfall on potential evaporation and runoff. The future of the Zambezi River

Basin exemplifies the challenges faced by decisions-makers weighing potential benefits of hydropower development against the risk of hydrological change.

The Zambezi River Basin is the largest in Southern Africa, with a total drainage area of approximately 1.4 million km². The Zambezi mainstem, with a total length of 2,574 km, originates in the Kalene Hills in northwest Zambia at an altitude of 1,500m and flows south and eastwards to the Indian Ocean. The river has three distinct stretches: the Upper Zambezi from its source to Victoria Falls, the Middle Zambezi from Victoria Falls to Cahora Bassa Gorge, and the Lower Zambezi from Cahora Bassa to the Zambezi Delta.

Zambezi waters are critical to sustainable economic growth and poverty reduction in the region. In addition to meeting the basic needs of some 30 million people and sustaining a rich and diverse natural environment, the river plays a central role in the economies of eight riparian countries – Angola, Botswana, Malawi, Mozambique, Namibia, Tanzania, Zambia, and Zimbabwe. The Zambezi provides important environmental goods and services to the region and is essential to regional food security and hydropower production.

Home to a rich biological diversity and some of the densest concentrations of wildlife in the world, the Zambezi River Basin features several of Africa's finest national parks. The Middle Zambezi Valley is a UNESCO Biosphere Reserve. Eight Zambezi Basin floodplains are designated as Wetlands of International Importance under the Ramsar Convention, including the Barotse Plain, Busanga Plains, Kafue Flats, Mana Pools (also a World Heritage Site), Lower Zambezi National Park, Elephant Marsh, and the Zambezi Delta. The Zambezi features the most important concentrations in Africa of endangered wattled cranes, African elephant, African buffalo, and many other species.

The Zambezi River Basin currently has approximately 5,000 MW of installed hydropower generation capacity. Major hydropower dams include Kariba and Cahora Bassa Dams on the mainstem Zambezi River, Itezhi-Tezhi and Kafue Gorge Upper Dam on the Kafue River, and the Kamuzu Barrage that partially regulates Lake Malawi water levels for downstream Shire River hydropower production at Nkula Falls, Tedzani, and Kapichira Stage I hydropower dams. An additional 13,000 MW of hydropower potential has been identified (World Bank 2010). None of the Zambezi hydropower development projects, current or proposed, has seriously incorporated considerations of climate change into project design or operation, despite a history of economically devastating droughts and floods that are predicted to become more commonplace in the future.

Numerous studies have addressed the socio-economic and ecological impacts of existing hydropower development in the Zambezi River Basin. Hydropower dams have resulted in significant shifts in the timing, magnitude, duration, and frequency of annual flood pulses and low-flow events on the Zambezi (Beilfuss 2002). Deleterious ecological changes associated with this hydrological degradation include down-cutting of the Zambezi channel below the adjacent floodplain and reduced floodplain water table, invasion of woody savanna and thicket vegetation into open grassland and wetland, abandonment of former distributary channels, displacement of freshwater grassland species with salt-tolerant grassland species, degradation of coastal mangroves, and reduction in breeding and feeding grounds for endemic and threatened mammal and waterbird species (Tinley 1975, Rees 1978a&b, Handlos and Williams 1985, Beilfuss et al. 2000, Davies et al. 2001, Bento et al. 2007). Socio-economic concerns include reductions in freshwater and prawn fisheries, floodplain and riverbank agriculture, floodplain water supply, and wildlife carrying capacity for tourism and trophy hunting (SWECO 1983, Bolton 1986, Sushka and Napica 1986, Anderson et al. 1990, Gammelsrød 1992, Beilfuss et al. 2002, Tha and Seager 2008). Many of these concerns will be exacerbated by the drier, and more drought- and flood-prone conditions resulting from climate change in the Zambezi Basin.

Part 2 of this report provides an assessment of the natural and regulated patterns of hydrological variability and change in the Zambezi River system, including long-term cycles of droughts and floods. In Part 3, we assess how this extreme variability influences, and is affected by, hydropower development in the basin. The impact of climate change on Zambezi Basin hydrology and hydropower development is addressed in Part 4. In Part 5, we examine the risks associated with current and planned hydropower development under climate change scenarios. Part 6 provides a series of recommendations for adapting present and future hydropower development to the realities of climate change and water scarcity in Africa.

Part 2: Hydrological variability and change in the Zambezi River Basin

The hydrology of the Zambezi River Basin was first described in detail by Balek (1971). The most comprehensive treatment of Zambezi hydrological variability is provided by Beilfuss (2002), covering natural and dam-induced patterns of runoff, indicators of hydrological change, characteristics of extreme flooding events, and the reliability of the long-term hydrological data. Recent hydrological assessments, including Euroconsult and Mott Macdonald (2008), World Bank (2010) and SWRSD Zambezi Joint Venture (2010), have focused on hydropower investment potential and improved dam operations. Key findings of these hydrological studies are provided in this chapter.

The basin's climate is largely controlled by the movement of air masses associated with the Inter-Tropical Convergence Zone (ITCZ). Rainfall occurs predominantly during the summer (November to March), and the winter months (April to October) are usually dry. The average annual rainfall over the basin is about 960 mm, but varies from more than 1,500 mm per year in the northern highlands to less than 600 mm per year in the low-lying south/southwestern portion of the basin. Rainfall is characterized by considerable variation across the basin and over time. Droughts of several years' duration have been recorded almost every decade. Large floods occur with similar frequency.

The natural flow regime of the Zambezi River reflects these rainfall patterns and is characterized by high seasonal and annual variability. Zambezi tributaries draining the steep gorges of the Central African Plateau peak rapidly with the rains, reaching their maximum discharge between January and March and decreasing to dry season minimal flows by October-November. In the Zambezi headwaters, Kafue River, and Shire River basins, large floodplain systems capture floodwaters and may delay peak discharges until late in the rainy season or early dry season. The average runoff efficiency[1] across the entire basin is only 8.3% – on average only 80 mm runoff is generated annually from nearly 1000 mm annual rainfall. Most rainfall is stored in floodplains and other landscape depressions or intercepted by plants, where it is lost to evaporation (average annual potential evaporation[2] is more than 1,560 mm) or infiltrates to groundwater to maintain Zambezi base flows during the dry season. The total volume of natural (unregulated) annual runoff is estimated to be 110,732 million m³ (Mm³), a flow rate of 3,511 m³/s.

For planning purposes, the Zambezi Basin is typically divided into three regions comprising 13 sub-basins (Figure 2). These include the Upper Zambezi, Kabompo, Lungwebungo, Luanginga, Barotse, and Cuando/Chobe sub-basins in the **Upper Zambezi** region, the Kariba, Mupata, Kafue, and Luangwa sub-basins in the **Middle Zambezi** region, and the Tete, Lake Malawi/Shire, and Zambezi Delta sub-basins **Lower Zambezi** region. Table 1 gives the catchment area sizes, the mean annual rainfall, potential evapotranspiration, mean annual runoff, and runoff efficiency for each of these sub-basins. A detailed description of the hydrological characteristics of the Zambezi sub-basins is provided in the Appendix. In the following sections, we examine the unique patterns of hydrological variability that characterize the Zambezi River Basin.

THE UPPER ZAMBEZI REGION

Physical description

The Upper Zambezi region (515,008 km²) includes two major landscapes, the Northern Highlands and the Central Plains. Deep, well-drained Kalahari sands cover the entire region (Balon and Coche 1974). The Northern Highlands consists of a belt of high ground on the south side of the Equatorial Divide that gives rise to the Zambezi and its headwater tributaries. From its origin near the Kalene hills in the far northwest corner of Zambia (elevation 1,370 m AMSL) the Zambezi winds through east-central Angola, capturing runoff from the Angolan highlands before re-entering Zambia at Chavuma Falls. Farther downstream near the town of Lukulu, the Zambezi captures runoff from its two largest headwater tributaries, the Kabompo River of northwestern Zambia and the Lungwebungu River of central Angola. The steep channels and open terrain of the Northern Highlands drains rapidly, with minimal floodplain retention – runoff rises sharply with the onset of rainfall, peaks between February and April, and then rapidly recedes to minimal flows between September and November (Balek 1971a).

Below Lukulu, the Northern Highlands give way to the broad flat plateau of the Central Plains. For the
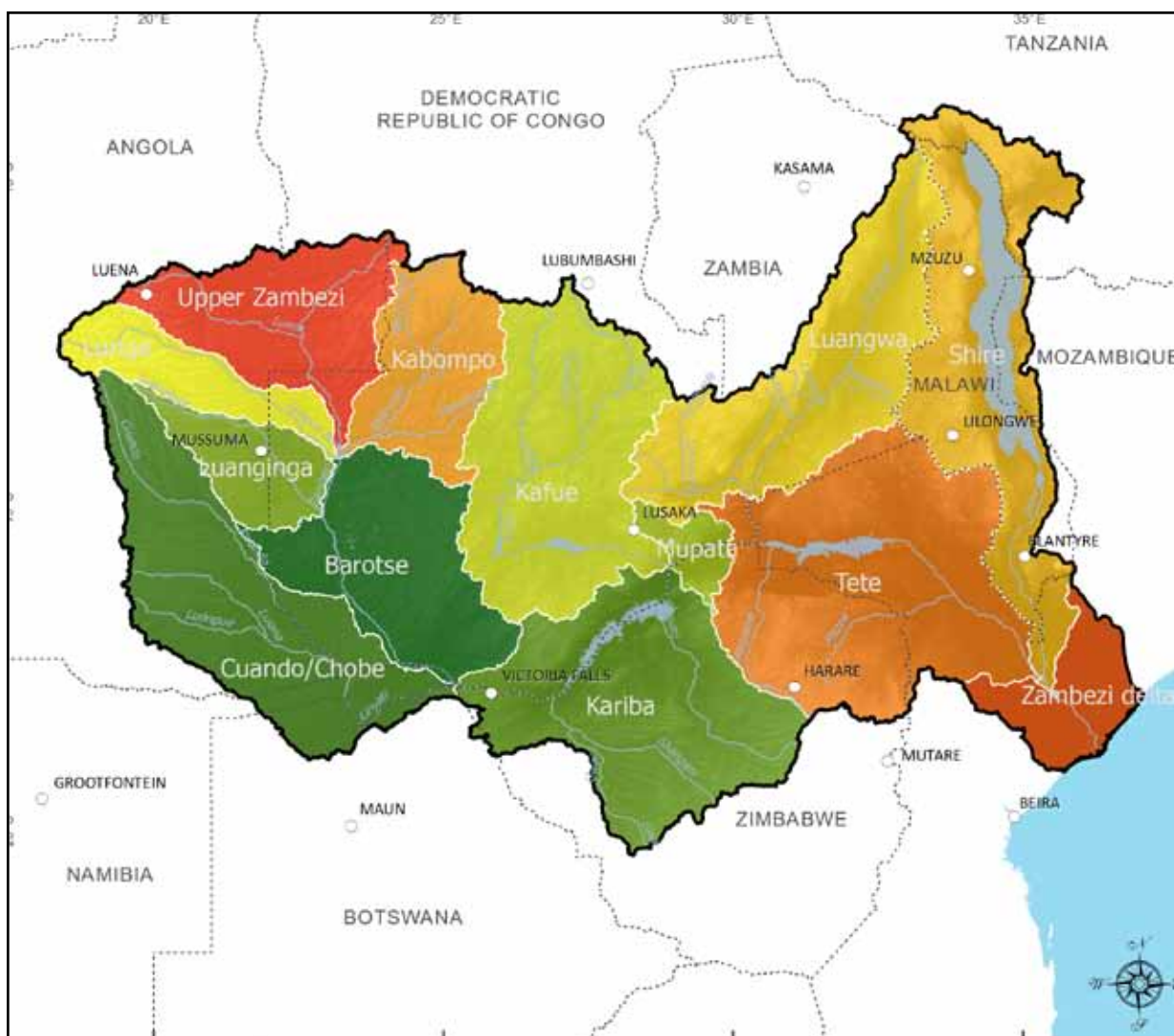
Figure 1. The 13 major sub-basins of the Zambezi River Basin. Map produced by J.-M. Mwenge Kahinda, CSIR-South Africa.

next 200 km, the Zambezi River meanders through the Barotse Plain, a vast floodplain grassland more than 40 km wide. During the rainy season, the floodplain is inundated by Zambezi floodwaters to form a large shallow lake that significantly attenuates Zambezi runoff. Peak runoff from the Northern Highlands typically reaches Lukulu during February-March, but Zambezi floodwaters take 4-6 weeks to pass through the Barotse Plain, and peak discharge downstream is often delayed until April or early May. Floodwaters recede slowly from the Barotse Plain during the six-month dry season, with high evaporation losses throughout the year.

Downstream of the Barotse floodplain, the Zambezi traverses another vast floodplain system, the Chobe Swamps, that further attenuates runoff from the Zambezi and the Cuando/Chobe headwaters system (which drains central Angola through the Caprivi Strip of Namibia and northeastern Botswana). During the early part of the flood season, the Chobe River flows in an easterly direction from the Chobe swamps towards the main Zambezi

channel, and may contribute substantial runoff to Zambezi system (Balek 1971b). As Zambezi levels rise, however, floodwaters spill from the Zambezi back into the Chobe swamps, and are lost through evaporation. Downstream of the Chobe River confluence, the Zambezi cascades over a series of basalt outcrops, including the Katambora Rapids, until plunging 98 m over Victoria Falls.

Patterns of hydrological variability and change

From the headwaters of the Zambezi to Victoria Falls, rainfall decreases with elevation (from 1,400 mm to 767 mm, respectively) and becomes much more variable. The drainage density[3] also decreases from north to south across this landscape (from about 1 km/km² in the headwaters to less than 0.03 km/km² in the lower plains), and runoff efficiency drops as well (from 0.20-0.25 near the Zambezi source to less than 0.07 near Victoria Falls). Between Chavuma Falls and Victoria Falls, the Zambezi catchment area increases seven-fold, but mean annual runoff only doubles. The semi-arid southern part of the catchment thus is especially vulnerable

Table 1. Hydrological variables for natural (unregulated) flows in the three regions and 13 major sub-basins of the Zambezi River Basin.

Sub-basin	Area (km²)	Mean Annual Rainfall (mm)	Potential Evapo-transpiration (mm)	Runoff efficiency	Mean annual runoff (Mm³)	Cumulative Zambezi mean annual runoff (Mm³)
UPPER ZAMBEZI REGION						
Upper Zambezi	91,317	1225	1410	0.21	23,411	23,411
Kabompo	78,683	1211	1337	0.09	8,615	32,026
Lunguebungo	44,368	1103	1472	0.07	3,587	35,613
Luanginga	35,893	958	1666	0.06	2,189	37,802
Cuando/Chobe	148,994	797	1603	—	0	37,802
Barotse	115,753	810	1578	—	-553	37,249
MIDDLE ZAMBEZI REGION						
Kariba	172,527	701	1523	0.05	6,490	43,712
Kafue	155,805	1042	1780	0.07	11,734	
Mupata	23,483	813	1708	0.09	1,703	57,127
Luangwa	159,615	1021	1555	0.10	16,329	
LOWER ZAMBEZI REGION						
Tete	200,894	887	1436	0.10	18,007	91,463
Shire River/Lake Malawi	149,159	1125	1643	0.09	15,705	
Zambezi Delta	33,506	1060	1652	0.10	3 564	110,732
Zambezi Basin	**1,409,997**	**956**	**1560**	**0.08**		**110,732**

Note: Mean annual runoff (MAR) volumes used in this report generally concur with estimates used for the World Bank (2010) *Zambezi River Basin Multi-Sector Investment Opportunities Analysis*. However, the World Bank report overestimates runoff for the Tete sub-basin (37.6 km³), which corresponds to an unrealistically high runoff coefficient of >0.21. The figure used in this report, sourced from Beilfuss (2002), reflects a more likely runoff coefficient of 0.10 for this sub-basin. Consequently, the long-term mean annual runoff volume for the Zambezi Basin estimated for this report is 11% lower (by 14.6 km³) than that estimated by the World Bank (2010).

to changes in temperature and rainfall associated with climate change, discussed further below.

Average annual rainfall for the Upper Zambezi region is about 1,000 mm, producing a mean annual discharge of 37,249 Mm³ (an average flow rate of 1,181 m³/s). Zambezi flows begin rising during the early rainy season months of December–January, increasing sharply from February to April. Flows recede steadily during the prolonged dry season, reaching an annual minimum during November. Approximately 50% of annual rainfall over the catchment, on average, contributes to Zambezi baseflow (Sharma and Nyumbu 1985). During drought years, the magnitude and duration of average peak flows may be reduced by 70% or more (Figure 2).

Extensive floodplains on the low-lying Central Plains provide substantial attenuation of headwaters runoff. During the major Zambezi flood of 1958, the Barotse Plain stored approximately 17,000 Mm³, nearly half of the mean annual inflows from the Zambezi headwaters region (Sharma and Nyumbu 1985). The role of floodplain storage in adapting hydropower generation to the economic risks of climate change is discussed in Part 6.

Upper Zambezi runoff varies considerably from year to year (0.40 coefficient of variation[4]), from a remarkable 72,800 Mm³ in 1957/58 to as low as 12,300 Mm³ in 1995/96 (Figure 3). The time series of annual flows reveals long-term cycles of high, medium, and low runoff. From 1907–46 and again from 1982–99, runoff from the Upper Zambezi region was appreciably lower than the long-term average. Runoff during the period 1947–81, and again since 2000, was significantly higher than average. Mean annual runoff during 1947–81 was 44,000 Mm³, including the 16 wettest years on record, whereas mean annual runoff during 1982-99 averaged only 23,200 Mm³, with 15 of 17 years below the long-term average. These cycles also influence runoff efficiency – a sequence of particularly low rainfall years in the catchment, such as occurred during the early 1900s and again during the period 1980-98, can significantly reduce the proportion of annual rainfall that occurs as runoff (Mukosa *et al.* 1995). Conversely, the maintenance of high water tables during sequences of wet years contributes to higher runoff efficiency (Mazvimavi and Wolski 2006). The cyclical flow patterns in the Zambezi basin have many similarities with
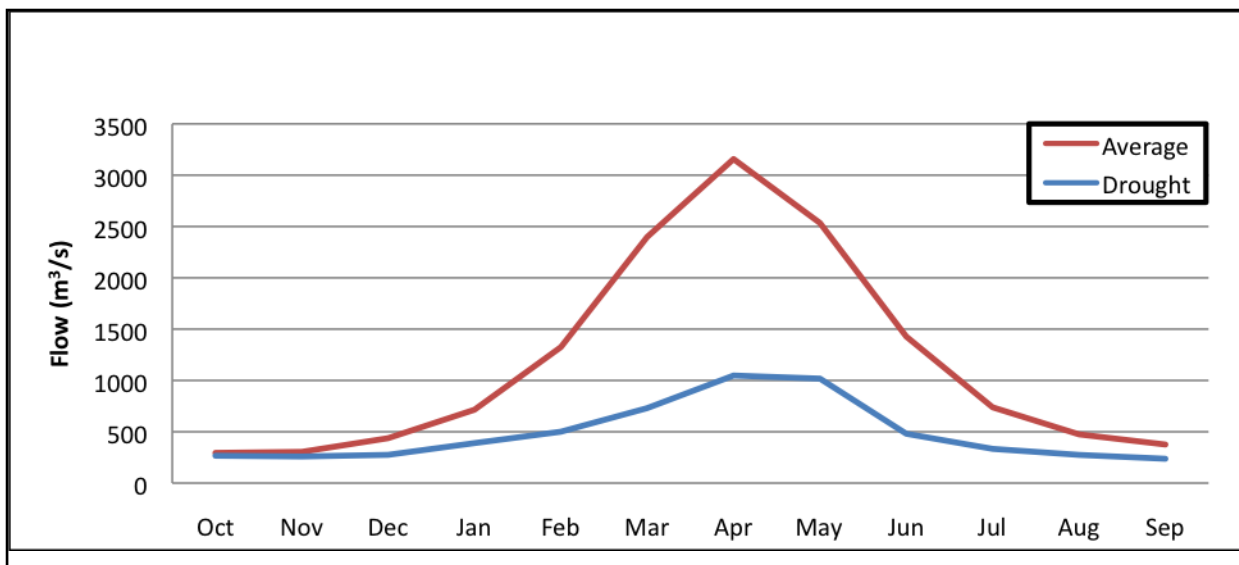
Figure 2. Mean monthly discharge from the Upper Zambezi region (at Victoria Falls), during average and drought years.

semi-arid regions of Australia in terms of climate change impacts and variable water flows (Chiew and McMahon 2002), discussed further below.

The Upper Zambezi region is a vital "water tower" for the entire basin. There are no major dams in the Upper Zambezi region. Water diversions for irrigation, domestic use, and other purposes (28.8 Mm³) are insignificant relative to basin runoff, although large-scale water transfers to thirsty cities in Namibia, Botswana, and even South Africa have been proposed (Scudder 1993). A range of valuable ecosystem services (Part 5) are supported by the naturally functioning river system, including fisheries, wildlife, and vast areas of floodplain crops irrigated using traditional flood-recession agricultural practices. This is in sharp contrast to the highly regulated, ecologically impoverished conditions in the Middle and Lower Zambezi regions.

THE MIDDLE ZAMBEZI REGION

Physical description

Between Victoria Falls and Cahora Bassa Gorge, the Zambezi River marks the international boundary between Zambia and Zimbabwe, draining the Middle Zambezi region (511,430 km²). Immediately downstream from Victoria Falls, the Zambezi flows through two deeply incised gorges, Batoka Gorge and Devil's Gorge – both proposed sites for large hydropower dams. There are no major tributaries in this reach. From Devil's Gorge to Kariba Gorge, the Zambezi River cuts through the Gwembe Rift Valley and receives runoff from the Gwayi and Sanyati Rivers which drain the western and northern Zimbabwe Highlands, respectively. Runoff from the Gwembe Valley generates a characteristic early Zambezi flood (known locally as *Gumbora)*, while the delayed runoff from the Upper Zambezi region generates the

major annual Zambezi inundation (known as *Mororwe*) that typically peaks in April-May (Davies 1986).

Kariba Gorge is dammed to form the massive Kariba Reservoir – the largest artificial reservoir (by volume) in the world – with a surface area of 5,577 km² and a live-storage volume[5] of 64,800 Mm³. The operation of Kariba Dam for hydropower generation has greatly altered the flow regime of the Zambezi River. Kariba regulates runoff from an upstream catchment area of 687,535 km², about 50% of the total Zambezi catchment. Kariba Reservoir, which has the capacity to store 1.4 times the Zambezi mean annual runoff volume, releases a constant turbine outflow, which is a dramatic change from the natural flow regime of seasonal highs and lows. Spillage resulting in downstream high flows occurs only during prolonged periods of above-average inflows, when the reservoir is at or near full supply level. Evaporative water loss from the surface of Kariba Reservoir exceeds 2,000 mm per year.

