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Accounting for water-, energy- and food-security impacts in developing country water infrastructure decision-making under uncertainty

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Declaration

I, Anthony Hurford, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Decision makers lack information and tools to help them understand non-revenue impacts of different water infrastructure investment and operation decisions on different stakeholders in developing countries. These challenges are compounded by multiple sources of uncertainty about the future, including climatic and socio-economic change. Many-objective trade-off analysis could improve understanding of the relationships between diverse stakeholder-defined benefits from a water resources system. It requires a river basin simulation model to evaluate the performance of the system resulting from different decisions. Metrics of performance can be defined in conjunction with stakeholders, relating the level of benefits they receive (monetised or otherwise) to flows or storages in the system. Coupling the model to a many-objective search algorithm allows billions of possible combinations of available decisions to be efficiently filtered to find those which maximise stakeholder benefits. Competition for water requires trade-offs, so a range of options can be generated which share resources differently. Uncertainties can be included in the analysis to help identify sets of decisions which provide acceptable benefits regardless of the future which manifests, i.e. perform robustly. From these options, decision makers can select a balance representing their preferences. This thesis reports the development of such a state-of-the-art approach through applications in three real-world developing country contexts, with increasing levels of complexity and uncertainty. The first application in Brazil's Jaguaribe Basin uses environmental and livelihoods indicators to help re-operate three existing dams. The second in Kenya's Tana Basin adds new irrigation infrastructure investment options to decisions about re-operating a cascade of five existing dams in a more complex case. Finally robust portfolios of new hydropower investments are identified in Nepal's Koshi Basin, accounting for climate and other uncertainties using a four-phased analytical approach. These applications confirm the approach's utility and inform future research and practical use.

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Additional contributions

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Laura Bonzanigo carried out the maximum regret calculations and scenario discovery analyses used in Chapter 5 to stress test investments in hydropower in the Koshi Basin work based on discussions with the author. She also produced the plots in Figures 35 and 36. Patrick Ray, Casey Brown and their team provided hydrological inputs and advice used to scale the climate change flows for the Koshi Basin work. Luna Bharati and Pennan Chinnasamy generated the baseline flow data for this study. Julien Harou was involved in stakeholder interactions in Nepal which fed into the Nepal case study application.

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List of Acronyms

ADB	Asian Development Bank
CDM	Clean Development Mechanism
CMIP5	Coupled Model Intercomparison Project – Phase 5
COGERH	Companhia de Gestão de Recursos Hídricos
DMU	Decision-making under (deep) uncertainty
DSS	Decision Support System
EC	European Commission
GCM	Global Circulation Model
GWP	Global Water Partnership
HPC	high performance computing
HSAF	Hydropower Sustainability Assessment Forum
HSAP	Hydropower Sustainability Assessment Protocol
ICFRE	Indian Council of Forestry Research and Education
IDH	Intermediate disturbance hypothesis
IEA	International Energy Agency
IFI	International Financial Institution
IHA	International Hydropower Association
IKI	International Climate Initiative
INPS	Integrated Nepal Power System
IPCC	Intergovernmental Panel on Climate Change
IRAS-2010	Interactive River-Aquifer Simulation – 2010
IUCN	World Conservation Union
IWRM	Integrated Water Resources Management
JICA	Japan International Cooperation Agency

MCDA	Multi-criteria decision analysis
MOEA	Multi-objective Evolutionary Algorithm
MORDM	Multi-objective Robust Decision Making
MoWR	Ministry of Water Resources
NEA	Nepal Electricity Authority
NGO	Non-governmental organisation
NPV	net present value
PRIM	Patient Rule Induction Method
RDM	Robust Decision Making
REN21	Renewable Energy Policy Network for the 21st Century
SAPP	Southern African Power Pool
SDDP	Stochastic dual dynamic programming
SOP	standard operating policy
SWAT	Soil and Water Assessment Tool
UAHP	Upper Arun hydropower project
WCD	World Commission on Dams
WCED	World Commission on Environment and Development
WEAP	Water Evaluation and Planning System
WISE-UP	Water Infrastructure Solutions from Ecosystems Services Underpinning Climate Resilient Policies and Programmes
ε-NSGAII	Epsilon-Dominance Non-dominated Sorted Genetic Algorithm II

1 Introduction

1.1 General Background

Global population growth and economic development are increasing demand for resources including water, energy and food. With no changes to current methods, agricultural production will need to increase 70% by 2050 and energy production 50% by 2035 (Hoff, 2011). There is a growing recognition of the fundamental need for 'security' in supply of these three resources (FAO, 1996; Beddington, 2009; Bazilian et al., 2011; Bogardi et al., 2012; Jung, 2012; Allouche et al., 2014; Leck et al., 2015) and in the case of water, security from the potentially damaging impacts of flooding (i.e. over supply) (Hall et al., 2014; Hall and Borgomeo, 2013). There are myriad interactions between the natural and human systems which provide and process these resources for human use. Water resources underpin ecological systems, production of subsistence and economic goods and hydroelectricity generation, supporting national energy independence and climate change mitigation, where the ratio of land use to generating capacity is low (Hertwich, 2013). Water resource availability, seasonality and variability are all projected to be affected by climate change (IPCC, 2014). Energy is required to treat water before human consumption and before returning it to the environment and is also required for agricultural production and processing and transportation of foodstuffs. Thermal methods of electricity generation often require water as a cheap and readily available coolant. Agricultural crops and livestock require water to grow. These limited examples of systemic interactions between supply systems of three key inputs to any economy serve to illustrate the challenges faced in the pursuit of water, energy and food security. These challenges are exacerbated by future uncertainties of climatic and socio-economic change (Heal and Millner, 2013). Water resources and the built and natural infrastructure which derive benefits from them are recognised as being fundamental to addressing them.

Water infrastructure systems need to share the benefits from water resources amongst many stakeholders and perform adequately under uncertain future conditions. Economic development can be constrained where demand for water, energy or food exceeds supply, making building new or adapting existing infrastructure to increase or better regulate supplies attractive. Such development can affect multiple stakeholders at various scales unevenly and inequitably however, and there is growing recognition of the need to consider broader impacts of such development than has historically occurred (de Almeida et al., 2005; Oud, 2002), primarily in the interests of sustainability. For example, costly delays can result from perceived imbalance in the provision of benefits for local and non-local people from new hydropower generating capacity (World Commission on Dams, 2000), affecting investor confidence and returns on investment. Methods of accounting for multiple stakeholder interests at the strategic planning stage are desirable for their potential to expedite project completion through resolution or avoidance of conflict. They also have potential to improve the sustainability of positive outcomes and if done well, help adapt to and mitigate climate change.

1.2 Research problem and hypothesis

Developing countries face many challenges in developing their water resource systems to support water, energy and food security. Stakeholders in a river basin can be the richest in society, relying on water supply and hydroelectricity for example, but living in cities far from the local impacts of any infrastructure development. Local stakeholders by contrast, may be some of the economically poorest in society, relying for their survival on non-market ecosystem services underpinned by water resources, such as riverine or wetland fisheries or regular flooding of land with water and nutrients to saturate and fertilise agricultural land. Infrastructure development can affect these two example stakeholders unequally with the poorest being most vulnerable owing to their constrained options – the rich are better able to buy bottled water, buy a diesel-fuelled generator, or change their food sources if necessary.

Established methods of assessing and selecting interventions in water resources systems use aggregated measures of costs and benefits (Block and Strzepek, 2010; Chakravarty, 1987; Jeuland, 2010; Medellin-Azuara et al., 2009; Harou et al., 2009; Matrosov et al., 2013a; Howe and White, 1999), which can hide the reality of unequal impacts on different stakeholder interests and the trade-offs between them. Multiple sources of future uncertainty are also now recognised in terms of water resources system planning, not least climate change (Pahl-Wostl, 2007; Borgomeo et al., 2014; Hall et al., 2012; Lempert and Groves, 2010; Mortazavi-Naeini et al., 2015; Girard et al., 2015). Established methods of considering uncertainties are unfit for purpose (Lempert, 2002), offering little information about the probability of a particular infrastructure investment performing satisfactorily throughout its lifetime. An investment which is optimal for a specific set of futures may not perform satisfactorily if conditions deviate from those used to select investments.

This thesis tests the hypothesis that cutting edge analytical techniques could be applied to real-world developing country decision-making about water infrastructure operation and investment to provide more equitable outcomes for stakeholders, which are also robust to future uncertainties.

1.3 Outline of the thesis

The following chapter presents a literature review of the challenges faced in pursuing water, energy and food security in developing countries, the policy context for these efforts and the evolution of technical paradigms for addressing these challenges. This illustrates the need for more advanced approaches to infrastructure selection, design and operation and justifies the investigation undertaken through this thesis. Subsequent chapters present three applications of increasing complexity, applied to three different water resources systems – the Jaguaribe Basin in north-eastern Brazil, the Tana Basin in Kenya and the Koshi Basin in Nepal.

The first application in Brazil considers how a system of three existing dams could be re-operated to change the balance of benefits accruing to diverse stakeholders. These benefits include basin-specific livelihood factors and environmental flows. In the second application, an existing cascade of five hydropower dams is re-operated but in the context of selecting and sizing proposed new irrigation investments downstream as well as the potential to re-balance the benefits to different stakeholders. Both the first two case studies are deterministic, using historical flow time-series' to investigate how the system might perform under a future which looks much like the past. The third application in Nepal addresses the challenge of selecting a portfolio of hydropower dams for the Koshi Basin which would prove both efficient and robust under uncertain future conditions. A four-phased approach is proposed for considering both physical water availability uncertainties and socio-economic uncertainties which could affect the expected financial returns on a given set of investments.

The final two chapters discuss the findings of the research, its limitations and implications for future work. The thesis concludes with a section on experiences and recommendations for practical application of the approach developed.

2 Literature review: water, energy and food security challenges in developing countries, the policy context and evolution of technical paradigms

This chapter presents a literature review of challenges faced in developing country water resources systems which are often expected to support domestic and industrial water supplies as well as competing energy generation and food production goals. The physical and policy context for these challenges is explored as well as the technical and stakeholder engagement methods available to address them. This informs the case study research applications in the subsequent chapters.

2.1 Water resources systems

Water resources systems are comprised of both natural and engineered infrastructure with various hybrids in between. Natural infrastructure generally includes river channels, flood plains and aquifers as well as more dynamic features such as water flows and flood waves which pass down the river channel. Ecosystem services provided by natural infrastructure are often the reason why engineered infrastructure is built, i.e. to capitalise on the goods and services available (Krchnak et al., 2011). Engineered infrastructure includes but is not limited to dams, weirs, hydroelectric powerhouses, diversion channels and abstraction pumps. The interactions between engineered and natural infrastructure lead to a complex mix of costs and benefits, varying spatially and temporally. This complexity is challenging to understand, plan and manage.

Dams have been used for thousands of years to try and ensure water is available where and when it is needed (Smith, 1971). Irrigation schemes often depend on storage of water to allow higher crop yields through controlled application of water. Dams are also used to manage floods, retaining water for controlled use and preventing destruction downstream. Some dams have hydropower schemes attached to them, allowing energy to be generated from the stored water. This can be the sole purpose of a dam, or one of its multiple purposes, alongside drinking water or irrigation supply, for example.

Hydropower is the most utilised renewable energy source in the world today, generating around 17% of electricity globally (representing 73% of installed renewable energy capacity) (REN21, 2015). The use of hydropower and its potential for expansion varies greatly between countries. In Asia and Africa, substantial large projects are still feasible, whereas in Europe and North America most feasible large schemes have been exploited but there exists plenty of potential for small-scale local or low head schemes (Bartle, 2002). In addition, environmental legislation in developed regions such as the EC Water Framework Directive makes it more difficult to promote and implement large schemes that modify natural flow regimes.

At the same time as extensive benefits have been realised, a significant amount of damage has been done to environmental and social systems through the process of building and operating large dams (World Commission on Dams, 2000). This has often resulted from inadequacies of the planning process in ignoring or undervaluing the natural systems and ecosystem services relied on by people for their livelihoods.

2.2 Policy context for developing country water resources development

The policy context for developing country water resources development in the present day has a decades long history. This section reviews the literature relating to key pressures and the international responses to them.

2.2.1 World Commission on Environment and Development

Realising the potentially serious consequences of degradation of the human environment and natural resources, the United Nations (UN) General Assembly established the independent World Commission on Environment and Development (WCED, also known as the Brundtland Commission after its Chair). The commission was tasked with analysing existing problems with the conflict between economic growth and environmental protection and ideas for their solution. In 1987 the WCED published its main report “Our Common Future”, which is credited with establishing the concept and the enduring definition that: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This concept has influenced much discourse (positive and negative) (Beck and Nesmith, 2001; Cash et al., 2003; Costanza and Daly, 1992; Dincer and Rosen, 2007; Folke et al., 2002; Gladwin et al., 1995; Hart, 1997; Lele, 1991; Lund, 2007; Malley et al., 2007; Pradhan and Shrestha, 2007; Stern et al., 1996) since its inception but degradation of natural resources has continued unabated (Balmford et al., 2002) and the ‘fuzziness’ of the definition has not been replaced by the intellectual clarity and rigor which Lele (1991) suggested it required if were to have a political impact. However, the concept has developed that well-functioning natural systems actually generate or support economic benefits, as well as human well-being (Costanza et al., 1997; Daily et al., 1997). Costanza et al. (1997) valued the global non-market economic value of a number of ‘ecosystem services’ as at least US$33 trillion per year, compared with a total global gross national product of US$18 trillion per year. Balmford et al. (2002) estimated the benefit:cost ratio of a global effort to conserve remaining wild habitats to be at least 100:1. Ecosystem services and natural capital have since developed into key concepts for the pursuit of sustainable development, which remains a challenging goal.

2.2.2 Agenda 21

The United Nations Conference on Environment and Development (UNCED) popularly know as the "Earth Summit" in Rio de Janeiro in 1992 agreed a non-binding action agenda for the UN, other multilateral organizations, and individual governments to work towards sustainable development at local, national, and global levels. The document containing this action plan is called Agenda 21, referring to the 21st century (UNCED, 1992). Chapters 10 and 13 of Agenda 21, focussing on land management and minimizing the trade-offs between the environment and agricultural development respectively, explicitly recognise that trade-offs are necessary in efforts to achieve sustainable development. Chapter 18 on protection of the quality and supply of freshwater resources also alludes to the necessity of trade-offs in water management without actually using the term. This is clearly a key concept in addressing the challenges of competition for limited resources.

2.2.3 The Dublin Principles

At the International Conference on Water and the Environment (ICWE), in Dublin, Ireland, in 1992, experts on water management and sustainable development agreed a statement recognizing the increasing conflict over water for multiple uses and the "Concerted action is needed to reverse the present trends of overconsumption, pollution, and rising threats from drought and floods" (ICWE, 1992). It set out four guiding principles for action:

1. Fresh water is a finite and vulnerable resource, essential to sustain life, development and the environment
2. Water development and management should be based on a participatory approach, involving users, planners and policy-makers at all levels
3. Women play a central part in the provision, management and safeguarding of water
4. Water has an economic value in all its competing uses and should be recognized as an economic good

The fourth principle created some controversy amongst NGO's and civil society as it appears to dismiss the concept of access to safe drinking water as a basic human right. However, the full text of this principle does state: "it is vital to recognize first the basic right of all human beings to have access to clean water and sanitation at an affordable price."

2.2.4 Ecosystem services

The concept of ecosystem services gained greater recognition through the Millennium Ecosystem Assessment (MEA, 2005) conducted over four years under the auspices of the United Nations (UN) and directed at policy makers. A further three-year UN initiative called the Economics of Ecosystems and Biodiversity (TEEB, TEEB Foundations, 2010) was widely publicised helping establish the concept of ecosystem services amongst a more public audience. Further support for and development of the concept has been provided by The World Business Council for Sustainable Development (WBCSD, 2011 and WBCSD, 2012). Diverse and extensive efforts are now underway to better understand, model, value and manage ecosystem services and natural capital (Daily et al., 2009; Braat and de Groot, 2012; de Groot et al., 2012; Abson and Termansen, 2011; Arias et al., 2011; Green et al., 2015; Lankford et al., 2011; Turner and Daily, 2008; Sagoff, 2008, 2011).

2.2.5 World Commission on Dams

In 1998 as the result of a meeting between IUCN and the World Bank, the World Commission on Dams (WCD) was formed, primarily to review development effectiveness (i.e. performance) of large dams and assess alternatives for water resources and energy development. The final report of this 2.5 year study ran to over 400 pages, covering both the science of and policy recommendations related to the development performance of large dams (World Commission on Dams, 2000).

The World Commission on Dams was the culmination of global dissatisfaction with the negative impacts associated with large dam building. It identified a range of aspects of the planning and execution of dam building which could be improved to better share the costs and benefits accrued. The key points for this research are that 1) early stakeholder engagement is recognised as being vital to reducing or preventing opposition to projects, 2) social and environmental costs must be better accounted for in the planning process for dams, and 3) all options must be explored to ensure that unnecessary dams are not built and alternatives such as upgrading existing dams are employed wherever possible.

Criticisms of the World Commission on Dams have claimed the process was dominated by environmental and social issue NGOs, leading to unbalanced outputs which are very difficult to operationalize (Nakayama and Fujikura, 2006; Fujikura and Nakayama, 2002; Briscoe, 2010).

2.2.6 Water, energy and food security under climate change

Integrated Water Resources Management (IWRM) (GWP, 2000) is the ideal for addressing complex interactions between water resource uses, incorporating social, economic and ecological goals. Developing countries often have little institutional capacity to coordinate government ministries to deliver IWRM however. Merrey et al. (2005) propose IWRM could better support rural livelihoods by taking a broader perspective, developing interdisciplinary models which integrate physical as well as social variables. Indeed, tools which help to bring stakeholders together to understand each other's plans and how they might interact and impact on their respective interests could be of great value.

An emerging theoretical framework considers the need to address the interactions between water, energy and food security to ensure that all three can be achieved. This has become known as the Water-Energy-Food (WEF) Security Nexus. Traditionally these sectors have been studied and managed in isolation, but under increasing stress the strong inter-linkages between WEF systems have become apparent. The context for this is increasing population leading to greater demands for water, food and energy, large emerging economies undergoing change in dietary patterns towards greater protein consumption, environmental degradation, biodiversity loss and climate change (Hoff, 2011; Leck et al., 2015). Energy and food production require vast quantities of water, with meat production requiring far more water per kilogram than crops – for example, beef production requires around 10 times as much water as cereal crops per kilogram (Mekonnen and Hoekstra, 2010). Water supply and wastewater treatment require substantial amounts of energy. Ecosystem services which constitute the foundations of the economy are highly reliant on the quantity, quality and timing of water availability in the environment while climate change is likely to change all three of these characteristics of water availability (IPCC, 2014). Many of the world's rural poor rely on ecosystem services provided by environmental resources. Their vulnerability increases and prospects for economic development reduce with degradation of these resources (Malley et al., 2007; Juana et al., 2012; McCully, 2001). Access to water and poverty are linked (GWP, 2003); increases in access to irrigation for example, can improve circumstances of economically marginalised groups (Lipton and Litchfield, 2003).

The Water-Energy-Food Security Nexus approach aims to understand the complex interactions in the system in order to manage it as a whole (Hoff, 2011). There is some debate about how different a nexus approach is from the earlier framework of IWRM and whether it has enhanced or replaced it, but the consensus seems to be that it is not a negative development (Benson et al., 2015; Muller, 2015; Leck et al., 2015). In the case of water management, the most appropriate scale is often considered to be the basin scale (Grey and Sadoff, 2003) but inter-related systems which reach beyond can sometimes not be limited to this geographical extent. There can be broader implications when water is transferred between basins and when products containing water are imported and exported (Bouwer, 2000; Hoekstra and Hung, 2005). This would include products which consume water in their production (i.e. agricultural produce). The latter issue is highlighted in water foot-printing studies (Chapagain et al., 2006; Demeke, 2012; Hoekstra and Chapagain, 2007; Hoekstra and Mekonnen, 2012; Ridoutt and Pfister, 2010; Rulli and D'Odorico, 2013), for example it takes an average of 155 litres of water to produce 1 litre of beer in South Africa and can be over three time this much for coffee, wine or apple juice production (WWF, 2009). It is important to note that water foot-printing can prove challenging as the impact of any given water use depends on the resources available in the location it occurs (Ridoutt and Pfister, 2010).

2.2.7 Changing political dynamics

The debate around large dams has moved on since the World Commission on Dams published its report in 2000. Acceptance of climate change has become much more widespread amongst governments and international organisations (Atkinson, 2010; Pielke et al., 2007). This has led to subsidies on one hand for hydropower and other sources of low carbon energy through the Clean Development Mechanism. Greenhouse gas emissions from dams are the subject of controversy and ongoing research however, as discussed below. By contrast acceptance of climate change has introduced an additional uncertainty into the planning process for water infrastructure as flows can no longer be considered stationary (Milly et al., 2008). Middle income countries such as China, India and Brazil are becoming more influential politically and economically - the World Bank and other International Financial Institutions are no longer the only source of funding for large infrastructure (hydropower, water supply, irrigation) projects as the middle income countries seek to exercise their economic power. Environmental and social impacts of new infrastructure are less strictly controlled by less established funders (Moore et al., 2010).

2.2.7.1 Greenhouse gas (GHG) emissions

Some uncertainty exists about the levels of greenhouse gases actually released through the construction and operation of dams, especially in the tropics (Fearnside, 2004). Far higher emissions may be occurring than expected but getting good data is difficult and preventing policy action. Hydropower is often promoted as a means of reducing carbon emissions from energy production worthy of Clean Development Mechanism (CDM) funding – hydropower is seen as being almost zero-carbon. Some controversy remains however about the levels of carbon dioxide and methane (a more powerful greenhouse gas) which are produced by hydropower facilities (dams, reservoirs and release structures). Lima et al. (2008) estimated reservoirs in the tropics could be contributing an additional 30% to existing estimates of global methane emissions. Gases can be generated by decay of standing and inflowing biomass, stratification of the water body and sudden pressure changes through turbine or other releases (St Louis et al., 2000; Giles, 2006; Fearnside, 2004, 2002). Factors such as climate, size and depth of reservoir all affect emissions. Hertwich (2013) suggests that a large proportion of GHG emissions can be avoided by ceasing to develop hydropower dams with a large land use per unit of electricity generated. Ramos et al. (2009) discuss the possibility of capturing methane emissions from reservoirs to use as an energy source.

In February 2006, the Kyoto Clean Development Mechanism (CDM) Executive Board ruled that large-scale hydropower projects must satisfy certain power density related conditions to be eligible as CDM projects. These conditions relate to the project emissions which must be considered as resulting from the impoundment of the water (Table 2.1). Limited scientific evidence underpins these restrictions and further research is needed, including the consideration of multi-purpose reservoirs.

Table 2.1 Restrictions on hydropower projects under the Clean Development Mechanism (CDM) (Mäkinen and Khan, 2010)

Power density of hydroelectric reservoir (installed generation capacity divided by flooded surface area), W/m^2)	Eligibility to use approved methodologies under CDM rules
<4	Excluded from using currently approved methodologies (ACM0002, AM0019 and AM0026)
4-10	Allowed to use approved methodologies, but project emissions must be included at 90 gCO$_2$-eq/kWh
>10	Allowed to use approved methodologies and project emissions can be neglected

Unfortunately, much of the research published on the topic has been produced by researchers connected to the hydropower industry, leading to questions about its objectivity (Mäkinen and Khan, 2010). The debate around this subject has largely been an academic one, although the issue became more mainstream through its inclusion in the WCD report. Policy-making to reduce these emissions is largely held up by the scientific uncertainties.

2.2.7.2 Clean Development Mechanism (CDM) funding

The new debate about the balance between costs and benefits of hydropower in terms of carbon emissions and changing hydrology mean there are big questions hanging over the design and economic evaluation and subsidising of new hydropower dams (Mäkinen and Khan, 2010). Under the Kyoto Protocol's Clean Development Mechanism (CDM) hydropower is currently the largest category of registered projects. Pittock (2010) perceives a problem with the hydropower industry advocating its schemes as a low carbon source of energy eligible for Kyoto Clean Development Mechanism (CDM) grants. The conditions of these grants are often not monitored or adhered to, i.e. requirements to fulfil challenging WCD recommendations and the financial viability of the project relying on the CDM grant. Furthermore, CDM grant conditions conflict with Convention on Biological Diversity and Ramsar Convention on Wetlands, presenting further potential for negative environmental impacts. Grants for a few large dams which do not necessarily fulfil the conditions or avoid environmental and social costs could consume much of the available funding so that more beneficial projects are unable to be funded. Claims that the CDM grant process has been strengthened are reportedly not substantiated (Pittock, 2010).

2.2.7.3 Land and Water grabs

A relatively new phenomenon with significant implications for water management are large-scale deals between developing countries and other countries or corporations for the sale or lease of relatively inexpensive and productive agricultural land. This is a result of increasing demands for food and biofuels and the food price crisis of 2007-2008 (Edelman et al., 2013; Giovannetti and Ticci, 2016; Rulli et al., 2013). While smaller such deals have had a long history, it is the scale of the recent activity which is of note and concern. Such deals have collectively become known as 'land grabs' because they can involve communal land utilised by local communities without legal rights being sold or leased to the exclusion or detriment of those users (Franco et al., 2013). While the term suggests a negative behaviour, there is likely a spectrum of legal structures and outcomes in the actual deals (Smalley and Corbera, 2012). There is often a lack of transparency around the deals, meaning it is hard to know the details. Large-scale land use deals often include access to large or unlimited quantities of water which could have severe impacts on other interests if these rights were exercised (Rulli and D'Odorico, 2013). In many cases however, the deals done have not yet been fully exploited or have been stalled by local opposition (Breu et al., 2016; Smalley and Corbera, 2012).