Below Kariba Dam, the Zambezi flows through a series of deep gorges and narrow floodplains, including Lower Zambezi National Park on the north bank and Mana Pools National Park on the south bank, and is fed by two major tributaries – the Kafue River and the Luangwa River. Although the catchments of these two river systems are similar in size, they differ significantly in geomorphology and yield very different runoff patterns, discussed below. The Kafue River rises in the Copperbelt region of Zambia on the Central Africa Plateau, and features vast floodplain systems including the Lukanga Swamp and Kafue Flats. The river is dammed at Itezhi-Tezhi Gorge and Kafue Gorge for hydropower production. The Luangwa flows for most of its length through an incised channel, fed by short, steeply falling tributaries draining from the Rift Valley escarpment, and there is no substantial floodplain development as in the Kafue River system. Three small hydropower plants on tributaries of the
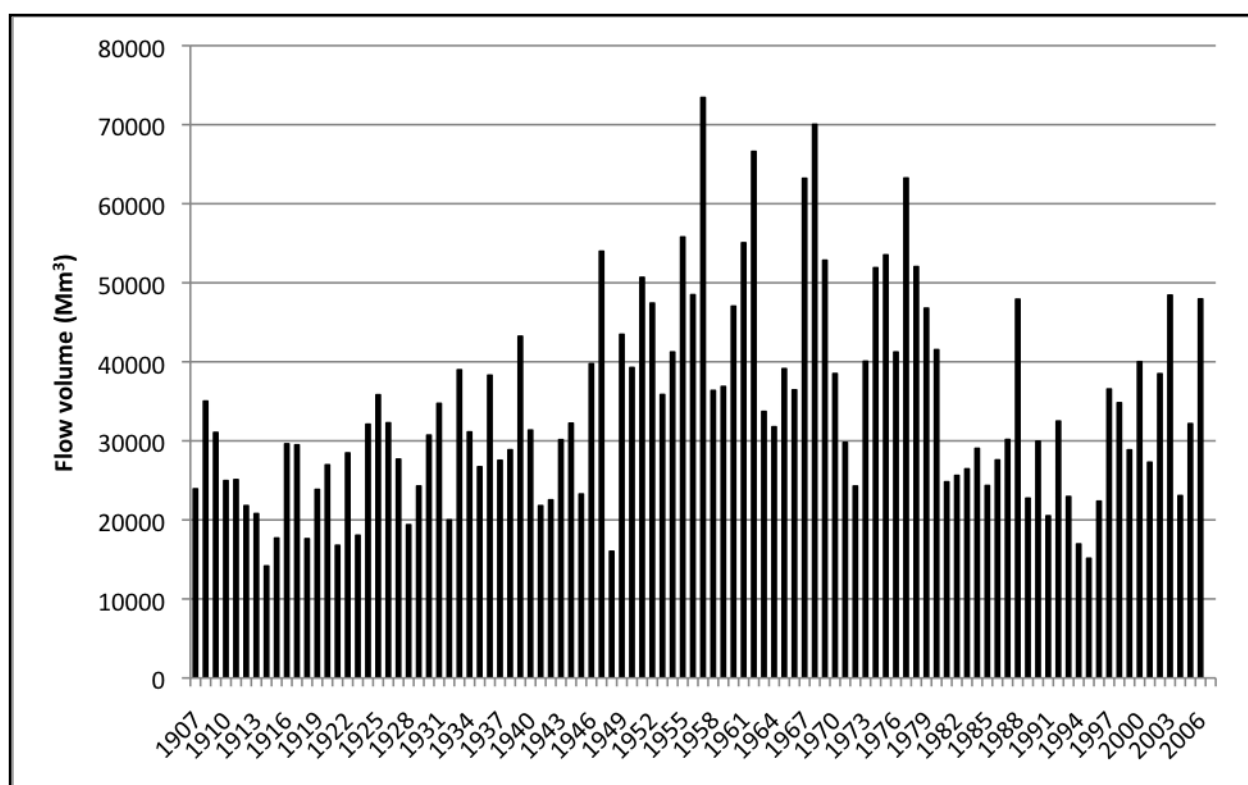
Figure 3. Time series showing variation in mean annual runoff from the unregulated Upper Zambezi region at Victoria Falls over the past century, 1907-2006.

Luangwa River have no measurable impact on Luangwa runoff patterns. The Luangwa catchment has 20% higher runoff efficiency than the Kafue sub-basin, and generates 40% more mean annual runoff than that of the similarly sized Kafue catchment. The Luangwa discharges to the Zambezi at the western end of Cahora Bassa Reservoir, where it forms the international boundary between Zambia and Mozambique.

Patterns of hydrological variability and change
The Middle Zambezi region is a hot, dry landscape, with mean annual rainfall (900 mm) decreasing sharply from north to south. Runoff efficiency also decreases from north to south, and most of the southern tributaries are reduced to seasonal flow. Mean annual runoff from the Middle Zambezi region is similar to that of the comparably sized Upper Zambezi region, but is even more variable from year to year (coefficient of variation 0.47).

Regulation of the Zambezi River for hydropower production at Kariba Dam on the Zambezi mainstem, and on the Kafue River at Itezhi-Tezhi and Kafue Gorge Upper dams, has greatly altered hydrological conditions and variability in the Middle Zambezi region. These dams have significantly altered the timing of downstream flows and reduced the frequency, depth, and duration of inundation at two of the most important floodplains in Africa for people and wildlife – the Kafue Flats and Mana Pools.

The impact of Kariba regulation on Zambezi flows is shown in Figure 4. The timing of average peak flows occurs months earlier under regulated conditions, with the magnitude of monthly flows sharply reduced by 37–48% during the natural peak-flooding season. Average dry season low flows have increased more than three-fold, from 250 m³/s to 820 m³/s in October. During drought years spillage from Kariba Dam is curtailed, and the hydrograph reflects constant year-round turbine outflows with no discernible flood peak downstream. According to the World Bank ESMAP, more than 16% of mean annual flows through the reservoir are lost to reservoir evaporation (Ebinger and Vergara 2011) – the most significant source of water loss in the Zambezi Basin, far exceeding the combined total of all agricultural, municipal, and domestic water diversions from the basin at present.

Runoff from the Kafue Basin likewise is highly modified by the operation of Itezhi-Tezhi and Kafue Gorge Upper dams for hydropower production. Releases from the 390 km² Itezhi-Tezhi Reservoir are dictated by power generation needs at Kafue Gorge Upper Dam, typically about 168 m³/s except during periods of exceptional runoff from the upper catchment areas. During a four-week period each March, an ecological water release ("freshet") of 300 m³/s is supposed to be released to the Kafue Flats, but this has been inconsistently implemented (McCartney *et al.* 2001) and is currently under review (Schelle and Pittock 2005). The hydrograph of Kafue River mean monthly flows under natural and regulated conditions is shown in Figure 5. Flows downstream of Itezhi-Tezhi Dam are reduced 37% during the peak
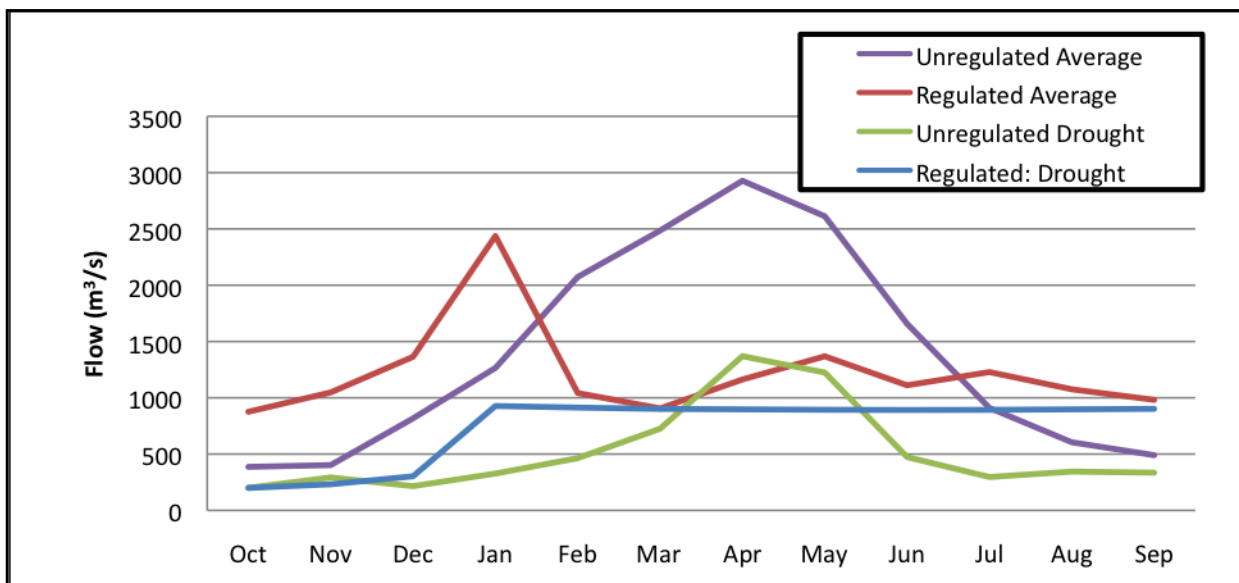
Figure 4. Mean monthly flows in the Kariba sub-basin during average and drought years, under natural (unregulated) and regulated conditions.
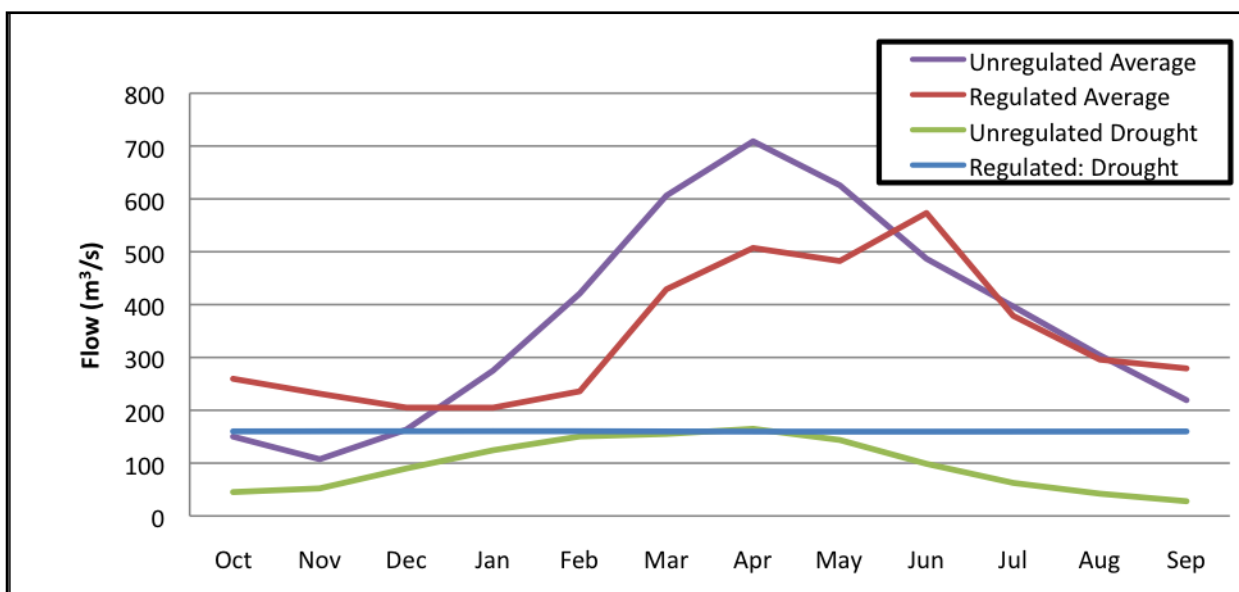

Figure 5. Mean monthly flows in the Kafue sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

runoff months of February to April, with a corresponding two-fold increase in dry season flows. There is a constant flow, with no discernible flood peak, during drought years when freshets are curtailed. Net water loss due to evaporation from Itezhi–Tezhi reservoir is 780 mm per year, about 3% of mean annual flows from the Kafue sub-basin – most evaporative water loss from the Kafue basin occurs from the large floodplains and swamps.

Cumulative Zambezi runoff through the Middle Zambezi region is 73,456 Mm³ (a flow rate of 2,375 m³/s). Prior to river regulation, the highest annual runoff volume on record (136,067 Mm³ during 1951/52) was

nearly four times greater than the lowest annual runoff volume (38,687 Mm³ in 1948/49) (Figure 6). Annual runoff volume dropped to 21,465 Mm³ during the filling of Kariba reservoir from 1958–61, and since that time mean annual runoff is reduced 23% due in large part to reservoir evaporative water loss from Kariba and (since 1972) the Kafue River. The Luangwa River provides the only significant source of unregulated runoff to the Lower Zambezi region.

The long-term cyclical pattern of mean annual runoff noted for the Upper Zambezi region is also evident in the Middle Zambezi region. A general increase
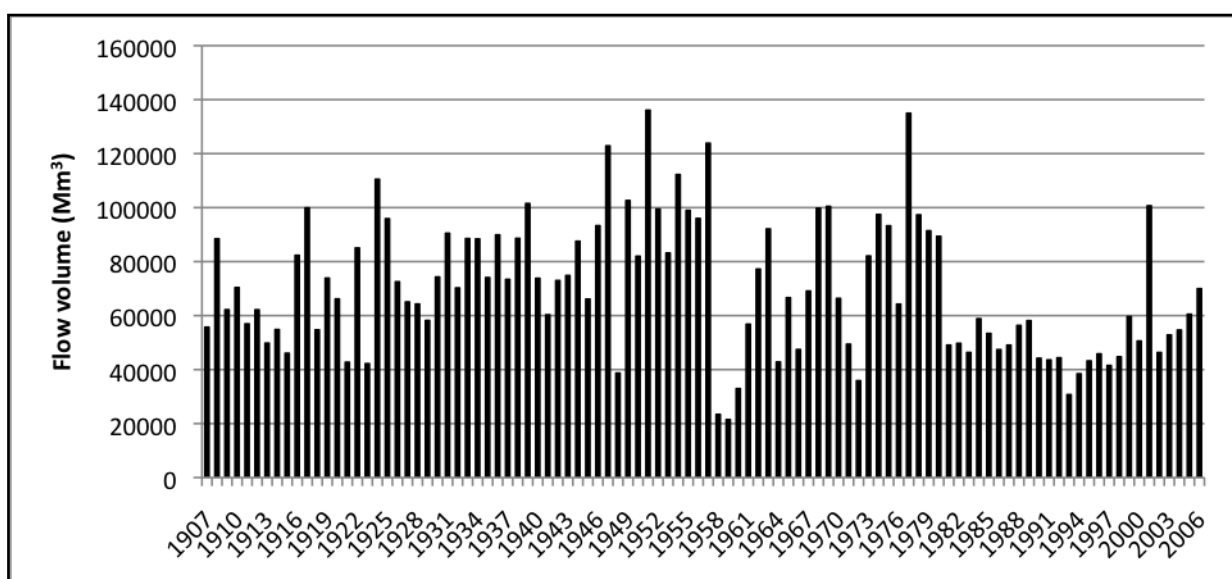
Figure 6 Time series showing variation in mean annual runoff from the entire Zambezi catchment above Cahora Bassa Gorge over the past century, 1907-2006. Since 1958, inflows to Cahora Bassa are regulated by upstream dams.
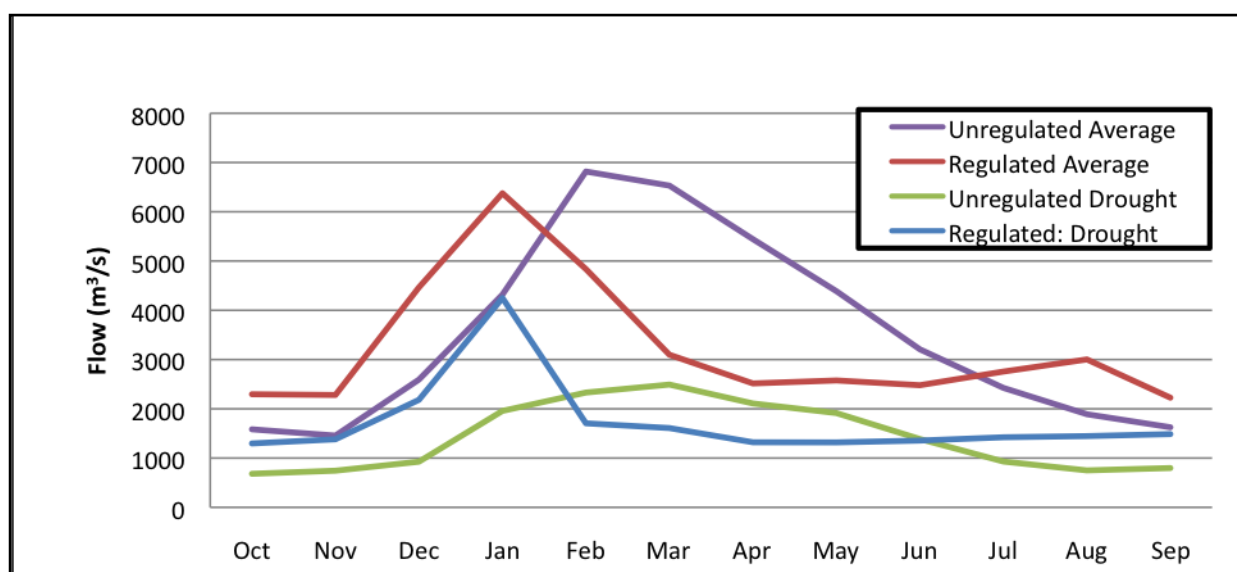
Figure 7. Mean monthly flows downstream of Cahora Bassa Dam at Tete during average and drought years, under natural (unregulated) and regulated conditions.

in runoff occurred in the Kariba and Kafue catchments from the late 1930s until the early 1980s, followed by a sharp decrease over the subsequent 20-year period. The Luangwa catchment showed a similar but slightly different cyclical pattern, with increasing runoff between the 1920s and 1970s followed by a sharp decrease in runoff over the next 30 years. These findings are consistent with regional studies indicating that the inter-annual variability of flows is significantly cross-correlated among a wide range of rivers in sub-Saharan Africa (Jury 2003). Increases in surface-water runoff per unit of rainfall from the Kafue headwaters region since the 1950s is attributed to

deforestation in the Copperbelt region (Mumeka 1986). Likewise, increasing runoff in the Luangwa catchment may in part have been the result of changes in the vegetation and land cover; Bolton (1984) noted that the valleys in the south and east of Zambia are actively eroding at a much higher rate than in central Zambia.

THE LOWER ZAMBEZI REGION

Physical description
The Lower Zambezi region (340,000 km²) extends from the upper reaches of Cahora Bassa Gorge – which is

dammed to form the immense Cahora Bassa Reservoir – to the Zambezi Delta on the Indian Ocean coast. Cahora Bassa Reservoir has a total surface area of nearly 2,700 km^2 at maximum storage, and an live storage volume of 51,700 Mm^3. Dry season temperatures often exceed 40° C in this semi-arid landscape, and most tributaries flow intermittently or on a seasonal basis. The perennial Manyame River, draining eastern Zimbabwe, is the only significant source of local runoff along the course of the Zambezi through Cahora Bassa reservoir.

Operation of Cahora Bassa Dam, which regulates a total catchment area of 1,050,000 km^2 (75% of the entire Zambezi Basin) for hydropower production has a profound effect on Zambezi flows (Figure 7). Inflows to Cahora Bassa, although significantly modified by upstream Kariba and Itezhi-Tezhi/Kafue Gorge Upper dams, resemble the characteristic pattern of natural inflows due to substantial unregulated runoff contributed from the Luangwa River catchment. Downstream flows occur 1-2 months earlier than under unregulated conditions, however, and are substantially reduced in magnitude and duration during the peak flooding months of February and March. Dry season flows have increased two-fold relative to unregulated conditions. These conditions are exacerbated during drought periods, when inflows are fully attenuated and downstream peak flows are negligible.

The Lower Zambezi below Cahora Bassa Dam is a complex physical system with four river-floodplain zones comprising narrow gorges, mobile sand-braided reaches, anabranching reaches, and coastal distributaries (Davies *et al.* 2001). Key tributaries include the unregulated Luia and Revuboe rivers draining the Mozambique highlands to the north, and Luenha River (known as the Mazoe River in Zimbabwe) contributing runoff from the Harare highlands. The Zangue River also is important as an historical hydrologic link between the Zambezi and major Pungue River system to the south.

The Shire River is the largest tributary in the Lower Zambezi region, draining the Great Rift Valley of southern Tanzania, Malawi, and Mozambique north of the Zambezi. The Shire River originates as outflow from Lake Malawi (catchment area 125,976 km^2), the third largest natural lake in Africa with a surface area of 29,601 km^2. Downstream of its Lake Malawi inlet, the Shire River spreads over Lake Malombe and the Liwonde floodplain, before dropping more than 380 m through a series of rapids and cascades – three of which have been dammed for hydropower production. In the lower Shire reaches the river opens up again and spreads across broad floodplains, including the Elephant and Ndindi marshes, before its confluence with the Zambezi.

About 40 km downstream of the Zambezi-Shire confluence, the Zambezi divides into three main branches and a series of smaller distributary channels, forming a large, flat alluvial delta that extends 120 km inland from the Indian Ocean coast and 200 km along the coast. The Zambezi Delta northbank drains the Morrumbula Plateau that separates the Shire and Zambezi Valleys. The Delta southbank, which includes the Marromeu Complex (the Marromeu Buffalo Reserve and four hunting concessions), receives runoff from the adjacent Cheringoma escarpment.

Patterns of hydrological variability and change
Mean annual rainfall for the Lower Zambezi region is about 1,000 mm, decreasing from north to south in the interior, and increasing steadily near the Indian Ocean coast where coastal systems and cyclones have significant influence. Runoff generated within the Lower Zambezi region (37,276 Mm^3) is similar to the Upper and Middle Zambezi regions, although the Lower Zambezi region is smaller in size, due to higher overall runoff efficiency (0.10). Flows are highly variable from year to year, as is true throughout the system (coefficient of variation of 0.45). Multi-year cycles of above-average and below-average runoff are evident in the historical record, but less pronounced than in much of the Upper and Middle
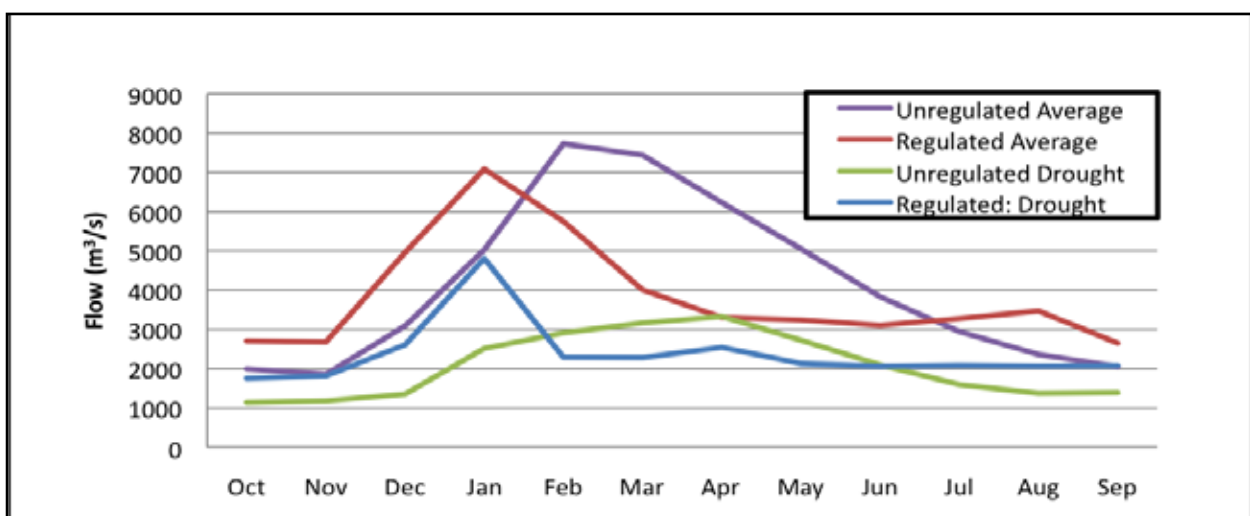

Figure 8. Mean monthly flows in the Zambezi Delta during average and drought years, under natural (unregulated) and regulated conditions.

Zambezi regions (Beilfuss 2002). Cumulative mean annual runoff from the Zambezi is an estimated 110,732 Mm³, a flow rate of 3,511 m3/s.

Regulation of the Zambezi River for hydropower production has a significant effect on hydrological conditions and variability throughout the Lower Zambezi region (Figure 8). Under unregulated conditions, river levels typically begin rising in late December in response to rainfall in the Lower Zambezi catchment, peaking between February and April as the runoff arrives from the Upper and Middle Zambezi catchments, and gradually receding to dry season low-flows in October and November. This pattern of gradual ebb and flow was repeated, though much diminished, during drought years. Runoff in the Zambezi Delta region is now strongly affected by upstream regulation for hydropower production, altering the timing, magnitude, and duration of runoff events. Mistimed flood pulses are often generated during the late dry season in response to required drawdown releases from Cahora Bassa Reservoir, discussed below. Peak flows occur 1-2 months earlier under regulated conditions, generated largely from unregulated flow contributions below Cahora Bassa Dam, and are characteristically "flashy" with rapid rise and recession. Flood flows in February, March, and April are substantially reduced; November low flows have increased more than 200%. The duration of flood pulses to the delta floodplains has been dramatically reduced, from 56.1 to 9.7 days on average, due to upstream hydropower production. Delta flooding is now more dependent on local rainfall and inflow from the Shire River/Lake Malawi catchment than prior to regulation. During drought condition, spillage of excess reservoir water is curtailed and flows reflect only constant turbine outflows

About 6% of inflows (4,400 Mm³) are lost through evaporation from Cahora Bassa Reservoir, far exceeding the combined total of all water off-takes from the Lower Zambezi region. Several additional large dams have been proposed for the Lower Zambezi region, most notably the Mphanda Nkuwa Dam located 60 km downstream of Cahora Bassa Dam, which is described below.

SUMMARY

The Zambezi River Basin has one of the most variable climates of any major river basin in the world, with an extreme range of conditions across the catchment and within and among years. Average annual rainfall is about 960 mm, but varies from more than 1,600 mm per year in some far northern highland areas to less than 550 mm per year in the low-lying south/southwestern portion of the basin. Runoff likewise is concentrated in the northern part of the basin, where five major catchments contribute almost two-thirds of the total Zambezi runoff. Average annual potential evaporation (about 1,560 mm) far exceeds rainfall across the basin. Vast floodplains provide significant flood attenuation and water storage capacity throughout the river basin.

Mean annual runoff is highly variable from year to year, and extreme floods and droughts are a regular feature of the historic flow record. The northern catchments show multi-year cycles of prolonged periods with alternating below-average and above-average flow conditions over the past century. These findings are consistent with regional studies of other sub-Saharan river flows. Thus, the entire Zambezi River Basin, especially the drier sub-basins, is highly susceptible to droughts (often multi-year droughts) that occur nearly every decade, and are likely to become worse with climate change, as discussed below. The implications of the extreme variability on hydropower development and vulnerability are discussed in the next section.

Zambezi River flows are highly modified by large dams in the Middle and Lower Zambezi regions, particularly Kariba and Cahora Bassa dams on the Zambezi mainstem, and Itezhi-Tezhi and Kafue Gorge Upper dams on the Kafue River tributary. Zambezi hydropower dams have profoundly altered the hydrological conditions most important for downstream livelihoods and biodiversity, especially the timing, magnitude, duration, and frequency of seasonal flood pulses. More than 11% of the mean annual flow of the Zambezi River is lost to evaporation from large reservoirs associated with hydropower dams. These water losses increase the risk of shortfalls in power generation, and have a significant impact on downstream ecosystem functions.

Because the dams are generally operated to maximize hydropower, overbank flood pulses now occur only during major runoff events in the basin, and are of inadequate volume and duration to sustain the healthy functioning floodplain systems of global importance, such as the Kafue Flats and Zambezi Delta. High flood pulses, when they occur, are generated during emergency flood releases or the late dry season in response to required drawdown releases. Dry season flood-recession is replaced by constant dry season flows generated from hydropower turbine outflows. The economic impact of these changes on downstream ecosystem services is an important factor in the overall financial risk associated with hydropower development, especially in changing climates, as discussed in Part 5.

NOTES

1. Runoff efficiency (defined in terms of a dimensionless runoff coefficient) is the fraction of total rainfall that occurs as runoff.

2. Potential evaporation or potential evapotranspiration (PET) is defined as the amount of soil and water evaporation and plant transpiration that would occur if a sufficient water source were available.

3. Drainage density is the total length of all streams and rivers in a drainage basin divided by the total area of the drainage basin. It is a measure of how well or how poorly a catchment is drained by stream channels.

4. The coefficient of variation is defined as the ratio of the standard deviation to the mean – it reflects the extent of variability relative to the mean flow condition

5. Live (or Active) storage is the portion of the reservoir that can be managed for power production, downstream releases, or other purposes. The remaining dead storage is the volume of water stored below the lowest outlet or operating level of the reservoir, which is thus inaccessible for management.

Part 3: Hydropower development and vulnerability in the Zambezi Basin

From source to sea, the Zambezi River Basin has significant hydropower development potential, and has long attracted investment interests (Hidrotecnica Portuguesa 1965, GPZ 1973, CRI Consortium 2001, Euroconsult and Mott Macdonald 2008, World Bank 2010, SWRSD Zambezi Joint Venture 2010, many others). The basinwide assessment of hydrological variability in the previous section, however, reveals that hydrological conditions in the Zambezi River system are extremely variable, with a high level of unpredictability and strong cyclical periods of severe drought (including two prolonged drought periods in past century) and extreme floods. The basin is characterized by low runoff efficiency, with significant fluctuations in runoff generated from small changes in rainfall. There also is considerable hydrological variability across the basin, ranging from high rainfall areas in the north to semi-arid to arid regions in the south/southwest.

The degree to which existing and planned hydropower developments have taken this variability into consideration is critical to understanding the long-term risk and uncertainty associated with hydropower production. Several engineering studies conducted during the 1970s argued that annual flows in the Zambezi system were increasing over time as a result of changes in land use and runoff patterns in the catchment (e.g., SWECO 1971, Balasubrahmanyam and Abou-Zeid 1982a), for example, and that the trends observed from the 1940s to 1970s would continue in perpetuity. These studies proposed rates of hydropower generation that far exceeded the Zambezi's potential when considered over the full 92-year flow record. This section examines current and proposed hydropower development in the Zambezi River Basin, and the hydrological assumptions upon which those developments are based. In the next section, we examine the impact of climate change on these patterns of hydrological variability, and the implications for hydropower in the basin.

EXISTING HYDROPOWER DEVELOPMENT

The Zambezi River Basin currently has approximately 5,000 MW of installed hydropower generation capacity (Table 2). Major dams include Kariba and Cahora Bassa dams on the mainstem Zambezi River, Itezhi-Tezhi and Kafue Gorge Upper dams on the Kafue River, and the Kamuzu Barrage that partially regulates Lake Malawi

Table 2. Existing hydropower projects and reservoirs in the Zambezi River Basin

Name	Utility	River	Country	Type	Capacity (MW)
Victoria Falls	ZESCO	Zambezi	Zambia	Run-of-river	108
Kariba	ZESCO, ZESA	Zambezi	Zambia, Zimbabwe	Reservoir	1470
Itezhi-Tezhi	ZESCO	Kafue	Zambia	Reservoir	n/a
Kafue Gorge Upper	ZESCO	Kafue	Zambia	Reservoir	990
Mulungushi	ZESCO	Mulungushi	Zambia	Reservoir	20
Lunsemfwa	ZESCO	Lunsemfwa	Zambia	Reservoir	18
Lusiwasi	Private	Lusiwasi	Zambia	Run-of-river	12
Cahora Bassa	HCB	Zambezi	Mozambique	Reservoir	2,075
Wovwe	ESCOM	Wovwe	Malawi	Run-of-river	4
Nkula Falls A& B	ESCOM	Shire	Malawi	Run-of-river	124
Tedzani	ESCOM	Shire	Malawi	Run-of-river	90
Kapichira Stage I	ESCOM	Shire	Malawi	Run-of-river	64

water levels for downstream Shire River hydropower production in association with Nkula Falls, Tedzani, and Kapichira Stage I hydropower dams. A review of these hydropower projects, and their impact on hydrological variability and uncertainty, is provided below.

Kariba and Cahora Bassa dams

Two large hydropower dams operate on the mainstem Zambezi River. Kariba Dam spans the border between Zambia and Zimbabwe, 397 km downstream of Victoria Falls. Cahora Bassa Dam occurs entirely within Mozambique, some 240 km downstream of the Zambia–Zimbabwe border. Kariba and Cahora Bassa share many similarities in their design and operation, as well as some important differences (Table 3). Kariba Dam has the largest reservoir by volume in the world (more than 180,000 Mm^3 at full supply level) and fourth largest reservoir with respect to surface area (5,577 km^2).

Kariba and Cahora Bassa dams are operated to maximize hydropower production, with a secondary flood control function. As described in the previous section, the operation of Kariba and Cahora Bassa dams has profoundly changed hydrological conditions in the Zambezi River, altering the timing, magnitude, duration, and frequency of natural flows. Evaporative water loss from the vast Kariba reservoir is approximately 16% of total inflows, and Cahora Bassa reservoir loses an additional 6% of inflows to evaporation.

Neither Kariba nor Cahora Bassa dams has sufficient discharge capacity to pass the maximum probable incoming flood. Both dams use a design flood rule curve[1] to set their maximum end-of-month reservoir water levels. Water storage in the reservoirs is balanced between maintaining water levels close to the maximum permissible elevation (to maximize hydraulic head on the turbines) and releasing water from the reservoir before each rainy season (to accommodate and store incoming floodwaters without breaching the dam wall).

The deep, narrow Cahora Bassa reservoir has a very high hydropower output per unit of reservoir area (1.4 MW/km^2) relative to Kariba (0.3 MW/km^2). The ratio of reservoir storage volume relative to mean annual runoff volume for Cahora Bassa Dam (0.69) is about half that of Kariba (1.4). This has important consequences for water-release patterns from both dams. Kariba reservoir is capable of storing the Zambezi's entire mean annual inflow volume. During the prolonged dry period from 1981-2001, Kariba reservoir released only turbine outflows without any excess spillage. As reservoir levels fell close to minimum operating levels in the mid-1980s and again in the early and mid-1990s, even relatively large runoff events in the Zambezi Basin (e.g., 1989, 1992, 1998) were completely absorbed by the reservoir. Cahora Bassa, however, does not have the capacity to store the mean annual runoff volume, and frequently spills water through sluice gates in addition to waters released through turbines for hydropower generation. The spillage of excess waters has important implications for downstream environmental flows, flood management, navigation, and other management concerns in the Lower Zambezi region. Environmental flow releases for social or environmental purposes are not stipulated for Cahora Bassa or Kariba Dam at present.

The flow series used to estimate Kariba firm power output, total energy generation, and the design flood was originally based on a 47-year record for flows at Victoria Falls (covering 1907-1954). The record included the extreme drought period of the early 1900s, followed by a relatively wetter period through 1950. Studies for SADC by Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990) later confirmed the current firm power and total energy targets based on an extension of the flow series through 1990.

The flow series used to estimate Cahora Bassa firm power output, total energy generation, and the design flood was originally based on a 34-year record (1930-1964) for flows at Dona Ana (near the Shire-Zambezi confluence) in Mozambique (Hidrotecnica Portuguesa 1965). This record reflects a relatively wet period in the historic record, without any prolonged drought. Modeling studies suggest that power production would have been curtailed for prolonged periods during the critical drought period of 1980-95, but the dam did not transmit energy during this entire

Table 3. Characteristics of Kariba and Cahora Bassa hydropower dams

	Kariba	Cahora Bassa
Year completed	1958	1974
Design	Double-curved concrete arch	Concrete arch
Height of wall	131m	163m
Width of wall	633m	303m
Generating capacity	1,470 MW*	2,075 MW
Surface area	5,577 km²	2,665 km²
Live storage volume	64,800 Mm³	51,704 Mm³
Full supply level	488.5 m asl	326 m asl
Power output per reservoir area	0.3MW/Km²	1.4 MW/km²
Storage to flow volume ratio	1.4	0.69
Turbines	12	5
Sluice gates	6	8 + crest gate
Maximum discharge capacity	9,515m³/s	16,250m³/s
Evaporative water loss	16%	6%

720 MW north bank power station and 750 MW south bank power station.

period until its international transmission lines, sabotaged during the civil war, were restored (Beilfuss 2010).

Beilfuss (2002) describes the management of extreme floods since the hydrological regulation of the Zambezi. Kariba and Cahora Bassa dams face significant long-term challenges in their management of extreme floods in the basin. Both dams are optimized for hydropower production, and seek to maintain maximum allowable water levels in their reservoirs, in accordance with the design flood rule curve. This strategy provides maximum head for turbine generation, but compromises the secondary (and subjugated) objective of flood control. Descriptions of major flooding events in the Lower Zambezi region dating back to 1830 are common in the oral histories of people in the delta region. Since the construction of large hydropower dams, however, rapid large flooding events had a severe social and economic toll. In 1978, flooding on the lower Zambezi caused an estimated $62 million worth of damage and necessitated flood relief operations costing an additional $40 million. Many of these costs can be attributed to the encroachment of people onto lowland areas of the Zambezi floodplains that had never been historically occupied before Kariba regulation. As noted by the engineering firm Rendel, Palmer and Tritton (1980), "this was the first flood since completion of Cahora Bassa, and destroyed the widely held belief that the dam would finally bring flooding under full control. "The flood resulted from a combination of emergency releases from Kariba and Cahora Bassa dams and heavy runoff from lower Zambezi tributaries. RPT (1980) showed that if the reservoir had released water in January and February, gradually stepping up the outflow to 7,000 m3/s, releases would have been significantly less than actually occurred with adequate time to evacuate the most flood-prone areas. Dam management during subsequent large flooding events in 1989, 1997, 2001, 2005, and 2008 also has been the subject of considerable public scrutiny (e.g., Hanlon 2001)

Itezhi-Tezhi and Upper Kafue Gorge dams

The Kafue River is the most regulated tributary of the Zambezi River. The first dam on the Kafue River was completed at the Upper Kafue Gorge site in 1972. Kafue Gorge Upper Dam is a gravity, earth-rockfill dam, with a crest height of 50 m at 981.5 masl and a total reservoir capacity of 885 Mm3 (SWECO 1971). Six turbines generate 900 MW at capacity[2], with a maximum discharge of 252 m3/s.

Because high evaporation losses from the Kafue Flats reduce the water available for power generation at Kafue Gorge hydroelectric station, a second dam was designed to stabilize river flows below 250 m^3/s, the discharge at which overbank flooding occurs (DHV 1980). Construction of Itezhi-Tezhi Dam commenced in 1973 and began impounding water in December 1976. The dam is a gravity earth-rockfill dam, with a crest height of 65 m and length of 1,800 m. Reservoir capacity is 5,700 Mm^3. Itezhi-Tezhi Dam has a maximum outlet capacity of 6,000 m^3/s. This spillway is inadequate to pass extreme

floods, and a design flood rule curve is adopted to draw the reservoir down prior to flood seasons.

Releases from Itezhi-Tezhi Dam are dictated by power generation needs at Kafue Gorge Dam (typically about 168 m^3/s, well below the level of required to inundate the floodplain) except during periods of exceptional runoff from the upper catchment.[3] As a result, the extent of flooding in the western portion of the Kafue Flats has been greatly reduced, while the eastern portion of the flats has been inundated by Kafue Gorge Upper reservoir. During March, an ecological freshet of 315 m^3/s is stipulated for the Kafue Flats, but it is irregularly released, as described above.

Lake Malawi/Shire River dams

Kamuzu Barrage at the outlet of Lake Malawi is operated to maintain high dry season flows in the Shire River for run-of-river hydropower generation at Nkulu A&B, Tedzani, and Kapichira 1 stations. The Nkula Falls hydropower development, commissioned in 1966 and located downstream of Liwonde, consists of two powerhouses with a total capacity of 124 MW. The Tedzani hydropower development, located downstream of Nkula Falls, has a total capacity of 90 MW. Kapichira Phase I, recently completed and located downstream of Tedzani, can generate a total of 64 MW. Above 475.32 masl, Kamuzu Barrage has no flow control function. The head ponds of all three power plants are severely affected by siltation and thus require periodic dredging.

Other hydropower projects

Victoria Falls hydropower consists of three power plants that produce 105 MW. The oldest of the generating stations was constructed in 1937. The power stations are fed by a left-bank diversion at the level of the falls. The power plants do not run year round; production is curtailed during low flows to maintain discharge at the falls.

Three small hydropower stations are located in the Luangwa sub-basin. The Mulungushi power plant located on the Mulungushi River tributary of the Luangwa sub-basin has four turbines with a generating capacity of 16 MW. A small reservoir with 230 Mm^3 storage capacity, located five kilometers upstream of the powerhouse, provides regulation. The Lunsemfwa powerhouse is located on the Lunsemfwa River, also a tributary of the Luangwa. Commissioned in 1945, its total capacity is 18 MW through three turbines. Flow regulation is provided by a reservoir (45 Mm^3) located 30 kilometers upstream from the powerhouse. The Lusiwasi powerhouse, located on the Lusiwasi River tributary, has a capacity of 4 MW.

The 4.5 MW Wovwe run-of-river hydropower dam is located in northern Malawi on the Wovwe River tributary of Lake Malawi.

PLANNED HYDROPOWER DEVELOPMENT

The Zambezi River Basin has considerable hydropower potential, estimated at greater than 13,000 MW basinwide. In addition to the 5,000 MW of developed capacity, 6,634 MW is proposed for development before 2025 and several other major sites are identified for construction over a longer time-frame. Major projects that have received serious consideration for each region are described below. Many additional project concepts persist in various reports and memos scattered across the region.

Upper Zambezi region

Significant hydropower generating potential has been identified in the Zambezi headwaters region, including key tributaries in Angola, but no hydropower projects are currently in planning. Large-scale irrigation projects are under consideration in Angola's Upper Zambezi sub-basin that could affect water availability downstream, however. The hydropower project that has received the most attention in the Upper Zambezi region is the proposed Katombora Dam, located 60 km upstream of Victoria Falls on the mainstem Zambezi. Katombora would stabilize water levels for firm energy production at two large power plants located downstream at Victoria Falls – a 390 MW station on the north bank (Zambia) to replace the existing Victoria Falls power plant and a second 300 MW station on the south bank (Zimbabwe). Katombora would also firm up energy production at the proposed Batoka Gorge and Devils Gorge hydropower stations downstream (World Bank 2010). However, development of hydropower at Katombora would have a serious impact on water flows over Victoria Falls, a World Heritage Site and major source of tourism revenue, and is unlikely to secure support.

Middle Zambezi region

The Middle Zambezi region has substantial hydropower potential, with new hydropower projects totaling more than 5,000 MW in various stages of consideration. Potential new power generation schemes include the 1,600 MW Batoka Gorge, 1,200 MW Devils Gorge, and 640 MW Mupata Gorge hydropower dams on the mainstem Zambezi, and the 450 MW Kafue Gorge Lower Dam on the Kafue River. Proposed extensions to existing power stations would increase power output by about 600 MW at Kariba and 80 MW at Itezhi-Tezhi.

Batoka Gorge, a bilateral hydropower project between Zambia and Zimbabwe, would be located 50 km downstream of Victoria Falls. The proposed dam has a 181 m high wall, and its reservoir would have a surface area of 25.6 km². North and south bank power stations would provide up to 800 MW of capacity each for Zambia and Zimbabwe. A full feasibility study was completed in 1993 (Batoka Joint Venture Consultants 1993). Project design

is based on the long-term time series of daily flows at Victoria Falls, dating back to 1907. The project received renewed media attention in mid-2012, with word of resumed high level talks and financial agreements between Zambia and Zimbabwe.[4] Climate change considerations have not been incorporated into project design, although Harrison and Whittington (2002, 2003) raised concerns about the financial susceptibility of the Batoka Gorge scheme to reduced runoff under future climate change scenarios, discussed further below.

Two other bilateral projects on the mainstem Zambezi are less likely in the foreseeable future. The proposed hydropower dam at Devils Gorge (1,200 MW) located between Batoka Gorge and Kariba, would include north and south bank power stations, each with a capacity of 600 MW. The project is not considered economically viable and has been postponed indefinitely (World Bank 2010). Mupata Gorge, located downstream of Kariba Dam on the Zambezi River near the Mozambique border, would have an installed capacity of between 640 and 1,200 MW. The Mupata Gorge reservoir would inundate Mana Pools, a UNESCO World Heritage Site located on the south bank (Zimbabwe), and also Lower Zambezi National Park on the north bank (Zambia), and therefore is not under serious consideration at present (World Bank 2010).

In addition to new dam construction, additional generating capacity is proposed for Kariba North Bank (360 MW) and Kariba South Bank (300 MW) in the near future (World Bank 2010). Adequate space for two additional units at Kariba North powerhouse was allocated when the original plant was constructed.

Among the major Zambezi tributaries, the Kafue River has the greatest hydropower development potential. The Kafue Gorge Lower Hydropower Project is proposed for construction two km downstream of the existing Kafue Gorge Upper Hydropower Project. A feasibility study for developing 600 MW capacity in the Kafue Gorge Lower, with an additional bay for 150 MW, was completed in 1995 (HARZA Engineering Company 1995). This project is under serious consideration by the International Finance Corporation (MHW/IFC 2009).

The Itezhi-Tezhi hydropower extension would be located at the existing dam site and consist of an underground powerhouse with two 60 MW Kaplan units. A feasibility study was completed in 1999 (HARZA Engineering Company 1999) and the project has been fast-tracked to meet existing power shortages. As discussed above, Itezhi-Tezhi reservoir is operated mainly for regulation of the Kafue Gorge Upper and is subject to various operational constraints. At this writing, construction of the hydropower plant was underway.

Additional multipurpose dams for irrigation and hydropower production have been proposed, most notably the Gwayi Shangani Dam on the Gwayi River (for water supply to Bulawayo, Zimbabwe) and the Lower Lusemfwa Dam (35WM) in Zambia and mainstem Luangwa Dam (40MW) in the Luangwa River Basin (SWRSD 2010).

Lower Zambezi region

The Lower Zambezi region also has considerable hydropower potential, including large mainstem hydropower schemes and many smaller tributary dams. Proposed hydropower dams on the mainstem Zambezi include Mphanda Nkuwa, Boroma, and Lupata Gorge dams. The proposed Mphanda Nkuwa project site is located 61 km downstream of the Cahora Bassa Dam. The project comprises a 101-meter-high roller-compacted concrete dam impounding a reservoir with a surface area of approximately 96.5 km² at full supply level. Proposed generating capacity is 1,300 MW, composed of four 325 MW units (LI-EDF-KP Joint Venture Consultants 2000). Climate change considerations have not been incorporated into project design. Development of up to 2,275 MW for peak power production is possible with an extension to the north bank power station or construction of a separate underground power station on the south bank. Operation of Mphanda Nkuwa Dam for peaking power would require the construction of Boroma dam downstream to stabilize (re-regulate) fluctuating river flows downstream (LI-EDF-KP Joint Venture Consultants 2000). Boroma itself would have a generating capacity of 444 MW. The feasibility studies for Mphanda Nkuwa rejected an alternative, mutually exclusive dam site at Cambewe Foz, due to higher construction costs (LI-EDF-KP Joint Venture Consultants 2000). Further downstream, the Lupata Gorge Dam site, with 654 MW generating potential, is not under serious consideration at present.

The 1,200 MW Cahora Bassa North Bank power station is proposed for peaking power. The project consists of a new underground powerhouse on the north bank of the Zambezi River with three 283.3 MW Francis units (Norconsult 2003). A new spillway, designed to increase the total discharge capacity of Cahora Bassa Dam by 3,600 m³/s, would eliminate the need for the present design flood rule curve (Beilfuss 2010).

The Zambezi Valley Development Authority of Mozambique proposed 53 small-scale hydropower development projects on tributaries in the Tete sub-basin, including 15 dams in the Luia Basin, 12 in the Revuboe basin, 12 in the Luenha basin, and 14 on other tributaries (Hidrotechnica Portuguesa 1965). Detailed follow-up studies of individual projects larger than 4 MW suggested that only two of the tributary projects were worth considering, the Luia 6 (16.5 MW) and the Luenha 7 (13.2 MW). Neither is currently in planning.

In the Lake Malawi/Shire River sub-basin, several hydropower projects are proposed on tributaries to Lake Malawi. Songwe I, II, and III were identified for hydropower development on the Songwe River, with a combined generating capacity of 340 MW (NORPLAN 2003). The Rumakali Hydropower Scheme (222 MW generating capacity) would be located on the Rumakali River, 85 km west of Njombe in southwestern Tanzania (SwedPower and Norconsult 1998). The Lower Fufu dam would regulate runoff from the north Rukuru and south Rumphi rivers,

> **Substantial evaporative water losses from large reservoirs, especially Kariba and Cahora Bassa, reduce water availability in the basin and will increase with climate change.**

routed through an underground power station with 70-145 MW generating capacity. None of these projects would significantly alter inflows to Lake Malawi.

The 180 MW Kholombidzo, 40 MW Tedzani 1 & 2 refurbishment, and 64 MW Kapichira II dams are proposed for the Shire River. Two alternatives have been analyzed for hydropower development at Kholombidzo – the High Kholombidzo Dam would partially control the outflow of Lake Malawi,[5] whereas the Low Kholombidzo Dam would not affect Lake Malawi water levels (Norconsult 2003). The second phase of the Kapichira hydroelectric power project entails a doubling of generation capacity from 64 to 128 MW as planned in the original design specifications.

HYDROLOGICAL VARIABILITY AND ZAMBEZI HYDROPOWER DEVELOPMENT

Hydropower generation is fundamentally dependent on river flows. As described above, natural flows in the Zambezi Basin vary seasonally, among years, and over longer-term climatic cycles, which include periods of prolonged drought. This variability has had a significant impact on the operation of existing large dams in the Zambezi River Basin, with respect to meeting firm power requirements and total power generation goals during droughts, and also with respect to managing extreme flooding events.

Extreme flooding events, a natural feature of the Zambezi River system, have become more costly downstream since the construction of large dams. Reservoir outflow capacity is inadequate to discharge the maximum probable inflows, and each dam follows a design flood rule curve to prevent over-topping that frequently result in poorly timed or sudden water releases. Increased spillway capacity, proposed for Cahora Bassa Dam, would eliminate the need for a rule curve and allow outflows to ebb and flow more gradually.

Substantial evaporative water losses from large reservoirs, especially Kariba and Cahora Bassa, reduce water availability in the basin and will increase with climate change. Evaporation from these two reservoirs currently results in an 11% reduction in mean annual flows in the Zambezi River. These water losses serve to further increase the risk of shortfalls in power generation, in addition to their significant impact on downstream ecosystem functions and values.