2.2.8 Development of new planning guidelines

In response to the World Commission on Dams (WCD) (2000) and in the context of the drive for sustainable development described above, a number of organisations have developed approaches for operationalizing WCD recommendations. The approaches taken varied according to the priorities and perspectives of the organisations involved, many focussing on hydropower development. Hydropower has likely been the focus of these guidelines owing to the greater commercial interest in this sector rather than traditionally public sectors of water supply and irrigation which also benefit from dam construction (Hartmann, pers.comm.). This section describes some of these approaches, highlighting their common themes of:

- inclusive development engaging with stakeholders from the earliest stage to involve them in decision-making,
- taking a system level view to aid with site selection and prioritisation,
- accounting for environmental and social impacts in decision-making, and
- mitigating environmental and social impacts where unavoidable.

2.2.8.1 Hydropower Sustainability Assessment Protocol (HSAP)

The hydropower industry initially rejected the specific recommendations of the WCD but has moved to a position of pro-actively moving towards sustainability guidelines which it feels should provide a degree of predictability (of outcomes and costs) to the planning and construction of hydropower or multi-purpose dams (Bosshard, 2010).

The International Hydropower Association (IHA) first developed Sustainability Guidelines for hydropower development in 2003. This led to a Hydropower Sustainability Assessment Protocol (HSAP) in 2006 and later the Hydropower Sustainability Assessment Forum (HSAF) – a process aimed at further developing the Protocol in partnership with governments, NGOs and the financial sector. This represents an attempt to take ownership of the need to change the industry, increasing potential performance of the sector in the future (Locher et al., 2010). Since 2008, IHA has been training assessors to use the protocol in assessing proposed developments.

The Final Draft protocol resulting from the HSAF is a set of four standalone assessment tools using multiple criteria to address a specific stage of the project cycle. The assessor interviews a range of stakeholders to gather evidence which informs the assessment of these criteria, in conjunction with observations and assessment of objective evidence. Each criterion is scored on a scale of 1-5 where 1 is very poor practice, 5 is proven best practice and 3 is basic good practice.

The Draft protocol does not directly address the WCD recommendations, although equivalents of various WCD content can be found in different forms within the protocol. In some cases, WCD issues are represented by the intent of a Draft Protocol aspect, in others an attribute will meet WCD recommendations if it achieves a score of 5 and in yet others WCD issues are embedded in guidance notes. It is therefore far from a direct method of implementing the WCD recommendations that environmental and social issues be given equal consideration to technical and financial considerations. Some (particularly civil society) groups expressed views during a consultation phase that the HSAP was not a legitimate way of implementing the strong guidelines of the WCD and properly values neither environmental nor social issues. These views were countered by those from within the hydropower industry which felt the WCD had been a flawed process and saw the HSAP Protocol as a positive alternative (Bosshard, 2010).

Bosshard (2010) ascribes some fundamental problems to HSAF, including: poor definition of the process goals at the outset leading to differing expectations of the outcomes; lack of process compliance with the code of good practice prepared by the International Social and Environmental Accreditation and Labelling Alliance (ISEAL) which could have allowed the Protocol to be used for third-party certification; requirements to consult with dam-affected people without conferring any rights on them; lack of requirement to comply with binding standards, laws or international conventions; and, the generous interpretations of what constitutes ‘objective evidence’ for the sustainability assessment.

Consultation on the draft Protocol in 2009 led to the following responses:

- Equator Bank representatives want guidelines to help them direct their project funding decisions, which they would like to set a minimum standard under which funding is not applicable.
- Environmental and social NGOs want a tool that dam builders, affected communities, governments and international organisations can refer to when building, planning and refurbishing dams and reservoirs.
- Donor governments would like a tool to help them assess the extent to which environmental and social standards are taken into account in dam building projects to inform their planning and funding decisions.
- The hydropower industry wants a sustainability standard to assess prior to an investment which issues will arise during the construction and commissioning of a dam. (All responses quoted verbatim from Ove Arup & Partners, 2009, cited in Bosshard (2010))

In 2014 the World Bank carried out an assessment of the protocol for use by World Bank clients, focussing on lessons learned and recommendations (Liden and Lyon, 2014). Relevant to this research, the assessment found that:

- The Protocol is a useful tool for guiding the development of sustainable hydropower in developing countries.
- It is suitable for the identification of areas of improvement in hydropower projects in a variety of localities and at various stages of project development.
- The assessment is heavily reliant on the cooperation of the developer in providing information and therefore should not be undertaken without this support. Experience has also shown that significant investments of time and financial resources are required to conduct a full assessment, although much less than for project development.
- For use in World Bank-supported projects, the Protocol will be useful if it can reinforce project preparation and/or supervision; it is likely to have more value during early preparation and less value during the short, intensive period of project appraisal.

2.2.8.2 Sustainable Hydropower

WWF has been involved in the HSAP process and is a keen advocate of the concept of sustainable hydropower through its “Dam Right” Initiative. WWF worked with Zambia’s Ministry of Water and Energy Development to introduce environmental flow releases from the Itezhi-Tezhi dam to improve ecological conditions in the Kafue flats wetlands. This provides huge benefits for local people and wildlife with minimal disruption to hydropower generation (WWF, 2003). The organisation has worked with the Icelandic and Brazilian governments, advocating the designation of ‘no-go’ rivers for hydropower development in selected areas of high value biodiversity. It also advocates the Gold Standard be met for dam building projects applying to the Clean Development Mechanism (CDM) and the Joint Implementation (JI) provision of the Kyoto Protocol to ensure its limited funds are not consumed by large projects which could be funded without this support and are furthest from meeting WCD Principles and Strategic Priorities. WWF estimates that it may be possible to develop 30% of the economically feasible small hydropower capacity in most river basins or nations without unacceptable impacts. Additionally, it estimates 250GW of large and 20GW of medium hydropower potential could be developed with relatively low impacts, particularly in the least developed parts of the world, such as in Africa.

WWFs most recent document on reducing the impacts of dams outlines what it calls the ‘Seven sins of dam building’ (Kraljevic et al., 2013). These sins are:

1. Building on the Wrong River
2. Neglecting Downstream Flows
3. Neglecting Biodiversity
4. Falling for Bad Economics
5. Failing to Acquire the Social License to Operate
6. Mishandling Risks and Impacts
7. Blindly Following Temptation / Bias to Build

WWF also focuses on the value of free flowing rivers in its undated report titled “Free-flowing rivers: Economic luxury or ecological necessity?”. This report consists of four parts. It initially analyses the contributions of freshwater systems to human welfare and biodiversity and contrasts the value of free-flowing rivers with those fragmented by dam building or modified in other ways. The second part assesses the current state of the world’s large (over 1000km) rivers, showing that only one third remain free-flowing and only 21 maintain a direct connection to the ocean. This is followed by more in-depth case studies and proposals for protecting the remaining free-flowing rivers. Through this report WWF asks governments to identify and protect rivers of great biodiversity and ecosystem service value and specifically calls for the immediate protection of a number of rivers, including the Amur, the Salween, the Chishuihe and the Amazon.

2.2.8.3 World Bank

A recent World Bank paper (Water Working Note no. 21, June 2009) sets out some criteria for sustainable hydropower infrastructure:

1. “internalising” its impacts on affected populations, i.e. including resettlement and other compensation in the project design and financing package
2. Undertaking responsible environmental management, affecting both ecosystems and social groups
3. Exploiting and promoting opportunities for social inclusion, poverty alleviation and social development

In the World Bank’s view, hydropower development is being held back by its high risk, due in turn to lack of local institutional and skill capacity, weak regulatory and policy frameworks, its inherent complexity, and its multi-sectoral and multi-objective nature. Overcoming these problems requires a strong risk management approach to the sector. Other key constraints to scaling up investment are a lack of financing, lack of comprehensive planning and adequately assessed project pipelines, limited hydrological data and unsettled conditions that discourage private involvement.

There is evidence that adopting a "holistic" approach to hydropower planning at the basin level can yield important benefits. A recent study of two river basins in North India came to the following conclusion:

"Planning for hydropower development needs to evolve from a project-based engineering approach to a more holistic one - an approach incorporating river basin planning and integrating potential social and environmental issues across multiple projects and the entire river basin. Such a framework would help to optimise the benefits and minimise the costs..." (Haney and Plummer, 2008).

The two river basins concerned have ambitious plans for developing a number of hydropower sites, including some earmarked for private developers. However, many of these are likely to be new and untested for the challenges facing them. A project-by-project approach will not take sufficient account of the system-wide aspects of multiple hydropower projects along the same river. The performance of the projects is likely to be enhanced by the use of basin-wide modelling, coordinated operational protocols, and catchment and environmental protection. Likewise for the anticipation of risks from fluctuations in flow and cumulative flooding.

2.2.8.4 International Energy Agency (IEA) Annex VIII

The Hydropower Implementing Agreement is a collaborative programme among member countries and consists of an Executive Committee and a number of task forces which have been set up within its organization to track specific study themes, called "Annexes". Particularly relevant to this research is Annex VIII – Hydropower Good Practices (International Energy Agency, 2006).

Over a six year period (2000-2006) expert meetings, open workshops and symposia and executive committee meetings were held to define and gather evidence of Good Practice in hydropower development and operation.

Good practice was defined in two ways:

1. Practices where environmental and social practices were resolved successfully as a result of mitigation measures.
2. Practices that provided social and/or environmental benefits through hydropower development.

Case study examples (60 in all from 20 countries) were gathered from all over the world, although 80% were from Asia and North America and 67% from temperate rather than tropical or continental climates. Trends were described under each of 15 key Indicators in 3 categories: Biophysical Impacts, Socio-economic impacts and

Sharing of development benefits. Good practice was documented in relation to a range of project types, with storage reservoirs accounting for 32% of cases and multi-purpose developments accounting for 25%. This demonstrates that storage-type systems do not necessarily place an unacceptable burden on the environment.

Case studies include reasons for success and the most commonly cited were: “implementation of environmental impact assessment”; “consultation with experts”; “detailed preliminary surveys”; and “appropriate planning and design”. The most common reason given for success in mitigating socio-economic impacts was “coordination with stakeholders”.

Annex VIII makes the following broad proposals for mitigating negative impacts of hydropower development and increasing positive outcomes:

1. Information on Good Practices should be effectively shared in the international hydropower community.
2. Good Practice information should be available to all stakeholders and used to objectively assess sustainability of new and existing hydropower projects.
3. Mitigation and enhancement measures must be project and context specific.
4. Cross-sectoral collaboration should be strengthened and international standards developed in place of disparate sets of guidelines.
5. New examples of Good Practice should be collated and added to the knowledge base required for points 1 and 2 above.

2.2.8.5 Southern African Power Pool (SAPP)

The guidelines for conducting Environmental and Social Impact Assessments for hydropower projects within the Southern African Power Pool (SAPP) are intended to provide a “level playing field” for the region, so that no party can gain a competitive advantage through degradation of their internal environment or impacts on co-beneficiaries of a shared water resource (Southern African Power Pool, 2007). At least 70% of water resources in the region are reported as shared by riparian neighbours, so this is an important issue. It is also intended to ensure compliance of projects with all relevant legal requirements. The guidelines use World Bank categories of project types to decide where an impact assessment is necessary.

An impacts assessment checklist is adapted from the ADB’s (1993) Environmental Guidelines for Selected Industrial and Power Development Projects. Stating that due to the stage of technological development in the hydropower sector, impacts and mitigation methods are “fairly standard” SAPP (2007) describes minimum acceptable mitigation measures are described for typical environmental and social impacts of dam building. A small number of benefits which may be achievable are also suggested for funding support through the development project.

Public involvement is described as an imperative from the very outset of a project, as resistance or opposition can cause costly time delays or failure of a project. Transparent planning and simple straightforward public education and involvement can turn opponents into supporters. Costs associated with public engagement need to be given proper consideration as part of the EIA and overall development budget.

2.2.8.6 Sustainable Development Planning

In their work on the sustainable development plan (SDP) for the Mphanda Nkuwa hydropower project in Mozambique, Dray and Pires (2013) describe the main barriers to implementation of the SDP. They stress the importance of engaging with stakeholders at an early stage in order to strengthen the relationship between local communities and the project team. They consider this crucial for the social license to operate; something which the hydropower industry has been fighting to regain for the last 10-15 years.

Forget et al. (2013) relate their experience of the Rusumo Falls hydropower project on the Kagera River at the border between Tanzania and Rwanda and conclude that hydropower project leaders should broaden decision-making processes to include local governance and rural planners. They also highlight the need to choose critical and meaningful decisional indicators. These should be developed by stakeholders at the beginning of the project to improve communication and mutual understanding between different parties. Consulting more broadly helps establish an adequate set of indicators to fully understand whether it is feasible to mitigate the costs and risks associated. During the initial stages of the Rusumo falls project an options assessment ruled out both full and intermediate development options involving storage reservoirs due to the number of affected families and the trade-off between such significant resettlement (17,500 households for full development or 5,200 for Intermediate development) and the additional power gained. A run-of–river scheme was decided upon to significantly reduce the social risks for only a marginal drop in energy benefits.

2.2.8.7 Gaining public acceptance

According to Dore and Lebel (2010) risk assessment should be a political process, rather than a purely technical one as the technical simplifications which are necessary provide lee-way for vested interests and bias. Stakeholder engagement has been shown to usually occur in the middle stages of projects, rather than throughout (Petkova et al., 2002). Such projects cannot be ‘stakeholder led’, and it is unlikely that they involve comprehensive options assessment. Stakeholder involvement is now widely accepted as a pre-requisite for successful water resources planning and development (Reed and Kasprzyk, 2009) although its effective implementation is by no means a simple task (Swallow et al., 2006;Carr et al., 2012;Hauck and Youkhana, 2010;Taddei, 2011).

2.2.8.8 Hydropower by Design

In light of the likely substantial increase in hydropower capacity internationally over the coming decades, The Nature Conservancy has taken an interest in the impacts of such dams on communities and nature, and developed an approach it calls 'Hydropower By Design' (Opperman et al., 2015). This is proposed as a contribution to existing planning and design processes at project and system scale. It involves:

- Avoiding the most damaging sites to direct development towards those that will have lower impacts
- Minimising impacts and restoring key processes through better design and operation of individual dams; and
- Ofsetting those impacts that cannot be avoided, minimised or restored by investing in compensation such as protection and management of nearby rivers that provide similar values.

(Opperman et al., 2015)

The analysis and testing of the impacts of these principles focussed primarily on changes to river flow patterns and the maintenance of connected river reaches. This assumed that the fragmentation of river reaches by dams can have one of the strongest impacts on their ecological health. The Nature Conservancy believes that hydropower must be planed at 'system scale' in order to prioritise the sites for development which will have the lowest impact, rather than proceeding on a project-by-project basis. It is noted that the system can refer to any appropriate level above the project, e.g river basin, region, country or electricity grid (Hartmann et al., 2013).

It is recognised that Hydropower by Design could increase investment costs by approximately 15 percent over business-as-usual approaches. Opperman et al. (2015) suggest that these costs could be offset by improved risk management associated with better planning and conflict mitigation as well as the increased non-monetary benefits such as ecosystem services.

2.2.9 Summary

This section has shown that water infrastructure decisions in developing countries are undertaken in a complex environment of pressures from both international institutions such as the United Nations and World Bank, national and international NGOs, as well as diverse national stakeholders including the poorest in society who are often most directly dependent on ecosystem services for their survival and basic economic needs. Increasing pressures from population and economic growth on land and water are likely to lead to greater competition for limited resources and trade-offs will have to be made where demands cannot be satisfied. Climate change could increase competition if water availability changes or present opportunities if availability increases, although patterns of change may be more complex than a simple increase or decrease. Decisions must also be taken in the context of this uncertainty and others relating to economic development pathways.

2.3 Water resource system planning and management

Water resources management has been described as a ‘wicked’ class of planning problem (Reed and Kasprzyk, 2009; Liebman, 1976; Lund, 2012) with difficult to predict “waves of repercussions” (Rittel and Webber, 1973) resulting from the complex interactions between social, environmental and economic impacts. The need to consider multiple concurrent and sometimes conflicting objectives is a salient feature of water resource management (Reed et al., 2013).

The challenge of managing complex water resources systems has stimulated extensive research into planning and managing these kinds of systems and an industry implementing available techniques for the benefit of private companies or government agencies tasked with these responsibilities. A wide range of techniques have been developed and applied since the 1950s beginning first with physical simulation models and progressing to computational simulation models as the technology became available (Maass et al, 1962). Computational models offer the opportunity to implement mathematical techniques such as optimisation, which has been extensively applied in practice (Barros et al., 2003; Braga and Barbosa, 2001; Chang et al., 2005; Chang et al., 2003; Chen, 2003; Chen et al., 2007a; Cheng et al., 2008; Coello et al., 2007a; de Farias et al., 2011; Draper et al., 2003; Fleming et al., 2005; Froehlich et al., 2009; Fu et al., 2012; Hamarat et al., 2014; Hassaballah et al., 2012; Hsu et al., 2008; Khan et al., 2010; Kirsch et al., 2009; Kollat et al., 2008; Koutsoyiannis and Economou, 2003; Labadie, 2004; Liebman, 1976; Loucks et al., 2005; Lund and Ferreira, 1996; Matrosov et al., 2015; McCartney, 2007; McPhee and Yeh, 2004; Medellin-Azuara et al., 2009; Mortazavi et al., 2012; Mortazavi-Naeini et al., 2014; Neelakantan and Pundarikanthan, 2000; Rani and Moreira, 2010; Reed et al., 2000; Reed et al., 2003; Shiau, 2009; Suiadee and Tingsanchali, 2007; Tran et al., 2011; Tu et al., 2008; Tu et al., 2003; von Lany et al., 2013; Woodward et al., 2014a; Wurbs, 1991, 1993; Yang, 2011; Yin et al., 2010).

Simulation models of various types are used to try and understand how a system functions, or how its function might change with one or more interventions in terms of, for example, operational changes (Chang et al., 2003; Cheng et al., 2008; Goor et al., 2010; Jager and Smith, 2008; Mulatu et al., 2013; Rani and Moreira, 2010; Reddy and Kumar, 2007; Tu et al., 2008; Yang and Cai, 2011), construction of new engineered infrastructure (Davidge et al., 2006; Ghile et al., 2014; Herman et al., 2014; Khan et al., 2010; Padula et al., 2013) or modifications of the natural infrastructure (Bennett et al., 2016; Yang and Cai, 2011). Change in function can imply altered allocation of resources to different uses, which is of course of interest to the users. Models are also useful for understanding how the occurrence of extreme natural conditions might affect the system and how such a situation might best be managed – different approaches can be tested without ever having to interfere with the actual system (Wurbs, 1993).

2.3.1 Issues around water resource development in developing countries

Developing countries face many challenges in developing their water resources to promote sustainable economic growth and human well-being. This section out lines some of the issues which complicate the planning process for new infrastructure.

2.3.1.1 Data availability

A common problem in developing countries is a lack of data or access to it, particularly for water management in terms of rainfall, river flow and detailed infrastructure data (Hughes, 2011; Li et al., 2012; Mendoza et al., 2012; Ritzema et al., 2010; Yuceil et al., 2007). These types of data are especially important as they play a big role in determining how much water is available for use in any particular location. Techniques which may be used to improve flow records are gap-filling of data records where they are not continuous and using ‘donor catchments’ with similar characteristics of climate, soil type and topography to suggest what the flows may have been like in another catchment with less flow data (Bardossy, 2007; Parajka et al., 2005). If rainfall and temperature are available but no flow data, then hydrological modelling may be able to generate flows, but without such data to calibrate against, it is difficult to know how accurate such flows are. Extensive international research efforts have been undertaken such as Predictions in Ungauged Basins (PUB), which was an International Association of Hydrological Sciences from 2003-2012, with the primary aim of reducing uncertainty in hydrological predictions (Sivapalan et al., 2003).

2.3.1.2 Environmental flows

In addition to data uncertainty, not all developing countries have defined environmental flows although efforts have been made to promote their establishment (Acreman and Dunbar, 2004). Environmental flows are defined as 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" (Brisbane Declaration, 2007). The situation is not necessarily better in developed countries, however as environmental flows are difficult to define in any river as various elements of a flow regime can be important, having different ecosystem functions. Various methods of defining environmental flows are available but none can be considered ideal for all situations (Acreman and Dunbar, 2004). Where environmental flows are defined, release from water infrastructure such as dams to maintain these flow levels may not always be enforced owing to lack of resources in agencies tasked with enforcement and other issues (e.g. Hurford et al., 2014).

The simplest methods of defining environmental flows rely on a fixed percentage of the flow or flow-duration curve and are rarely based on empirical evidence. The ignore the complexity of natural systems and their inherent variability (Smakhtin et al., 2004). In response to the weaknesses of these approaches, various more comprehensive methods have been developed which are typically resource intensive but tailored to local needs (Pahl-Wostl et al., 2013).

A significant challenge with defining environmental flows which protect ecological function is linking different aspects of flow alteration with impacts on different species. A recent review of related literature was unable to identify robust statistical relationships between flow alterations and species impacts (Poff and Zimmerman, 2010). It was however possible to confirm the general conclusion that flow alteration affects ecological quality.

Poff et al. (2010) present a consensus view from a group of international scientists on a framework called Ecological Limits of Hydrological Alteration (ELOHA) for assessing environmental flow needs for many streams and rivers simultaneously to foster development and implementation of environmental flow standards at the regional scale. This requires stakeholders and decision-makers to use available ecological and hydrological data and explicitly evaluate acceptable risk as a balance between the perceived value of the ecological goals, the economic costs involved and the scientific uncertainties in functional relationships between ecological responses and flow alteration. It is also proposed as an adaptive approach, to be combined with monitoring and data gathering to provide more information for decision-making over time.

Webb et al. (2015) report on some work undertaken in Australia to develop a general quantitative response modelling framework for environmental flow impacts, drawing on available literature, expert elicitation and monitoring data. The framework aims to develop general flow-response models to assess the ecological return on investment in environmental flows and be incorporated into planning and decision-making processes.

In response to the various challenges associated with both assessing and implementing appropriate environmental flows to safeguard socio-ecological systems, Richter (2010) has proposed a re-think of the way in which these activities take place. Richter believes environmental flows should be treated in a similar fashion to water quality, requiring regulation of impacts on a watercourse to maintain a high standard. The proposed ‘Sustainability Boundary Approach’ is intended to more fully realize the diverse value associated with water.

2.3.1.3 Agricultural economies

Many developing countries remain heavily dependent on an agricultural sector and especially in rural areas (Alexandratos, 1999; Mavrotas et al., 2011; Wright et al., 2012). Water supply for agriculture is a critical issue for the livelihoods of many rural populations and especially so in arid or semi-arid climates where rainfall is limited. Approximately 70% of water abstracted is used for irrigation of agriculture globally and in many basins food production is limited by the availability of water (Comprehensive Assessment of Water Management in Agriculture (CAWMA), 2007). Over the last 50 years, the world population has doubled and water abstraction from rivers has trebled alongside an increase in consumption of meat which requires more water for its production than crops. CAWMA (2007) stresses that the increases in food production needed to feed a growing world population can be achieved, and that improved water management is key to increased productivity. It acknowledges that strategies will need to be context specific, so for example Sub-Saharan Africa requires wise investments in infrastructure, considering the full range of options available. By contrast, in much of Asia where infrastructure is already in place, the focus needs to be on improving productivity, reallocating supplies, and rehabilitating ecosystems. In all cases, supporting institutions, adapted to changing needs, will be essential.

The study made eight main policy recommendations as follows:

1. Change the way we think about water and agriculture in order to achieve the triple goals of food security, poverty reduction and ecosystem conservation. This means thinking in a more integrated way about how agricultural systems can be multifunctional and interact with other ecosystems.
2. Fight poverty by improving access to agricultural water and its use through better rights and infrastructure including storage and distribution as well as roads and access to markets for goods produced.

3. Manage agriculture to enhance ecosystem services – some ecosystem change may be unavoidable owing to intensification of land and water use, but lasting damage is often avoidable.
4. Increase the productivity of water to reduce demand, limit environmental degradation and ease resource conflicts.
5. Upgrade rainfed systems to better retain soil moisture or include supplementary irrigation during dry periods as this has the greatest potential to rapidly lift people out of poverty.
6. Adapt existing irrigation schemes for contemporary needs through a mix of managerial and technical changes to improve responsiveness to user needs and better integrate them with livestock, fisheries and forest management.
7. Reform the reform process for institutions as this cannot be blueprinted owing to specific institutional and political contexts. Reform is necessary however to improve investment policies by breaking down barriers between rainfed and irrigated agriculture and better linking fisheries and livestock practices into water management. Reform will require negotiation and coalition building.
8. Deal with trade-offs and make difficult choices by making bold steps to engage with stakeholders. “Informed multistakeholder negotiations are essential to make decisions about the use and allocation of water. Reconciling competing demands on water requires transparent sharing of information. Other users—fishers, smallholders without official title, and those dependent on ecosystem services—must develop a strong collective voice.”