The major existing hydropower dams on the Zambezi were designed based on an inadequate time series of inflows to adequately characterize the full range of natural variability experienced over the past century. As a result, firm power production is vulnerable to periods of prolonged droughts, and dam safety and downstream flood risk is vulnerable to extreme flooding events. Large reservoirs associated with hydropower dams can mitigate this risk somewhat by smoothing out seasonal variations and, in the case of enormous reservoirs with high storage to inflow ratios, such as Kariba, some annual fluctuations. The flow series observed on the Zambezi River and the Kafue River show extended periods of above and below normal flow, however. Hydropower models using this entire time series for the Zambezi River Basin (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990; Beilfuss 2010) indicate that at the end of periods of prolonged drought, including 1907–1924 and 1981–1995, reservoir levels fall to the minimum supply level and turbine discharges may be curtailed for prolonged periods.

Recently proposed hydropower projects have access to a more complete hydrological record of the past century and can presumably better account for long-term patterns of inflow variability. If past infrastructure and energy commitments had been based on our present knowledge of this variability, for example, the impact of drought on energy production might have been reduced. As we discuss in the next section, however, historic flows from the past century are not a reliable indicator of future mean annual flows or the seasonal and annual fluctuations in runoff variability expected over the next century with global climate change.

NOTES

1. The Design Flood Rule Curve stipulates the maximum permissible end-of-month water levels in the reservoir to prevent over-topping of the dam. The curve is derived from the maximum discharge capacity of the dam relative to the maximum probably flood. The rule curves do not stipulate that the water must reach a particular level at a particular time, but only that it cannot exceed (or must remain above) a particular level at a particular time.

2. The Kafue Gorge Upper power plant is being upgraded from 900 to 990 MW.

3. Itezhi-Tezhi reservoir must release a minimum flow of 40 m3/s, which includes 25 m3/s for baseflow maintenance and 15 m3/s for various water abstractions.

4. For example, *The Times of Zambia* headline on 16 February 2012 proclaims "Zim, Zambia ink $4bn Batoka deal."

5. This proposed project replaces the original high dam design, which featured a higher crest level that would have allowed full control of the Lake Malawi drawdown with higher generating capacity. The original proposal was abandoned, however, as it would have flooded prime agricultural land and infrastructure, displaced a large population, and increased the potential for severe flooding downstream.

Part 4: Impact of climate change on Zambezi Basin hydrology and hydropower

The African continent is highly vulnerable to climate change, and the Zambezi River Basin is particularly at risk. Part 2 characterized the climate cycles and natural hydrological variations in the Zambezi Basin, including long-term cycles of wet and dry periods over the past century. Zambezi runoff is highly sensitive to these variations in climate, as small changes in rainfall produce large changes in runoff. Over the next century, climate change is expected to increase this variability, and the vulnerability of the basin – and its hydropower dams – to these changes. Concerns about the impact of climate change on water resources development in the Zambezi River Basin are given prominent treatment in the recent "investment opportunity assessment" commissioned by the World Bank (2010) and the "dam synchronization and reoperation study" commissioned by SADC/GTZ (SWRSD 2010).

The details of climate change trends and forecasts for Southern Africa can be difficult to discern from the high level of natural variability in temperature, rainfall, and runoff; and confounded by the relatively low density of long-term monitoring stations across the continent. Most climate change assessments for Africa rely on large-scale General Climate Models (GCMs), developed for a range of different emission scenarios (which, in turn, are based on different assumptions about economic growth, population expansion, and technological change). A few Regional Climate Models (RCMs) downscaled from global models recently have been constructed for Africa (Christensen *et al.* 2007), but further modeling efforts (now underway) are needed to improve the accuracy of climate forecasts specific to the Zambezi Basin and its sub-basins. River basin managers often site this "uncertainty" as a justification for ignoring or downplaying climate change.

The general climate picture for Southern Africa is increasingly clear, however, based both on observed trends over the past century and increasing confidence in the range of climate change scenarios already developed. The following sections describe the current state-of-the-art predictions for climate change in Southern Africa, including temperature, evapotranspiration, rainfall, and runoff, based on the IPCC and other peer-reviewed technical reports.

TEMPERATURE

The Zambezi River Basin is expected to experience a significant warming trend over the next century. The general consensus emerging from modeling suggests an increase of 0.3-0.6° C per decade. Figure 9 shows observed and simulated trends in temperature for the previous century, and projected temperature trends over the next century for Southern Africa.
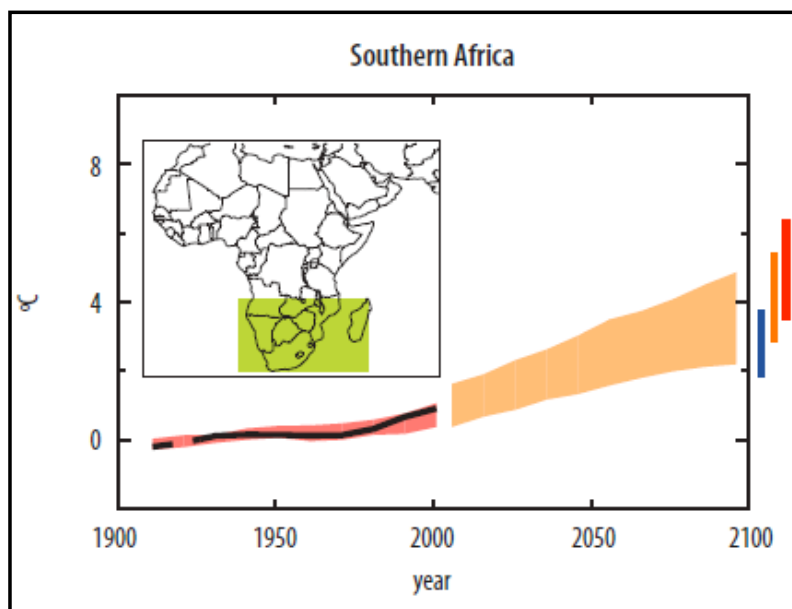
Figure 9. Trends in temperature for Southern Africa. The black line shows observed temperatures, 1906-1999. The range of temperatures simulated by IPCC climate models for the observed period are shaded red; those for the projected period, 2001-2100, are shaded orange. The bars at the end of the area shaded orange represent the range of projected scenarios for 2091 to 2100 in relation to estimated carbon dioxide (CO_2) emission (low in blue, medium in orange, and high in red). With permission from IPCC (2007a).

Direct observations over the period 1960–2000 in Southern Africa indicate a warming trend of 0.1–0.3° C per decade. Under a medium to high emissions scenario (A1B) from the Special Report on Emissions Scenarios (SRES),[1] and using the average of 20 GCMs for the period 2080-2099, annual mean surface air temperature is expected to increase by 3-4° C relative to the 1980-1999 period, with less warming in equatorial and coastal areas (Christensen *et al.*, 2007). Other models (e.g., Ruosteenoja *et al.* 2003), assuming more intensive use of fossil fuels and corresponding emissions, indicate warming over this period up to 7° C for Southern Africa (which equates to approximately 0.7-1.0° C per decade). Downscaled regional climate models predict smaller but still significant temperature increases for Southern Africa (Kamga *et al.* 2005). Temperature increases are projected to be most significant for the highly arid south/southwestern portions of the Zambezi River Basin. Climate models for Southern Africa predict more significant warming during the winter months than summer. Hudson and Jones (2002) forecast a 3.7° C increase in mean surface air temperature in summer (December to February) and a 4° C increase in winter (June to August) by 2080.[2]

EVAPOTRANSPIRATION

The increase in temperatures across the Zambezi Basin will result in higher rates of evaporation and transpiration. Much of the Zambezi River Basin is semi-arid, and substantial water loss occurs due to evapotranspiration. At present, mean annual potential evapotranspiration across the basin is 1,560 mm, and potential evaporation exceeds rainfall during every month of the calendar year, in each of the 13 sub-basins. Over the next century, the Zambezi River Basin is expected to experience a significant increase in the rate of potential evapotranspiration, based on projected increases in temperature coupled with decreased humidity associated with reduced rainfall (below). Arnell (1999, as cited in IPCC 2001) projected an increased rate of evapotranspiration in the basin of 10-25% over the next 100 years.

RAINFALL

The Zambezi River Basin receives about 960 mm rainfall per year, mostly concentrated in the wet season. Considerable variability in rainfall occurs across the basin, from arid/semi-arid regions in the south and southwest to high rainfall regions in the north. Inter-annual variability in rainfall is also high (coefficient of variation = 0.35). Long-term rainfall patterns are difficult to discern from this spatial and temporal variability. However, three significant trends in rainfall for the Zambezi region are apparent from direct observations over the past 40 years (IPCC 2007a):

- A slight reduction in annual precipitation;
- Increased inter-annual variability with more intense and widespread droughts;

> Climate change predictions, based on the average (not extreme) of diverse climate models, have profound implications for future hydropower production and development in the Zambezi River Basin.

- A significant increase in heavy rainfall events in many Zambezi Basin countries (including Angola, Namibia, Mozambique, Malawi, and Zambia), including evidence for changes in seasonality and extreme weather events.

Over the next century, multiple studies cited in IPCC (2007a) estimate that rainfall across the Zambezi Basin will decrease by 10-15%. The predicted decrease in rainfall is associated with a reduction in the number of rainy days and in the average intensity of rainfall. Based on the average of six GCMs, Shongwe *et al.* (2009) project a decreasing rainfall trend with more extreme droughts in northern Botswana, western Zimbabwe, and southern Zambia; generally drier conditions in Zambia and Malawi; and less clear precipitation trends in eastern Zimbabwe and Central Mozambique during the 21st century.

Significant changes in the seasonal pattern of rainfall over the Zambezi River Basin are also predicted, although the magnitude of change is less certain. Shongwe *et al.* (2009) indicate a 10-16% reduction in rainfall during autumn (March-May), 31-35% reduction during winter (June-August) and spring (September-November), and a slight 1% reduction in summer (December-February) (Figure 11). The simulated annual climatic cycles suggest that the rainfall season may begin one month later than the recorded norm, effectively shortening the duration of the rainy season in the northern parts of the Zambezi Basin.

Tadross *et al.* (2005) and New *et al.* (2006) noted evidence of increasing weather extremes in several Zambezi Basin countries, including Mozambique, Malawi, and Zambia. Usman and Reason (2004, cited in IPCC 2007a) predicted a significant increase in heavy rainfall events over Southern Africa (including Angola, Namibia, Mozambique, Malawi, and Zambia). According to the IPCC models, the frequency of extremely dry austral winters and springs will increase to roughly 20%, while the frequency of extremely wet austral summers will double in Southern Africa. There is an emerging consensus that the intensity of tropical cyclones will increase, with less certainly about whether the frequency of these events will increase.[3]

RUNOFF

Zambezi runoff is affected by changes in temperature, evapotranspiration, and rainfall. The Zambezi catchment

> All Zambezi Basin countries will experience a significant reduction in streamflow. Multiple studies estimate that Zambezi Basin runoff will be reduced by 26-40% by 2050.

is characterized by low runoff efficiency, low drainage densities[4], and relatively high aridity, indicating a high sensitivity of runoff to climate change. Given the nonlinearity of rainfall-runoff processes, a small change in annual precipitation or annual potential evaporation can have a large impact on annual river flows. Observed impacts of rising temperatures on runoff in other, comparable basins, for example, indicate that an increase of 1° C leads to an approximate 15% reduction in annual flows, exacerbating flow reductions resulting from decreasing rainfall in the catchment (Cai and Cowan 2008).

Of the 11 African basins reviewed by IPCC (2001)[5], the Zambezi exhibited the "worst" effects in response to climate change, due to the resonating effect of increases in temperature and decreases in rainfall on potential evaporation and runoff. Based on ten scenarios, derived by using five different climate models in conjunction with the SRES-A2 and B2 emissions scenarios, Strzepek and McCluskey (2006) indicate that all Zambezi Basin countries will experience a significant reduction in streamflow. Multiple studies cited in IPCC (2001) estimate that Zambezi Basin runoff will be reduced by 26-40% by 2050.

The World Bank (2010) assessed the percentage change in runoff for each of the major Zambezi sub-basins by 2030, relative to the 1961-1990 baseline. Using the mid-range of 23 GCMs with emissions scenario SRES-A1B, they estimated a 16% reduction in runoff from the Upper Zambezi, 24–34% reduction in the Middle Zambezi, and 13-14% reduction in the Lower Zambezi. Norconsult (2003) carried out a sensitivity analysis of climate change on Lake Malawi using a simple water balance to show that small changes in temperature and evaporation could have a significant impact on outflow to the Shire River.

De Wit and Stenkiewicz (2006) assessed changes in surface water supply (especially perennial water availability) across Africa with predicted climate change. They noted that most of Southern Africa (including the Zambezi River Basin) is an "unstable" rainfall region that receives between 400-1000 mm rainfall per annum with high seasonality. Their models examine perennial drainage density and suggest that a 10% drop in rainfall would result in a 17% reduction in surface drainage for regions receiving ~1000 mm rainfall and a shocking 50% reduction in surface drainage for regions receiving 500 mm rainfall. They note also that the Zambezi sub-basins currently receiving 500-600 mm per year could switch from perennial to seasonal surface water supply under climate change forecasts.

Based on average annual rainfall throughout the Zambezi River Basin (about 960 mm), a ~20% reduction in basin-wide runoff is expected. But rainfall is distributed very unevenly across the basin, with the southern and western parts receiving much less rainfall than the northern and eastern parts. Regions around Harare, Zimbabwe and Chipata, Zambia are each predicted to have a 19% reduction in perennial drainage corresponding to a 10% reduction in rainfall. Maun, Botswana, just west of the Zambezi River Basin in the Okavango River basin, is predicted to have a 72% reduction in runoff corresponding to the same 10% reduction in rainfall. Some tributaries of the Middle Zambezi (draining from Zimbabwe) and lower Zambezi (draining the Mozambique highlands) could likewise experience severe reductions in perennial drainage, perhaps shifting to seasonal periods without flow. As the authors note, the extent to which reduced flow in major rivers reflects direct changes in rainfall-runoff discharge and groundwater flow, rather than reduced perennial drainage, requires further study. However, the results indicate that future availability of water, especially in headwater streams, is a serious concern in many parts of the Zambezi Basin.

CLIMATE CHANGE AND ZAMBEZI HYDROPOWER PRODUCTION

By 2050, the Zambezi River Basin is expected to become hotter and drier, with a 0.3-0.6° C increase in temperatures per decade (0.8° C in the summer months), and a 10-25% increase in evaporation and 10-15% reduction in rainfall across the basin, relative to the 1961-1990 baseline. Runoff is projected to decrease by 26-40% on average over this time period. A shift in the timing (a delayed onset) of the rainy season is expected, as are more amplified seasonal variations (increasing high flows and reducing low flows). The intensity of rainfall will increase, compounded by a high likelihood of more frequent and intense tropical cyclones. Overall, the Zambezi will both be drier and more variable, experiencing more prolonged drought periods and more extreme floods.

These staggering climate change predictions, based on the average (not extreme) of diverse climate models, have profound implications for future hydropower production and development in the Zambezi River Basin. According to the World Commission on Dams (WCD 2000), climate change has the potential to affect hydropower installations in at least five important ways:

■ Reduced reservoir inflows on a seasonal and annual basis, due to decreased basin runoff and more frequent and prolonged drought conditions, reducing energy generation capacity;

■ Increased surface water evaporation, especially from upstream reservoirs and floodplains, further reducing energy generation capacity;

■ Increased extreme flooding (inflow) events, due to higher rainfall intensity and more frequent and intense

Table 4. The effect of a selected number of combinations of temperature, precipitation, and evapotranspiration on inflows to Kariba reservoir, for the period 2030-2050 (SWRSD 2010).

Temperature Change (degree C)	Precipitation change (%)	Potential Evaporation Change (mm/yr)	Runoff Coefficient Change (%)	Total Runoff Change (%)
0	-30	0	-50	-65
0.5	-30	25	-52	-66
1	-30	45	-53	-67
1.5	-30	70	-55	-68
2	-30	90	-56	-69
0	-15	0	-26	-37
0.5	-15	25	-28	-39
1	-15	45	-30	-40
1.5	-15	70	-32	-42
2	-15	90	-34	-44
0	0	0	0	0
0.5	0	25	-3	-3
1	0	45	-5	-5
1.5	0	70	-8	-8
2	0	90	-10	-10

Table 5. The effect of a selected number of combinations of temperature, precipitation, and evapotranspiration on inflows to Cahora Bassa reservoir, for the period 2030-2050 (SWRSD 2010).

Temperature Change (degree C)	Precipitation change (%)	Potential Evaporation Change (mm/yr)	Runoff Coefficient Change (%)	Total Runoff Change (%)
0	-30	0	-53	-67
0.5	-30	25	-55	-68
1	-30	45	-56	-69
1.5	-30	70	-58	-70
2	-30	90	-59	-71
0	-15	0	-27	-38
0.5	-15	25	-30	-40
1	-15	45	-32	-42
1.5	-15	70	-34	-44
2	-15	90	-36	-45
0	0	0	0	0
0.5	0	25	-3	-3
1	0	45	-5	-5
1.5	0	70	-8	-8
2	0	90	-10	-10

tropical cyclones, affecting dam safety and operational rule curves designed to prevent over-topping;
- Altered timing of the wet season flows, especially delayed onset of the rainy season, affecting dam operations as well as downstream release patterns;
- Increased sediment load to reservoirs, resulting from higher rainfall intensity and corresponding erosion, resulting in reduced reservoir capacity (lifespan) and water quality.

Numerous studies have assessed the impact of climate change on hydropower development in the Zambezi River Basin. Some of earliest studies of Zambezi Basin climate change, using first generation climate change models, suggested the potential for significant reductions in hydropower generation (Salewicz 1996), with one study suggesting that Kariba would fail to meet its generation capacity due to low water levels, even in tandem with the proposed Batoka Gorge (Urbiztondo 1992). IPCC (2001) found that hydropower production at Kariba Dam decreased under different two climate change scenarios due to the reduction in river flows caused by higher surface temperatures and associated increase in evapotranspiration.

World Bank (2010) assessed the potential impact of climate change on multi-sector development scenarios for the Zambezi River Basin. They simulated modest basin development with a system of new hydropower production plants as envisaged under the Southern African Power Pool, using moderate climate change scenarios. The projected impact on energy productivity is substantial. Compared to baseline, firm energy[6] falls by 32% from 30,013 to 20,270 GWh per year. Similarly, a significant reduction is seen in the average annual energy production, falling by 21% from 55,857 to 44,189 GWh per year. With less optimistic climate change assumptions, more

> When climate considerations are incorporated, the financial risks may significantly undermine the feasibility of existing and future hyropower projects.

substantial reductions in firm power (43%) and average energy (25%) are predicted.

The SADC-GTZ (SWRSD 2010) study generated a series of simple models to test the sensitivity of hydropower production to climate change and hydrological variability at Kariba and Cahora Bassa Dams, for the period 2030-2050. The model simulated more extreme variability in the predicted flow series, by taking the long-term historic inflow series for each dam, and multiplying the deviation of the historical flow series from the long-term mean by a constant factor for years drier than the mean and another constant factor for years wetter than the mean (effectively making the dry years drier, and wet years wetter). The model results suggest that very substantial reductions in inflows to Kariba (Table 4) and Cahora Bassa (Table 5), would occur under widely accepted climate forecasts, resulting in significant reductions in generating capacity.

The African Dams Project (Beck and Bernauer 2010) examined the effects of three different localized climate change scenarios[7], coupled with different levels of water demand for agriculture, municipalities, and other uses, for the Zambezi River Basin, 2000-2050, including effects on hydropower. Current consumptive water use is about 15-20% of total Zambezi runoff. The research aimed to test how sensitive the basin is to different types and degrees of changes in water demand and supply. The scenarios suggest a reduction in average basinwide runoff ranging from 5% for the best-case scenario to 70% for the worst-case scenario. Flows reaching the Indian Ocean (Zambezi Delta) are reduced by 5-43%. These basinwide effects are even stronger during the dry season, with 10%, 70%, and 93% reductions in mean annual flow, respectively. Correspondingly, the scenarios reflect significant reductions in hydropower generation for Kariba and Cahora Bassa Dams on the Zambezi mainstem. For the worst-case scenario, hydropower is reduced by 60% at Cahora Bassa and by 98% at Kariba. Kafue Gorge Dam, a run-of-river operation, is only minimally affected.

Finally, Beilfuss (2010) developed a simulation model using a 97-year historical flow series, aimed at assessing trade-offs between environmental flow scenarios and firm power reliability[8] and total power generation from Cahora Bassa Dam. The flow series captures the full range of natural variability observed over the past century. The sensitivity of model output to a reduction in mean monthly inflows was also tested. The impact of a 10% reduction in mean monthly flows was moderate; firm power reliability remained at an industry-acceptable 95% level, with a 3.9% reduction in total power generation. More substantial reductions in runoff resulted in unacceptable levels of firm power reliability, however. For a 20% flow reduction, for example, firm power reliability fell to 91.8% with a 13.7% reduction in total power production. These results indicate that firm power contracts and other energy commitments will require renegotiation for modest reductions in future Zambezi River runoff, with corresponding reduction in revenue generation.

Collectively, these diverse studies suggest that future hydropower development in the Zambezi Basin could be very risky from a hydrological perspective. However, misperceptions about this risk are commonplace. A scoping study conducted for the World Bank by Vattenfall Power Consultant (Rydgren et al. 2007), for example, notes:

> "Most hydropower/reservoir operators do not see climate change as a particularly serious threat. The existing hydrological variability is more of a concern, and the financially relevant planning horizons are short enough that with variability being much larger than predicted changes, the latter do not seem decisive for planning."

It is hard to understand this attitude, given the long life of dams, the scale of these investments compared to the size of many African energy sector budgets, and the hydrological uncertainty that climate change is surely bringing. Substantial economic risks are associated with reduced mean annual flows, more extreme flood and drought cycles, and increased evaporative water loss – including risk of structural failure if the design flood is underestimated, and financial risk associated with overestimated firm power generation, reduced revenue from total energy production, and other uncertainties. Water-dependent ecosystem services affected by over-designed hydropower development also are at risk. The financial implications of these risks are discussed in the next chapter.

NOTES

1. The Special Report on Emissions Scenarios of the IPCC (Nakićenović *et al.*, 2000) describes four climate global emissions scenarios that relate future greenhouse gas emission levels to key driving forces:

   SRES-A1: An "integrated" world with a rapid economic growth, a global population that reaches 9 billion and then gradually declines, quick spread of new and efficient technologies, and convergent incomes and way of life among nations. Subsets of SRES-A1 emphasize the relative balance of fossil intensive and non-fossil energy sources.

   SRES-A2: A "divided" world with regionally oriented economic development, continuously increasing population growth, and fragmented technological change (independent, self-reliant nations).

   SRES-B1: An "integrated and more ecological friendly" world with a global population that reaches 9 billion and then gradually declines (as in A1), rapid economic growth (as in A1), but with rapid changes in economies towards service and information, reductions in material intensity introduction of clean and resource efficient technologies, and an emphasis on global solutions to economic, social, and environmental stability.

   SRES-B2: A "divided but more ecologically friendly" world with continuously increasing population (but at a slower rate than A2), emphasis on local rather than global solutions to economic, social, and environmental stability, intermediate levels of economic development, and less rapid and more fragmented technological change than in A1 and B1.

   Three SRES-A1 groups are distinguished by their technological emphasis: fossil fuel energy intensive (A1FI), non-fossil fuel energy intensive (A1T) and balanced across all energy sources (A1B). Here, balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies.

2. Major climate simulation models and their sources for this analysis include the CSIRO2 (*Commonwealth Scientific and Industrial Research Organisation, Australia*), HadCM3 (*Hadley Centre for Climate Prediction and Research, UK*), CGCM2 (*Meteorological Research Institute, Japan*), ECHAM (*Max Plank Institute for Meteorology, Germany*), GISS-NASA (*U.S. National Aeronautics and Space Agency/Goddard Institute for Space Studies*), GFDL (*U.S. Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory*) and PCM (*National Center for Atmospheric Research, U.S.*).

3. Cyclonic events are not explicitly modeled by existing GCMs.

4. **Drainage density** is the total length of all the streams in the drainage basin divided by the total area of the drainage basin – a measure of how well or how poorly rainfall-runoff drains from a given catchment.

5. Other African river basins assessed by IPCC (2001) include the Nile, Niger, Volta, Schebeli, Congo, Ogooue, Rufiji, Ruvuma, Limpopo, and Orange.

6. **Firm Energy** is contractual, non-interruptible power guaranteed by the supplier to be available at all times, except for uncontrollable circumstances.

7. The three scenarios reflect a range of assumptions about changes in population, urbanization, irrigated agriculture, industrial activity/mining, and water storage/hydropower production for the Zambezi Basin, ranging from status quo to strong growth in each sector.

8. Firm power reliability reflects the dependability with which contractual obligations for firm energy supply are satisfied. Firm power reliability can be event-based (number of months during which the target firm output could be met relative to total months of generation) or quantity-based (number of megawatts generated relative to target production) criteria. A 95% firm power reliability indicates that firm energy obligations are met on average in 95 of 100 months.

Part 5: Economic risk of hydropower dependency

T he Zambezi River Basin is highly vulnerable to the negative effects of climate change. Increasing water scarcity due to increasing temperatures and evaporation, decreasing rainfall, and a dramatic reduction in mean annual runoff are predicted before the end of the century. These hydrological changes will fundamentally alter the economic benefits and risks associated with river management, including existing and future hydropower development, and the valuable ecosystem services sustained by river flows. Cumulatively, these economic risks require a careful reconsideration of the future dependency on hydropower development in the basin.

FINANCIAL RISKS ASSOCIATED WITH HYDROPOWER DEVELOPMENT

Numerous studies have indicated that hydropower economics are sensitive to changes in precipitation and runoff (Alavian *et al.* 2009; Gjermundsen and Jenssen 2001; Mimikou and Baltas 1997; Harrison and Whitington 2001, 2003). Uncertainty about future hydrology presents a great challenge for infrastructure planning and engineering. Most hydropower projects are designed on the basis of recent climate history (typically a 30-50 year historic time series of flow data) and the assumption that future hydrological patterns (average annual flows and their variability) will follow historic patterns. This notion that hydrological patterns will remain "stationary" (unchanged) in the future, however, is no longer valid (Milly *et al.* 2008). Under future climate scenarios, a hydropower station designed and operated based on the past century's record of flows is unlikely to deliver the expected services over its lifetime. It may be over–designed relative to expected future water balances and droughts, as well as under-designed relative to the probability of extreme inflow events in the future.

Over-designed projects, resulting from reduced and more variable inflows relative to the historical time series, incur financial risk by generating lower levels of power production than forecast, leading to reduced electricity sales and revenue, including failure to meet firm energy commitments. Capital costs for hydropower are high compared with alternative energy options, and the financial risk of over-design is significant (World Bank 2010). Development of the hydropower sector according to the generation plan of the Southern African Power Pool (NEXANT 2007), for example, will require an investment of $10.7 billion over an estimated 15-year period. A comparable investment in energy efficiency and renewable technologies including biomass, solar, wind, and small-scale hydro, would aggressively expand decentralized (on- and off-grid), clean energy access and markets in Africa (Hankins 2009).

Financial and technical analyses to assess the feasibility of hydropower projects typically evaluate the financial impacts of a range of factors on the ability to generate a positive cash flow; these analyses apply traditional engineering cost/financial analysis to characterize construction and operational costs (e.g., size and location of the project) and future trends that could affect project revenues (e.g., changing demand, new supply, and economic drivers affecting the price of electricity). These assessments rarely evaluate potential power generation and associated revenue changes associated with climate change. When climate considerations are incorporated, the financial risks may significantly undermine the feasibility of existing and future hydropower projects.

The regional economic impacts of reduced hydropower generation from Kariba Dam during the 1991-92 drought, for example, included an estimated $102 million reduction in GDP, a $36 million reduction in export earnings, and the loss of 3,000 jobs (Magadza 2006). Droughts of this magnitude (or worse) will occur more frequently with regional climate change.

Harrison and Whittington (2002) examined the susceptibility of the proposed Batoka Gorge hydroelectric scheme to climate change, with an emphasis on financial risks associated with the project. They reconstructed a flow series for inflows to Batoka Gorge, using the U.S. Army Corps of Engineers HEC-5 reservoir routing program. Inflows to the model were generated using rainfall-runoff models based on precipitation according to three different climate change scenarios (IPCC 2001). Their simulations suggest a strong sensitivity of the Batoka Gorge project to changes in climate. The models indicate significant reductions in river flows (mean monthly flows fell between 10–35%, and both wet season and dry season flows declined), declining power production (mean monthly production fell between 6-22%), reductions in electricity sales and revenue, and consequently an adverse impact on a range of investment measures. Harrison *et al.* (2006) note that climate change scenarios alter not only the financial performance of hydropower schemes such as Batoka, but also the financial risks they face. Changes in climate lead to significant variability in economic performance − reducing not only the mean values for

> By building the "wrong" infrastructure in future, we may actually limit our future options for climate adaptation. An alternative path, focused on climate-smart investments that factor in financial risk and the ecological functions of river systems, is urgently needed.

energy production, but also the reliability of electricity sales income.

In the face of hydropower blackouts caused by low water levels, governments are often forced to buy expensive emergency power, which is not included in the risk analysis for large-dam hydropower. For example, after the 2009 drought in Kenya brought reservoirs to their lowest levels in 60 years, the government brought in Aggreko PLC, a U.K. firm that supplies temporary diesel generators. For an extended period, reports the *New York Times*.[1] Aggreko was delivering roughly 140 MW at a cost of $30 million per year, not including fuel purchases. Meeting future needs through diesel generation could cost the Kenyan government more than $780 million a year – a key reason Kenya is now building wind farms and geothermal plants to bring its hydro-dependency down from 60% to 35%.

Hartman (2008) notes that hydropower planners have been aware of climate change for years, but until recently it was assumed that climate trends were too uncertain, and the range of natural variability too high, to make reliable predictions. From a financial point of view, it was argued that changes beyond 20-30 years from present would have little impact on the financial return of hydropower investments– introducing a mismatch between financial time horizons and water resource management implications, as the physical lifespan of hydropower assets is much longer than the pay-back period. Large and financially powerful hydropower operators from the temperate regions, who might be expected to lead the way in terms of new policy and research, are also the ones expected to be less affected by climate change. Environmental impact assessments and other planning guidelines still do not usually include guidance on hydrological variability and climate change, beyond the impact of extreme flood events on dam safety. Together, these factors have led to a neglect of climate change risks in hydropower planning – in an approach that might be called either "wait-and-see" or "head-in-the-sand" (Hartman 2008).

Among the major hydropower projects in operation or planning for the Zambezi River, the financial risks of climate change were considered by hydropower developers only for the Kafue Gorge Lower project

(Stenek and Boysen 2011). This analysis, for the International Finance Corporation (IFC), combined three GCM models and two SRES emission scenarios to project a set temperatures and precipitation levels over four time periods (base, early-, mid-, and late-century) for the Kafue River Basin. The outputs from each GCM/emission scenario combination were used as inputs for the hydrologic flow modeling of the Kafue River Basin, which provided climate-modified flow rates across four time horizons for each of the GCM/emission scenarios. The flow series was routed through a reservoir model to assess energy production, and a financial risk model.

IFC results indicate that future emission projections have a significant impact on the operations, and therefore the financial viability, of Kafue Gorge Lower project. None of the scenarios exceeded the average annual generation of about 2,450 GWh needed to satisfy investor requirements, and most of the scenarios considered did not yield acceptable returns to investors. The study notes that, "given the significance of water flow on the financial viability of hydropower projects, adaptation planning should include considerations such as climate change, conservation, and development that introduce variability into available water flow to the project." The study concluded that climate change will significantly impact the financial performance of ZESCO's hydropower plants, with the financial viability of hydropower investment dependent on the relative severity of climate change on the basin. These impacts highlight the importance of considering changes in water supply due to climate change when implementing financial analyses for hydropower projects. Governments and investors must become better informed about climate change risks to future hydropower projects by analyzing projects for projected changes in available water flow and power generation, rather than assuming constant flows and power generation rates.

The financial risks of climate change are not under serious consideration for other proposed hydropower projects in the Zambezi River Basin. The design and operation of Mphanda Nkuwa Dam in Mozambique, for example, assumes the continued validity (stationarity) of the mean and variability of the historic flow series, despite climate change forecasts to the contrary. The project has not been evaluated for the risks associated with reduced mean annual flows and more extreme flood and drought cycles, which include the risk of structural failure if the design flood is underestimated, financial risk associated with overestimated firm power generation, reduced revenue from total energy production, and other uncertainties.

Under-design of hydropower projects also poses significant financial risk with respect to future climate change scenarios. The occurrence of extreme flooding events on a more frequent basis (Boko *et al.* 2007) may threaten the stability of large dams and/or force more frequent spillage, which exacerbates downstream flood

damage. The design flood rule curve that governs the risk associated with over-topping Kariba and Cahora Bassa Dams, for example, is based on the historical hydrological record and may not result in adequate reservoir storage capacity for large flood events. The financial and social impact of a major dam failure in the Zambezi River Basin would be nothing short of catastrophic.

> There has been a neglect of climate change risks in hydropower planning – in an approach that might be called either "wait and see" or "head in the sand."

FINANCIAL RISK ASSOCIATED WITH LOST ECOSYSTEM SERVICES

In addition to the direct financial risk associated with over- or under-designed hydropower systems in the face of climate change, continued dependence on hydropower systems in the future will compound the economic and social impacts of reduced ecosystem services already associated with river development. Ecosystem services are the benefits people obtain from ecosystems, and include provisioning services such as crops, livestock, fisheries, timber, medicinal plants and fresh water; regulating services such as climate regulation, flood control, erosion protection, water purification and disease control; cultural services such as spiritual, recreational and cultural benefits, and supporting services such as primary productivity, nutrient cycling and water cycling that maintain conditions for life on earth (Millennium Ecosystem Assessment 2005).

Numerous peer-review studies have attempted to quantify the value of ecosystem services, recognizing a range of economic values including direct and indirect use values (Constanza *et al.* 1998; Brander *et al.* 2006). Direct-use values are derived from the direct utilization of ecosystem services, and may include: commercial fishing; timber extraction; wood for charcoal-making, cooking and heating; drinking, washing and cooking water; and recreational uses such as boating, fishing and tourism. The replacement value[2] of these services, if lost, is even higher – especially in remote areas like the Zambezi Valley.

Indirect-use values are usually harder to define, since they are often neither obvious nor directly marketable. They can include flood protection, storm surge protection, groundwater recharge, sediment retention, erosion prevention, carbon sequestration, and habitat for species of conservation concern. These services are often harder to value since their relationships with marketable goods are often non-existent, and are typically under-valued in important decision-making about wetland and water resources (Brander *et al.* 2006). Collectively, these direct and indirect services, along with option, bequest, and existence[3] values related to current and future enjoyment, have a very significant economic value to society (Constanza *et al.* 1998).

Zambezi Basin stakeholders have identified a range of river-dependent ecosystem services that are vital to food security and socio-economic development for millions of basin inhabitants (Turpie 1999; Beilfuss and Brown 2010; Scott Wilson Piesold 2003). These include:

- Forest and woodland products: Construction wood, fuelwood, wild fruits, honey, medicinal plants, and other forest and woodland resources that can be sustainably harvested;
- Carbon sequestration: Woodlands, grasslands, and peatlands linked to carbon-offset markets;
- Wetland products: Papyrus and reeds used to make a variety of household items, palms used to make palm wine, thatching harvested from seasonal floodplain grasslands, and other resources that can be sustainably harvested from wetlands;
- Grazing lands for livestock: Includes grasslands of the floodplains, pans, and drainage lines, most notably late dry-season grazing lands supported by persistent high water table conditions;
- Nutrient-rich lands for flood-recession agriculture: Floodplain agricultural lands receiving irrigation waters and nutrients from the natural ebb and flow of the mainstem Zambezi River and distributary channels;
- Riverine and floodplain freshwater fisheries;
- Clean and abundant freshwater for drinking, cooking, cleaning, bathing, and other household uses provided by surface water and groundwater recharge;
- Estuarine *Penaeid* shrimp fisheries produced in mangroves and harvested off the Mozambique coast;
- Storm surge and coastal erosion protection from mangroves and coastal dune vegetation;
- Flood storage and mitigation (the capacity of the floodplain to store or attenuate large runoff events and reduce flood damage to settled areas);
- Diverse landscapes and wildlife for ecotourism;
- Wildlife for sustainable trophy hunting and subsistence meat supply.

The Millennium Ecosystem Assessment (2005) concluded that efforts to reduce rural poverty and eradicate hunger are critically dependent on ecosystem services, particularly in Sub-Saharan Africa. The assessment emphasized that continued loss and degradation of forests, wetlands, and other ecosystems will ultimately undermine progress towards achieving the Millennium Development Goals of reducing poverty and hunger and ensuring environmental sustainability. Hanson *et al.* (2008) further noted that ecosystem services degradation can pose a number of risks to corporate performance.

Globally, the impact of hydropower development on rivers and their ecosystem services is well described. Hydrology is the most important determinant of wetland functions and values worldwide (e.g., Finlayson and Moser

1991, National Research Council 1995, Mitsch and Gosselink 1993). In large floodplains such as those found in the Zambezi River basin, the composition, structure, and function of ecosystems – from the basic biological processes of primary production, decomposition, and consumption to the complex reproductive adaptations of plants and animals – depend on the hydrological connection between river and floodplain (e.g., Welcomme 1979, Poff and Ward 1990, Sparks 1992, Bayley 1995, Heiler *et al.* 1995). The Flood Pulse Concept was postulated by Junk *et al.* (1989) to describe the importance of this connection for the lateral exchange of nutrient and sediment-rich floodwaters between a river and its floodplain. When the flooding regime is disrupted due to large dams or other water resources development, the hydrological connection between river and floodplain is altered or severed (e.g., Sparks *et al.* 1990, Johnson *et al.* 1995, Ward and Stanford 1995a, 1995b). Numerous studies have documented the adverse effects of regulated flood flows on ecosystem services worldwide, including reduced silt deposition and nutrient availability, channel degradation, loss of shallow wetland and open water areas, altered food-chain dynamics, habitat fragmentation, intrusion of saltwater, displacement of wetland vegetation by upland species, disrupted reproductive patterns for fish and wildlife species, and loss of coastal mangroves (e.g., Baxter 1977, Brooker 1981, Petts 1984, Amoros 1991, Nilsson and Dynesius 1994, Ligon *et al.* 1995, Church 1995, Ward and Stanford 1995b, Nilsson and Jansson 1995, Welcomme 1995, McCully 1996, Colonnello and Medina 1998, others). Social and economic impacts may include failed flood-recession agriculture, loss of grazing lands at end of dry season, reduced fishery and shellfish harvest, reduced availability of various natural resources on the floodplain, and decreased access to groundwater (e.g., Welcomme 1979, Scudder 1989, Barbier *et al.* 1997, Adams 1992, others).

In the Inner Niger Delta, for example, a million people earn their livelihoods as fishermen, cattle breeders, or farmers (Zwarts *et al.* 2005). The construction of upstream dams reduced the level of floodwaters in the delta and had a dramatic impact on the livelihoods of the people who depend on the river, as well as broader biodiversity such as migratory birds, fish and mammals. A third dam under consideration would further reduce water levels during the critical dry season. An extended cost-benefit analysis was performed using a combination of four scenarios that aimed at quantifying the costs to biodiversity and socio-welfare to users against the benefits of hydropower generation and increased area for irrigation upstream. The results demonstrated that the construction of the third dam was not economically desirable, because the costs of impacts on downstream users would be greater than the expected benefits from the new development. Similar economic benefits have been described for threatened ecosystem services in other African basins (Polet and Thompson 1996; Barbier *et al.* 1997; Bruwer *et al.* 1996,; Horowitz and Salem-Murdock 1990; Wesseling *et al.* 1996; Acreman 1994; Japanese International Cooperation Agency 1997).

The value of the ecosystem services threatened by hydropower development in the Zambezi River system is astonishing. A recent economic valuation study for the Zambezi Delta estimates that the annual total value of river-dependent ecosystem services ranges between US$0.93 billion and $1.6 billion (Guveya and Sukume 2008). The lifecycle of prawns, for example, depends on a wet season flood pulse and dry season low flows; the lost economic value of prawn fisheries in Mozambique due to dam-induced changes in Zambezi annual runoff patterns is valued at $10-20 million per annum (Gammelsrod 1992, 1996; Hoguane 2002). Turpie *et al.* (1998) estimated the net economic value of fisheries in four floodplain systems of the Zambezi Basin at $16.4 million per annum, providing more than $9.5 million in cash per annum to rural households. The reduction in freshwater fisheries directly related to reduced flooded area and duration, and mistimed flooding regimes is estimated at 30,000-50,000 tonnes per annum for the Zambezi Delta alone (Tweddle 2006). Economic assessment of annual floods for subsistence agriculture suggests additional millions of dollars per annum in lost value due to mistimed flow releases that damage riverbank cropping, and increase drought vulnerability due to failed floods (Beilfuss *et al.* 2002). Commercial agriculture is also affected: salinity intrusion associated with a reduction in flooding (flushing) events is considered a significant threat to sugar production in the Zambezi Delta. Hydrological changes related to hydropower production are linked to a reduction in the extent and quality of end-of-dry-season grazing lands for cattle and the prevalence of cattle disease caused by ticks (Bingham 1982), and reduced potential for revenue from wildlife ecotourism and safari hunting where wildlife populations are limited by water resources or a reduction in suitable floodplain habitat (Anderson *et al.* 1990). In the Kafue Flats, the invasion of mimosa pigra shrub is resulting in substantial reduction in feeding grounds for several threatened species, including the endemic Kafue Lechwe and Vulnerable Wattled Crane (Rees 1978b; Mumba and Thompson 2005; Shanungu 2009).

The loss of other ecosystem services, more difficult to quantify, has a profound effect on community life. Reduced presence of floodplain water bodies and shallow groundwater tables caused by diminished recharge from annual floods

forces villagers to use the main Zambezi River channel rather than floodplain water bodies for domestic water uses, where they are more vulnerable to crocodile attacks and waterborne disease. The encroachment of permanent settlements and fishing camps on river banks and sandbars – an adaptation to the reduction in floodplain inundation – results in higher social and economic costs, including injury and death, during very large (uncontrollable) floods (Hanlon 2001). Important cultural values linked to Zambezi waters – including ceremonial, recreational, aesthetic, and spiritual values – also are affected by changes in flow regime (Beilfuss *et al.* 2002). Cumulatively, the economic value of water for downstream ecosystem services exceeds the value of water for strict hydropower production – even without valuation of biodiversity and culture.

Climate change will exacerbate the trade-offs between water allocations for hydropower development and ecosystem services. In their study of the impact of climate change on the financial feasibility of further hydropower development in the Kafue River basin, Stenek and Boysen (2011) noted that operation of Itezhi-Tezhi Dam for hydropower will result in higher levels of conflict between the current operating rules for power generation and the need for water releases for downstream users and conservation purposes on the Kafue Flats. Anticipated increases in temperature and changes in precipitation, combined with increasing development and population growth, will increase water demands for irrigation, fisheries, and floodplain conservation. Heavy reliance on hydropower in the Zambezi River Basin will also be increasingly challenged by growing water needs for addressing conservation goals in light of impacts of climate change and variability on water supply.

NOTES

1. http://www.nytimes.com/gwire/2010/05/10/10greenwire-droughts-turn-out-the-lights-in-hydro-dependen-40458.html?pagewanted=all
2. **Replacement value** refers to the amount individuals or society would have to pay to replace these benefits, at the present time, according to their current worth.
3. **Option value** is the value that people place on having the option to use or enjoy something in the future, although they may not currently use it. **Bequest value** is the value that people place on knowing that future generations will have the option to use or enjoy something; it is measured by peoples' willingness to pay to preserve ecosystem services for future generations. **Existence value** is the value that people place on simply knowing that something exists, even if they will never see it or use it.

Part 6: Recommendations

The financial risks associated with continued dependency on hydropower development in the face of climate change are increasingly clear. There is a growing consensus, certainly in Africa, that "despite uncertainties about climate change, we know enough to act" (Walther *et al.* 2005) Water infrastructure and its management must be considered strategically, over scales and time periods that are relevant to climate change. By building the "wrong" (under- or over-designed) infrastructure in the future, or by not modifying existing structures and operations to reflect emerging climate constraints, we may actually limit our future options for climate adaptation.

Adaptation attempts to reduce the vulnerability of human livelihoods, economies, and natural systems to the impact of climate-induced changes. The United Nations Framework Convention on Climate Change (UNDP 2004) states: "The most effective climate change adaptation approaches for developing countries are those addressing a range of environmental stresses and factors. Strategies and programs that are more likely to succeed need to link with coordinated efforts aimed at poverty alleviation, enhancing food security and water availability, combating land degradation and reducing loss of biological diversity and ecosystem services, as well as improving adaptive capacity."

Reducing the economic risks associated with climate change in hydro-dependent systems must address current as well as planned infrastructure, and must take into account the financial risks associated with hydropower schemes and the broader ecosystem services potential of rivers. We recommend the following actions:

Assess Hydropower In The Context Of Comprehensive Basin-Wide Planning

More than 15,000 MW of hydropower potential exists in the Zambezi River Basin, but development of that potential would come at significant social and economic cost to many water users in the basin and entail substantial financial risk in the face of climate change. Holistic approaches to future developments are essential to ensure the sustainability of the basin. Planners need to carefully consider how climate change will shape the supply of water in terms of future river flows (and shifts in their mean and variability) as well as the demand for power, conservation, domestic use, agriculture, industry and other water services. Basin-wide approaches to hydropower and land-use planning are increasingly adopted by decision-makers in other major river basins of the world, notably including the Mekong (King *et al.* 2007, ICEM 2010).

Comprehensive basin-wide planning must consider a full accounting of the values of ecosystem services supported by river flows. Community- and ecosystem-based adaptation approaches that integrate the use of biodiversity and ecosystem services into an overall strategy aimed at empowering people to adapt to climate change must be central to any comprehensive planning efforts (Girot *et al.* 2012). When these values are fully considered and integrated along with all other management objectives, the prospects for optimizing both dam- and ecosystem-related objectives are greatly enhanced (Krchnak *et al.* 2009).

Incorporate Climate Change Scenarios into Hydropower Design and Operation

The major implication of climate change for dams and reservoirs is that the future is uncertain, and can no longer be assumed to mirror the past. Until now, the design and operation of hydropower dams have been based on the best historic river discharge data obtainable. For the Zambezi River Basin, a substantial time series of monthly flow data is available dating back to 1907. These flow data provide a useful picture of the natural variability of river flows over the past century, including several cycles of wet and dry periods. These data are unreliable, however, for predicting the variance of future flows under climate change, including fundamental design criteria such as mean annual runoff and maximum probable floods. Milly *et al.* (2008) argue that stationarity – the idea that hydrological systems fluctuate within an unchanging envelope of variability, a foundational concept that permeates training and practice in water-resource engineering – is no longer valid, and should not serve as a central assumption in water-resource risk-assessment and planning. Hallegatte (2009) notes that new infrastructure not only will have to be able to cope with new climate states, but also a large range of changing climate conditions over time, which will make design more difficult and construction more expensive.

The reality of climate change demands more adaptive, flexible water management, which includes the use of both moderate and strong climate change scenarios for estimating future dam safety and reservoir reliability for individual and cascades of dams. The risk assessment must include the safety and operation of cascades of dams, given the heightened potential for catastrophic failure of structures under new climate realities. Uncertainty in future climate makes it impossible to directly use the output of a single climate model as an input for infrastructure design, and the needed climate information will not be available soon (Hallegatte 2009). New models must be developed

to incorporate climatic uncertainty into dam design and management, combining historical records of past flow volumes and periodicities (often insufficiently known, due to poor historic records) with projections of multiple climate models using stochastic (probabilistic) elements, driven by multiple climate-forcing scenarios. Research is needed into statistical techniques for separating climate-change impacts from natural variability; improvements in regional climate models, with a stronger focus on prediction in the short- to medium-term, and the inclusion of land-use and ecosystem expertise in the prediction of hydrological impacts on hydropower and reservoirs (Harrington *et al.* 2007). The information base for developing these models is likely to change rapidly as climate science advances during the coming decades, and will require innovative training of hydrologists, engineers, and managers (Milly *et al.* 2008).

Projects should be approached with extreme caution. New developments should be subject to substantial analysis of the hydrological and financial risks, performed by expert teams including hydrologists, energy economists and climate-change scientists. As an example, Hydro Tasmania is already downrating their power production due to climate change.[1]

Hallegatte (2009) provided a useful decision-making framework for adapting uncertainty-management methods to hydropower development:

- Selecting "no-regret" strategies that yield benefits even in absence of climate change;
- Favoring reversible and flexible options;
- Buying "safety margins" in new investments;
- Promoting soft-path adaptation strategies;
- Reducing decision time horizons and projected lifetime of investments.