CAWMA, 2007

It is this last point which is most explicitly being addressed by the work in this thesis, which aims to inform and support more inclusive decision-making about water infrastructure. However, points 1, 2, 3, 4 and 6 are also strongly related to decision-making about water infrastructure in developing countries.

2.3.1.3.1 Impacts of irrigation on crop yield

As described above irrigated agriculture can promote economic development but if supplies are not reliable then crop yields can be affected. The UN Food and Agriculture Organisation has carried out research on crop yield response to water deficit and produced two documents on this subject – FAO 33 (Doorenbos and Kassam, 1979) and FAO 56 (Allen et al., 1998). Each document provides formulae for calculating the impact of water stress on crop yields. FAO 33 takes a whole growing season approach to water deficit, while FAO 56 breaks down the impact of deficits in different crop growth phases.

2.3.2 Technical methods for water resources planning and management

This section describes in more detail the main technical methods available for water resources planning and management in the context described in the previous section.

2.3.3 Simulation models

This section describes in more detail the different types of simulation models available for water resources planning and management.

Water resources simulation models can be classified according to how they function; using rules to represent logical decisions about what should happen at each time-step, or using optimisation routines to dictate what should happen. Different types of models are more appropriate for different contexts. For example, optimisation-driven models may be better suited to complex systems with multiple options for supplying water to the same demand based on economic decisions involving varying costs of each option with multiple interdependencies. Rule-based models are good at representing rule-based systems, and tend to complete simulations in less time because decisions made at one location in the model depend on conditions at relatively few other locations. More details are provided on simulation models and optimisation routines below.

2.3.3.1 Rule-based simulation models

Simulation models which take a rule-based approach apply rules at each location in the model where they are defined, according to the conditions occurring there and/or at a limited number of other locations. Their approach is logic-based and sequential, processing a list of locations in a fixed order, generally from upstream to downstream corresponding to the flow of water resources represented. Each incremental time period (i.e. time step) modelled during a simulation run may be broken down into a number of increments at which adjustments can be made to respond to changing conditions. The higher the number of increments used, the more accurately the simulation is likely to represent the real world.

Simulation models are often used to support decision making around operations and investments, as well as to investigate the response of a system to conditions for which there is no historical precedent. Because of their usefulness a wide variety of models have been and continue to be developed academically and commercially and are in common usage. Some examples of software supporting this kind of modelling are RIBASIM (River Basin Simulation Model) (WL Delft Hydraulics, 2004), HEC-ResSim (Klipsch and Hurst, 2007) and IRAS-2010 (Matrosov et al., 2011).

Features vary greatly between the implementations of these types of software, in terms of whether they include links to hydrological models, or have them integrated, the performance indicators they output, the flexibility of the time-step at which they are able to simulate, links to optimisation routines and the comprehensiveness of their user interfaces to name only some. A comparison is provided in Table 2.2.

Table 2.2 Examples of rule-based simulation models

Software	RIBASIM	HEC-ResSim	IRAS-2010
Availability	Restricted	Free download	Free
Code	Restricted	Restricted	Open source
Hydrology	link to HYMOS	link to other HEC products	External input
Water quality	link to DELWAQ	N/A	N/A
Graphical User Interface	GIS-oriented	Map-based	None
Relative simulation duration	Long	Long	Short
Performance measures output	Fixed	Fixed	User defined

2.3.3.2 Optimisation-driven simulation models

Optimisation-driven simulation models optimise operating rules of various kinds (e.g. reservoir releases, allocations) according to an objective function representing the performance of the system. The objective function is usually some representation of efficiency, such as cost. The use of optimisation-driven models allows the user to pay less attention to defining complex logic rules involving multiple assets, which would be required for rule-based simulation. However, the rules which are generated by optimisation-driven simulations may be less easy to implement in practice (Schluter et al., 2005). Rules are generated by using objectives functions to drive the optimisation towards those which perform best, i.e. objective function evaluation describes the performance of the system under a given set of rules. The model knows one set of rules performs better than another because it’s objective function value is more desirable. Objective functions may represent for example the volume of water supplied, the amount of hydropower generated or some economic cost or benefit (Wurbs, 1993). This objective function would be maximised or minimised within defined constraints.

Constraints could include demand for water, water treatment works capacity or minimum reservoir offtake levels, for example. The optimisation methods employed vary amongst the implementations of this approach, but typically include linear programming, non-linear programming, dynamic programming and their variants. These are known as classical methods of single or multiple objective optimisation. Some examples of optimisation-driven simulation models are WATHNET (Kuczera, 1992), MIKE-BASIN (Jha and Das Gupta, 2003), MODSIM (Labadie, 2006), AQUATOR (Oxford Scientific Software Ltd., 2015), and WEAP (Kirshen et al., 1995). Labadie (2004) describes in more detail the optimisation-driven simulation approach.

2.3.4 Model inputs

Model inputs depend on the type of model chosen as software which includes a hydrological model component will require precipitation and temperature data and perhaps other data such as land use, depending on the complexity of the hydrological model used. A water resources system model without a built-in hydrological component, by contrast, requires a flow times series at defined inflow points to the system and demand data (time-varying if appropriate) to represent points in the river basin to which water should be directed. Where flows only are required, alternative flow series can be generated to assess the impacts of different catchment conditions, including land cover, land use and climatic changes. Input uncertainties such as demand uncertainties owing to socio-economic uncertainty can be represented by sensitivity testing the model outputs with a range of possible demand scenarios to evaluate their impact.

2.3.5 Model outputs

A wide range of outputs can be provided by water resources models, depending on their complexity. Proprietary software tends to be limited in terms of the outputs which it can provide, whereas open source software can be adapted to provide any type of output desired. Generally flow and storage information is available at points defined within the model but there may be additional information about the extent to which demands are satisfied through time, the amount of energy produced where hydropower is represented, pollution loads will be available if a water quality component is available.

2.3.6 Optimisation

Optimisation tools, sometimes called decision support systems (DSS) are often employed for two types of dam-related decision making; at the project planning stage to decide how big a project should be in relation to hydrological, social and environmental conditions and the economic implications, or to manage existing systems to optimise their operations or adaptively manage their impacts.

McCartney (2007) reviews the DSS used for Large Dam planning and operation in Africa. He describes in some detail the classical optimisation methods which have been used to obtain maximum hydropower benefits, simulation methods used to test the impacts of various options for operating hydropower systems and also the multi-criteria methods being used to incorporate more social and environmental considerations in decision making. These techniques often involve a significant component of multiple stakeholder engagement. The conclusion is that DSS used in dam planning and operation, contribute to decision-making processes which:

- facilitate examination of the wider social and ecological context of a particular dam;
- assist in conflict mitigation, enabling compromises to be found;
- enable integration of more and diverse sources of information from different scientific disciplines, but also include non-scientific inputs including local community knowledge;
- sharpen the focus on stakeholder involvement in decision-making so that all stakeholders participate from early on in the process; and
- facilitate negotiation-based approaches to decision-making that hopefully lead to increased cooperation and consensus building between different stakeholders.

Management decisions are described as difficult with regards to the trade-offs inherent in water resources systems. In some cases, simple optimisation can be used for single-purpose reservoir management. In other cases the complex relationships between benefits of using water for multiple uses must be understood to make the best management decisions.

Tilmant et al. (2010) used a classical Stochastic Dual Dynamic Programming (SDDP) approach to optimise operation of reservoirs on the Zambezi River to provide a more natural flow regime to ecologically sensitive areas. This represents a classical optimization approach to defining trade-offs resulting from the operation of four dams on the river. The reliance on linear programming as a component of SDDP requires simplifications to represent non-linearities in the system such as hydropower production, which is a function of both head and flow through turbines. An iterative process of adjusting inputs is also necessary in order to define trade-off curves between a small number of objectives.

2.3.7 Simulation-Optimisation

A large body of literature considers the optimisation of water resources management using classical methods. With these methods the water system model must be embedded in the mathematical programme which typically requires simplifying assumptions to represent (i.e. linearise) the non-linear features common in water resources systems. Pre-assigned (*a priori*) weights or procedures are also required to combine the multiple objectives which are typical of water resources systems (Yeh, 1985;Cohon, 1978). The challenges of identifying Pareto-optimal trade-offs with complex forms or more than 2 objectives using classical multi-objective methods (Shukla et al., 2005) has limited their application to real-world problems (Bhaskar et al., 2000). These real world trade-offs have more often been lost through the optimisation of fewer aggregated objectives to maintain computational tractability of the problems (Woodruff et al., 2013). Shukla et al. (2005) contrasted classical optimisation methods with a multi-objective evolutionary algorithm (MOEA) continuing to perform well as trade-off complexity and number of objectives increased.

Explicitly considering many disaggregated objectives can help avoid negative impacts of human decision biases in complex planning problems (Brill et al., 1982). Considering fewer objectives can lead to “cognitive myopia” (Hogarth, 1981), where the diversity of possible solutions is unrealistically constrained, or lead to “cognitive hysteresis” (Gettys and Fisher, 1979), where preconceptions about the nature of a problem are reinforced by lack of new insight. Decision makers may feel that they fully understand their system while actually lacking any understanding of innovative possibilities (Woodruff et al., 2013). Kollat et al. (2011) show that increasing the number of objectives considered can change decision makers’ preferences about system performance.

2.3.7.1 Multi-objective evolutionary algorithms (MOEAs)

Multi-objective evolutionary algorithms (MOEAs) (Coello et al., 2007) are heuristic search techniques which perform thousands of simulations to ‘evolve’ the best policies for the given objectives. As the algorithm can be separated from the simulation model, known as simulation-optimisation, trusted existing simulators can be used in the optimisation. Further, simulation-optimisation using MOEAs is attractive because preferences about performance in relation to objective functions need not be expressed *a priori* through weightings as is required by classical optimisation and MCDA alike. This is significant because the desirability of any given level of benefit depends to some extent on the sacrifice required to achieve it; this cannot be known *a priori.* Preference decisions are made after trade-offs are revealed, representing an *a posteriori* approach (Coello et al., 2007). MOEAs have been under development for two decades and can now consider up to 10 objectives in some cases (over 4 objectives is termed ‘many-objective’ (Fleming et al., 2005)). Non-commensurate (e.g. non-monetary) objectives can be optimised, meaning stakeholder-specific benefit functions can be developed without direct reference to monetary value and optimised alongside traditional economic objectives.

Simulation-optimisation with MOEAs generates discrete solutions which approximate the continuous Pareto-optimal curve or surface. A Pareto-optimal trade-off (Cohon, 1978) occurs where no further performance gains can be achieved in any one objective, without reducing performance in one or more of the others. A trade-off curve is composed of discrete solution points between two axes. The trade-off curve represents the ‘non-dominated set’ of solutions, meaning that other (dominated) solutions are available but all are outperformed by one or more of the non-dominated results. Figure 2.1 illustrates these concepts with two example solutions within a trade-off curve: solution A performs better in objective f2, while B performs better in objective f1 (both are Pareto-optimal). There is a trade-off between f1 and f2, so a decision must be made about how much to sacrifice f1 performance in order to improve f2 performance.

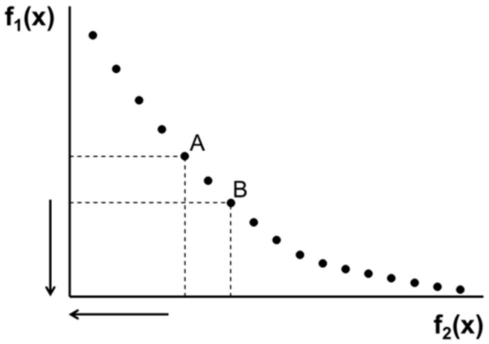

Figure 2.1 Pareto optimal trade-off curve between two objectives f1 and f2. Arrows indicate the direction of best performance.

Trade-off curves or surfaces representing Pareto-optimal relationships between conflicting management objectives are a recognised tool of water management (Loucks et al., 2005). Trade-offs were illustrated numerically (Haimes and Hall, 1974) or with simple visualisations (Ryu et al., 2009; Loucks, 2006) until the advent of advanced visual analytic tools (Keim et al., 2008) allowed multiple dimensions (objectives) and richer information to be explored in a more intuitive and interactive way. These tools have recently been applied to the results of many-objective water resources planning and management optimisations (Kasprzyk et al., 2009; Reed and Kollat, 2012; Kollat and Reed, 2006; Matrosov et al., 2015).

Several authors (e.g. Kasprzyk et al., 2009; Kollat and Reed, 2007a) have demonstrated use of trade-off plots to analyse solutions revealed by MOEA optimisation of water resources problems. Non-optimised information can be added to enhance understanding of the optimised policy implications for different stakeholders. Large datasets (1000s of points) can be analysed in a time-efficient manner facilitating more informed decision-making (Kollat and Reed, 2007b; Lotov, 2007). As the complexity of datasets increases, the value of visual analytics for exploring and understanding it also increases. For complex problems, the most effective formulation must be developed over time, involving a number of iterations and exploration of the asscoiated results. Visual analytics help to facilitate this process (Kasprzyk et al., 2012).

In relation to water resources, MOEAs have been used to optimise reservoir rules (continuous storage-release relationships) (Shiau, 2009) and reservoir operating rule curves (target storage levels throughout the year) (Chang et al., 2005), groundwater monitoring and management (Kollat et al., 2008), water distribution system design (Fu et al., 2013), water supply portfolio planning (Kasprzyk et al., 2012) and water resources system infrastructure portfolio design (Kasprzyk et al., 2009). Ecological and economic objectives have been optimised simultaneously using MOEAs (Suen and Eheart, 2006). Reed et al. (2013) review the state-of-the-art. MOEAs have been shown to be particularly effective for multi-objective water management applications when linked to external simulators, which are best able to represent the non-linearities which often occur (Nicklow et al., 2010). External simulators can also be established tools, already trusted by stakeholders to manage their system. With external simulators it is beneficial if run times are as low as possible to ensure the many thousands of simulations needed to define trade-offs iteratively can be completed with a reasonable timescale.

2.3.7.1.1 Problem formulation

Testifying to its longevity, Reed and Kasprzyk (2009) support Liebman’s (1976) assertion that *the problem* is defining problems of use in real world decision making. This means that the formulation of a problem is all important in generating a useful output. If the right questions are not being asked, or the interests of stakeholders are not represented in the right way, then trade-offs could be derived which cause more problems than they solve. Problem formulation is a difficult challenge such that Reed and Kasprzyk (2009) believe that it is best addressed by collaborative model development, allowing evaluation of outputs by diverse stakeholders for their transparency, validity and equity of impacts. An iterative approach is useful as generating trade-offs with one problem definition can elucidate its flaws, prompting revaluation, and/or raise new questions.

2.3.8 Summary

This section has shown that diverse demands on water resources systems and the uncertainties related to both measuring and understanding the current situation and the future context present an increasingly severe challenge to planning and management. A range of models are available for analysing such challenges, but it is important to carefully define the problem which is being analysed. Problem definition can strongly influence the solutions found and there is a consensus in the literature that the process of problem definition should draw on a wide range of stakeholder knowledge and ideas. This requires the application of approaches to planning with stakeholder inputs, considered in the following section.

2.4 Approaches to planning with stakeholder inputs

Stakeholder participation is often sought in addressing environmental management problems owing to their inherent complexity and the perceived value of integrating diverse knowledge and values (Pahl-Wostl et al., 2007). Inclusive decision-making is also felt to be more transparent (Reed, 2008). There is objective evidence that participatory approaches can enhance the quality of decisions although Reed (2008) argues that for this to occur, participation must emphasise empowerment, equity, trust and learning and begin as soon as practicable in a process before being institutionalised.

Where once technical experts were expected to manage water resources, primarily through infrastructural interventions, with the authority of the state behind them. A major paradigm shift is underway towards more inclusive consideration of problems and the uncertainties that surround their usefulness and impacts. ‘Social learning’ is becoming a popular concept, meaning that whole social groups need to be engaged in learning about a problem in order to contribute to building a consensual solution (Pahl-Wostl et al., 2007). This recognises that multi-scale, polycentric governance is in fact the best way to manage a resource where a large number of stakeholders have the institutional capacity to impact on management outcomes.

In water resources system planning and management, ecological and social impacts are often considered after monetisable benefits from sectors like irrigation and hydropower, if at all (GWP, 2003;McCully, 2001). Political conflict can result where poor or marginalised groups are not involved in decision-making processes, jeopardising the sustainability of benefits (Nguyen-Khoa and Smith, 2004; McCully, 2001; WCD, 2000). Combining scientific and local knowledge to consider the inherently complex impacts of any policy show promise for more sustainable management of environmental resources (Bryant, 1998; Reed, 2008).

Stakeholder participation in planning and managing reservoirs can mitigate conflict and ensure wider societal knowledge and objectives are considered (Uphoff and Wijayaratna, 2000; Roncoli et al., 2009; Poff et al., 2003; Johnsson and Kemper, 2005). Some participatory approaches overlook the trade-offs inherent in water management decisions, however (Kallis et al., 2006). Reed and Kasprzyk (2009) support Liebman’s (1976) assertion that the best way to address problem formulation is through collaborative model development, allowing evaluation of outputs by diverse stakeholders for their transparency, validity and equity of impacts.

Methods of accounting for multiple stakeholder interests at the strategic planning stage are desirable for their potential to expedite infrastructure project completion. This section discusses some of the options available for gaining stakeholder inputs to water resources planning and management.

2.4.1 Cost benefit analysis

Traditionally economic approaches have been used to suggest efficient water allocation and management policies (Wilson and Carpenter, 1999; Birol et al., 2006; Winpenny, 1993). Cost benefit analysis aims to assess which is the best of a selection of options for management or development according to which gives the highest ratio of benefits to costs. Environmental and social factors are often included through ‘willingness to pay’ type analysis, which tries to ascertain how much people would be willing to pay to maintain a particular benefit. Concerns have been raised however, regarding the ability of economics (Sagoff, 2008, 2011; Steele, 2009; Paton and Bryant, 2012; Abson and Termansen, 2011) and cost benefit analysis tools such as ‘willingness to pay’ (Sagoff, 2000) to assign value to non-market ecosystem goods and services or ensure their sustainability.

2.4.2 Multi-criteria decision analysis techniques

Multi-criteria decision analysis (MCDA) describes any structured approach for ranking or scoring the overall performance of decision options against multiple objectives (Hajkowicz and Collins, 2007). It is particularly useful where a single-criterion approach, such as cost-benefit analysis, fails because significant environmental or social impacts cannot be monetised. MCDA explicitly recognises that a variety of both monetary and non-monetary objectives may influence policy decisions (UNFCCC, 2005). It has been widely applied to water policy evaluation, strategic planning and infrastructure selection (Behzadian et al., 2012; Calizaya et al., 2010; Chen et al., 2007b; Chen et al., 2006; Hyde et al., 2005, 2004; Ma et al., 2008; Marttunen and Hamalainen, 2008; Rohde et al., 2006; Weng et al., 2010). MCDA methods are diverse, but fuzzy set analysis, paired comparison and outranking methods are some of the most common. MCDA is based on subjective valuation and different methods of combining such valuations can lead to different outcomes (Kujawski, 2003). Weighting of objectives is also applied which biases results without considering the impacts of this. MCDA approaches can be used to assess trade-offs between different options for development, (e.g. Brown et al., 2001; Sanon et al., 2012)

Mendoza and Martins (2006) confirm the suitability of MCDA for planning and decision-making for natural resource management, but note that MCDA presents challenges when dealing with the complexity of natural resources systems, particularly that subjective judgement should not always be used as a substitute for more objective analytical methods such as modelling; that the selection of alternatives to consider may be restrictive, that the motivations for stakeholders to take part may be misunderstood or misrepresented and that there is a lack of value framework beyond ‘utilitarian precepts’. They make the case for moving away from innovation in methods for problem solving to methods for problem structuring or formulation. This should involve ‘softer’ approaches whereby alternative solutions are sought as part of the process, traditional knowledge or social judgements are incorporated with more analytical knowledge, transparency and simplicity are increased, people are actively involved in planning from the bottom up and uncertainties are accepted as a necessary part of the problem.

2.4.3 Shared vision planning (SVP)

“Shared vision” or “Participatory and integrated” planning (Palmer, 2007; Castelletti and Soncini-Sessa, 2006) and “collaborative” or “participatory” modelling (Voinov and Bousquet, 2010; Tidwell and van den Brink, 2008) are examples of practical approaches to participation. These are disciplined planning approaches where stakeholders collaboratively develop and use simulation models which allow them to visualise the impacts of their proposals and reach consensual solutions (Ryu et al., 2009; Ahmad and Simonovic, 2000; Castelletti and Soncini-Sessa, 2007; Van Cauwenbergh et al., 2008; Tidwell et al., 2004). These approaches have many benefits such as fostering cooperation between disparate parties, but continuing conflict is not uncommon and strengths vary between techniques (Tidwell and van den Brink, 2008; Kallis et al., 2006; Keyes and Palmer, 1995). Trade-offs inherent to a system can be concealed or overlooked by certain techniques, but should not be ignored (Kallis et al., 2006).

Furber et al. (2016) report on the use of shared vision planning in a case of re-operating a dam and its impact on river and lake management in North America. They claim a number of successes in terms of conflict management, primarily the inclusion of the First nation concerns in the proposed plan, but note difficulties in including a group of stakeholders whose perception was that they could only lose from any changes occurring. The authors suggest that bringing the prospect of compensation to the negotiation could help to engage these stakeholders.

Palmer et al. (2013) include the same case study as Furber et al. (2016) as one of three examples of successful application of SVP. Some key reasons for the success are reported to be:

- Extensive stakeholder participation
- Development of a shared vision planning model which integrated the technical research on economic and environmental impacts
- Transparency of the modelling through a public portal into the model's plan evaluations
- Addressing technical questions collaboratively to develop stakeholder trust
- Avoiding protracted debate about scientific results by objective modelling and research
- Focussing on appropriate trade-offs and synergies and balancing impacts among various impacts

Palmer et al. (2013) also note one example of successful SVP application (the Alabama-Coosa-Tallapoosa and Apa lachicola-Chattahoochee-Flint Shared Vision Planning Application) which after a period of time reverted to protracted legal battles over the water resources rather than collaborative planning and management. This highlights the political limitations of Shared Vision Planning as the agreements which came out of the SVP exercise were simply allowed to lapse, despite the potential to extend the existing agreements.

2.4.4 Summary

This section has shown that there are structured ways of addressing water resources planning and management challenges with extensive inputs from stakeholders. The approaches which have been applied are time consuming and involve significant investments of time, but can lead to much more positive outcomes in terms of the consensus around development strategies. The tools developed through this research should lend themselves to such inclusive approaches.

2.5 Assessing investments in water resource systems

This section describes some approaches to water infrastructure investment decision-making utilising combinations of technical methods and stakeholder interaction.

2.5.1 Conventional least cost planning

Historically, least cost and levelised cost have been used to compare alternative investments in water infrastructure for water supply and hydropower (Matrosov et al., 2013; Padula et al., 2013). The lowest cost option, usually in financial terms, for the utility charged with closing any supply-demand gap is considered the most attractive in this type of analysis. Both supply-side and demand-side measures may be considered (International Rivers, 2013). Least cost planning can be thought of as a form of cost benefit analysis where the benefits are the increased water supply or reduction in forecasted deficit. The process usually involves forecasting demand and making assumptions about the capital and operational costs involved in a limited set of options. Optimisation is then used to find the least cost way of meeting the forecast demand (e.g. Loucks et al., 1981; Loucks and Van Beek, 2006; Padula et al., 2013). Levelised cost is used to compare different options on equal terms – in energy system planning this means the cost per kWh generated. The forecast for demand is very important here as if it is incorrect, the system can be left with too much or too little capacity, especially in energy systems where large-scale storage is generally not available. Forecasts for energy are usually developed ‘behind closed doors’ by a small committee of representatives of ministries, utilities and consultants. Forecasts of energy demand growth are usually linked to forecasts of GDP growth, but the multiplier can vary depending on the state of development of an economy. Energy demand will grow quickly at first as a developing country economy starts to grow, but as saturation is reached in terms of the grid-connected population and efficiencies are found, the multiplier should reduce. If this effect is ignored it can lead to highly inaccurate forecasting (International Rivers, 2013). Other factors which can heavily influence least cost planning outcomes are the discount rate for the investments and in the case of levelised costs of different generation technologies, assumptions about fuel price. High discount rates generally favour lower upfront investment, i.e. capital costs, and therefore thermal generation plants rather than hydropower which has higher capital but lower operational costs.

Newborne (2014) describes in some detail the process for forecasting future electricity demand in Brazil and how limited the group is which is tasked with making such fundamental decisions based on privileged information which remains hidden from the public. A stakeholder consultation process is included only as ‘a kind of mandatory validation step’ (Newborne, 2014). Future demand forecasts dictate how much installed capacity must be added to ensure sufficient supplies, and this in turn dictates which dams may be built to provide a hydropower contribution to this supply. The lack of transparency means there is no opportunity for assumptions to be challenged or for a broader consensus to form about the most appropriate development strategy on the basis of a debate. Newborne (2014) proposes an alternative approach to planning for Brazil which would still be led by the Ministry of Energy but involve much more effective and broader stakeholder consultation on the programme of new power plants. The Ministry would still make the final decisions, but based on a greater consensus.

Some typical failures of least cost planning applications are that they sometimes count only generation costs in the energy expansion plan and ignore costs of new transmission lines which can be substantial and vary from project to project. Another way in which applications have been poor is in not including environmental and social costs, treating these as externalities. Furthermore uncertainties relating to, for example, fuel costs have often been poorly addressed with the optimisation considering only a single assumed cost. Some progress has been made in the USA by implementing a requirement for Integrated Resources Planning (IRP) which prescribes for example, the inclusion of environmental and social costs by monetising them, the consideration of demand reduction measures alongside supply increase measures among, including diverse additional costs such as transmission and distribution capacity and engagement with stakeholders (International Rivers, 2013).

Least cost planning approaches take a narrow financial view of their planning problems. While this facilitates optimisation of a single objective problem (minimising cost) the real performance of a system is inevitably judged in the long-term against multiple criteria –monetary and non-monetary.

It remains challenging, as described above, to monetise environmental and social benefits and values produced are often vulnerable to controversy around the methods used. Furthermore, a single monetary unit (e.g. 1 US dollar) has a different value for a subsistence farmer than for the operator of a hydropower dam and combining their interests into a single financial value obscures this reality.

2.5.2 Decision-making under uncertainty

Water resources system planning and management has traditionally been based on the assumption of stationary availability of water resources. Climatic changes mean previous assumptions of stationarity of water resource availability are no longer considered valid (Milly et al., 2008), creating uncertainty around the selection and design of water infrastructure. This is especially important as large and long-lived infrastructure have the potential to reshape society around them (Hallegatte, 2012). The relative benefits from different hydropower investment location and design options may become skewed. Climate-related uncertainties can interact with other sources of uncertainty such as population, economic and demand growth, in a future subject to ‘severe’ (Ben-Haim, 2001), ‘deep’ (Lempert, 2002) or Knightian (Knight, 1921) uncertainty – synonymous terms. Deep uncertainties are defined as those where decision makers neither know nor agree on the probability of future conditions, the best model of the outcomes from different decisions, or the value of potential outcomes (Lempert et al., 2003). Such uncertainties can stall project development or lead to poor performance if they are either not addressed or addressed inappropriately.

Decision-making under uncertainty (DMU) is a broad term which can apply to the use of a wide-range of tools to address deep uncertainties. DMU involves inverting the traditional ‘predict-then-act’ approach to planning for uncertain future conditions (Lempert et al., 2013). Predict-then-act approaches work well where there is a high degree of confidence in the prediction, but less well where predictions are subject to a high degree of uncertainty. In uncertain cases decision-making can become mired in debate about the quality of the prediction or which prediction to use, or else over-optimism can result about the likely future performance as the decision has not been tested for performance under plausible conditions not predicted by a model.

In the case of climate change uncertainty one approach has been to use global circulation models (GCMs) usually by downscaling them to be applicable at river basin scale, to try and project what the future will be like, selecting and designing infrastructure to work well under these projected conditions (e.g. Wilby and Wigley, 1997). Sensitivity analysis can then be carried out to check how sensitive the selected infrastructure design is to the projected conditions. However, with GCMs sometimes disagreeing not only about the extent of change but also the direction, this can present a challenge for designing water infrastructure (Nassopoulos et al., 2012). It also does not necessarily provide decision relevant information (Brown and Wilby, 2012). DMU approaches start with all the available options for developing a system, systematically analysing the vulnerabilities of each in terms of the conditions which would cause them to fail. Those with lower vulnerabilities may be preferred, or it may be necessary to carry out adaptations to reduce vulnerabilities. Identified vulnerabilities can be assessed in terms of the likelihood of their occurrence, informed by GCM outputs and other objective or subjective information such as the risk averseness of the decision-makers. The key difference is that there is no reliance on the accuracy of GCMs, which are considered to be arbitrary manifestations of the future. Such an approach is often termed bottom-up (Brown et al., 2009) or scenario-neutral (Prudhomme et al., 2010).

In planning for an uncertain future, it has been argued that robustness of infrastructure development should be the goal, replacing optimality for stationary conditions (Lempert and Collins, 2007; Dessai and Hulme, 2007; Hipel and Ben-Haim, 1999). Robustness differs by favouring adequate performance over a range of possible future conditions rather than best possible performance for a single set of conditions. Herman et al. (2015) consider a range of robustness frameworks (i.e. Info-Gap (Matrosov et al., 2013b; Hipel and Ben-Haim, 1999), RDM (Lempert, 2002), Decision-scaling (Brown et al., 2012) and MORDM (Kasprzyk et al., 2013)) to explore the decision relevant consequences of selection between them for an established test case. On this basis they recommend: decision alternatives (e.g. investment and operation options) be searched for using multi-objective algorithms, rather than pre-specified; identifying dominant uncertainties through sensitivity analysis and carefully eliciting a satisficing measure of robustness to help stakeholders achieve their performance objectives.

2.5.2.1 Robust decision making (RDM)

Robust decision making (RDM) (Lempert et al., 2006) is a planning framework which provides decision-makers with information about the robustness of development proposals affected by deeply uncertain future conditions. This is achieved by testing each proposal by modelling its performance under a range of conditions statistically sampled from plausible ranges. Proposals are considered robust and therefore attractive if they perform satisfactorily (i.e. above some defined minimum standard) across a wide range of future conditions. This contrasts with the conventional view of optimal performance for defined (i.e. predicted) conditions being the most attractive.

Scenario discovery tools (Lempert and Groves, 2010) are used to identify combinations of future conditions which best characterise unsatisfactory performance of the proposal under analysis. Adaptations can then be considered in order to increase performance under those conditions so that the process increases proposal robustness (Hall et al., 2012). Trade-offs associated with undertaking these adaptations are assessed before deciding on which to pursue (Lempert et al., 2006).

If a proposal is shown to have low robustness or the trade-offs are too significant to justify adaptation, then a proposal may need to be discarded and the process repeated for a new proposed strategy.

RDM has been applied to a wide range of water and non-water related problems. Jeuland and Whittington (2014) applied such an approach to water resources planning on the Nile under climate change. Matrosov et al. (2013a) contrasted RDM with least cost water supply portfolio and demand management planning, recommending that the approaches be combined to provide a schedule of least cost interventions which are also robust considering multiple performance criteria across a wide range of futures.

2.5.2.2 InfoGap

Like RDM, Info-Gap uses a simulation model to predict the outcomes of different development proposals for a river basin under a range of conditions (Hipel and Ben-Haim, 1999). Info-Gap uses a different method than RDM of generating combinations of uncertain conditions against which to test performance. The approach aims to define the maximum level of deviation from a ‘best estimate’ of combined uncertainty values at which performance of the system remains acceptable (robustness) as well as the minimum level of deviation required to achieve a defined level of ‘windfall’ benefit (opportuneness) (Hall et al., 2012). Robustness and opportuneness curves are then calculated for each proposed intervention to allow proposals to be directly compared. Analysts must assess whether the uncertainty at which performance fails or delivers windfalls is likely to occur.

Info-Gap has been applied to a wide variety of contexts. Matrosov et al. (2013b) compare the use of RDM and Info-Gap for water resource system planning using the Thames Basin as a case study. Although the two approaches initially produce different recommendations, they are shown to be complementary in better understanding different proposals although individually capable of skewing results towards particular options.

There are many proposals in the academic literature about how to make water resources decisions under uncertainty employing one or both of RDM and Info-Gap, (e.g. Korteling et al., 2013; Hipel and Ben-Haim, 1999; Borgomeo et al., 2014; Dessai and Hulme, 2007; Herman et al., 2014; Jeuland, 2010; Kasprzyk et al., 2009; Kasprzyk et al., 2012; Stakhiv, 2011; Matrosov et al., 2013b). These approaches are beginning to be adopted by large organisations like the World Bank. A Society for Decision Making under Deep Uncertainty has been established with an annual conference now in its third year, promoting the benefits of the diverse range of approaches available to government, donor and international institution policy level.

2.5.2.3 Optimisation-based methods under uncertainty

A number of authors have been advancing the use of optimisation-based methods for decision making under uncertainty (Beh et al., 2015a, b; Borgomeo et al., 2014; Hamarat et al., 2013; Herman et al., 2014; Kasprzyk et al., 2012; Kwakkel et al., 2016; Matrosov et al., 2013; Reed and Kollat, 2012; von Lany et al., 2013; Woodward et al., 2014b). Multi-Objective Robust Decision Making (MORDM) (Kasprzyk et al., 2013) combines concepts and methods from many-objective optimisation, RDM and interactive visual analytics, to help manage complex environmental systems. A many-objective search algorithm linked to a system model produces intervention options to support analysis and consideration of the trade-offs within the system. In a second stage, RDM methods are used to assess the robustness of selected options to deeply uncertain future conditions and facilitate decision makers' selection of promising candidate solutions. This entails testing selected options under a range of plausible combinations of future conditions to discover the breadth of conditions under which satisfactory performance is achieved. Scenario discovery methods can then be used to identify the key vulnerabilities of a particular intervention option in terms of its cost-effectiveness, efficiency and reliability. Awareness of these vulnerabilities can help to mitigate the risks of under-performance. MORDM has been demonstrated for managing a single city's water supply in the Lower Rio Grande Valley (LRGV) in Texas, USA (Kasprzyk et al., 2013).

Mortazavi et al. (2012) demonstrated the need to use long time series and severe drought sequences to identify robust Pareto-approximate interventions to maximise drought security for Sydney’s water supply. They also demonstrated that failure to consider the complex operational interactions in the system could lead to inefficient investments. Mortazavi-Naeini et al. (2014) extended the 2012 work, showing how a multi-objective optimisation approach can help to move away from the established cost minimising approach to scheduling investments in bulk water supply and achieving greater equity between planning stages. This takes advantage of joint optimisation of operations and infrastructure investments compared to the established method which considers only infrastructure investments. Case study applications of the approaches described are limited to the Australian context. In a further extension of this work Mortazavi-Naeini et al. (2015) developed a three component approach to identifying robust interventions for maximising drought security under conditions of deep uncertainty, involving: 1) a stochastic model of multi-site streamflow, conditioned on future climate change scenarios; 2) Monte Carlo simulation of the urban bulk water system incorporated into a robust optimization framework and solved using a multi-objective evolutionary algorithm; and 3) a comprehensive decision space including operating rules, investment in new sources and source substitution and a drought contingency plan with multiple actions with increasingly severe economic and social impact. The main objective of this approach was to minimise the costs of achieving the desired level of service but a second stage of analysis allowed the trade-offs between efficiency and robustness to be revealed and considered. They were able to demonstrate that a stronger preference for robustness rather than efficiency could lead to significant changes in the best interventions and were also sensitive to the robustness measure applied.

Beh et al. (2014) demonstrate optimal sequencing of urban water supply augmentation options under deep uncertainty using multi-objective optimisation. The approach is adaptive in that optimal long-term sequence plans are updated at regular intervals using trade-offs between the robustness and flexibility of the interventions to consider the best course of action. The proposed approach is demonstrated to provide sequences of investments which perform better than those using static approaches.

2.5.2.4 Limitations and benefits of current approaches

A benefit of established approaches is that they are established and can be easily carried out by a broad range of experts, thereby driving down the costs of analysis. The results they produce are well understood and users of the outputs are comfortable interpreting the implications for their own activities.

Least cost planning of water resources investments fails to account for the disaggregated impacts on different stakeholders because it lumps impacts under a single cost objective, to be minimised. In developing and low-income countries the relative (compared to others in their society) or absolute vulnerability of some stakeholders due to their reliance on non-market ecosystem goods and services can be much higher than in developed countries. This increases the importance of considering impacts on them of infrastructure development options. This may not result in different infrastructure being built, but if the impacts on these stakeholders can be recognised and quantified, then any compensation arrangements can be better informed.

Current approaches to uncertainty including but not limited to climate change are unsatisfactory. Although some users of the established approaches are comfortable with GCM projections as representations of the future, systematic analysis of the vulnerabilities of different options to aid in their differentiation in the mind of decision-makers has clear advantages. One problem with applying RDM type analyses to complex systems with millions or billions of combinations of interventions is that they are somewhat limited in the range of options to which they can apply the wide range of scenarios to test vulnerability.

Approaches such as RDM are a positive step in terms of their bottom-up analysis, identifying vulnerabilities before selecting from the options analysed. The restricted set of options they are able to analyse could, however, be expanded through the use of many-objective trade-off analysis to generate promising investment and operation alternatives which perform well across a range of future conditions. Optimisation-based approaches which integrate aspects of RDM with multi-objective trade-off analysis appear to have great potential for application to developing country water infrastructure decision-making under uncertainty as they have been demonstrated in a number of other contexts, and have the ability to represent diverse interests in both monetary and non-monetary terms.

2.6 Summary of literature review

The literature review has addressed the challenges faced in developing country water resources systems and the physical and policy context for these challenges. It has shown that future methods of planning investments in water infrastructure need to better account for impacts on water, energy and food security, including through ecosystem services. It has shown clearly that this could be achieved through more effective engagement with the full range of stakeholders in this development, i.e. any affected groups. Collaborative technical approaches can help open up a previously technocratic process with objective information on which to base debates and build consensus. The review has shown that simulation-optimisation using many-objective evolutionary algorithms (MOEAs) could act as the technical basis of an approach to shared-vision planning which would draw on diverse stakeholder knowledge and perspectives to build an objective model for appraising options and their trade-offs for river basin development. The ability of MOEAs to optimise conflicting benefits in non-commensurate units seems particularly suitable to developing country contexts where there is often a high reliance on non-market environmental goods and ecosystem services. Complex socio-environmental systems also tend to affect numerous stakeholder interests, so the ability to incorporate up to 10 objectives is attractive. The Pareto-approximate trade-offs produced are a quantified and transparent way to assess options and the features of the curves can help identify tipping points and diminishing returns which may not otherwise be apparent. The following chapters apply MOEA simulation-optimisation to three increasingly complex decision-making situations in developing countries.

3 Re-operating reservoirs to enhance environmental and livelihoods related benefits

3.1 Introduction

As discussed in sections 2.1 and 2.2.6; in operating dams, trade-offs must be made between market and non-market system performance. Being able to visually assess these trade-offs is of benefit for effectively managing water resources. If the trade-offs assessed are between the best available options, even more is gained. This application shows how to generate an approximately Pareto-optimal set of environmental management policies and assess the trade-offs implied using visual analytic tools (Keim et al., 2008). The *a posteriori* approach requires no pre-judgement of weights/priorities; stakeholders need only to ensure the simulator outputs their measures of performance. The application is a first step towards more sophisticated analysis, involving only the re-operation of existing major infrastructure, and therefore demonstrates the applicability of the modelling and optimisation technology to this type of context. This is the first use of many-objective trade-offs analysis including benefits of disadvantaged social groups, ecological and traditional economic objectives (irrigation and hydropower).

In this application a water resource simulator was linked to a many-objective genetic algorithm to optimise multi-reservoir operating policies (hedging rule sets) considering social, ecological and economic objectives simultaneously. Visual analytics tools help explore the trade-offs using stakeholder relevant units of measurement. Such intuitive results could help stakeholders better understand their system, allowing them to explore available solutions and find an equitable balance between the different system objectives.

The approach is applied to the semi-arid Jaguaribe basin in Brazil, where current water allocation procedures favour sectors with greater political power and technical knowledge. A range of reservoir operating policy options are selected based on Pareto-optimal trade-offs between 10 performance metrics. Selected operating policy rule sets from the trade-off surface are then analysed as the basis of negotiations between sectors.

3.2 Jaguaribe Basin case study

3.2.1 Physical context

The state of Ceará in the north east of Brazil is semi-arid with annual average rainfall between 500 to 900mm (Krol et al., 2006). Ceará’s largest city, Fortaleza is expanding with a water transfer from the nearby Jaguaribe Basin meeting its growing needs. At 610km the Jaguaribe River is the world's longest naturally dry river which although now perennialised, historically ran dry for up to 18 months during severe droughts; at worst killing hundreds of thousands of people (Taddei, 2005). Flow variations are extreme and evaporative losses are significant at over 2000 mm/year (Krol et al., 2006). Reservoir operation is a critical issue as a large population of rural poor depend on surface water for their livelihoods. The basin's three largest reservoirs are Castanhão (6700 Mm^3), Orós (1940 Mm^3) and Banabuiú (1601 Mm^3), totalling over 75% of the basin's storage capacity (Figure 3.1).

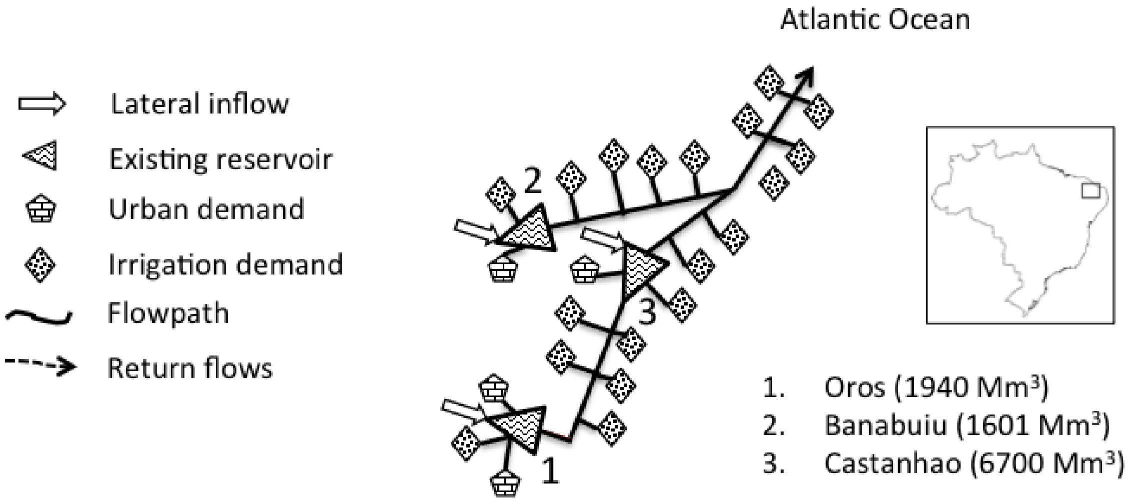

Figure 3.1 A schematic of the major water resources system (inset: location in Brazil): three large reservoirs and major perennialised river reaches. Modelled existing reservoirs are numbered for reference.

3.2.2 Stakeholder and institutional context

The basin is home to over 2 million people (Johnsson and Kemper, 2005) and diverse stakeholders and the inter-basin transfer to Fortaleza further diversifies the interests in the basin's resources to the residents and water supply utility of this city of over 2.5 million people. Table 3.1 lists the key stakeholder groups in the basin's water resources.

A biannual participatory negotiation of reservoir releases, based on current storage, has been implemented for each of the three reservoirs individually. This organised and run by the water management agency COGERH (Companhia de Gestão dos Recursos Hídricos). Its effectiveness in empowering vulnerable groups is still questioned (Taddei, 2011; Broad et al., 2007; Johnsson and Kemper, 2005), as poorer stakeholders such as farmers and fishermen are often under-represented or marginalised in the negotiation and ineffective in comparison to the politically powerful and technically knowledgeable (Taddei, 2005).

Table 3.1 Stakeholders in the Jaguaribe water resources system

Stakeholder	Interests
COGERH (Companhia de Gestão dos Recursos Hídricos)	State water resources management company, responsible for licensing abstraction and maintaining environmental flows in the Jaguaribe Basin
City of Fortaleza	Transfers water from the Jaguaribe Basin for both municipal and industrial uses. This accounts for around 43% of water demands on the river (Campos et al., Undated)
Municipalities within the basin	Abstractions are drawn from the reservoirs and river for piped supply to local municipalities
Industry within the basin	Abstractions are drawn from the reservoirs and river for industrial uses within the basin
Irrigators within the basin	Abstraction from reservoirs and river for large and small, public and private irrigation schemes
Itinerant fishers	Fishing in the large reservoirs
Estuary fishers	Fishing for crabs and fish where the river meets the Atlantic Ocean – populations of these fish are affected by environmental flow levels
Vazanteiros (poor landless farmers)	Farming the floodplain of the reservoirs when they are drawn down using water pumped from the reservoir to irrigate
Aquaculturalists	Abstractors from the river to farm prawns

Modelling results of limited release scenarios form the basis of negotiation and eventually consensus. The primary conflict in all three negotiations is between users who benefit from water retention or release. Policy dictates that 30 months of municipal supply must be guaranteed from the date of negotiation (Sankarasubramanian et al., 2009).

For this case study application it was not possible to undertake any engagement with stakeholders.

3.3 Modelling methodology

As described in Section 2.3.7, simulation-optimisation with MOEAs allows a simulator representing complex water systems to be used which can represent a range of performance impacts and identify trade-offs between them. This is well suited to water resources applications in developing countries where a wide range of stakeholder benefits need to be represented. Proprietary water resources systems models are limited in the information they are able to output, so open source code which can be modified to fit the problem formulation at hand provide substantial advantages; it is not necessary to post process results from the outputs available which would anyway restrict the ability of an MOEA to trade-off the actual benefits of interest. It is also important for MOEA analysis that simulators are fast running (a few seconds or less) to allow a large number of simulations to be completed in a reasonable time to allow refinement and re-running of the model as it develops. The generic IRAS-2010 water resources system model (Matrosov et al., 2011) was therefore used to simulate the Jaguaribe basin as it fulfils all the criteria described above. The section below describes how the model was parameterised and how system performance was measured.

3.3.1 Jaguaribe basin model

The model comprised 119 reservoir and abstraction nodes connected by 174 river, abstraction and return flow links. The initial storage of each reservoir was taken to be the average for the beginning of January (the start point of the model) over the 2002-2010 period for which data were available from the World Bank contact for this case study. The upstream boundaries were a 90-year historical (1911-2000) inflow time-series for each of the three main reservoirs, again provided by the World Bank. The downstream boundary was an unrestricted outflow node – not accounting for tidal influence from the Atlantic Ocean.

Transmission losses were estimated as 0.6% of discharge per km (Rêgo, 2001). Return flows were based on information provided by de Araújo (pers. comm.) based on measurements in a Middle Jaguaribe River (Rêgo, 2001). Evaporation was accounted for using monthly mean daily evaporation rates applied to each reservoir.

A monthly (30-day) time step was used so modelled flow entering a river reach passed through it within a time-step, removing the need for flow routing. This has little impact on how realistic the results are as the flow times within the real system dictate that water will have moved into storage or out of the system within one month. Abstractions are monthly averages and return flows are assumed to occur within the same time-scale.

3.3.1.1.1 Demands

A water demand prioritisation feature of IRAS-2010 was used to ensure the model allocated water realistically when availability is limited. At each abstraction node along the rivers higher priority demands downstream dominated allocation calculations. This kept the water they required in the river so it was not abstracted before it reached them. The priority of demand sectors was Municipal, Livestock, Irrigation, Aquaculture then Industry based on personal communication with de Araújo and representing actual priorities. Aggregated monthly demand data from abstraction license data, accounted for both fixed and varying demands in each sector.

Table 3.2 Summary of Jaguaribe model features and inputs

Modelling software	**IRAS-2010**
No. of system model nodes	119
No. of system model links	174
Inflows	90-year historical time series (1911-2000)
Transmission losses	0.6% of discharge per kilometre (Rêgo, 2001)
Return flows	Municipal, 25%; Irrigation 30%; Livestock, 10%; Aquaculture, 50% - all assumed to occur within a single model time-step
Reservoir evaporation	Monthly mean daily evaporation
Reservoir rating curves (storage-elevation)	From COGERH
River evaporation	Assume none
Model time-step	30 days
Flow routing	No routing - assumes all flows reach storage or exit system within 30 day time-step
Water demands	From World Bank project on water allocation

The configuration of supply regions in the model is shown in Table 3.3. Transfer to Fortaleza was prioritised equally with Municipal demands in the Castanhão and Lower Jaguaribe supply areas, but the Trabalhador transfer canal from the Lower Jaguaribe was not prioritised owing to its low capacity and hydraulic gradient which make it ineffective as a transfer to Fortaleza. Demand volumes by supply region and sector as supplied by the World Bank, are shown in Table 3.4.

3.3.2 Performance metrics/Problem formulation

This section describes the problem formulation, applying sixteen metrics to evaluate and compare the performance of the system under different management strategies. These were developed and coded into the open-source IRAS-2010 software based on various needs identified in the basin by the author, based on literature review and conversations with project partners. Analysing the results of MOEA runs helped to define which metrics were best suited to application as search objectives, being limited in number to 10.