Diversify the Regional Power Pool to Reduce Hydropower Dependency

Climate change adaptation requires diversified investments to "avoid putting all eggs into one basket" in a time of increasing hydrological uncertainty (Goodland 2011). The Southern African Power Pool (SAPP) was created to provide a reliable and economical electricity supply to power consumers across Southern Africa, and provides an excellent framework for diversifying power production in Southern Africa and reducing dependency on hydropower.[2] The SAPP vision includes ensuring sustainable energy development through sound economic, environmental and social practices, as part of a competitive electricity market for the Southern African region. In practice, however, the SAPP has emphasized large-scale coal and hydropower development to feed the regional grid, without serious consideration of climate change impacts (Hankins 2009).

SAPP can play a key leadership role in adapting the regional power grid to the realities of climate change and water scarcity by promoting decentralized energy technologies, energy efficiency standards, demand-side management, and feed-in tariff pricing to encourage the adoption of renewable technologies. Region-wide funds are needed to develop renewable energy projects that benefit SAPP. Many SAPP countries have a huge untapped potential for solar, wind, geothermal, and other renewable energy technologies that are well-suited for both urban and rural energy development. In failing to integrate these technologies with the regional grid, Southern Africa is missing out on critical global developments in new clean sources of energy that could benefit its population; create new industry, jobs and capacities, and bring clean power to the region (Hankins 2009).

Improve Existing Hydropower Capacity Rather than Investing in New Infrastructure

Existing hydropower structures should be rehabilitated, refurbished, renovated, or upgraded prior to the construction of new hydropower facilities. Adding new turbines or replacing old turbines with more efficient or bigger ones is almost always much lower impact than building new dams. Pumped-storage hydropower is one promising alternative, using off-peak electric power to pump water from a lower elevation downstream reservoir to a higher elevation upstream reservoir for energy production during peak demand (Miller and Winters 2009). In addition, hydropower can be added to existing water supply dams and water piping systems (known as no-dam or "unconventional hydro"). For example, Andritz Hydro has estimated that South Africa alone has 63 MW of unconventional hydropower potential in its irrigation canals and industrial water-conveyance systems.[3]

In the Zambezi Basin, Kariba Dam was recently upgraded to increase generation capacity without further impact, and plans are underway for upgrades to Cahora Bassa Dam and new generation capacity at Itezhi-Tezhi. Increased spillway capacity at Cahora Bassa Dam to enable passage of the maximum probable flood likewise would enable increased power generation by eliminating the need to dump excess reservoir waters during the dry season according to the design-flood rule curve (Beilfuss 2010).

These and other rehabilitation measures should be considered before new dams are contemplated, just as investments in energy conservation and demand management should be prioritized before new generation is permitted. New legislation limiting the licensing time-period for new and existing hydropower dams also may serve as a tool for encouraging rehabilitation, allowing for regular reviews of safety and risk of failure as well as socioeconomic and environmental impacts (Pittock and Hartmann 2011).

Prioritize Investments that Increase Climate Resilience

An estimated 60 to 120 million people in Southern Africa face water stress in the next 50 years due to climate variability and governance issues (Arnell 2006). Climate models warn about the impact of changing rainfall and runoff patterns on grain yields, water availability, and the survival of plant and animal species that are expected to shift production seasons, alter productivity, and modify

the set of feasible crops. A large part of the population is engaged in subsistence agriculture on marginal lands that are particularly vulnerable to the adverse effects of climate change (Ndaruzaniye *et al*. 2010). By the 2080s, a significant decrease in suitable rainfed land for agriculture is estimated due to climate change (Boko *et al*. 2007). Wheat production is likely to disappear from Southern Africa, and notable reductions in maize production are expected (Fischer *et al*. 2005; Stige *et al*. 2006).

In this context, it is essential that future investments in the Zambezi River Basin increase the resiliency of agriculture and water sectors to climate change. Yet large hydropower dams threaten to decrease, rather than enhance, climate resilience – especially for the rural poor. There often are inherent incompatibilities between generation of electricity and provision of water supply during the dry season, when water is scarce but most needed. When dam operators must choose one over the other, electricity generation almost always supersedes water supply (Harrison *et al*. 2007). Hydropower dams diminish or eliminate the annual flood pulse downstream, reducing the productivity and extent of floodplain and riverbank agricultural systems, an important alternative to drought-prone rainfed cropping practices (Scudder 1989). Evaporative water loss from large reservoirs further decreases water availability for downstream use.

Integrated river basin development investments should be prioritized to enhance climate resilience by helping poor and vulnerable communities prepare for, withstand, and recover from the negative effects of climate change (African Development Bank *et al*. 2003). While more water storage will be needed (World Bank 2006), decentralized solutions that preserve river-based ecosystem services are better suited to the needs of the rural majority, who face the greatest adaptation challenges. Resilience strategies should be an integral part of research, development, planning, training, capacity building, and implementation in Zambezi Basin countries.

Implement Environmental Flows for Climate Resilience

Environmental flows are an important tool for restoring river systems and the goods and services they provide (Arthington *et al*., 1992; Acreman, 1996; Postel and Richter, 2003; King and Brown, 2006). Environmental flows describes the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. Maintaining and strengthening the delivery of ecosystem goods and services is an important aspect of adaptation to climate change (Bergkamp *et al*. 2003; Le Quesne *et al*. 2010). Environmental flow requirements will be critical to help communities living downstream of dams adapt to a changing climate, and therefore should be incorporated into existing hydropower operations, as well as future infrastructure planning and design. Two recent World Bank documents provide recommendations for integrating environmental flows into hydropower dam planning, design, and operations (Krchnak *et al*. 2009), and support improved protection of environmental flows across projects, plans, and policies (Hirji and Davis 2009).

Reoperation of existing infrastructure to realize environmental flows may include redistributing the spillage of excessive reservoir waters to better mimic seasonal fluctuations, or setting specific targets for outflows to meet stakeholder-defined goals for ecological, social, or economic outcomes. For cascades of dams, dam operators and water managers should investigate opportunities to re-regulate flows by capturing flows in the lowest dam of the cascade and then releasing flows to mimic natural patterns. Opportunities for integrating groundwater storage with dam storage should also be investigated. Releases may be timed to coincide with periods when downstream tributaries are contributing peak flows, or "piggy-backing" water releases with water diversions for human use, to increase opportunities for overbank flow to reach floodplains and wetlands. Conversely, environmental flow strategies may target dry-season releases to enhance water security.

Future structures should be designed to ensure compatibility with environmental flow releases, including adequate outflow capacity to realize a range of target outflows; multi-level intakes to allow for water releases corresponding to a range of reservoir storage levels, to improve downstream water quality; and designing dams that enable movement of fish and other organisms and sediments around dam walls. Where possible, existing dams should be retrofitted to achieve these outcomes.

Within the Zambezi River Basin, environmental flows were first considered in the Kafue River as early as the 1960s. Itezhi–Tezhi Dam was designed to generate a flood of 300 m^3/s during a four-week period in March for the maintenance of agricultural and biological productivity in the Kafue Flats (Scudder and Acreman 1996). Although the additional reservoir storage capacity increased project costs by 15%, the Ministry of Power, Transport, and Communication agreed to the plan because of the importance of the annual floods for aquifer recharge, alluvial deposition, flood recession agriculture, livestock grazing, and floodplain fisheries (Handlos and Williams 1985). The World Wide Fund for Nature (WWF) is now working with dam operators to further modify these releases to improve the timing of outflows to better restore ecosystem services downstream (Schelle and Pittock 2005).

The importance of environmental flows for restoring the Lower Zambezi Basin below Cahora Bassa Dam was first proposed to the Government of Mozambique by consultants SWECO (1983). SWECO recommended an environmental flow release (*freshet*) from Cahora Bassa to coincide with high flows from downstream tributaries, aimed at reducing the impact of soil salinization on natural vegetation, improving agricultural productivity and the carrying capacity of grasslands, expanding floodplain waterbodies, and reducing the growth of invasive aquatic macrophytes in river channels. In 1997, under the auspices of the Zambezi Valley Planning Authority, the operators of

Cahora Bassa Dam hosted a workshop on the Sustainable Management of Cahora Bassa Dam and the Zambezi Valley (Beilfuss 1997). More than 50 participants from government agencies, academic institutions, and development NGOs concluded that environmental flow releases from Cahora Bassa Dam were necessary to restore human livelihoods and ecosystems downstream (Davies 1998).

Most recently, SADC (SWRSD 2010) recognized six objectives that can be addressed through environmental flow management in the Zambezi River Basin in addition to hydropower objectives:

- **Dam Safety:** Managing releases to avoid the reservoir reaching unsafe levels. Provide adequate capacity to safely store and pass the design flood;
- **Flood management:** Avoiding loss of life and reducing socio-economic impact;
- **Environmental management:** Providing quantity and quality of water required to maintain ecosystems and enable them to provide sustainable services and good quality water;
- **Dry season floodplain agriculture:** Accommodating the harvest period in release management;
- **Plantation irrigation:** Providing adequate yield for crop production, and
- **Water supply:** Setting priorities based on economic or social considerations, including poverty alleviation.

Simulation modeling of the Zambezi system dam operation (Beilfuss 2010) indicates that modest environmental flow releases from Cahora Bassa Dam can be realized without a significant reduction in hydropower production, by revising the operational rule curve to redirect the spillage of excess reservoir waters from the dry season to early wet season. Beilfuss and Brown (2010) demonstrate that the majority of Lower Zambezi water users would benefit from annual flood releases, that the trade-offs among different water users is minimal in terms of the timing, magnitude, or duration of releases, and that the economic value of releases to downstream users exceeds the value of waters used solely for hydropower production.

In practice, dams of the Zambezi basin have been operated fairly independently, without regard to economic requirements of other stakeholders in the basin. Dam operations have focused primarily on dam safety and maximizing hydropower production on a one-year operating window. New modes of operation which consider multiple-objective environmental flows over a multi-year operating window should be considered for the Zambezi River system.

A unique partnership between the Zambezi River water authorities, dam operators, and power companies, NGOs (the World Wide Fund for Nature, International Crane Foundation), and regional universities is uniquely positioned to build on these findings and implement environmental flows in the Zambezi River Basin. The partnership seeks to incorporate environmental flows into the operating rules of hydropower dams in the Zambezi River Basin, and ensure that essential freshwater resource areas in the Zambezi River Basin are well protected and properly managed. This partnership could play a vital role in facilitating climate change adaption for vulnerable Zambezi Basin communities, and illustrates the potential for environmental flows to overcome conflict in shared water resources and create opportunities for cooperation.

Ensure that Monitoring and Evaluation Systems Support Adaptive Management

Climate-change adaptation requires adoption of an iterative, risk-based approach to water management (Le Quesne *et al.* 2010). Monitoring and evaluation systems are an essential element of this strategy. The monitoring and evaluation system should help society understand clearly whether current water management practices are delivering on their "promised" outcomes, and enable decision-makers to apply any lessons learned to improve present and future management. Monitoring is critical to building trust and confidence among riparian states, and it is absolutely necessary for developing and implementing water allocation plans.

A system for information collection and sharing in the Zambezi River Basin would serve to:

- Increase our understanding of the impacts of climate change, and help develop and implement climate change adaptation and mitigation measures;
- Foster more efficient and effective use of the basin's water resources;
- Allow for diversification in the use of water resources, including adding agricultural and environmental uses that are not currently factored into water allocations;
- Support the implementation of environmental flows;
- Increase scientific understanding of the distribution of water resources in the basin over time;
- Make it possible for dam operations and other water management decision-making to be based on real-time, basin-scale hydrological and ecological data;
- Enable a more complete accounting of ecosystem services and their value to society.

Monitoring and evaluation systems are most effective and informative when designed to answer clear, focused management questions (Cottingham *et al.* 2005). The monitoring system should be based on specific hydrological, socio-economic, and ecological indicators that will respond to water flows in a clearly discernible manner that reveals the direction of the response (e.g. increased or decreased abundance of biota or productivity) and the level of the effect (i.e., the strength of the response to flow conditions). Careful monitoring of these indicators contributes to three important actions:

- Quantifying the benefits and costs of different water management alternatives, for dissemination to decision-makers and stakeholders;
- Applying the monitoring results to improve the management of flows through an adaptive-management framework; and
- Evaluating and improving the monitoring system over time.

These indicators also serve as early-warning

indicators of climate-change-related shifts in important traits in systems, as adaptive management requires constant attention to new signals that conditions are changing.

Rethink Flood Management Strategies

Many hydropower projects, including Kariba and Cahora Bassa dams, are justified on the basis of providing flood control in addition to energy generation. However, providing flood control storage means the reservoir must be drawn down to provide flood capture space (according to design flood rule curves) at the very time the capacity is most needed to supply the regional energy demand. This is a direct compromise in the hydropower benefits being sought, in terms of energy production and revenue (Harrison *et al.* 2007). These economic and ecological conflicts suggest that alternative operating scenarios for existing dams and better approaches to flood management should be considered. Because summer (wet season) high flows and seasonal high energy demand occur simultaneously, a modified "run-of-river" (full reservoir) operation could be adopted to provide more natural flow patterns downstream of the dams and maximize water levels (hydraulic head) for energy generation.

Re-envisioning Zambezi dams for run-of-river operation near reservoir storage capacity would require a reduction in flood storage space in the reservoir. Natural or enhanced floodplain storage in the river basin could provide an important alternative to lost reservoir storage capacity. As described in Part 2, the Zambezi River Basin is characterized by numerous large floodplain systems with exceptional water-holding capacity, including the Barotse and Chobe floodplains upstream of Kariba Dam, the Lukanga Swamps above Itezhi-Tezhi Dam, and the Kafue Flats upstream of Upper Kafue Gorge Dam, as well as the Zambezi Delta below Cahora Bassa Dam. Harrison *et al.* (2007) suggest that the differential hydropower revenue gained from run-of-river operation could be utilized for restoring flood storage capacity and insuring against flood risks in the floodplain. A portion of the consequent higher hydropower revenues could be dedicated to reducing flood risks in the floodplain or to restoring river-floodplain connectivity to enhance the conveyance of floodwaters to floodplain systems (Opperman *et al.* 2009). Agencies responsible for flood control could identify opportunities for securing or rehabilitating floodplains, including the purchase of floodplain easements. Revenues also could be allocated for improved flood forecasting capacity, enforcement of existing floodplain settlement policies, and effective and well-tested flood warning systems.

Allocate Hydropower Revenues to Restore Ecosystem Services

Many dams are designed and financed on the basis of "multipurpose" operation, suggesting that in addition to generation of electricity, other benefits such as flood control, water supply, fisheries, navigation, irrigation, and other downstream benefits are operational priorities. In most cases, however, these other purposes are subsidiary to power generation, which earns the most revenue – and

there is rarely a full accounting of the values of ecosystem services. The regulation of rivers for strict hydropower generation, in turn, is associated with adverse impacts to river systems and the ecosystem services they provide.

New financial mechanisms are needed to reallocate revenue from hydropower sales to directly compensate downstream water uses that are negatively affected by dam operations, and to restore ecosystem services. In the Lower Zambezi River Basin, the economic impact of river regulation by Cahora Bassa Dam has been estimated for freshwater and estuarine (prawn) fisheries, agriculture, livestock, water supply, tourism, and other concerns. Investments of hydropower revenues in these sectors would encourage ecologically sustainable livelihood activities and diversification of flow-related livelihoods and income streams. These investments also would counter regional inequities in the distribution of electricity supply – the majority of the power generated by Cahora Bassa Dam, for example, is exported to South Africa rather than serving local demand. At a basin level, hydropower revenue could be used to reduce pressures on river systems, including removal of exotic invasive species and negative impacts from land-use changes such as clear-cutting riparian forests, which directly threaten the long-term viability of hydropower schemes.

Ensure Best Social and Environmental Practices

Dams in the Zambezi Basin are being planned under a variety of standards, with very little public input, and with very little if any attention to the broad social and environmental impacts these projects bring. Given the importance of well-functioning river systems to climate adaptation efforts in Africa, standards must be improved to minimize these risks and properly evaluate all alternatives. These standards should mandate that a meaningful proportion of stakeholders are fully consulted with ample opportunity to debate controversial decisions (Bosshard 2010).

The World Commission on Dams (WCD 2000) provides best-practice guidelines for hydropower selection, planning, construction, and monitoring that are highly relevant for climate change adaptation. The WCD recommendations are based on a set of five core values for future decision-making – equity, efficiency, participation, sustainability and accountability. The WCD emphasizes a "rights and risks" approach for identifying stakeholders in negotiating development choices and agreements. Seven strategic priorities are identified for water and energy resources development, which include: gaining public acceptance; assessing all options; addressing existing dams before new dams are constructed; sustaining rivers and livelihoods through their ecosystem services; recognizing entitlements and sharing benefits; ensuring compliance based on a set of clear criteria; and sharing transboundary rivers for peace, development, and security. The WCD recommends 26 guidelines for review and approval of projects during five stages of decision-making. Best practice measures should be incorporated throughout the Environmental and Social Impact Assessment

(ESIA) process – beginning with adequate pre-project demographic, environmental, health, and socio-economic baseline surveys, and continuing throughout construction, operations, and decommissioning (Goodland 2011).

Another tool that is being promoted by the dam industry, the Hydropower Sustainability Assessment Protocol (IHA 2010), provides a sustainability assessment framework for hydropower development and operation. The IHA protocols include an Early Stage tool for risk assessment and discussion prior to detailed planning, and Preparation, Implementation, and Operation tools that use a graded spectrum of practice calibrated against reference conditions for basic good practice and proven best practice. The IHA protocols were developed to serve as a certification standard for hydropower projects, but the protocols are voluntary and do not define any minimal requirements of sustainability or a bottom-line of acceptability for hydropower projects (Bosshard 2010). Both the IHA protocols and the WCD guidelines must be mandated in a more rigorous regulatory context to ensure best practice going forward.

Develop Strong Institutional Capacity for Water Resources Management

The development of strong institutional capacity may be the single most important factor in the successful adaptation of existing hydropower systems to cope with climate change. Significant technical, financial, and social capacity is required, at different scales, from strong and well-governed national water ministries and river basin operators, through regional departments and basin councils, to local river basin offices and water user associations (Matthews and Le Quesne 2009). As new risks and uncertainties arise with climate change, a water resources management style is needed that is flexible enough to adjust to ongoing change (Bergkamp *et al.* 2003). Those responsible for hydropower management at all levels must be trained in new modes for dam operation and equipped with models and tools for implementation, including flood forecasting systems, routing models, conjunctive management systems, and monitoring and adaptive management protocols. Substantial investment in water management institutions is essential to facilitate new perspectives and proficiencies. For example, climate-change adaptation in Rwanda includes a series of training and technical assistance activities with hydropower operators and managers to improve operation and maintenance of the stations, and with decision-makers in the Ministry of Infrastructure to facilitate the integration of climate change considerations into the management of Rwanda's hydroelectric sector.[4] Training opportunities for water resource managers, authorities, and users in the Zambezi River Basin may be provided through innovations in curricula at training facilities that already service hydropower professionals, such as the International Centre for Hydropower, the Global Water Partnership, and UNESCO's Institute for Water Education.

CONCLUSION

The ecological goods and services provided by river basins, which are key to enabling societies adapt to climate change, are under grave threat from climate change as well as existing and planned hydropower development schemes. Successful adaptation in a highly vulnerable region such as the Zambezi River Basin requires a major shift in thinking, planning, and designing water investments for the future. Reductions in river flows will have a direct impact on hydropower generation, decreasing electricity grid stability and reliability, with consequent effects on the regional economy. More frequent drought and flood events will stretch water infrastructure and management systems to their limits. The pace of climate change may be uneven and sudden rather than gradual and smooth.

The major hydropower developers, utilities and lenders – led by the World Bank, International Finance Corporation, and African Development Bank – openly acknowledge these concerns, yet continue to recommend large-scale investments in hydropower development, at the expense of alternative energy systems that would pose less of a climate risk, and be better suited to adaptation needs. China and Brazil, both bilateral dam builders active in Africa, have acknowledged the climate adaptation challenges they face at home, but aggressively support additional large hydropower dams in climate-challenged African river basins. An alternative pathway, focused on climate-smart investments that explicitly factor in financial risk and the ecological functions and the values of river systems, is urgently needed.

It is hoped that this report will help basin countries make informed decisions on incorporating hydrologic variability and adaptation strategies into long-term planning and investment decisions for the Zambezi River Basin and beyond.

NOTES

1. See http://www.dpac.tas.gov.au/__data/assets/pdf_file/0005/154427/FINAL_Hydro_Tasmania_Case_Study_2.pdf and http://www.nccarf.edu.au/content/climatefuturestasmania

2. See http://www.sapp.co.zw

3. See http://tinyurl.com/7up5n52

4. Rwanda Environment Management Authority (2011) *Guidelines to mainstream climate change adaption and mitigation in the energy and infrastructure section.* http://www.rema.gov.rw/rema_doc/IMCE_Doc/Guidelines-Energy&Infrastructure.pdf

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Appendix: Hydrological description of the Zambezi sub-basins

THE UPPER ZAMBEZI BASIN

The Zambezi River originates in the northwest corner of Zambia near the Kalene hills. The river drops about 400 meters in elevation from its source at 1,500 meters to the Chavuma Falls, over a distance of about 400 kilometers. Mean annual rainfall exceeds 1225 mm, with considerably higher rainfall near the Zambezi source. The runoff efficiency (runoff produced from rainfall) for the Upper Zambezi sub-basin (0.21) is the highest in the entire Zambezi Basin. The steep channels and open terrain drain rapidly, with minimal floodplain retention – runoff rises sharply with the onset of rainfall, peaks between February and April, and then rapidly recedes to minimal flows between September and November (Figure A1). Mean annual runoff volume is 23,411 Mm^3, generating an average flow rate of 742 m^3/s. This pattern is repeated, but much diminished, during dry years when average flow rates fall to about 250 m^3/s. Rainfall and hence runoff are highly variable from year to year, with runoff volumes exceeding 14,000 Mm^3 in extremely wet years and dropping to less than 56 Mm^3 in very dry years. No dams have been constructed in the sub-basin, although significant hydropower potential exists in Angola. Water withdrawals for irrigation and other purposes are insignificant compared to runoff from this sub-basin (about 3.6 Mm^3).
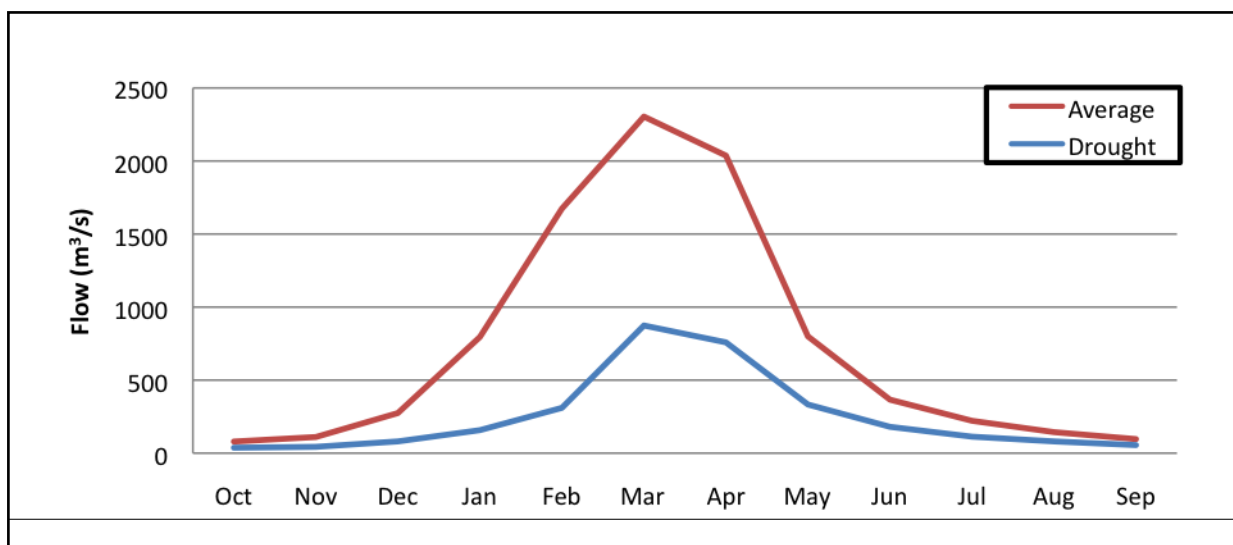
Figure A1. Mean monthly flows in the Upper Zambezi sub-basin during average and drought years.