Table 3.3 Configuration of model supply regions

Supply region name	Orós	Castanhão	Banabuiú	Lower Jaguaribe
Demands included	Direct abstractions from Orós reservoir Abstractions from river downstream of Orós reservoir but upstream of Castanhão reservoir	Direct abstractions from Castanhão reservoir Abstractions from Jaguaribe river downstream of Castanhão reservoir but upstream of confluence with Banabuiú river	Direct abstractions from Banabuiú reservoir Abstractions from Banabuiú river downstream of Banabuiú reservoir but upstream of confluence with the Jaguaribe river	Abstractions from the Jaguaribe river downstream of the confluence with the Banabuiú river
Origin of supplies	Orós reservoir	Castanhão reservoir	Banabuiú reservoir	Castanhão and Banabuiú reservoirs

Table 3.4 Summary of water demands included in the model, by sector and supply region (mean flow demand in thousands m^3/day. Range stated for time varying demands)

	Orós	Castanhão	Banabuiú	Lower Jaguaribe
Municipal	20.6	15.8	14.6	10.4
Irrigation	116.8 – 625.4	754.0 – 1,031.5	569.7 – 813.2	208.8 – 242.7
Livestock	12.0 – 14.6	10.9	1.7 – 3.4	0 – 1.3
Aquaculture	8.4	**-**	**-**	35.2 – 40.5
Industry	0.05	0.40	60.3	0.55
Transfer	-	743.9	-	45.5

3.3.2.1 Losses

System losses were calculated as the sum of mean annual evaporative loss from all three reservoirs plus uncontrolled releases (also a surrogate for flood protection) from the Castanhão and Banabuiú reservoirs. Uncontrolled releases from Orós reservoir are captured by Castanhão reservoir and therefore not lost to the system. System losses are of interest as they are affected by the levels at which reservoir storages are maintained - evaporation being lower when storage is lower (a function of surface area) and spills being lower when storage is lower. Because this is an extremely dry area, efficiency of water use is of primary importance, so losses are undesirable.

3.3.2.2 Hydropower deficit

Hydropower deficit was calculated as the mean annual number of months when the hydropower generation potential at Castanhão reservoir falls below 100% of the proposed capacity. Little information was available in relation to the proposed hydropower plant at the site, but it was considered interesting to investigate how operating dams to support this would affect other benefits. The proposed hydropower plant is relatively small and therefore the production not high. As so little information was available it would not have been meaningful to provide an absolute deficit metric so dropping below 100% of proposed capacity was deemed appropriate.

3.3.2.3 Fisheries deficit

Fisheries production deficit was represented by the mean annual number of months with poor fisheries in all three reservoirs (based on Hardy (1995), Table 3.5). Poor fisheries were considered to be months when storage in all three reservoirs was below 25% of their maximum. All three reservoirs was the threshold defined as fishermen are reported to be itinerant so likely to move if better conditions are available elsewhere.

Table 3.5 The AZCOL Model Resource Classifications for reservoirs used to define poor fisheries (adapted from Hardy (1995))

Classification	Percentage of reservoir maximum storage capacity
Optimal	50-100
Good	25-50
Poor/fair	Dead pool - 25
Degraded	Empty

3.3.2.4 Land availability

Within the floodplains of the reservoirs the poorest farmers (Vazanteiros) are able to use land for irrigable crops – the land is not otherwise owned and they do not have their own so this is a practical solution (Van Oel et al., 2008). The amount of land available increases as the reservoir level drops, but this means more pumping is required to raise water from the reservoir to irrigate the crops. There is therefore an optimal balance between land available and distance from water. This land availability benefit was evaluated as the mean annual proportion of the maximum land available when the growing season begins (based on van Oel et al. (2008), Figure 3.2). The non-dimensional proportion from each reservoir was summed across all three reservoirs to give a single metric value as only 10 metrics could act as objectives simultaneously in the MOEA search process.

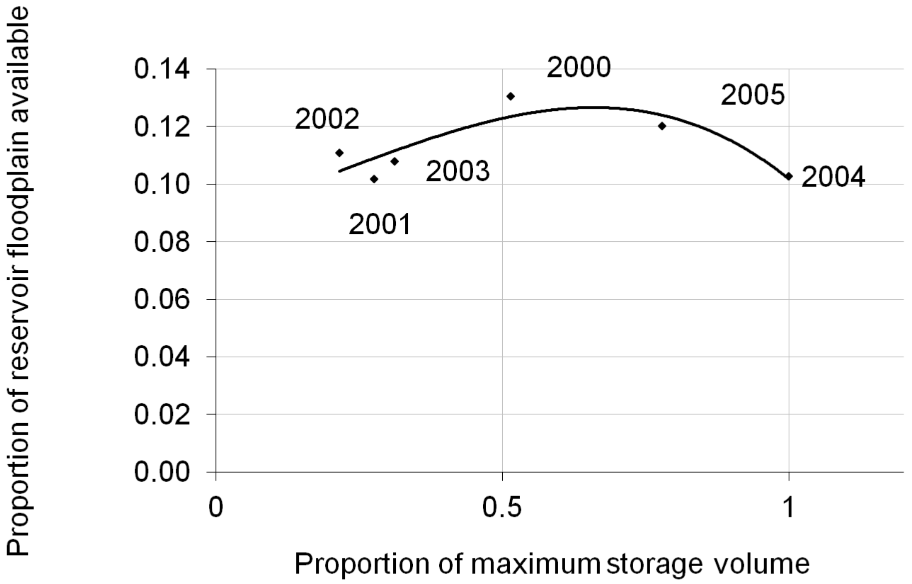

Figure 3.2 The relationship between the maximum reservoir storage at the end of June and the reservoir floodplain availability for farming by poor farmers (Vazanteiros) (Van Oel et al., 2008).

3.3.2.5 Agricultural deficit (evaluated for 4 regions & aggregate)

The agricultural deficit was assessed for the four supply regions separately to consider the trade-offs between them. This metric represented supply deficits in general owing to the prioritisation of allocations; before agriculture lost any of its allocation, aquaculture would be receiving no water. The metric was calculated as the mean annual volumetric deficit from the 90% level of supply reliability (supply/demand). An aggregated metric – the sum of regional deficits - was calculated to allow higher level trade-offs to be explored. Crop type data were not available to increase the information available in relation to this metric, only general monthly irrigation demands were available.

3.3.2.6 Flow alteration (evaluated for 2 seasons & aggregate)

There is concern that the altered flow regime at the mouth of the Jaguaribe river is having significant impacts on estuarine ecosystems. Mangrove intrusion on agricultural land and declines in economically important crab and fish populations are of particular note (Marins and Lacerda, 2007). Following Connell's (1979) Intermediate Disturbance

Hypothesis (IDH) it was assumed that the variability represented by the unregulated flow frequency curve is most likely to support healthy native ecosystems. Accounting for Gao's (2009) eco-surplus and eco-deficit approach, we used a flow alteration metric which assessed the deviation of the regulated from the unregulated flow frequency curve. Flow alteration was assessed seasonally to correspond with the temporal resolution of the reservoir release rules (described in Section 3.3.3.2).

The flow alteration metric was computed as the negative sum of Nash-Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for ten corresponding deciles of the regulated and unregulated curves at the outlet of the basin (the location of concern for Marins and Lacerda, 2007). The Nash-Sutcliffe efficiency is a method of comparing the fit of modelled with observed flow time series when calibrating/validating models so was equally able to provide an objective measure of the difference between flow frequency curves. The negative sum was used in place of the positive sum to make the metric more intuitive, i.e. it is desirable to minimise flow alteration, rather than maximise it. Deciles were used to avoid favouring any particular range (e.g. high flows). The range of the metric was -10 to infinity, although physical limits in the system meant the value was unlikely to approach infinity. Perfectly matching curves were evaluated as -10. An aggregated metric – the sum of seasonal alterations - was calculated to allow higher level trade-offs to be explored.

3.3.2.7 Security of municipal supply (3 reservoirs & aggregate)

The simulation model registered the minimum volume of municipal reserves reached during each 90-year simulation (Figure 3.3). This indicated the security of municipal supply provided by the release rule set under evaluation because a drought could theoretically begin at any moment – the worst case being it begins when reserves are lowest. As the climate is semi-arid with only a wet and dry season, storages are necessarily drawn down in the dry season. They must always be ready however for the next rains to fail, thereby limiting the benefits available from releasing water in any one dry season. This index was also intended to help evaluate gains in other aspects of system performance available by relaxing the current policy guaranteeing 30 months of municipal supply. This metric was calculated for each reservoir, Lower Jaguaribe municipal demand being divided between Castanhão and Banabuiú proportional to storage capacity. An aggregated metric – the sum across all reservoirs - was calculated to allow higher level trade-offs to be explored.

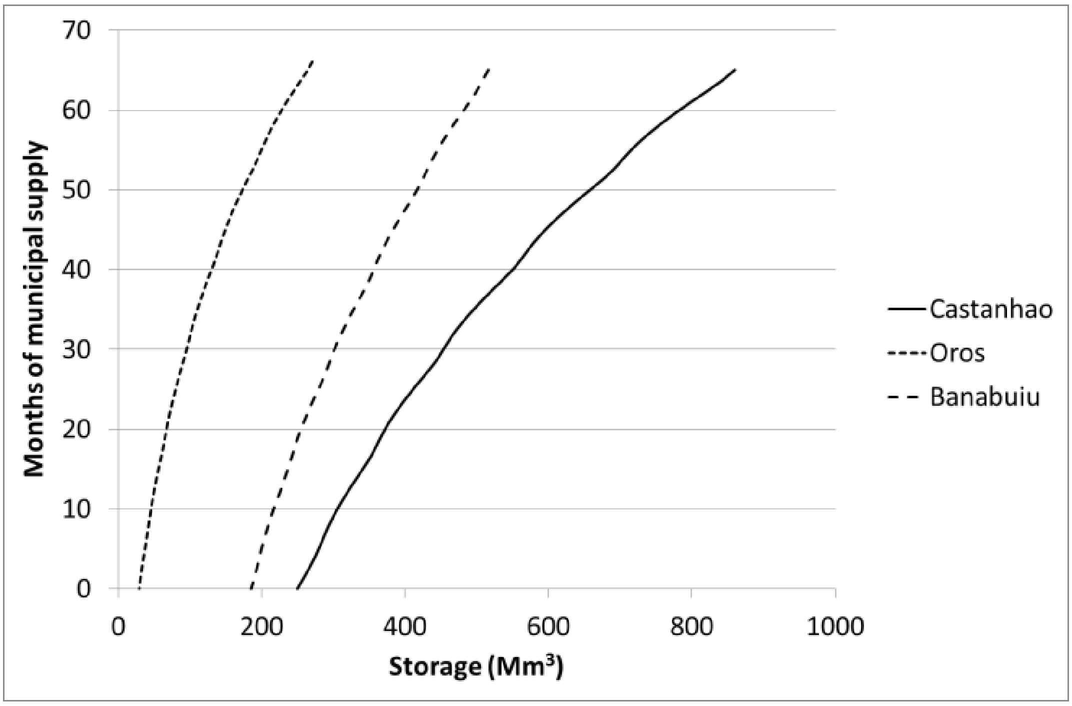

Figure 3.3 Curves showing the months of municipal supply represented by low storage levels in each reservoir. Curves were produced by modelling under conditions of evaporation and municipal supply only. The months equivalent was capped to represent the curves using polynomial equations.

3.3.3 Optimisation model formulation

The IRAS-2010 model was linked via a C++ wrapper to the Epsilon Dominance Non-dominated Sorted Genetic Algorithm-II (ε-NSGAII) (Kollat and Reed, 2006) to provide optimisation functionality. This algorithm was selected owing to its strong performance against other algorithms of this type in benchmarking (Kollat and Reed, 2006). The optimisation formulation is described in Appendix A, Section 3.3.3.2 describes the decision variables used to represent different management strategies and Section **Error! Reference source not found.** describes the objective functions used to assess erformance of each policy. This section starts by describing the interaction between the algorithm and the simulation model.

3.3.3.1 Simulation-optimisation interactions

The optimisation algorithm adjusts decision variables within the model to alter its behaviour and simulate the impacts of different operating policies. Variables are selected at the beginning of each simulation and apply for its duration. Impacts are measured in terms of defined objectives for (or benefits from) the system. Over thousands of simulation runs, the algorithm iteratively increases benefits based on objective evaluations of previously simulated policies. Initial policies (sets of variables) are drawn randomly from defined decision variable ranges. The best performing policies and their results are archived and used to generate new sets of policies by processes of crossover and mutation, akin to evolutionary processes (Coello et al., 2007b). New randomly generated policies are injected periodically to increase the ‘diversity’ of the population and the Pareto-optimal ‘frontier’ is revealed as the algorithm finds and explores the performance limits of the system. A small number of parameters must be set to control the processes of crossover and mutation. This study followed recommendations by Kasprzyk et al. (2009) as exploring the impact of changing these variables was not the focus of this work. Results comprise a set of individually unique trade-off solutions and the release policies required to achieve them.

3.3.3.2 Decision variables

Decision variables are numerical values within the system model which are varied to represent decisions. The search algorithm varies and mixes sets of these values according to its routines, to iteratively develop the best combinations of decisions. The decision variables optimised in this application were individual reservoir release rules. IRAS-2010 has a feature for implementing the standard operating policy (SOP) (Maass et al., 1962) for reservoirs. This feature was used to create less formulaic hedging rules similar to those used by Shih and Revelle (1994) but using only present storage to decide releases as information about any forecasting undertaken in managing the system was not available. Reservoir-specific curves dictate the release rate at each simulation time-step. To limit the complexity of the optimisation problem and considering the current biannual negotiation process, wet season (January – June) and dry season (July – December) rules were separated. The release rules can be visualised as piece-wise linear curves leading to 21 decision variables, i.e. seven for each reservoir (Figure 3.4).

3.3.3.3 Objective functions

Ten of the model performance metrics (Section **Error! Reference source not found.**) ere used as objective functions to direct the many-objective algorithm’s search for Pareto-approximate trade-offs. Cutting edge algorithms such as that employed here tend to perform poorly beyond ten dimensional (i.e. ten objective) problems (Reed et al., 2013). Results intervals were assigned to ensure suitable resolution to meaningfully differentiate results – there was little to be gained from differentiating between two evaporative/spill losses only separated by 1m^3. Results precision was selected by a process of iteration as interim results revealed likely ranges – precision was then approximately one tenth of the range. Metrics, search goals (maximise or minimise) and results intervals are listed in Table 3.6, objective functions are detailed in Appendix A.

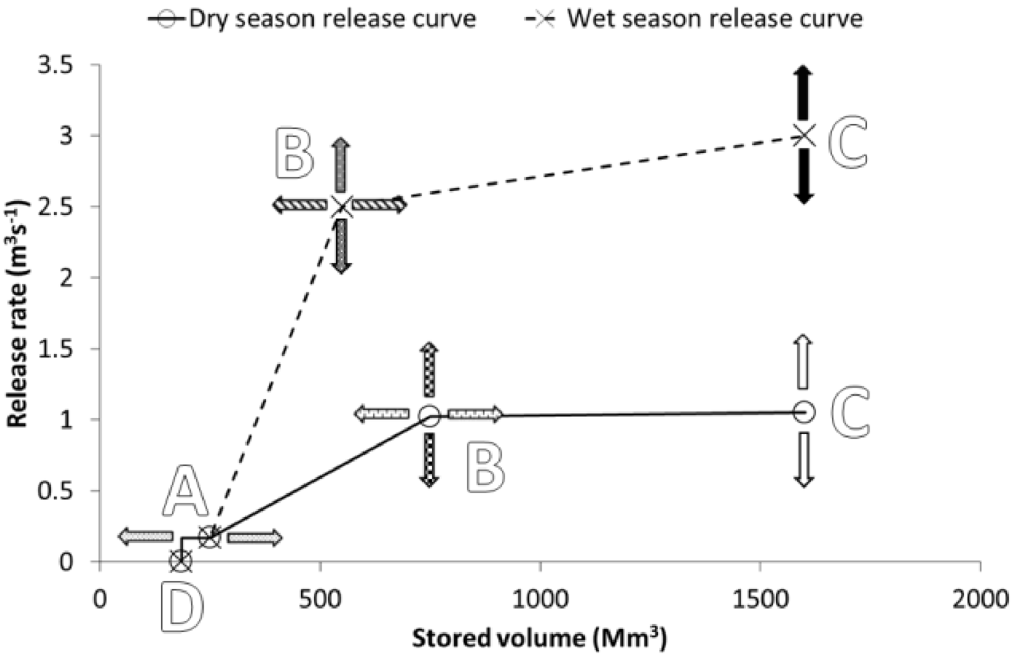

Figure 3.4 Seasonal release rule curves as represented by the IRAS-2010 Jaguaribe model. Each patterned pair of opposing arrows represented an optimisation decision variable. Point D was the dead storage of the reservoir. Point A was the storage level at which releases were restricted to municipal supply. B points were varied in two dimensions for hedging. C points represented the controlled release when the reservoir was full. In total 7 decision variables defined each reservoir's operations.

3.3.3.4 Optimisation parameters and verification

Table 3.7 shows the optimisation parameters applied in the many-objective optimisation algorithm. Initial population size controls the diversity of the initial set of simulations where decision variables are randomly drawn from their respective value ranges. Population scaling factor dictates how archived good solutions are mixed with randomly generated solutions at the end of each run comprised of a number of generations. The number of function evaluations controls the maximum number of times the simulation model (taking the role of function evaluator) is run. The probabilities of crossover and mutation control how big the deviations in characteristics are which the algorithm generates to try and improve on high performing solutions which it has already discovered. As parameter value impacts were not the focus of this work, the recommendations provided by Kasprzyk et al. (2009) were followed. The results of a single seed analysis were verified by a 50 random seed analysis to check the results were not sensitive to initial random seed. Figure 3.5 compares the results, confirming that the results from the single seed satisfactorily represent the whole results space.

Table 3.6 Performance metrics and their objective functions, goals and results intervals

Performance Metric	Objective Function (Appendix A)	Minimised/ maximised	Results precision & units
Evaporative/spill losses	f_{losses}	Minimised	50 Mm^3
Hydropower deficit	f_{hydro}	Minimised	1 month
Fisheries deficit	f_{fish}	Minimised	1 month
Land availability	f_{land}	Maximised	0.02
Agricultural deficit - Orós	$f_{agr}^{Orós}$	Minimised	0.05 Mm^3
Agricultural deficit - Castanhão	$f_{agr}^{Castanhão}$	Minimised	0.1 Mm^3
Agricultural deficit - Banabuiú	$f_{agr}^{Banabuiú}$	Minimised	0.1 Mm^3
Agricultural deficit - Lower Jaguaribe	$f_{agr}^{Lower\ Jaguaribe}$	Minimised	0.025 Mm^3
Flow alteration – wet season	f_{flow}^{wet}	Minimised	2.5
Flow alteration – dry season	f_{flow}^{dry}	Minimised	2.5

3.3.4 Visual analytics

Trade-off plots were built using interactive visual analytics (e.g. Kasprzyk et al., 2009; Kollat and Reed, 2007a; Keim et al., 2008) to explore trade-offs between competing objectives and other relationships, adjusting the information displayed to highlight different features. Interactive trade-off visualisation provides a broad perspective on the multiple objective performances and decisions which produced them. Large solution sets can be analysed in plots with high information content facilitating more informed deliberation and decision-making (Kollat and Reed, 2007b; Lotov, 2007). Interactive trade-off visualisation can help make decisions about the preferred balance of benefits by showing how different societal goals trade-off against each-other. Any selected solution point from the trade-off curve/surface represents the performance achieved for all objectives by a specific set of decision variables (a 'policy'). Decision-making processes based on this approach afford the opportunity for decision-makers to interactively explore solutions incorporating different layers of information as part of a larger iterative process of improving problem definitions and solutions.

Table 3.7 Optimisation parameters

Algorithm parameters	Value
Initial population size	24
Population scaling factor (for injection)	0.25
Number of generations per run	250
Number of function evaluations	25,000
Probability of crossover	1
Probability of mutation	0.5
Distribution index for SBX crossover	15
Distribution index for polynomial mutation	20
Simulated time horizon	90 years
Simulation time-step	1 month (30 days)

3.4 Selecting a re-operation policy

3.4.1 Retention-release

The first trade-off analysed is between reservoir retention (storage) and release (Figure 3.6): the key conflict of reservoir management in the Jaguaribe basin. A balance must be struck between the two and this balance has implications for all stakeholders. In Figure 3.6 and all subsequent figures, the aggregate agricultural deficit metric (benefiting from release) is used to show high-level trade-offs, except where aggregation is addressed in Section **Error! Reference source not found.**. Land vailability (benefiting from retention, see 3.3.2.4) also represents fisheries deficit as the two metrics are correlated (not conflicting). Dominated solutions are not shown in subsequent figures to simplify illustration of trade-offs.

3.4.2 Flow regime alteration

Storage of water to support river flow during the dry season interrupts natural flow regimes (see Section 3.3.2.6). Figure 3.7 shows the same trade-off as Figure 3.6 but with a third axis showing the flow alteration metric. In three dimensions, rather than a

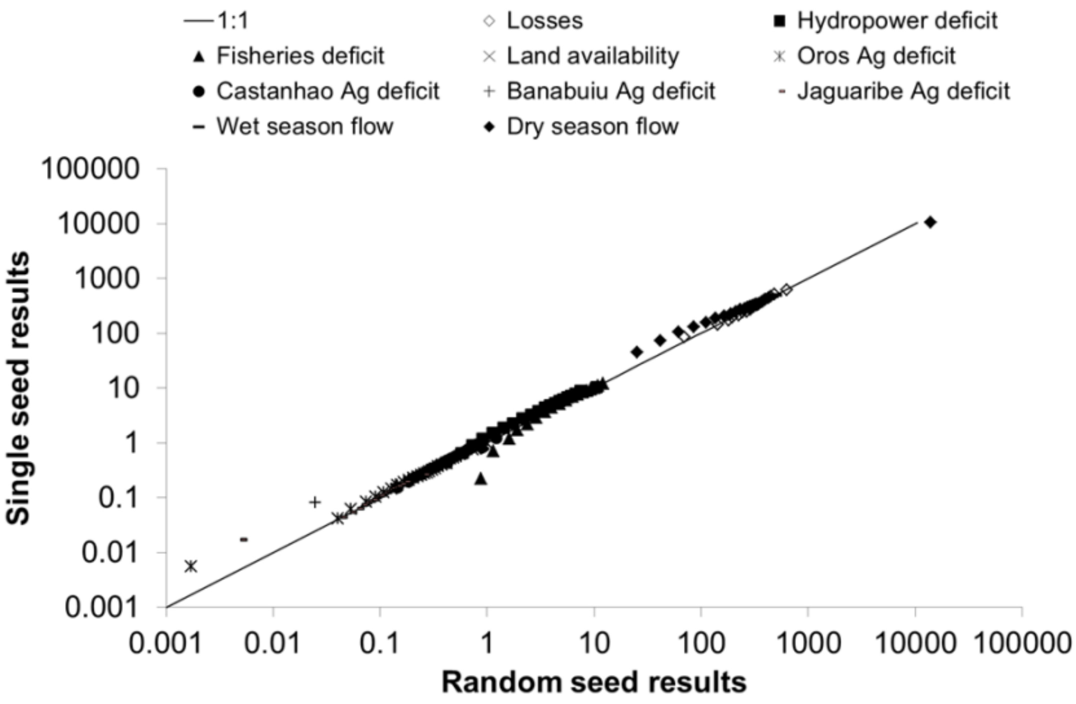

Figure 3.5 Comparison of the results from a single seed optimisation and 50 random seeds using every corresponding 5th percentile value

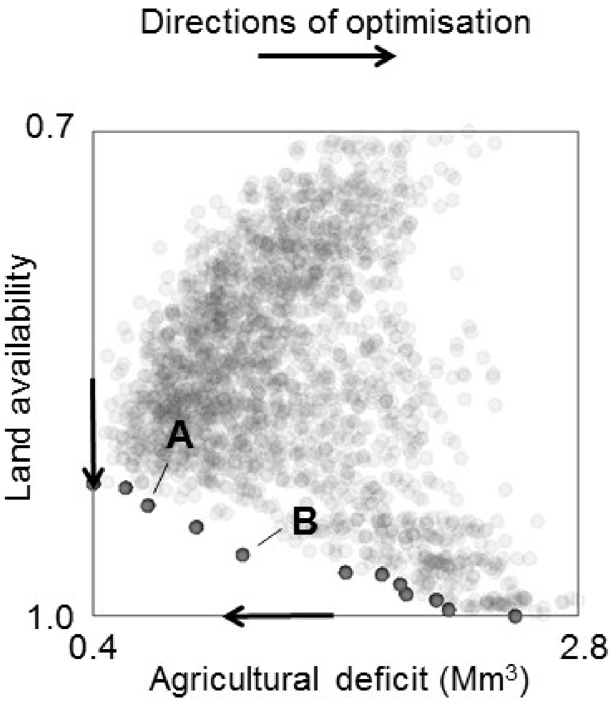

Figure 3.6 Solid (non-dominated) solution points show the Pareto-optimal trade-off between Land availability and aggregated Agricultural deficit. Dominated solution points are greyed out. Arrows show the direction of improved performance (optimisation). Each point represents the performance achieved when simulating one release rule policy for the three reservoirs.

trade-off curve we now have a trade-off surface which visualises how performance across all three metrics is distributed for the best reservoir management policies. Figure 3.7 shows that as land availability increases (benefit), flow alteration increases (disbenefit). The lowest agricultural deficits (benefit) are in the mid-range of flow alteration benefits. At high flow alteration (poor ecological performance), decreasing flow alteration initially improves agricultural deficits but at around the mid-point of the alteration range (500) further ecological improvement requires loss of agricultural benefits.

It is worth recalling from Section 3.3.2.6 that the flow alteration metric represents not only purely ecological interests, but impacts on the ecosystem services of the Jaguaribe estuary. Trade-offs between flow alteration and land availability therefore imply trade-offs between the support of upstream and downstream livelihoods.

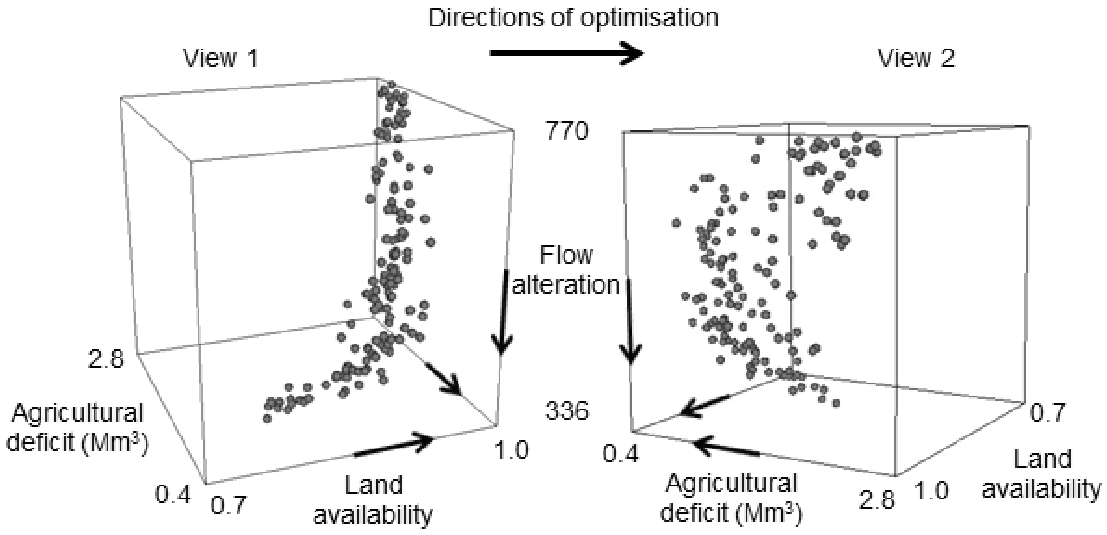

Figure 3.7 Trade-off curve from Figure 3.6 expanded into a trade-off surface by also considering the Flow alteration metric (vertical axis). Both panels show the same surface; two angles are used to aid orientation. As the number of axes (dimensions) increases, so the number of points comprising the trade-off surface increases.

3.4.3 Expanding the trade-off surface

In Figure 3.8(a) the optimised hydropower deficit metric is displayed (using cone orientation, where up is high deficit and down is no deficit) on the same trade-off surface displayed in Figure 3.7. Two viewing angles (left and right panels) are displayed to enhance 2D visualisation. Figure 3.8(b) shows the municipal reserves using cone size, where large cones indicate large reserves and small cones small reserves. Municipal reserves increase with land availability and flow alteration, i.e., retention rather than release. Figure 3.8(c) uses colours to highlight which metric performs best for each solution. Regions of high performance for different metrics become apparent in the objective space. In Figure 3.8(d) transparency is used to highlight the solutions likely to constitute high performing compromises, using regret analysis (Savage, 1954). Low regret solutions are opaque while high regret solutions are transparent.

Regret (*R*) quantifies how much a policy's (*s*) performance (*P*) deviates from the performance of the best-performing policy (*s'*) in each performance metric (*c*), for the same set of input parameters (inflow timeseries) (*j)* and is normalised by the range between the best and worst-performing (*s''*) policies (Eq. 3.1). The best performing result has a Regret of 0 and the worst performing a Regret of 1.

$$R_c(s,j) = \frac{|P_c(s',j) - P_c(s,j)|}{|P_c(s',j) - P_c(s'',j)|}$$ **Equation 3.1**

3.4.4 Investigating details of selected Pareto-optimal operating rule sets

Five points representing specific interesting management policies were selected from the trade-off surface of Figure 3.8 to demonstrate their reservoir storage, release rule and flow regime implications. The best performing policy was selected for each objective function plus one example ‘compromise’ policy. The location of each point is highlighted on the trade-off surface in Figure 3.9.

3.4.5 Reservoir storage levels

Figure 3.10 shows how the five selected reservoir operating rule sets impact monthly reservoir storage levels (as percentage of full capacity). Retention and river regulation is minimised in Figure 3.10(a) to preserve the unregulated flow regime. Conversely, Figure 3.10(e) shows storage maximised around the best level for Land availability, which also means Fisheries deficit is low. Figure 3.10(d) illustrates a recognised (Lund and Guzman, 1999) policy for reservoirs in series supporting hydropower generation - Orós storage is sacrificed to maintain hydraulic head for generation at Castanhão. Figure 3.10(b) & (c) represent balances between release and retention to increase dependability of supply; in (b) to minimise Agricultural deficit and in (c) to balance all the objectives.

3.4.6 Aggregated metrics

The Agricultural deficit and Flow alteration metrics used to define the trade-off surface in Figure 3.7 & 9 were aggregated for different regions and seasons respectively. Visual analytics allow us to examine the trade-off within these aggregations and consider the balance between the component metrics. Should a particular region of the sub-trade-off curve/surface be preferred, this could inform constraining the surface in Figure 3.9 during a decision-making process. Figure 3.11 for example, shows the

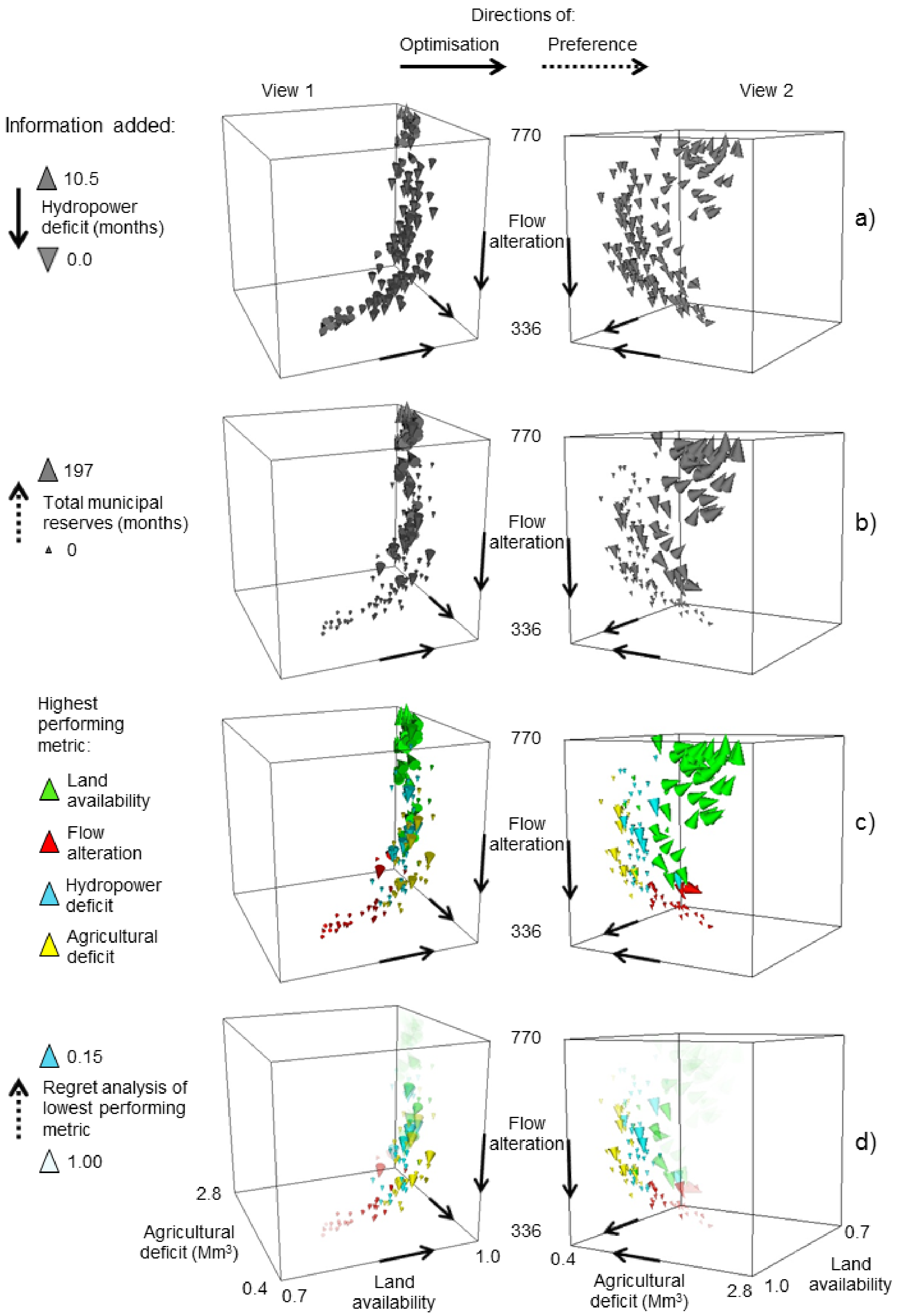

Figure 3.8 Progressive addition of information to the trade-off surface from Figure 3.7. The x- and y-axis are labelled only in the bottom panel (d) for simplicity but apply to all panels. Initially a fourth optimisation dimension is added to show Hydropower performance (a), then visual effects are used to illustrate further features of the solutions: b) the minimum total municipal reserves reached, c) the region of the trade-off

surface where each metric performs best, and d) gradation of regret to emphasise where best performing compromises are likely to be.

selected rule set locations within the context of the disaggregated Agricultural deficit trade-off. This shows how much less than optimal performance must be accepted in these metrics in order to achieve high performance in other metrics or the example compromise rule set.

3.4.7 Release rules

Each solution point in the previous plots comprises a set of reservoir release rules of the form shown in Figure 3.4. Figure 3.12 illustrates the five selected rule sets (policies) in the same form. The rule curves demonstrate the conflict between Pro-poor and Eco-flow policies as curve shapes are almost mirror images of each other – Pro-poor favours retention while Eco-flow favours release. These points also lie at opposite ends of the trade-off surface (Figure 3.9). Other policies balance or mimic the two extremes, to varying degrees, seasonally to achieve their respective high or balanced performance.

3.4.8 Flow alteration

Examining flow frequency curves (Figure 3.13) resulting from each selected release rule set helps understand Flow alteration metric optimisation. Figure 3.13 shows how different regions of the unregulated curve are affected by particular release rule sets. These plots help decide how far regulated flows should be allowed to stray from unregulated (natural) flows. The gap between regulated and unregulated curves in the wet season (Figure 3.13(a)) represents the volume stored – it is not possible to achieve natural flow conditions and at the same time store water. Regulated flows are closer to the natural regime in the dry season (Figure 3.13(b)) as the flows are an order of magnitude lower than in the wet season. Less water needs to be released to meet these flows, with less impact on storage.

Further data pertaining to the requirements for maintaining perennial flows would allow constraining the optimisation within particular limits.

3.4.9 Comparing optimised to current operation

Comparison of optimised solutions with observed reservoir releases is limited by the fact that the reservoirs were built at different times. There were only 7 years of observed conditions when all reservoirs were active and had accomplished their fill-up period. Inflow data were not available for modelling this period, so it was not possible to account for the hydrological validity of the comparisons made here. Nevertheless Figure 3.14 shows marked differences between reservoir storages implied by the

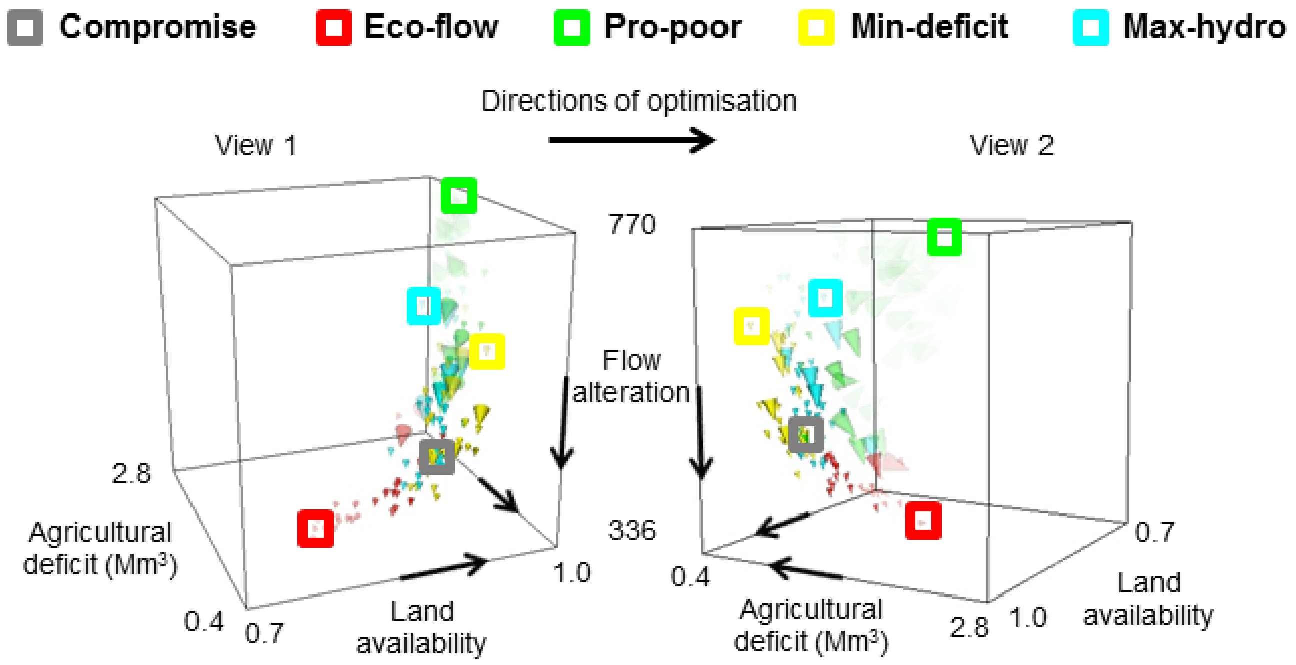

Figure 3.9 The trade-off surface from Figure 3.8(d) with coloured boxes highlighting the location of selected policies. The policies span the whole trade-off surface so they help to understand the implications as release rules change across the surface.

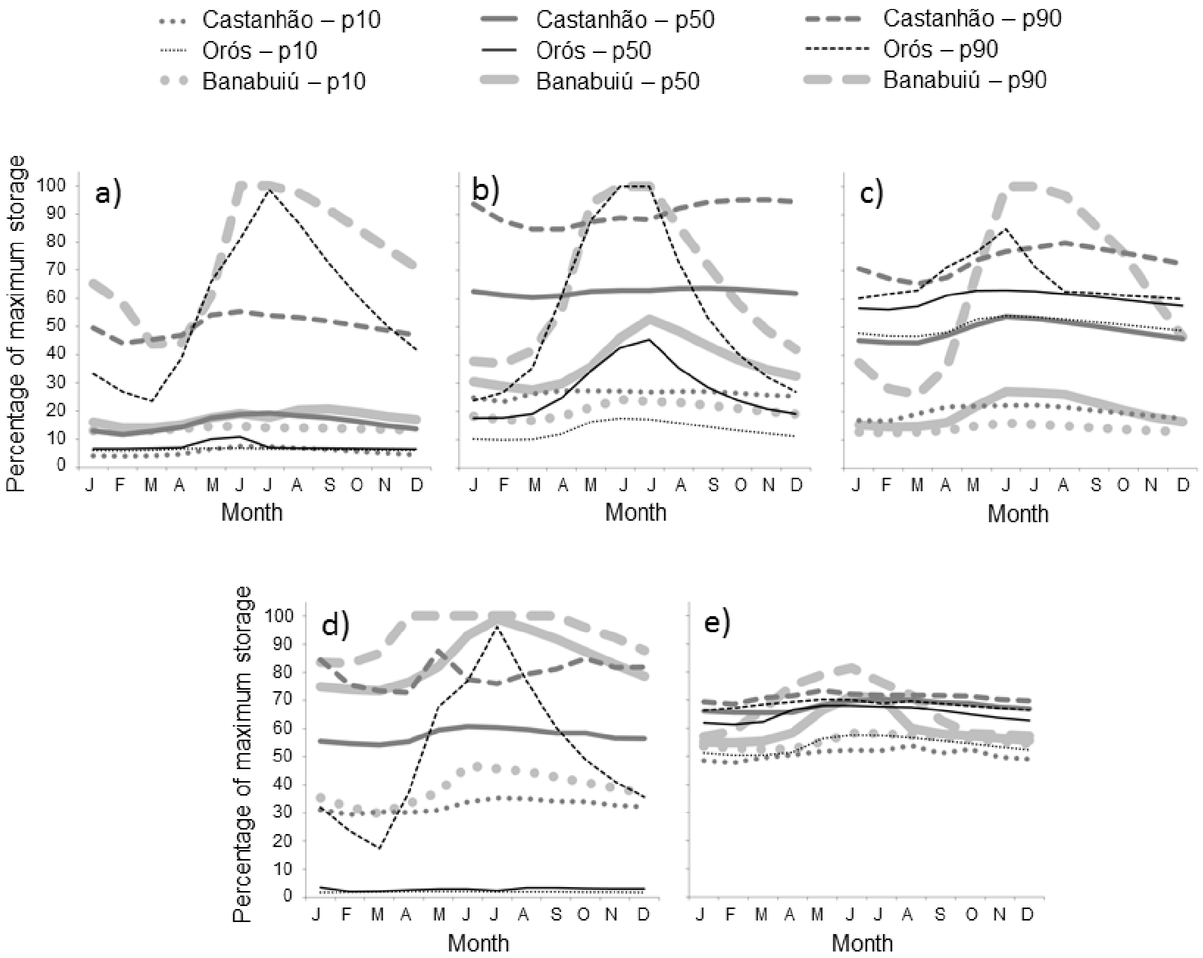

Figure 3.10 Average reservoir storage profiles over the 90-year simulation period for selected release rule sets; a) Eco-flow, b) Min-deficit, c) Compromise, d) Max-hydro, e) Pro-poor. The range of storage generated by each rule set is indicated by 10th, 50th and 90th percentile plots; colour tones and line thickness differentiate between reservoirs.

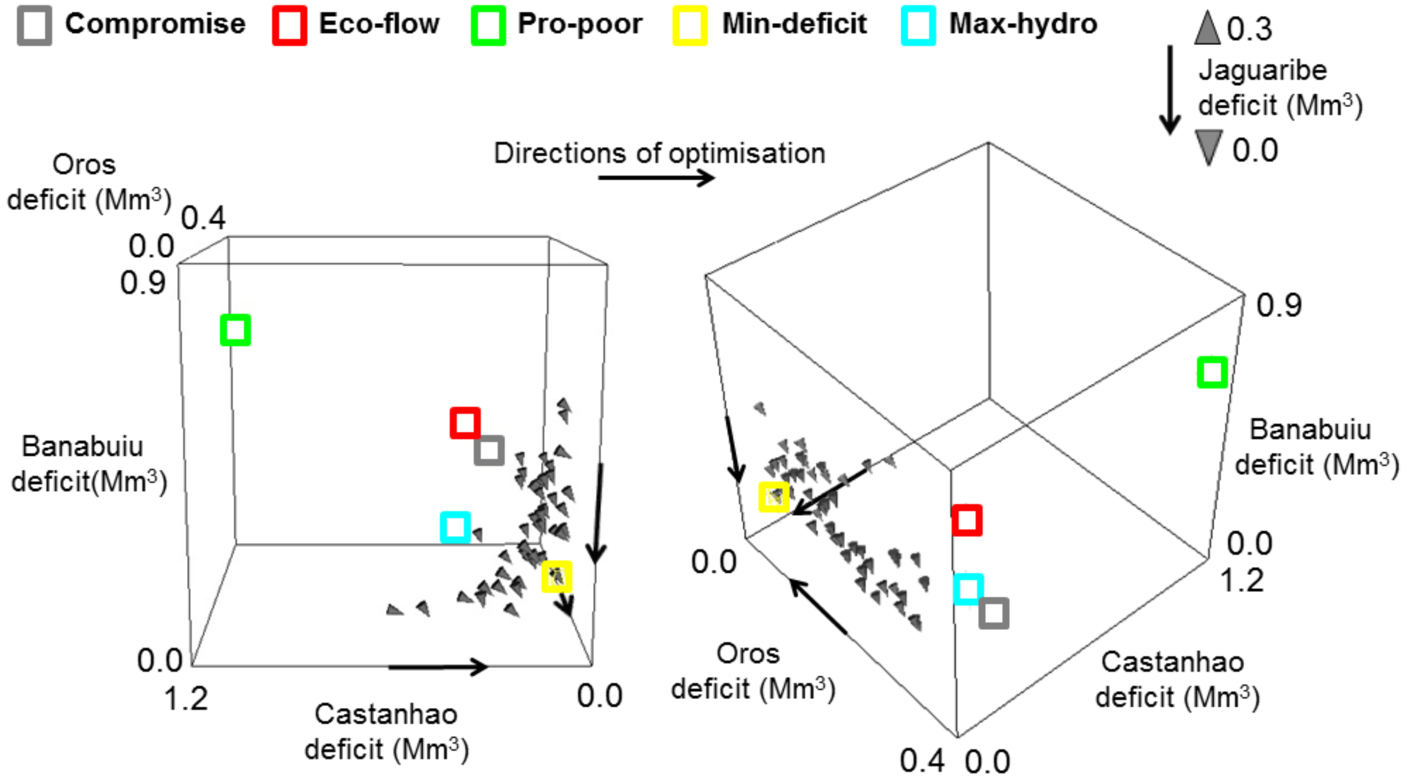

Figure 3.11 Trade-off between regional Agricultural deficits. Coloured boxes highlight the location of selected policies. This shows how less than optimal agricultural deficits in some regions must be accepted in order to achieve high performance (green, red, blue) or the example compromise rule set (grey).

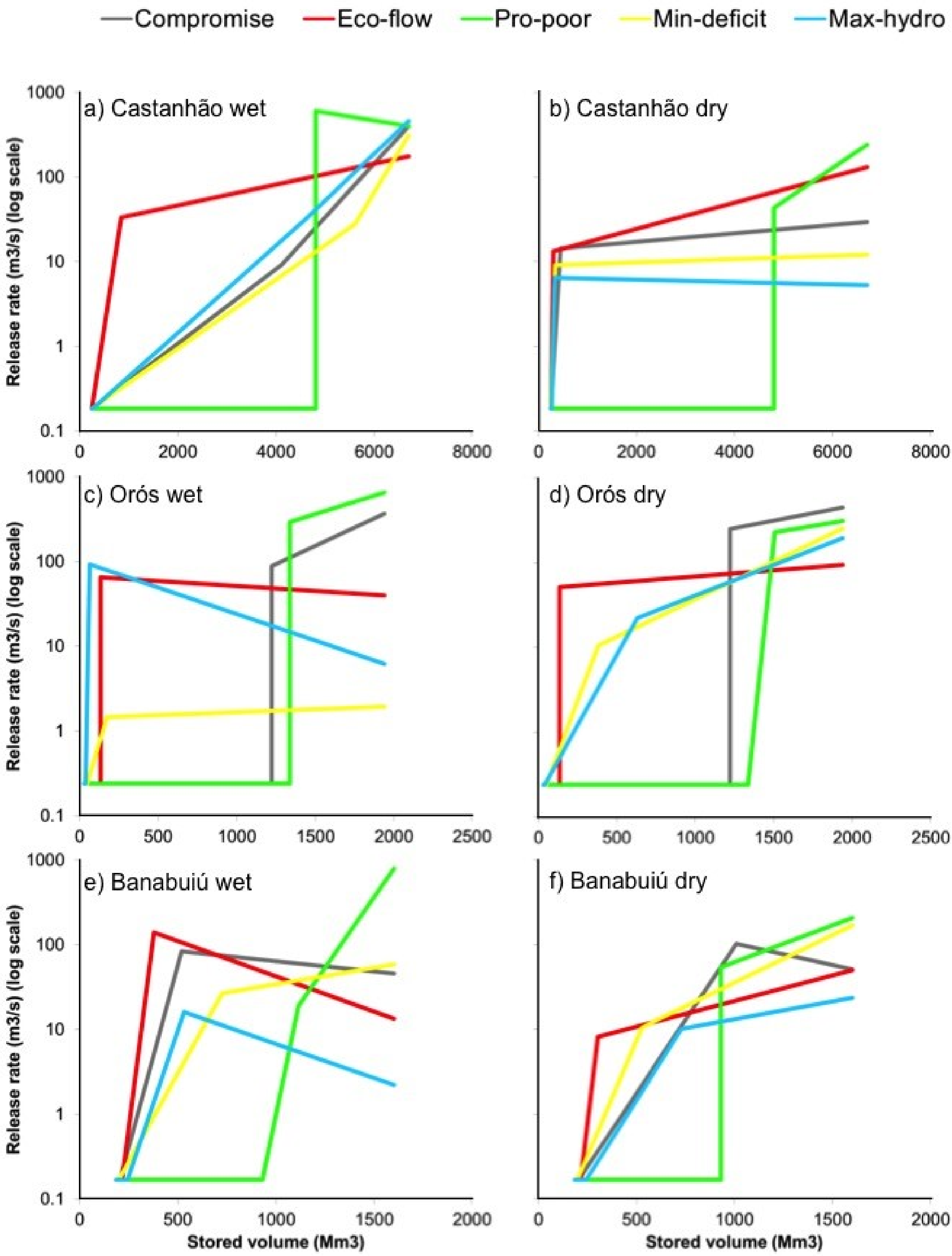

Figure 3.12 Seasonal release rule sets for each reservoir (NB: x-axis changes according to reservoir storage capacity).