Kabompo Sub-Basin

Patterns of runoff from the Kabompo sub-basin in northwestern Zambia are similar to that of the comparably sized Upper Zambezi sub-basin, with peak runoff occurring between February and April followed by rapid recession to dry season low-flows (Figure A2). Runoff efficiency (0.09) is considerably lower, however. Rapid runoff from the upper reaches of the river and its tributaries (mostly confined to distinct, steep-sloped channels) is partially attenuated by riparian swamps in the lower reaches with high evaporative water loss. Mean annual runoff is 8,615 Mm^3 (a 273 m^3/s average flow rate), but falls to about half that level (138 m^3/s) during drought years. Water withdrawals for irrigation (estimated at 4.8 Mm^3 per annum) are minor relative to these flows. No dams or large infrastructure have been planned or constructed in the sub-basin.
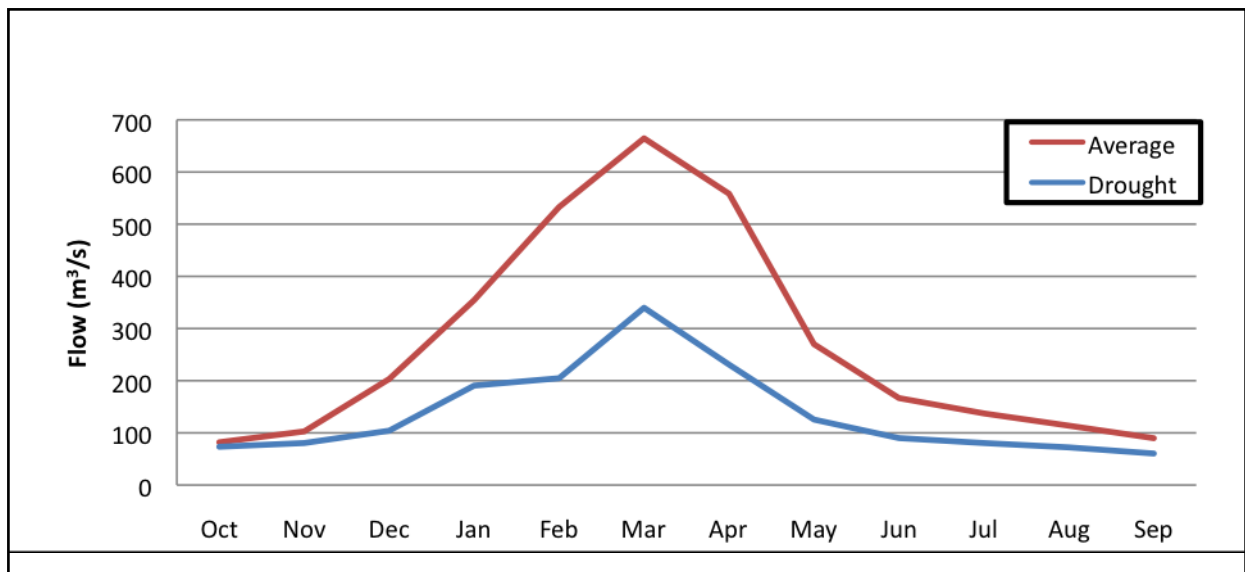
Figure A2. Mean monthly flows in the Kabompo sub-basin during average and drought years.

Lungwebungu Sub-Basin

The Lungwebungu River, the longest tributary of the upper Zambezi region, enters the Zambezi River just downstream of its confluence with the Kabompo River. The headwaters of the Lungwebungu rise in central Angola at an elevation of around 1,400 m, and flow southeast across the Angolan plateau. Along most of its course, the river flows over swamps that attenuate flows, and runoff efficiency is low. Near its confluence with the mainstem Zambezi, the Lungwebungu river–floodplain system widens and merges with the vast Barotse plain. The mean annual runoff contribution is 3,587 Mm^3, a flow rate of 114 m^3/s. Runoff is extremely variable – as little as 754 Mm^3 annual runoff (with a barely perceptible flood peak) may occur during drier years (Figure A3) but individual monthly runoff volumes exceed 3,725 Mm^3 during wet years. Water withdrawals from the Lungwebungu are less than 3.7 Mm^3 per year. No dams or hydropower plants have been planned or constructed in the sub–basin.
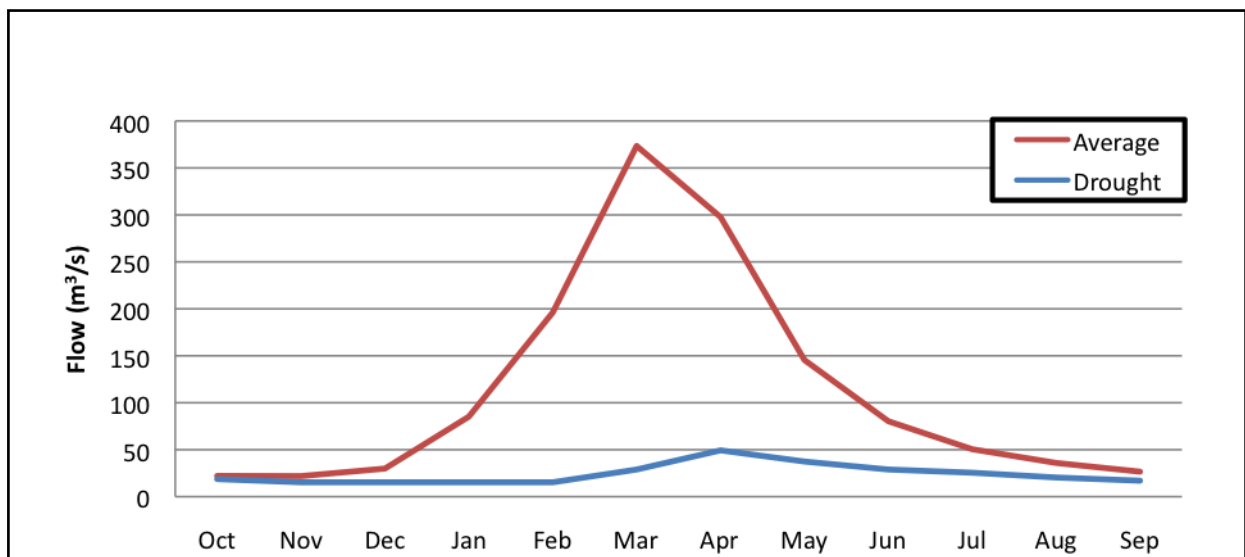
Figure A3. Mean monthly flows in the Lungwebungu sub-basin during average and drought years.

Luanginga Sub-Basin

The Luanginga catchment (34,600 km²) is one of the smallest sub-basins in the Zambezi system. The Luanginga drains runoff from the Angolan central plateau. Runoff follows rapidly from rainfall events, but is attenuated by the Nyengo Swamps and low-lying Barotse Plain, and runoff efficiency is low.

Extreme variability occurs from year to year, as in the other headwater basins. Mean annual runoff volume is 2,190 Mm³ (69.4 m³/s) from the sub-basin, but maximum monthly runoff volumes have exceeded 2,270 Mm³ in wet years while total annual runoff has fallen to less than 750 m³/s during dry years (Figure A4). As with the other Upper Zambezi headwater sub-basins, water off-take for irrigation and other purposes is insignificant (4.7 Mm³ per year), but water loss due to evapotranspiration may exceed 1,660 mm/annum. No dams or hydropower plants have been planned or constructed in the sub-basin.
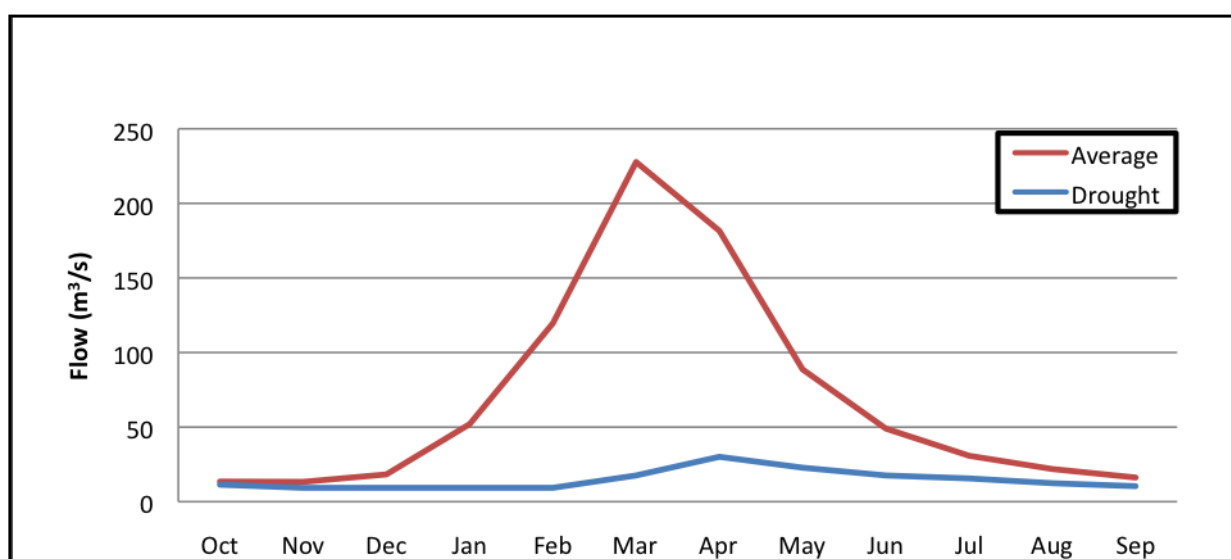
Figure A4. Mean monthly flows in the Luanginga sub-basin during average and drought years.

Barotse Sub-Basin

The Barotse sub-basin encompasses the vast Barotse floodplain (7,700 km²), extending 200 km in length and 40 km wide along the Zambezi waterway. During the rainy season, the plains are inundated by floodwaters from the four upstream sub-basins to form a large shallow lake that significantly attenuates Zambezi runoff. During the major Zambezi flood of 1958, total storage within the Barotse Plain was estimated to be approximately 17,000 Mm³, half of the mean annual runoff (Sharma and Nyumbu 1985). Zambezi floodwaters take 1-2 months to pass through the Barotse Plain, delaying peak discharge until April or early May (Figure A5), and recede more gradually during the six-month dry season. Average annual water storage capacity on the Barotse Plain is high (8,500 Mm³), and evaporative water losses throughout the year greatly exceed local rainfall-runoff, resulting in a negative contribution (-553 Mm³) from this sub-basin to Zambezi mean annual runoff (Table 1).

Downstream of the Barotse floodplain, the Zambezi traverses another vast floodplain system that further attenuates runoff, the Chobe Swamps (part of the Cuando-Chobe sub-basin, described below). The Zambezi then cascades over the Katombora Rapids before plunging 98 m at Victoria Falls. Irrigation potential in this sub-basin is limited (though vast areas of floodplain crops are irrigated using traditional flood-recession agricultural practices). Water withdrawals are minimal (about 3.5 Mm³ per year, or 1/100th of one percent of mean annual runoff), though large-scale water transfers to thirsty cities in Namibia, Botswana, and even South Africa have been proposed (Scudder 1993). There are no dams or hydropower plants in the Barotse sub-basin. A reservoir has been proposed at Katombora to stabilize flows for improved power generation capacity at Victoria Falls, 60 km downstream.
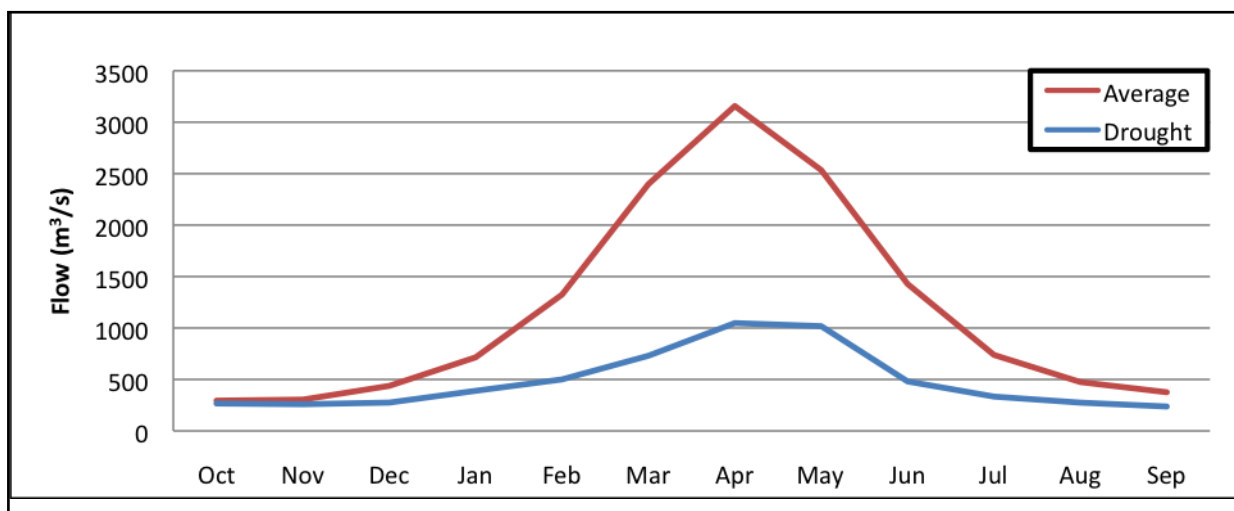
Figure A5. Mean monthly flows in the Barotse sub-basin during average and drought years.

Cuando/Chobe Sub-Basin

The Cuando River rises in the central plateau of Angola and drains approximately 22% of the Upper Zambezi region. With rainfall of less than 800 mm the sub-basin is the driest in the Upper Zambezi region. Mean annual runoff from the headwaters is 1,100 Mm^3 (32.5 m^3/s), but substantially lower during dry years. As the Cuando River reaches the broad, flat plains of the Eastern Caprivi Strip, it discharges into the upper end of the Chobe River floodplain. During the early part of the flood season, the Chobe River conveys this runoff to the Zambezi River, and may contribute substantial runoff in some years. As Zambezi levels rise, however, the Chobe River reverses direction and flows back to the northwest where it discharges into Lake Liambezi (Debenham 1948). When runoff from the Cuando/Chobe is in phase with Zambezi River flooding, an area as large as 1700 km^2 may be inundated. The unusual hydrograph resulting from these fluxes is shown in Figure A6. Overall, the contribution of Cuando River runoff to Zambezi River flow is counterbalanced by evaporation losses from Zambezi floodwaters that overflow into the Chobe floodplain, and net discharges to the Zambezi are negligible relative to runoff from the headwaters region (Table 1). Withdrawal for irrigation and other purposes (8.5 Mm^3 per year) are higher than elsewhere in the Upper Zambezi region, but still minuscule compared to river flows (Heyns 1995). There are no existing or planned dams or hydropower plants, although water resource development planning is underway in Angola.
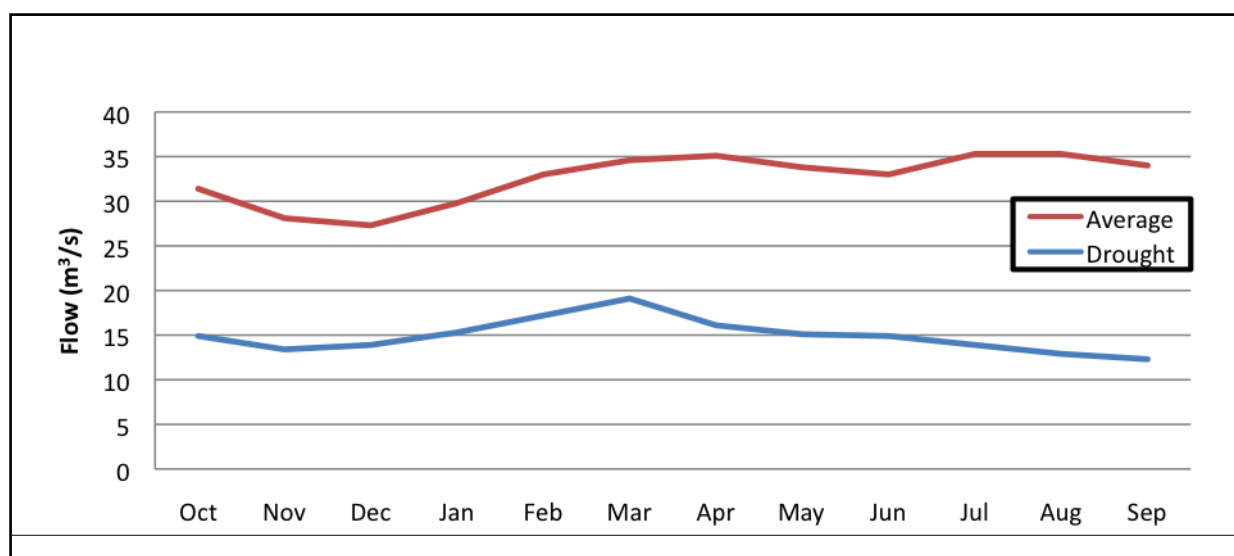

Figure A6. Mean monthly flows in the Cuando/Chobe sub-basin during average and drought years.

THE MIDDLE ZAMBEZI BASIN

The Kariba Sub-Basin

The Kariba Sub-Basin (172,527 km[2]) extends from Victoria Falls to Kariba Gorge. Immediately downstream from Victoria Falls, the Zambezi flows 120 km through two deeply incised basalt and granitic gorges, Batoka Gorge and Devil's Gorge – both proposed sites for large hydropower dams. There are no major tributaries in this reach. From Devil's Gorge to Kariba Gorge, the Zambezi River cuts through the Gwembe Rift Valley at the eastern extent of the vast Central African Plateau, and receives runoff from the Gwayi and Sanyati Rivers that drain the western and northern Zimbabwe Highlands, respectively. The Gwembe valley floor is inundated by the massive Kariba Reservoir – the largest artificial reservoir (by volume) in the world – which extends 280 km downstream to Kariba Dam, with a surface area of 5,577 km[2] and a storage capacity of 64,800 Mm[3].

The Kariba sub-basin is the driest of the Zambezi sub-basins, with a mean annual rainfall of about 700 mm. Runoff efficiency is a very low 0.07. As a result, most rivers in the sub-basin flow seasonally. The mean annual runoff contribution from the Kariba sub-basin is 6,490 km[3] (206 m[3]/s), and highly variable (0.44 coefficient of variation[1]). There is little to no natural regulation of river discharges and runoff tends to be flashy in response to rainfall events. Runoff from the Kariba sub-basin thus generates a characteristic early Zambezi flood, known locally as Gumbora, while the delayed runoff from the Upper Zambezi region (estimated at 21,690 Mm[3] per annum) generates the major annual Zambezi inundation (known as Mororwe) that typically peaks in April–May (Davies 1986) (Figure A7). Cumulative Zambezi discharge through and including the Kariba sub-basin is 43,710 Mm[3]. The highest recorded peak discharge volume, 23,600 Mm[3], is seven times greater than the lowest observed annual discharge (3,100 Mm[3]).

The operation of Kariba Dam for hydropower generation has greatly altered the flow regime of the Zambezi River. Kariba regulates runoff from an upstream catchment area of 687,535 km[2], about 50% of the total Zambezi catchment. Kariba Reservoir, which has the capacity to store 1.4 times the Zambezi mean annual runoff volume, captures inflows and releases a constant turbine outflow of 1,800-1,900 m[3]/s. Spillage resulting in downstream high flows occurs only during prolonged periods of above-average inflows, when the reservoir is at or near full supply level. The hydrographs for unregulated and regulated mean monthly inflows and outflows are contrasted in Figure 9. The timing of average peak flows occurs months earlier under regulated conditions, with the magnitude of monthly flows sharply reduced by 37-48% during the natural peak-flooding season. Average dry season low flows have increased more than three-fold, from 250 m[3]/s to 820 m[3]/s in October. During drought years spillage from Kariba Dam is curtailed, and the hydrograph reflects constant year-round turbine outflows with no discernible flood peak downstream.
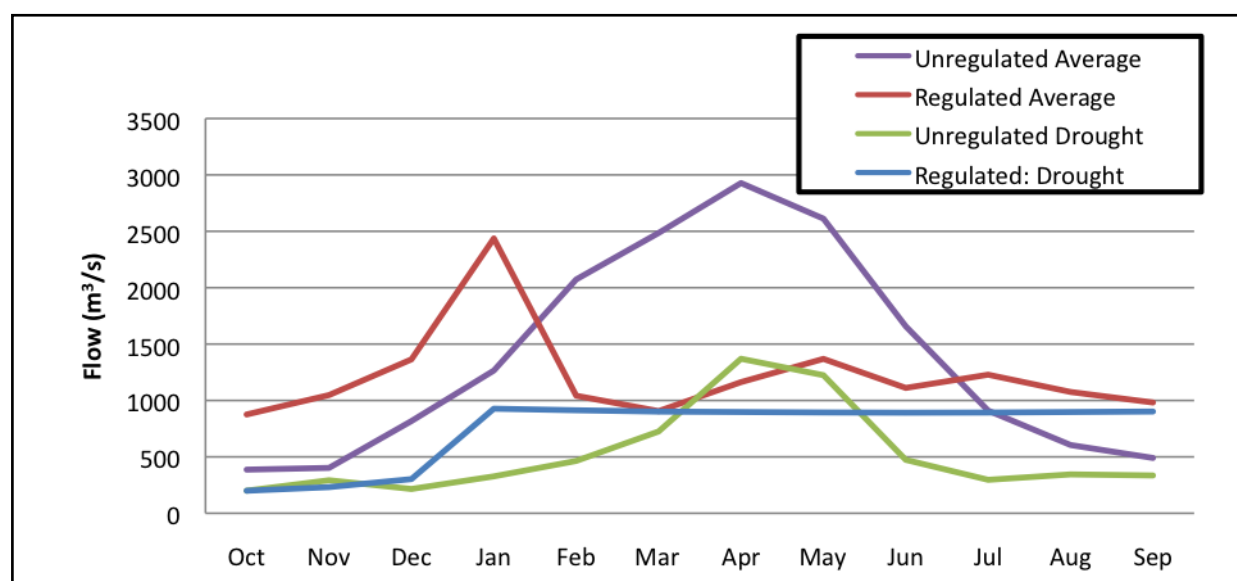

Figure A7. Mean monthly flows in the Kariba sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

Evaporative water loss from the surface of Kariba reservoir may exceed 2,000 mm per year, according to the World Bank ESMAP. More than 16% of mean annual flows through the reservoir are lost to reservoir evaporation (Ebinger and Vergara 2011) – the most significant source of water loss in the Zambezi Basin, far exceeding the combined total of all agricultural, municipal, and domestic water diversions from the basin at present. Water transfers to Zimbabwe, especially Bulawayo, have been proposed for nearly a century, but water offtakes are minimal at present (Durham 1995).

Kafue Sub-Basin

The Kafue Sub-basin (155,805 km^2), entirely within Zambia, drains most of the northern portion of the Middle Zambezi Region. The Kafue River headwaters rise on the plateau of the South Equatorial Divide in the Copperbelt region of Zambia, and flow south and east. Runoff from the upper basin is attenuated by the vast Lukanga Swamp (2600km^2). Further downstream, the river flows through Itezhi-Tezhi gorge which has been dammed to regulate Kafue flows for downstream hydropower generation at Kafue Gorge Upper Dam. Between Itezhi-Tezhi to Kafue Gorge dams, the Kafue River meanders over the Kafue Flats, an extensive floodplain area up to 60 km wide and 250 km long with an average gradient of only 2.7 cm/km. Floodwaters spread slowly over the flats for several months, inundating up to 5650 km^2 during very wet years. Below Kafue Gorge, the Kafue joins the mainstem Zambezi River some 60 km downstream of Kariba Dam.

Mean annual rainfall across the Kafue sub-basin is 1,050 mm, with a low runoff efficiency of 0.08 due to substantial floodplain attenuation of flows. Average runoff volume is 11,735 Mm^3 (an average flow of 372 m^3/s), and extremely variable (0.50 coefficient of variation). The Kafue catchment has contributed several major flood peaks to the Middle Zambezi River (Mukosa *et al.* 1995). During the worst drought on record, annual runoff volume fell to 3,266 Mm^3 (World Bank 2010).

Runoff from the Kafue Basin is highly modified by the operation of Itezhi-Tezhi and Kafue Gorge Upper dams for hydropower production (Figure A8). Releases from the 390 km^2 Itezhi-Tezhi Reservoir are dictated by power generation needs at Kafue Gorge Upper Dam, typically about 168 m^3/s except during periods of exceptional runoff from the upper catchment areas. During a four-week period each March, an ecological water release ("freshet") of 300 m^3/s is supposed to be released to the Kafue Flats, but this has been inconsistently implemented (McCartney *et al.* 2001) and is currently under review (Schelle and Pittock 2005). The hydrograph of mean monthly flows under natural and regulated conditions is shown in Figure A8. Flows downstream of Itezhi-Tezhi Dam are reduced 37% during the peak runoff months of February to April, with a corresponding two-fold increase in dry season flows. There is a constant flow, with no discernible flood peak, during drought years when freshets are curtailed.
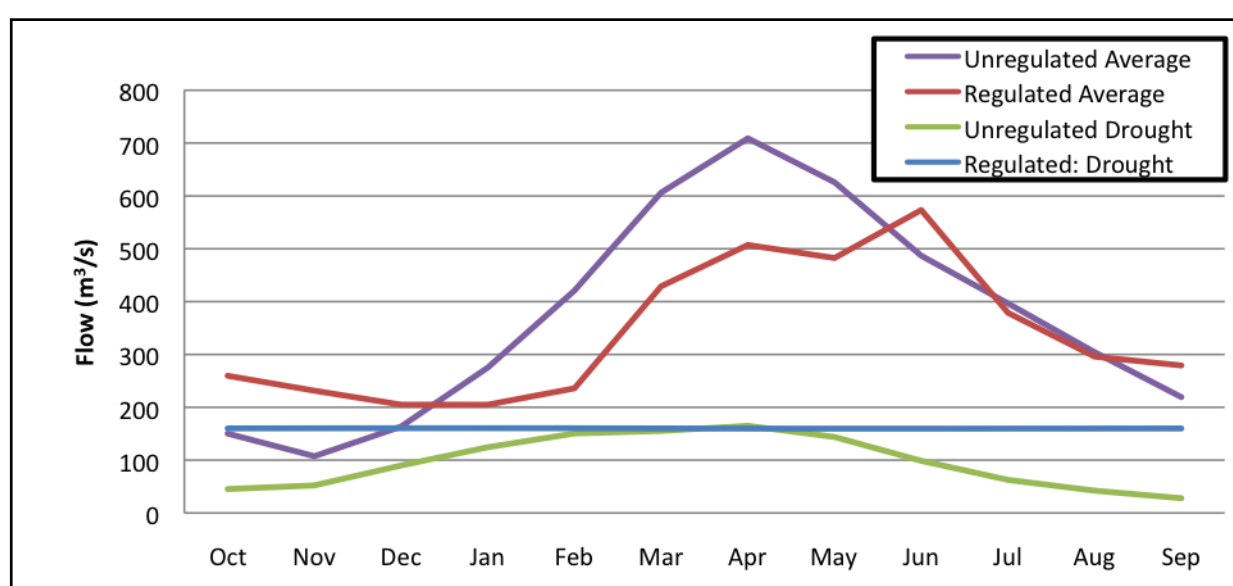

Figure A8. Mean monthly flows in the Kafue sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

Net water loss due to evaporation from Itezhi-Tezhi reservoir is 780 mm per year, about 3% of mean annual flows from the Kafue sub-basin – most evaporative water loss occurs from the large floodplains and swamps. Irrigation withdrawals are more substantial than in the Upper Zambezi Basin, an estimated 536 Mm^3, but far less than evaporative water losses and insignificant relative to runoff. Two new hydropower schemes are planned on the Kafue River, including construction of the Kafue Gorge Lower Dam and installation of a power station at Itezhi-Tezhi Dam that may serve to further alter Kafue runoff patterns; this is discussed below.

Mupata Sub-basin

The Mupata Sub-Basin (23,483 km^2) includes the Mupata Gorge region between Kariba Gorge and the confluence of the Zambezi and Luangwa rivers at the upper end of Cahora Bassa Reservoir, the border between Zambia/Zimbabwe and Mozambique. Below its confluence with the Kafue River, the Zambezi River is flanked by Lower Zambezi National Park on the north bank (Zambia) and Mana Pools National Park on the south bank (Zimbabwe), featuring narrow zones of riparian floodplains, pans, and pools covering about 360 km^2. Further downstream, the deeply incised Mupata Gorge has been proposed for hydropower development. Mean annual rainfall in the Mupata Sub-Basin is 813 mm. The incremental additional of runoff (1,680 Mm^3) is limited due to the small size of the sub-basin (Table 1).

Cumulative runoff volume from the Zambezi Basin through Mupata sub-basin, including contribution from the Kafue sub-basins, is 57,127 Mm^3 per annum. The upstream operation of Kariba and Itezhi-Tezhi Dams for hydropower generation, described above, has greatly altered the flow regime of the Zambezi River through the Mupata sub-basin. The hydrograph of mean monthly flows under natural and regulated conditions is shown in Figure A9. The altered timing and reduced magnitude and duration of high flows translates to a dramatic decrease in floodplain inundation at Mana Pools (Du Toit 1994). The dry season character of the Zambezi River has shifted from a meandering sandbank river to a single down-cut channel (Guy 1981, Nugent 1983). There are no hydropower plants in the Mupata sub-basin.
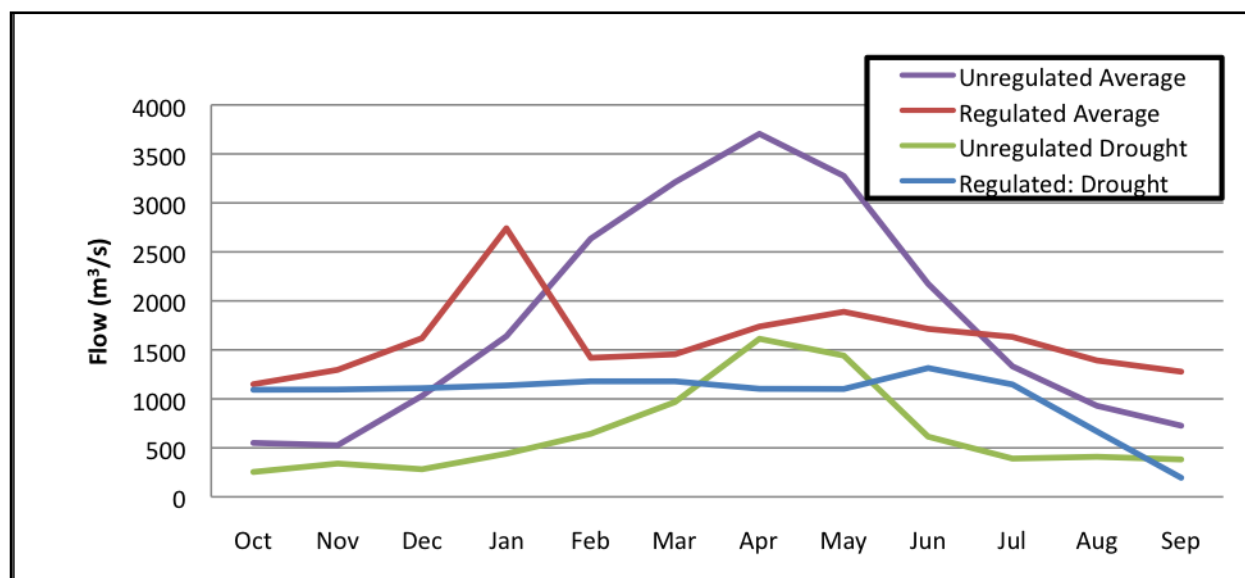

Figure A9. Mean monthly flows in the Mupata sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

Luangwa Sub-basin

The Luangwa sub-basin (159,615 km^2) rises on the South Equatorial Divide west of Lake Malawi. The Luangwa generally follows the base of the Luangwa Rift Valley, an extension of the East African rift system (Mhango 1977), and discharges to the Zambezi at the western end of Cahora Bassa reservoir, where it forms the international boundary between Zambia and Mozambique.

Mean annual rainfall in the Luangwa sub-basin is comparable to the Kafue headwaters region, about 1,021 mm per year (Table 1). The Luangwa flows for most of its length through an incised channel, fed by short, steeply falling tributaries

draining from the rift escarpment, and there is no substantial floodplain development as in the Kafue River system. The Luangwa catchment thus has a 20% higher runoff efficiency than the Kafue sub-basin, and generates 40% more mean annual runoff (16,329 Mm³) than that of the similarly sized Kafue catchment. Luangwa flows typically rise rapidly in December with the onset of the rainy season, with peak discharge typically in February and March following peak rainfall in the catchment (Figure A10). Peak flows during drought periods tend to occur early in the wet season, and are much reduced.

Extraction for irrigation is low (120 Mm³ per year). Three small hydropower plants on tributaries of the Luangwa River – the Mulungushi, Lunsemfwa, and Lusiwasi – have a minimal impact on Luangwa runoff patterns. Additional hydropower production on the mainstem Luangwa and tributaries has been proposed.
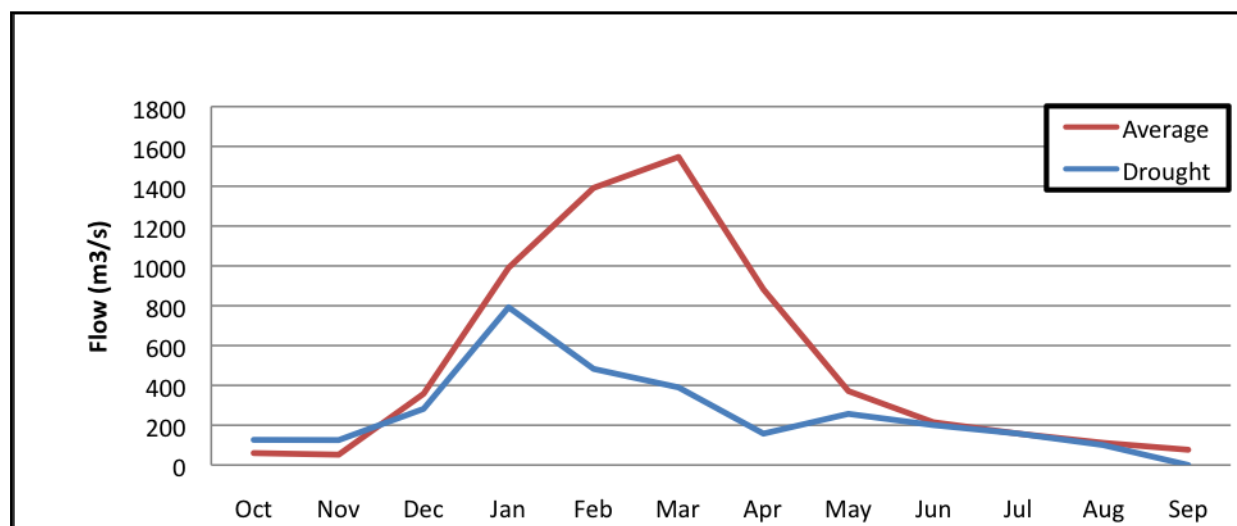

Figure A10. Mean monthly flows in the Luangwa sub-basin during average and drought years.

THE LOWER ZAMBEZI BASIN

Tete Sub-Basin

The Tete sub-basin (200,894 km²) is the largest in the Zambezi River system, extending from the upper end of Cahora Bassa Reservoir at the Mozambique border with Zambia/Zimbabwe, down to the Shire River confluence near the Zambezi Delta. The sub-basin includes the immense Cahora Bassa Reservoir, with a total surface area of nearly 2,700 km² at maximum storage, and an active storage[2] volume of 51,700 Mm³. The climate in the reservoir region is semi-arid and dry season temperatures often exceed 40ºC. Average annual rainfall for the sub-basin (887 mm) varies from 550-650 mm in low-lying areas to more than 1000 mm in the northern highlands. The sub-basin includes four perennial tributaries of note. The Manyame River drains from eastern Zimbabwe, contributing unregulated inflows to the reservoir. Downstream of Cahora Bassa dam, the Luia and Revuboe rivers drain the Mozambique highlands to the north and the Luenha River (known as the Mazoe River in Zimbabwe) contributes runoff from the Harare highlands. Catchment geomorphology and runoff efficiency (0.10) for the Tete sub-basin is similar to that of the adjacent Luangwa sub-basin. Incremental mean annual discharge is an estimated 18,000 Mm³ (570 m³/s), including about 13,000 Mm³ from tributary catchments downstream of Cahora Bassa Dam. As elsewhere in the basin, flows are highly variable from year to year (coefficient of variation of 0.45).

Cumulative Zambezi River runoff at the outlet of the Tete sub-basin is about 91,464 Mm³ (2,900 m³/s flow rate). Operation of Cahora Bassa Dam, which regulates a total catchment area of 1,050,000 km² (75% of the total Zambezi Basin) for hydropower production, has a profound effect on these flows (Figure A11). Inflows to Cahora Bassa, although heavily attenuated by upstream Kariba and Itezhi-Tezhi/Kafue Gorge Upper dams, resemble the natural pattern of inflows due to substantial unregulated runoff contribution from the Luangwa River sub-basin. Outflows from the dam occur 1-2 months earlier than under unregulated conditions, however, and are reduced by 46% during the peak

flooding months of February and March, and 20% in January and May. Dry season flows have increased two-fold relative to unregulated conditions.

About 6% of inflows (4,400 Mm³) are lost through reservoir evaporation, far exceeding the combined total of all water off-takes from the Lower Zambezi Basin. Several additional large dams have been proposed for the Tete sub-basin, most notably the Mphanda Nkuwa Dam located 60 km downstream of Cahora Bassa Dam, which is in advanced planning, and described below.
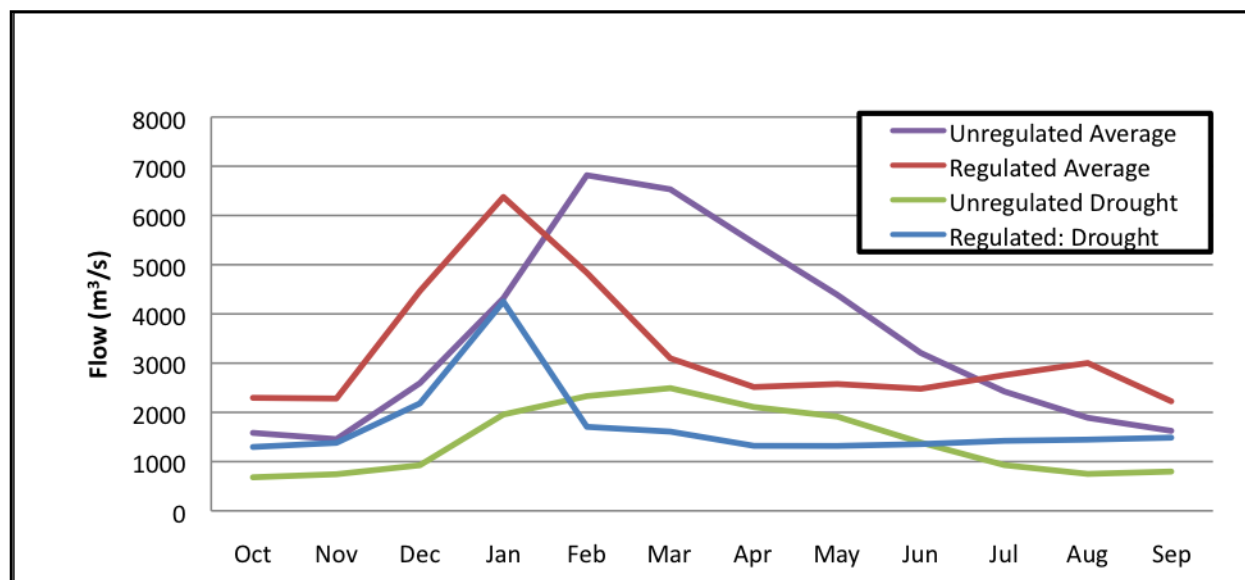

Figure A11. Mean monthly flows in the Tete sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

Lake Malawi/Shire Sub-Basin

The Shire River, the largest tributary in the Lower Zambezi Region, drains 149,159 km² of the Great Rift Valley in southern Tanzania, Malawi, and Mozambique north of the Zambezi. The Shire River originates as outflow from Lake Malawi (catchment area 125,976 km²), the third largest natural lake in Africa with a surface area of 29,601 km². A natural sandbar at the Shire inlet from Lake Malawi historically controlled outflow from the lake, but since 1960 the Kamuzu Barrage partially regulates Lake Malawi outflows to maintain high dry season flows in the Shire River for run-of-river hydropower generation. At high lake levels, outflow to the Shire is unaffected. Downstream of Lake Malawi, the Shire River spreads over Lake Malombe and the Liwonde floodplain. In its middle reaches, the Shire drops more than 380 m through a series of rapids and cascades, three of which (Nkulu, Tedzani, and Kapichira Falls) have been dammed for hydropower production. In the lower Shire reaches the river opens up again and spreads across broad floodplains, including the Elephant and Ndindi marshes, before its confluence with the Zambezi. Floodplain evaporation is high, averaging more than 2,000 mm per year, and greatly exceeds average annual rainfall (750 mm) in the Shire Valley.

The estimated mean annual discharge of the Lake Malawi/Shire River sub-basin to the Zambezi River is about 15,700 Mm³ (a flow rate of 498 m³/s). Although the sub-basin is a headwaters catchment, Lake Malawi and downstream floodplains have a large attenuating effect on Shire flows and runoff efficiency is low (0.09). Peak runoff occurs between February and April, gradually receding until the onset of the next rainy season in December (Figure A12). Water level fluctuations in Lake Malawi have a significant effect on flow rates in the Shire River – seasonal fluctuations are typically 1–1.2 m (up to 2 m), and long-term cyclical fluctuations of more than 6 m are known. During cycles of high water levels, outflows from Lake Malawi, especially when combined with substantial runoff from Shire River tributaries, can result in very large floods in the lower Zambezi. Peak flooding events may exceed 18,150 Mm³ in wet years, falling to about half of that level (9,200 Mm³) during cycles of low water levels or drought periods.

Figure A12. Mean monthly flows in the Shire/Lake Malawi sub-basin during average and drought years.
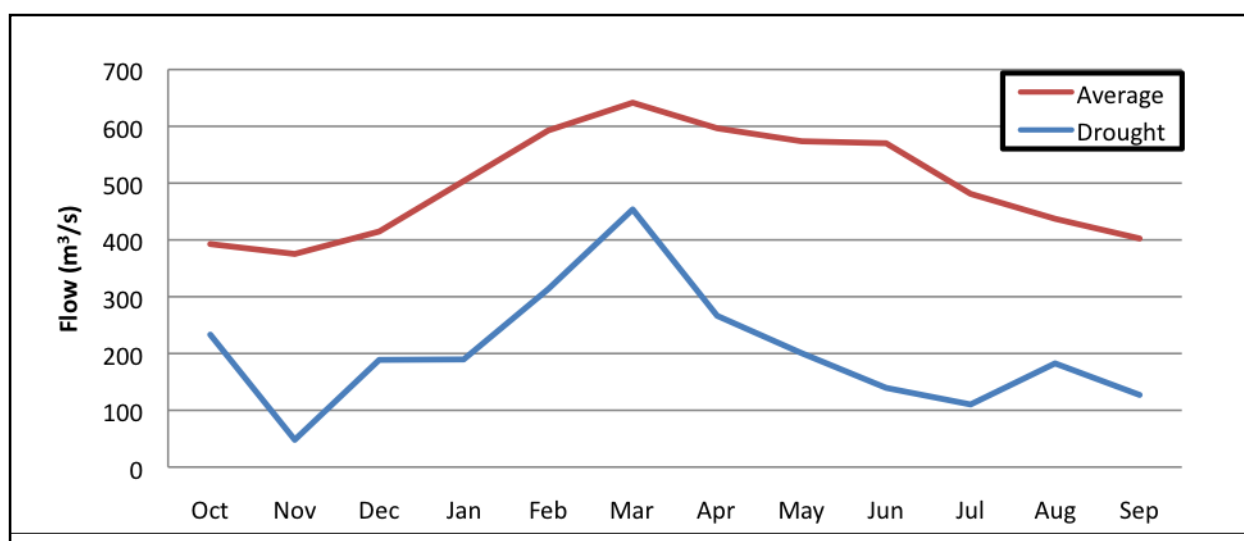
The Zambezi Delta Sub-Basin

The Zambezi Delta sub-basin (33,506 km²) occurs at the downstream terminus of the Zambezi River, from the Zambezi–Shire confluence to the Indian Ocean. The Zambezi divides into three main branches and a series of smaller distributary channels, forming a large triangle that extends 120 km inland from the coast and 200 km along the coast from the Zuni River in the south to the Cuacua River outlet near Quelimane in the north. The Delta northbank (23,303 km²) drains the Morrumbula Plateau that separates the Shire and Zambezi Valleys. The Delta southbank (10,203 km²), which includes the Marromeu Complex (the Marromeu Buffalo Reserve and four hunting concessions), receives runoff from the Cheringoma escarpment.

Mean annual rainfall over the Zambezi Delta sub-basin is 1060 mm. Rainfall is highest along the coast, and decreases gradually moving inland. The main rainy season in the delta usually occurs over a 4-6 month period between October and April. The volume of annual runoff contributed from the Zambezi Delta sub-basin is approximately 3,564 Mm³. Under unregulated conditions, river levels typically begin rising in late December in response to rainfall in the lower Zambezi catchment, peaking between February and April as the runoff arrives from the Upper and Middle Zambezi catchments, and gradually receding to dry season low-flows in October and November (Figure A13). This pattern of gradual ebb and flow was repeated, though much diminished, during drought years. Runoff in the Zambezi Delta
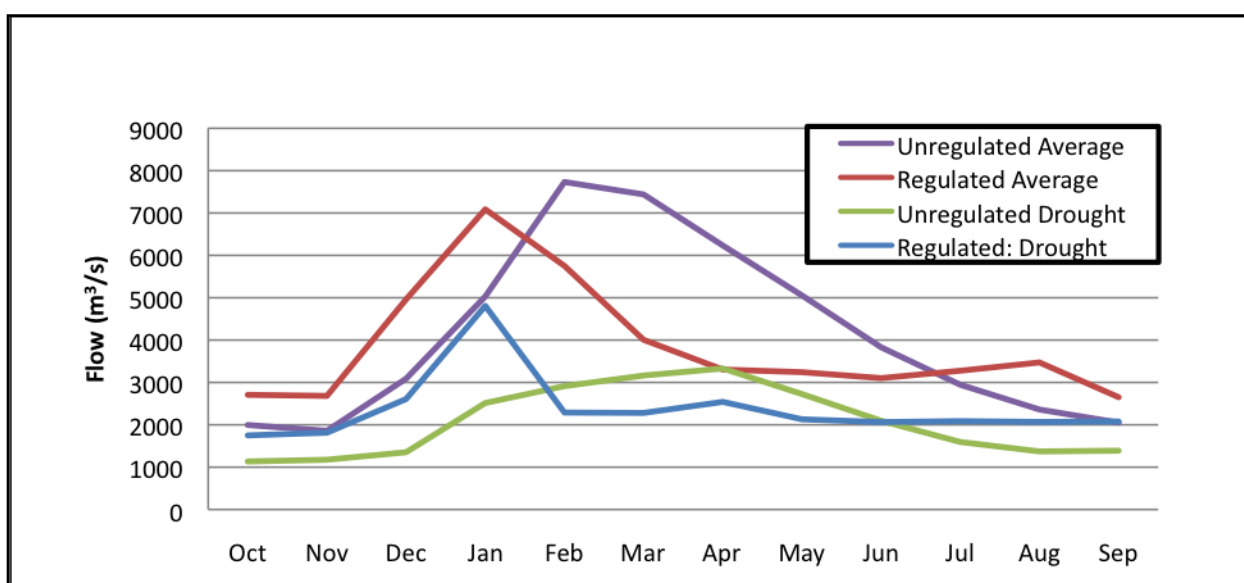

Figure A13. Mean monthly flows in the Zambezi Delta sub-basin during average and drought years, under natural (unregulated) and regulated conditions.

region is now strongly affected by upstream regulation for hydropower production, altering the timing, magnitude, and duration of runoff events. Peak flows occur 1–2 months earlier under regulated conditions, generated largely from unregulated flow contributions below Cahora Bassa Dam, and are characteristically "flashy" with rapid rise and recession. Flood flows in February, March, and April are substantially reduced; November low flows have increased more than 200%. The duration of flood pulses to the delta floodplains has reduced from 56.1 to 9.7 days, on average due to upstream hydropower production. Delta flooding is now more dependent on local rainfall and inflow from the Shire/ Lake Malawi sub-basin than prior to regulation.

Withdrawals of water for irrigation in the delta (127 Mm^3 per year) are minor and mainly associated with sugar production. The mainstem river gradient is too low in this reach to support hydropower production.

NOTES

1. The coefficient of variation is defined as the ratio of the standard deviation to the mean – it reflects the extent of variability relative to the mean flow condition.

2. Active (or live) storage is the portion of the reservoir that can be managed for power production, downstream releases, or other purposes. The remaining dead storage is the volume of water stored below the lowest outlet or operating level of the reservoir, which is thus inaccessible for management.