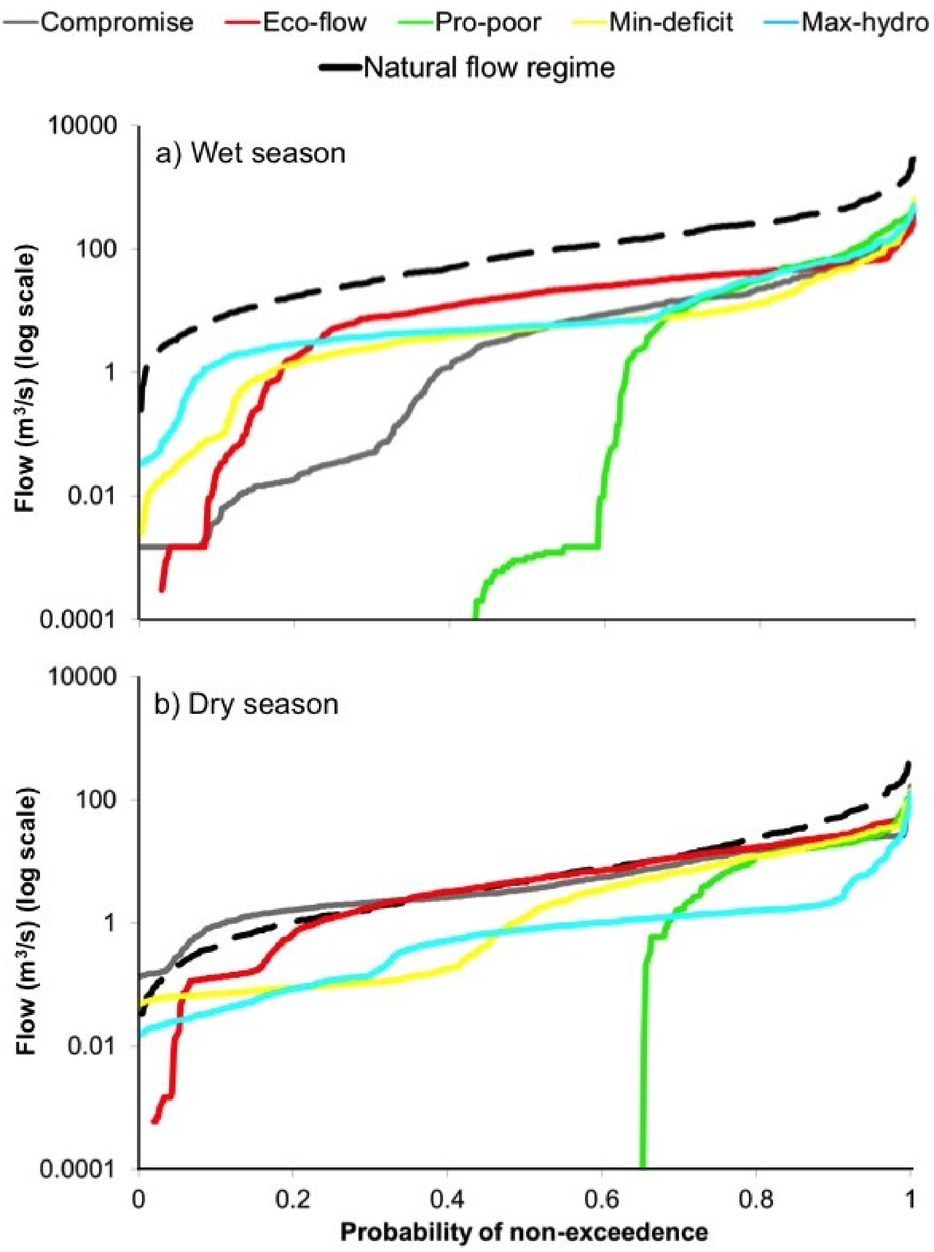

Figure 3.13 Unregulated (natural) basin outlet flow frequency curve compared to results of selected release rule sets. Flow frequency curves provide the probability that a given flow will not be exceeded. Flow is zero where lines do not contact the Y-axis.

example optimised release rule set and observed storages resulting from both recent negotiated releases and those before the construction of the Castanhão reservoir.

Comparison of observed dry season release data for 1998-2010 (Orós and Banabuiú) and 2002-2010 (Castanhão), with dry season releases resulting from the optimised Compromise release rule set shows the Castanhão releases are similar although greater for the optimised rules, but substantial differences are apparent between releases for the other two reservoirs – release rates varying more widely with the

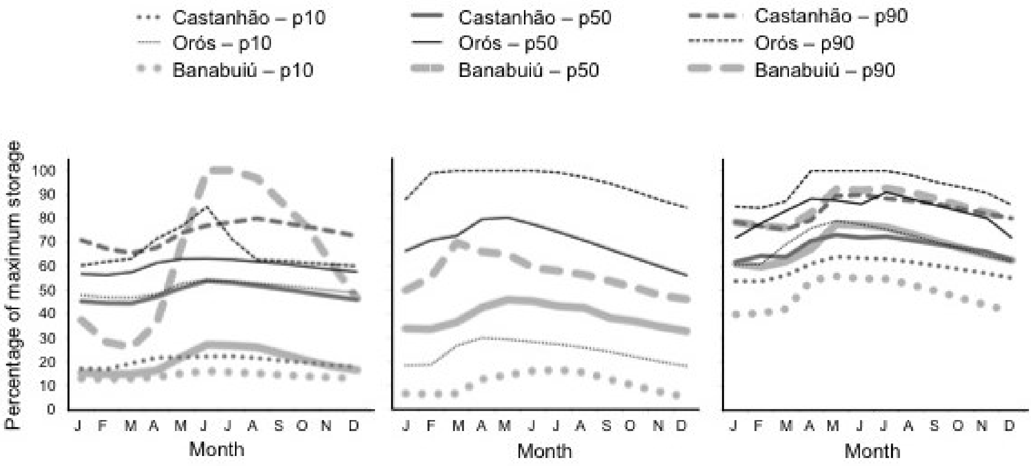

Figure 3.14 Reservoir storages for (a) the optimised Compromise release rule set simulated using 1911-2000 flows, (b) the 1968-2004 observed Orós and Banabuiú reservoirs pre-Castanhão construction, and (c) and observed 2004-2011 reservoir storages. Storages (b) and (c) show the impact of the Castanhão reservoir construction and also suggest different priorities in management than those represented in (a).

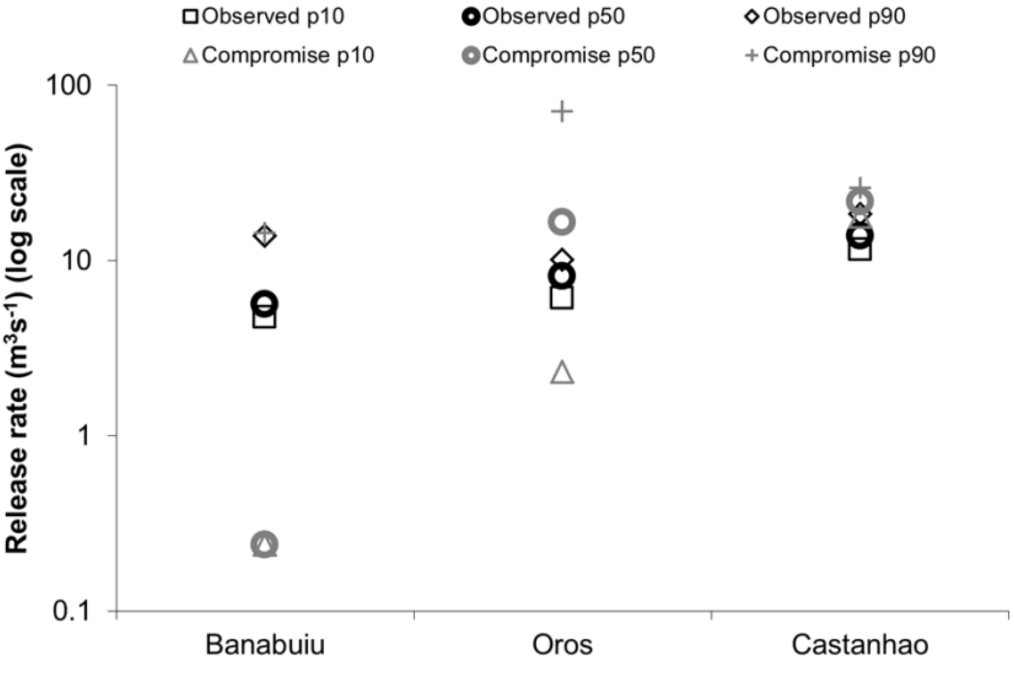

Figure 3.15 Comparison of observed and optimised mean dry season release rates (10th, 50th, 90th percentiles) for the three reservoirs

optimised rules, perhaps indicating caution on the part of the dam operators (Figure 3.15).

The same example optimised rules increase median Land availability performance over that calculated from observed reservoir levels by 25% - from a baseline of 0.8 the optimised release rules achieve a median difference of 0.05 from the observed, constituting 25% of 0.2 (Table 3.8).

Table 3.8 Comparison of Land availability performance for poor farmers resulting from observed reservoir levels (33 years between 1971 – 2011) and optimised Compromise release rules

Percentile	Observed	Optimised release rules
0	0.80	0.82
10th	0.85	0.86
50th	0.91	0.96
90th	0.99	0.98
100th	1.00	1.00

3.5 Discussion of the application

The rich information revealed by visual analytic plots of Pareto-optimal solutions could allow technically literate stakeholders to understand environmental management conflicts in an intuitive way. Considering many benefits in a single visualisation helps maintain a broad perspective in comparing policies. It is more difficult to ignore the benefits available to poor and marginalised groups when they are explicitly represented alongside traditional measures of economic performance. This type of information could lend itself well to enhancing group decision-making such as that currently used in the Jaguaribe basin and could supplement current analytical outputs considered during reservoir release negotiation. This application has shown that it is possible to provide new information using many-objective trade-off analysis which could support consensual decision making about the operation of existing water infrastructure.

The trade-off analysis showed how performance varies across the Pareto-optimal surfaces for different objectives. High-level trade-offs with aggregated metrics showed the implications for reservoir levels and seasonal flow regimes (Figure 3.10 and Figure 3.13). Once a decision is made about the balance between benefits, the approach can quickly provide information about the policy (release rule set in our case) required to achieve the selected balance.

It is important when optimising to carefully consider the spatial and temporal resolution of performance metrics. This can help avoid compensation effects whereby one region or time period has high benefits to 'subsidise' low benefits in other regions or time periods. These imbalances may or may not be acceptable in real management decisions and justified using seasonal flow alteration and regional agricultural deficit metrics. Even so, compensation effects are apparent in the example Compromise policy; Agricultural deficit in the Oros region is allowed to be high at times to keep Oros reservoir water levels high to enhance fisheries and land availability there. In this case the disaggregated trade-off (Figure 3.11) can be used to help apportion deficits between the four regions.

Current releases appear from Figure 3.14 and Figure 3.15 to be more conservative than the example optimised releases generated through this analysis, favouring storage over release. Available release data (COGERH, 2011) suggest that releases are often lower than those agreed to during negotiations. The reasons for this are unclear, but regional water manager risk-aversion could be a factor. It is also likely in this case that the 7-year period is insufficient to compare optimised and current management owing to lack of sufficient hydrological variability in that period. Land availability increases suggest optimised rules can simultaneously increase benefits dependent on both storage and release.

Demonstrating the advantages of Pareto-optimal solutions may be difficult in developing country contexts where observed data are scarce against which to either calibrate & verify models or to compare benefits. These data are however, often the only ones available to support any type of decision-making. The application of this approach under conditions of extreme data scarcity could still be used as a guide for decision-making, or the data scarcity could be considered to represent an additional uncertainty and treated as such in more sophisticated analyses such as that demonstrated in Chapter 5. It would be necessary to carefully attempt to quantify the confidence limits relating to any assumptions made. Hypothetically stakeholders who trust the environmental system simulator and who develop their own benefit functions (to represent their interests in the model) through shared vision modelling exercises are more likely to support the balanced solutions output by this approach. The case-study described here was deterministic; an explicitly stochastic analysis may be more appropriate for management where climate change impacts are relevant over the time-scale considered in the decisions. Much more detailed data about the demands and the function of the system would be required for analysis using these methods to support real decision-making. The details about agricultural demands in particular and the details of hydropower production as well as uncertainties about environmental flow requirements would all need to be dealt with to the satisfaction of all stakeholders.

4 Informing investment decisions in large-scale irrigation

4.1 Introduction

This second application builds on the first by undertaking a more sophisticated analysis, dealing with decisions around investment in irrigation schemes in addition to re-operation of dams. As such it seeks to identify and help decision-makers visualise combined reservoir management and irrigation investment strategies which would result in the best possible (Pareto-optimal) trade-offs between achievable benefits. The decisions or ‘levers’ of the management problem are volume dependent release rules for the three major dams and extent of investment in proposed new irrigation schemes for rice, cotton and biofuel. These decisions are optimised for objectives covering provision of water supply and irrigation, energy generation and maintenance of ecosystem services which underpin local livelihoods and tourism. More data were available for this second application, increasing the quality of the results generated.

4.2 Tana Basin case study

4.2.1 Physical context

The Tana is Kenya’s longest river at around 900km (Baker et al., 2015) and most significant hydropower resource (Figure 4.1). Generally rainfall patterns are bimodal in the basin with long rains between March-May and shorter rains from October-November. However, in the highest parts of the basin around Mount Kenya and the Aberdare Mountains lower intensity rainfall also occurs between May-October. Average rainfall varies from 2,400mm per year at these higher elevations, down to 300mm in low-lying parts of the baisn, although these lower regions can experience as little as 200mm per year. The river experiences flood peaks in May and November resulting from the long and short rain peaks.

Currently the five hydropower plants of the Seven Forks project in the Tana basin provide around 40% of Kenya’s electricity. Three plants are associated with storage dams – Masinga, Kiamburu and Kiambere. The other two (Gitaru and Kindaruma) are run-of-river plants with pondages upstream of their dams. Masinga and Kiambere reservoirs also provide water for irrigation and municipal demands. The dams have disrupted the flow regime of the river by augmenting low flows, reducing peak flows and reducing the number of days riparian land is flooded (Maingi and Marsh, 2002). Richter et al. (1996) discuss the importance of hydrological factors in maintaining ecological function.

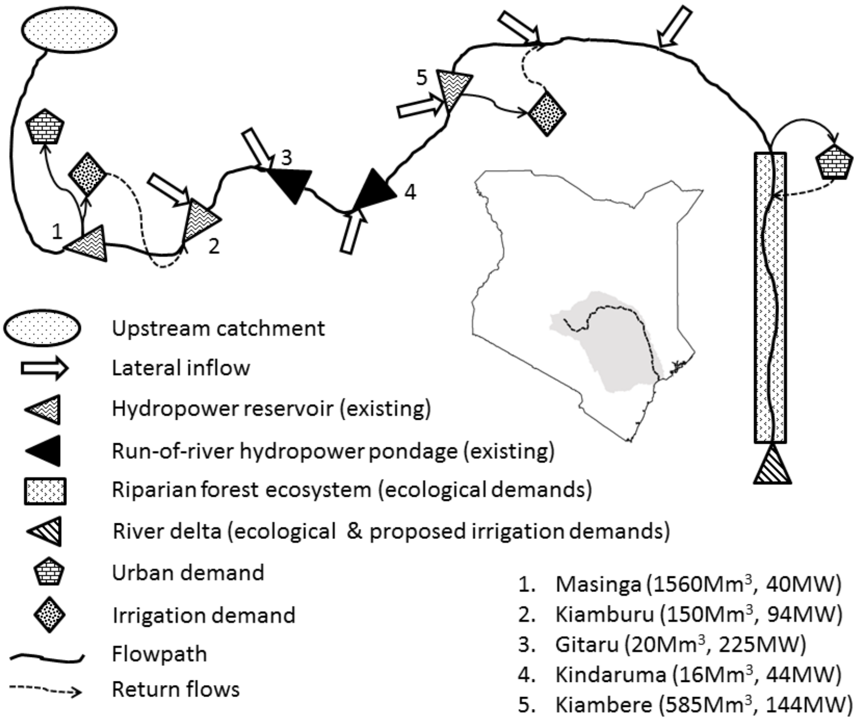

Figure 4.1 Tana River basin schematic. Inset map shows the location of river and catchment within Kenya.

The Tana River Delta was recently classified as a protected wetland (Ramsar, 2012), requiring consideration of the sustainability of management practices in terms of both the local ecosystems and livelihoods. The physical, chemical and biological characteristics of this wetland have resulted from the historic extent, timing duration and frequency of flood events (Mitsch and Gosselink, 2000). Maintenance of these characteristics amounts to a major demand for water, in competition with other demands. In the dry season the delta provides high quality grazing land for large numbers of pastoralists constituting a high value ecosystem service (Davies, 2007).

Protected high biodiversity riverine forests upstream of the delta are home to endemic and endangered species of primates (Karere et al., 2004) and rely on regular floods (Hughes, 1990) and low flows (Kinnaird, 1992) to maintain ecosystem health. Documented flow changes will have a negative impact on these forests (Maingi and Marsh, 2002). The natural variability of flows historically replenished nutrients on riparian agricultural lands and in the delta. Sediments deposited lead to beneficial morphological change. These ecosystem services are under threat from alteration of the flow regime (Emerton, 2005; Leauthaud et al., 2013).

Several large irrigation schemes are planned for the Tana Delta including 20,000 ha of sugar cane, 16,500 ha of cotton and 21,600 ha of irrigated rice. If implemented these schemes could threaten current social and ecological functions of the delta and potentially decrease its value as a tourism resource (Mireri et al., 2008).

4.2.2 Stakeholder and institutional context

The Tana Basin is home to 4.7 million people (Baker et al., 2015) with a diverse range of livelihoods dependent to varying degrees on the river and the ecosystem services it provides. Table 4.1 lists various stakeholders and their interests in the basin. In the lower basin there are two main groups focussed on pastoralism or agriculture. These groups come into conflict over access to water resources because agricultural activities often take place along the banks of the river and when this land is fenced off, pastoralists can be denied access to the river banks to graze and water livestock as they have done traditionally. This conflict has on occasions become violent (Baker et al., 2015). Other stakeholders have interests which conflict, such as Nairobi City Water and Sewerage Company, whose abstraction withdraws water from the basin which could otherwise be utilised for hydropower generation or irrigation downstream.

4.3 Innovations to the modelling methodology

As proposed investments were considered in this example it was helpful to initially define a baseline performance trade-offs case without investment but with dam re-operation options. This facilitated a comparison with the second case where new irrigation water demands were introduced to investigate their impact on trade-offs. This demonstrates how adding irrigation investments impacts the trade-offs that map the social-economic-ecological and engineering performance of the system. This section first describes the features of the basin model before explaining how the search algorithm interacted with it and how trade-off plots help understand results.

In this case study application it was not possible to interact with stakeholders, although much of the data available drew on previously interaction with stakeholders (Kiptala, 2008).

4.3.1 Water resource management simulator

As in the first application, IRAS-2010 (Matrosov et al., 2011) was used to model the Tana basin water resources system. Model nodes represented storage reservoirs, run-of-river pondages, abstraction points, demands and flow monitoring locations. Links connected nodes to provide flowpaths representing the main river channel, dam release gates and spillways, hydropower turbines, abstractions and return flows. Table 4.2 summarises the model features and data inputs used.

Table 4.1 Stakeholders in the Tana River water resources system

Stakeholder	Interests
Water Resources Management Authority (WRMA)	National regulator under Ministry of Water, Environment and Natural Resources, responsible for abstraction licensing and maintaining environmental reserve flows in the river
Tana and Athi Rivers Development Authority (TARDA)	Has a mandate to "enhance equitable socio-economic development through sustainable utilization and management of resources in the Tana and Athi Rivers Basins" (TARDA, 2016). TARDA therefore has a focus on environmental protection, natural resource management, sustainable development and socio-economic well being of the people. TARDA owns the main dams on the river and runs its own irrigation schemes on the lower river.
KenGen	Operator of the hydropower plants at the five dams on the river – controls releases from the dams
Pastoralist communities	Need access to the river to water livestock and river banks for grazing. Benefit from flooding of the river which fertilises and waters grasslands for grazing
Flood recession agriculturalists	Mostly along the river banks to take advantage of flooding from the river or access to irrigation pumped from it.
Large formal irrigation schemes	Large irrigation schemes exist in the middle and lower Tana. In the middle Tana abstraction is from Masinga reservoir or smaller dedicated storage. In the lower region the take-offs are direct from the river through formal engineered schemes. New large irrigation schemes are proposed in the lower Tana – these are the subject of this chapter's analysis.
Nairobi City Water and Sewerage Company	Abstracts water from the Thika and Sasumua reservoirs in the upper Tana to transfer to Nairobi, which is in the Athi River basin.
National Irrigation Board (NIB)	Provision of irrigation to both large and small scale schemes, development of new dams for provision of irrigation.
Local water utilities	A number of smaller water utilities provide piped supplies to municipalities within the basin.

Initial reservoir/pondage storages were set at 50% of their maximum capacity as historical level data were not available. The upstream boundary condition was a 42-year historical (1934-1975) inflow time-series from a point downstream of the dams. This represented pre-dam development conditions and was used as the basis for analysing variations from the natural flow regime. The flow series was disaggregated based on relative flow proportions in Kiptala (2008) into an upstream catchment inflow series and 7 lateral inflow series. The downstream boundary at the delta did not account for tidal backwater effects restricting river flow. A monthly (30-day) time step was used; modelled flows entering the system passed through it within a single time-step making flow routing unnecessary. This reduced flood peaks by averaging them but maintained the seasonal flood flows.

Table 4.2 Summary of Tana Basin model and data inputs

Modelling software	IRAS-2010
No. of system model nodes	36
No. of system model links	42
Inflows	42-year inflow series used by Kiptala (2008) disaggregated to catchment of each dam
Transmission losses	Assume none (partly accounted for by river evaporation)
Return flows	Municipal, 0% (Most settlements far from river and main transfer is to Nairobi in separate basin); Irrigation 30% - all assumed to occur within a single model time-step
Reservoir evaporation	Monthly mean daily evaporation transposed from Muguga (Dagg, 1970), scaled by 10% using Dagg,1970 annual evap map using location of reservoirs, then scaled 30% for plains
Reservoir rating curves (storage-elevation)	From Kiptala (2008)
River evaporation	Evaporation transposed from Muguga (Dagg, 1970), scaled by 10% using Dagg,1970 annual evap map using location of reservoirs, then scaled 30% for river on plains
Model time-step	30 days
Flow routing	No routing - assumes all flows reach storage or exit system within 30 day time-step
Water demands	From Kiptala (2008)

In the current water demand case, public water supply and irrigation were abstracted from reservoirs taking precedence over hydropower releases. This meant the hydropower plant would receive no water until other demands were satisfied. It was necessary to prioritise demands in IRAS-2010 and this approach had little impact while storage was high but best represented the likely results of political pressure under drought conditions. Current demands on the reservoirs for irrigation and municipal supplies are shown in Table 4.3; proposed additional demands are in Table 4.4.

Consistent with Kiptala (2008) as no alternative information was available, return flows to the river were a constant 30% of irrigation abstractions, except for the proposed schemes in the delta. These were assumed to return flows to multiple minor channels flowing to the ocean so were not included in flow measurements at the delta. It was assumed that no return flows to the Tana occur from public water supply as the major abstraction is for Nairobi which lies outside its basin.

Table 4.3 Non-hydropower demands by month on reservoirs in the Seven Forks project (in m^3s^{-1}) (Kiptala, 2008) applied to both cases

Reservoir	**Masinga**			**Kiambere**
Month	**Rice**	**Horticulture**	**Municipal (Nairobi &Kitui)**	**Maize**
Jan	17.6	1.3	2.2	3.9
Feb	18.9	0.0	2.2	1.4
Mar	19.7	0.7	2.2	0.0
Apr	0.0	2.3	2.2	0.0
May	0.0	5.0	2.2	2.5
Jun	0.0	5.3	2.2	4.8
Jul	13.8	1.6	2.2	4.3
Aug	13.4	0.0	2.2	1.3
Sep	19.5	1.6	2.2	0.0
Oct	18.7	3.1	2.2	0.7
Nov	0.0	4.3	2.2	1.7
Dec	16.7	3.5	2.2	3.2

The reservoirs and rivers in this semi-arid region evaporate roughly 2000 mm $year^{-1}$. The monthly mean daily evaporation rate for Muguga was increased by 10% according to maps and data supplied by Dagg et al. (1970) for reservoir evaporation and by 43% for river channel evaporation in the lowlands.

4.3.2 Optimisation approach/Problem formulation

As for the first application in Brazil (Chapter 3) the IRAS-2010 simulator was linked to the epsilon dominance non-dominated sorted genetic algorithm-II (ε-NSGAII) based on its performance in benchmarking (Kollat and Reed, 2006; Reed et al., 2013)). This section describes the optimisation problem formulation.

Table 4.4 Monthly demands for proposed irrigation crops in the Tana Delta (in m^3s^{-1}) (Kiptala, 2008) applied only in the proposed demands case according to the proportions determined by related decision variables

	Crop			
Month	**Rice Season 1**	**Rice Season 2**	**Cotton**	**Sugarcane**
Jan	20.2	0.0	3.3	112.0
Feb	21.8	0.0	0.0	83.5
Mar	22.7	0.0	0.0	29.9
Apr	0.0	0.0	0.0	44.8
May	0.0	0.0	0.0	121.7
Jun	0.0	0.0	0.0	159.7
Jul	0.0	16.0	3.6	156.8
Aug	0.0	15.5	6.3	160.5
Sep	0.0	22.5	10.5	167.4
Oct	0.0	21.5	8.9	143.4
Nov	0.0	0.0	8.4	116.5
Dec	19.3	0.0	8.3	99.3

4.3.2.1 Decision variables

The decision variables of the optimisation were the release rules of the 3 managed hydropower reservoirs (Masinga, Kiambere and Kiamburu) and (for the 2nd case only), the proportion of each proposed irrigation scheme implemented. The other two hydropower stations (Gitaru and Kindaruma) are run-of-river and received flows limited only by available storage and their maximum turbine flow capacities.

Similar to the first application, release rule decision variables comprised 3 plotting coordinates (i.e. 5 values) defining a continuous piecewise linear curve which related stored volume to release rate (Figure 4.2). In total 15 decision variables control releases. The release ranges were 0-400 m^3s^{-1} consistent with Kiptala (2008). The storage variable ranges were from dead to maximum storage, specific to each reservoir. A single curve was applied throughout the year to represent a conservative approach (i.e. likely to conserve/maintain storage) – release rates were dictated only by current storage volume, unaffected by anticipation of a forthcoming wet season inflows (Information on whether or how forecasts are currently used in Tana reservoir operation was not available for this study). This could impact on the amount of water released for uses downstream because operators of the real system would be likely willing to release more water in anticipation of recharge during the wet season. By contrast it could support abstractions better during drought conditions as more water could be available due to the conservative approach. Over the inflow time series these effects could balance each other as the impact of different release rules manifest. The search algorithm will however discover release rules which work best despite these impacts and specific to the inflow time series. Although irrigation abstractions were directly from the reservoir and prioritised over hydropower releases, they were limited by the release rule.

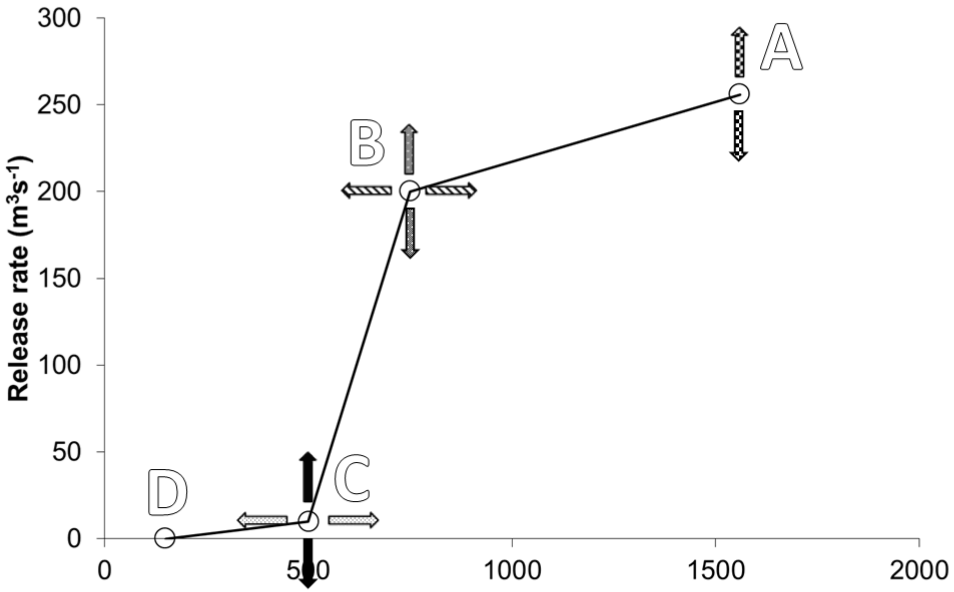

Figure 4.2 Reservoir release rule (hedging) curves as represented by the IRAS-2010 model. Each patterned pair of opposing arrows represents an optimisation decision variable. Point D is the dead storage of the reservoir. Point A represents the controlled release when the reservoir is full. B and C points can be varied in two dimensions for hedging. In total 5 decision variables define each reservoir's release rule.

There are four proposed new irrigation schemes in the delta (Table 4.4). The proportion of each scheme included in an individual simulation was dictated by a decision variable of range 0-100%. In the current demands case, these variables were all fixed at 0%.

4.3.2.2 *Objectives*

The impacts of each set of decision variables (operation and development policy) were evaluated with respect to eight objectives, each being either maximised or minimised by the algorithm. Objectives are detailed in Appendix B and outlined below.

4.3.2.2.1 Municipal deficit

Masinga reservoir supplies Nairobi and Kitui and an abstraction from the river downstream of the dams serves small local urban centres. Shortfall in these supplies was minimised by evaluating a ‘municipal deficit’ objective.

4.3.2.2.2 Hydropower

Hydropower revenue was maximised dependent on hydraulic head levels in the associated reservoir or pondage, flow rate through the turbines and timing of releases, as bulk energy prices vary though the year. Failure to meet electrical base load or peak demands causes economic losses and could hamper economic productivity and development. A ‘firm energy’ objective was employed to maximise the electrical output (GWh) at 90% reliability over the course of the simulation. Firm energy is of national interest because it represents the reliable level of electricity available form the system. Peaking power demands by contrast, which typically manifest at the sub-daily timescale were not analysed in this study as they could not be captured by the monthly model time step. The amount of water allocated to hydropower generation could in some cases be used for peaking generation rather than more constant production within the month time step. This is dependent on waiting to release water through turbines not leading to spills however. Longer timescale demand variations were captured by monthly bulk energy prices which fluctuate with demand.

4.3.2.2.3 Irrigation

Existing irrigation provision in the basin does not place a strain on water resources as the volume required (Table 4.3) is small relative to storages and annual flows in the river (Kiptala, 2008). In re-operating the system however, crop revenues can vary as a result of policies causing irrigation deficits. Agricultural revenue was maximised dependent on minimising crop water deficits during growing seasons. In the proposed demands case it depends also on the selection of crop type, which dictates water requirements and yield response to deficit. A module was added to IRAS-2010 to evaluate crop specific yields and reductions due to irrigation shortfall (Appendix C).

4.3.2.2.4 Environmental flows

The same approach to assessing environmental flow deviation from the natural regime was used as described in Section 3.3.2.6. In this application the assessment was annual rather than seasonal.

4.3.2.2.5 Flood peak reduction

Flood magnitude and timing are components of Richter et al.’s (1996) indicators of hydrological alteration relevant to ecological health. Flood peaks in the Tana basin support ecological function and supply agricultural and grazing lands with nutrient rich sediments. Two flood peak objectives were evaluated at the delta; the most important provider of flood related ecosystem services. One objective was evaluated for each of the long and short flood seasons (Apr-Jun and Nov-Dec respectively) to minimise the difference between the natural and modified flood peaks.

4.3.2.3 Problem formulation

Trade-offs were generated for the two cases which shared a common problem formulation (Eq. 4.1). Objective functions included in the formulation are detailed in Appendix B. In the current demands case there was no abstraction for proposed irrigation schemes between the locations where $f_{flowFOR}$ and $f_{flowDEL}$ were evaluated, so these objectives had similar values (evaporation caused reductions downstream). As in the previous application optimisation algorithm parameters were applied as recommended by Kasprzyk et al. (2009).

$$F(x) = \left(f_{mun}, f_{hydro}, f_{firm}, f_{agric}, f_{flowFOR}, f_{flowDEL}, f_{flood}^{long}, f_{flood}^{short}\right) \qquad \text{Equation 4.1}$$

$$\forall x \in \Omega$$

$$x = (X_i)$$

where *i* is a reservoir, $i \in \{Masinga, Kiamburu, Kiambere\}$ and $\mathrm{i} \in \{\mathrm{Masinga, Kiamburu, Kiambere}\}\mathrm{X_i}$ represents a reservoir *i*'s release rule. The decision variables optimised were individual reservoir release rules, where X_i represents reservoir *i*'s release rule for each of the 3 managed reservoirs.

4.4 Trade-off analysis

This analyses trade-offs generated by the two optimised cases, starting with the current demands case. Although the computational burden of many-objective optimisation is high, this was mitigated by the use of parallel computing. The search process requires many simulation runs and is carried out using high performance computing available on university clusters or commercially using the cloud. The two cases presented here each completed 100,000 function evaluations (42-year simulations) in 1.75 hours using 48 2GHz processors. Visual analysis of the search progress and a random seed analysis (e.g. Kollat et al., 2008) testing 50 iterations of the same optimisation process and visual analysis of results confirmed that 100,000 evaluations led to no further search progress and only diversification of results would be gained by extending the search. If decision makers focus on a relatively small area of the initial trade-off surface, an extended search could be undertaken to help diversify the options over that limited area.

4.4.1 Current demands case

This section steps through the construction of a six-dimensional trade-off surface. Varying impacts of selected policy solutions are highlighted.

Support of ecological function and ecosystem services is investigated first from the perspective of the three flow related objectives. Trade-offs exist between reduction of the two annual flood peaks (Figure 4.3a) because water which is released to increase one flood's magnitude is no longer available to increase the other. Flow regime alteration trades off against both flood peak objectives. Greater overall disturbance of the flow regime is required to support flood peaks closer to those naturally occurring. The volume of water released to maintain the highest 20% of flows can alternatively maintain the lowest 80% of flows (Figure 4.3b). The trade-off surface is non-linear incorporating convexities and concavities with respect to the origin (where the perfect solution would lie). Gain-sacrifice gradients vary across the surface.

Firm energy production is added to the trade-off surface through sizing of the spheres. Larger spheres indicate higher firm energy levels. Hydropower revenue is represented by a colour range applied to the spheres (Figure 4.4a).

In this and subsequent figures trade-off surfaces are simplified by controlling the resolution at which solutions are displayed. As this reduces the number of solutions shown, decision makers would be asked to choose a preferred region of the surface before all Pareto-optimal points are reintroduced for investigation of detailed solutions. As objectives (dimensions) are added to the surface, the number of solutions included in it increases. An objective's poorest performance can decline further as it is traded off against additional objectives. Maximum flow alteration is increased to 135 in Figure 4.4a to accommodate the new surface.

Firm energy trades off against flood peak objectives as it increases when flood water is stored to secure generation during drier periods. It also trades off against the flow alteration objective as relatively constant flow provides higher firm energy than natural variability.

Between Policy D and E (Figure 4.4a) there is a trend for increasing hydropower revenue as flow becomes more natural but flood peaks reduce. Exceptions to this trend result from the limited scope for upstream dam operations to increase revenue without impacting on the flow related objective values controlled by Kiambere - the last hydraulic structure in the system.

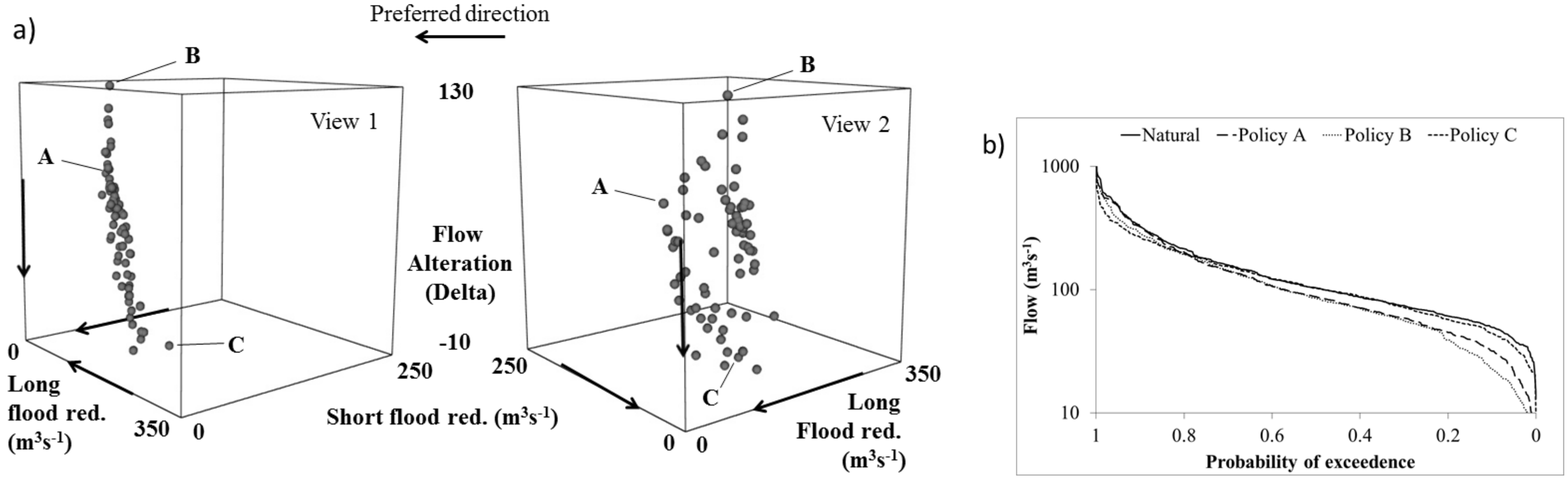

Figure 4.3 a) Two views of the trade-off surface between flow related objectives. Flow regime alteration decreases as flood peaks are reduced allowing lower flows to be maintained closer to the natural regime. Three policies are highlighted and referred to in the text and subsequent figures. b) Comparison of the flow duration curves resulting from Policies A, B and C in a). Policy C allows around 20% of highest flows to diverge from the natural curve to augment lower flows, maintaining them closer to the natural regime. Policy A achieves the reverse.

Flow alteration is decreased from Policy D to E by releasing water to maintain low flows rather than high flows (Figure 4.4b). This increases the proportion of flows released through the turbines of the Kiambere hydropower plant because they don’t exceed its flow capacity; thereby increasing revenue. The flow duration curve from Policy E departs from the natural curve at the turbine capacity of the Kiambere plant as additional flow beyond this magnitude generates no additional revenue.

Policy F brings around 10% more flow duration within the productive capacity of the Kiambere turbines than Policy E. In addition some of the high flow volume made available is released to increase the lowest flows above the natural level (Figure 4.4b). This more constant flow achieves higher firm energy generation (Figure 4.4c).

Agricultural revenue is added to the trade-off surface by converting spheres to cones whose orientation indicates its magnitude (Figure 4.5). Cones pointing down indicate the lowest revenues; cones pointing up show high revenues. Maximum flow alteration is increased to 195 to accommodate the new surface.

High agricultural revenue depends on both reliable supply (storage) and release rates at the Masinga and Kiambere reservoirs. Storage levels alone are not a predictor of agricultural revenue as without the operating rules allowing releases, crops cannot be irrigated. Agricultural revenue trades off against reduction of flood peaks and alteration of the flow regime which increase these storage levels. There is also a trade-off with hydropower revenue, which benefits from some storage but requires higher releases which impact on storage. The maximum mean annual revenue achieved by the optimisation represents no reduction from the maximum possible annual revenue, i.e. there are no irrigation deficits.

4.4.2 Proposed demands case – implementing irrigation schemes in the delta

Having identified the trade-offs in the system under current water demands, these are now compared with the Pareto set involving a supplemental decision: ‘what proportions of the proposed irrigation schemes to implement?’. Figure 4.6 shows the trade-off surface combining both cases to illustrate how the surface changes following the introduction of potential irrigation investments. Maximum flow alteration is increased to 1072 and maximum agricultural revenue increased to US$285M.

Figure 4.7 shows the trade-offs between the same metrics as Figure 4.5; this shows how ecological flow characteristics trade-off with increased agricultural revenues. New irrigation can lead to a more altered regime.

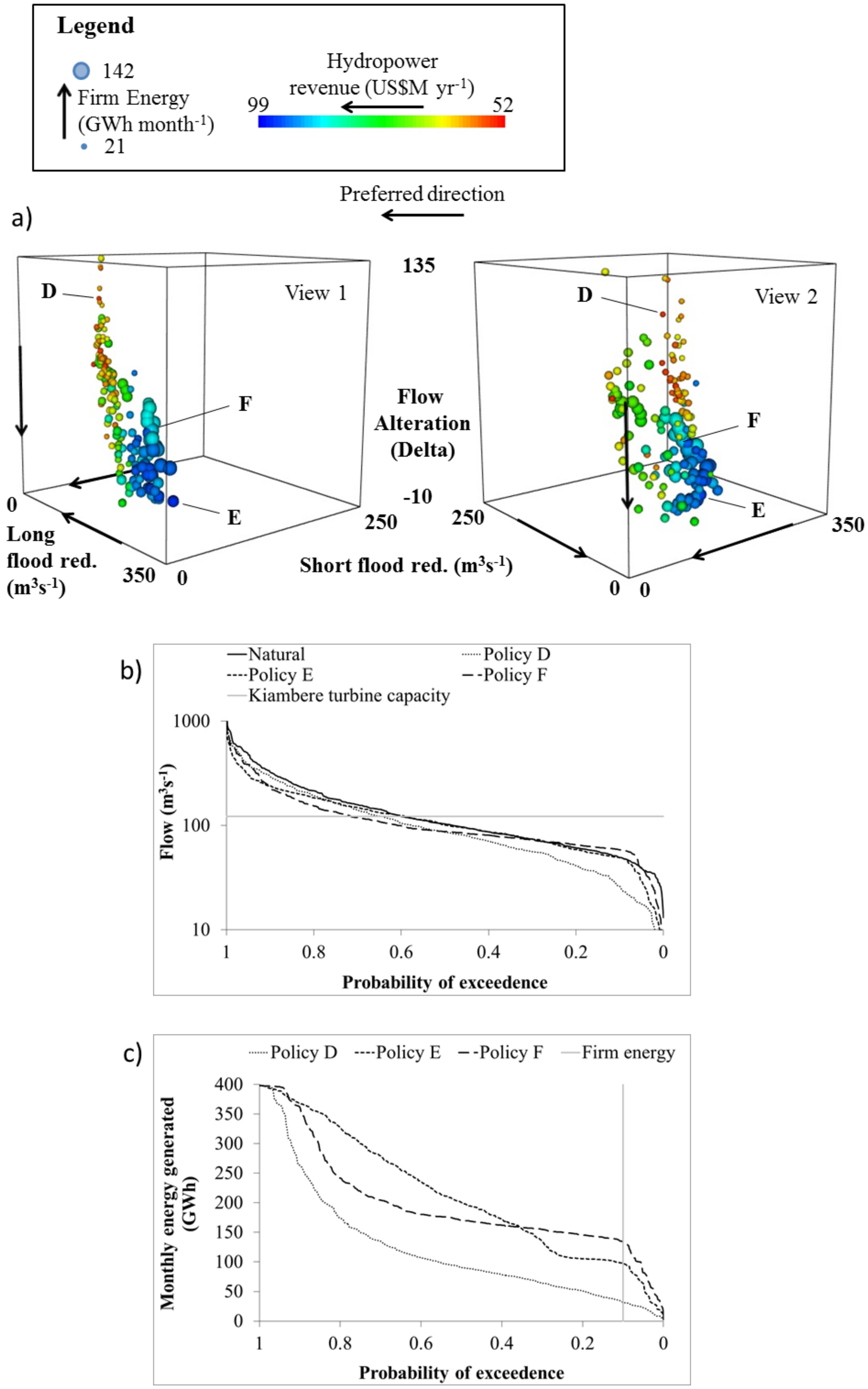

Figure 4.4 a) The same trade-off surface as Figure 4.3a with firm energy added using sphere size and hydropower revenue shown with colour. Larger spheres indicate higher firm energy; blue spheres mean high revenues. Three policies (D, E, F) illustrate trends

across the surface. Moving from D to E, hydropower revenue increases as flood peaks are reduced but flow regime alteration becomes less pronounced. From E to F long flood peaks are increased as a result of higher storage levels increasing uncontrolled releases and flow regime alteration is increased to conserve water for firm energy generation. b) Comparison of the natural flow duration curve with those resulting from the 3 selected policies of a). Lower flows are increased by sacrificing higher flows as we move across the trade-off surface in a) from Policy D to E. This results in 79% higher hydropower revenue. The Policy E curve departs from the natural curve at the turbine flow (i.e. productive) capacity of the Kiambere plant. Policy F brings around 10% more flows within the productive capacity at Kiambere than Policy E and increases low flows above the natural regime. c) Energy generation implications of the three policies labelled in a). Firm energy is the level of generation which can be provided with 90% reliability. Policy F best sustains energy generation to achieve firm energy 326% higher than Policy D and 37% higher than Policy E

In the current demands case agricultural revenue could be increased without irrigation development in the delta by reducing the long flood peak magnitude. With the new delta irrigation schemes, the short flood peak is further reduced to provide further increases in agricultural revenue, even with increased long flood peaks. The sugar cane crop requires year round irrigation and cotton is irrigated through the short flood season.

Whilst it is not possible to generate more hydropower than that obtained in the current demands case, it is possible to maintain generation levels while almost doubling agricultural revenues. When attaining the highest agricultural revenues however, hydropower revenue decreases. Increased agricultural revenues must be traded-off against the associated impacts on hydropower revenue, flows, floods and associated ecosystem services.

Figure 4.8 relates the details of the delta irrigation schemes implemented in Figure 4.7, showing the combinations of schemes which achieve different total agricultural revenues. The highest revenues can be gained either with or without cotton cultivation. A high proportion of the rice and sugar schemes must all be implemented to maximise revenue.

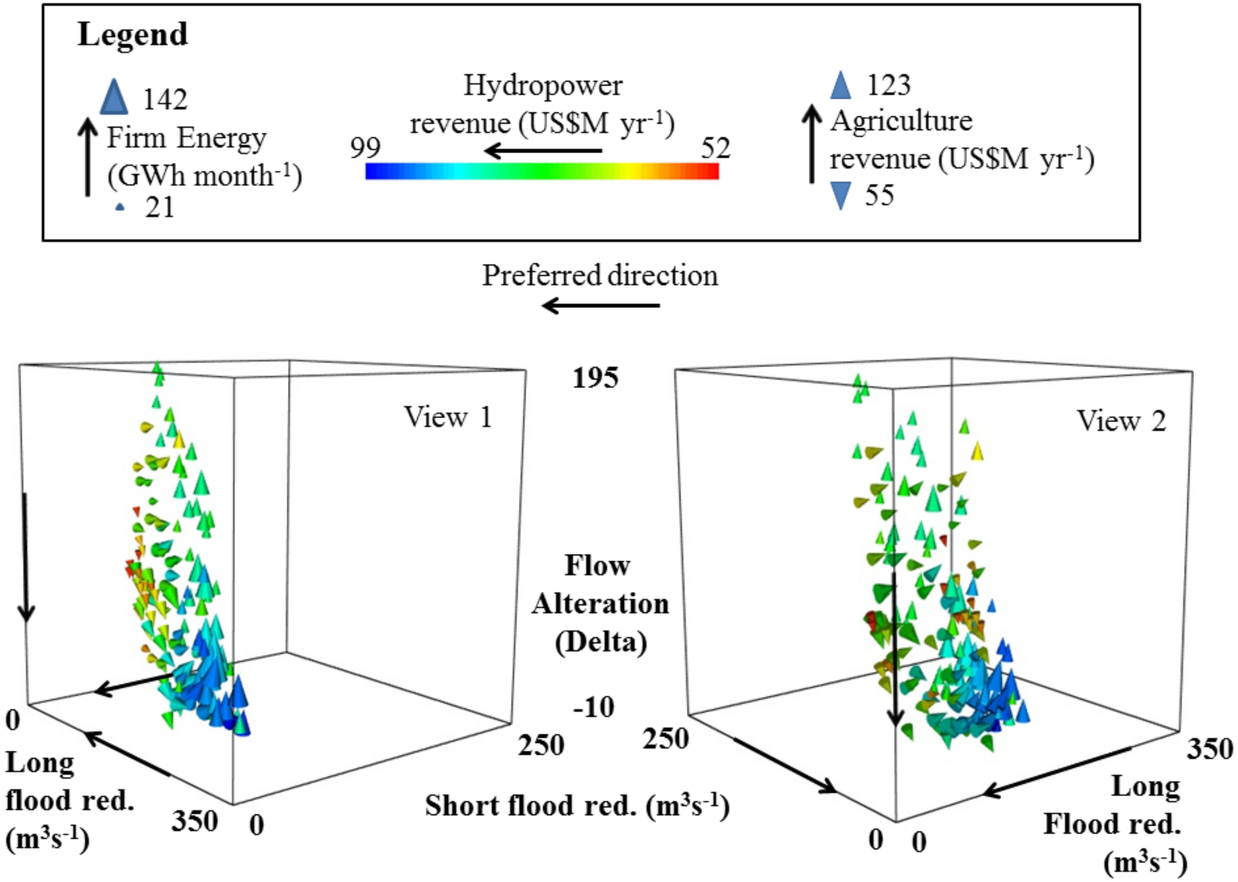

Figure 4.5 The same trade-off surface as Figure 4.4a with cones replacing spheres. Their orientation shows agriculture revenue from lowest (pointing down) to highest (pointing up). Agriculture revenues trade-off against flood peak objectives and correlate with firm energy, except at the highest agricultural revenues, where there is a trade-off.

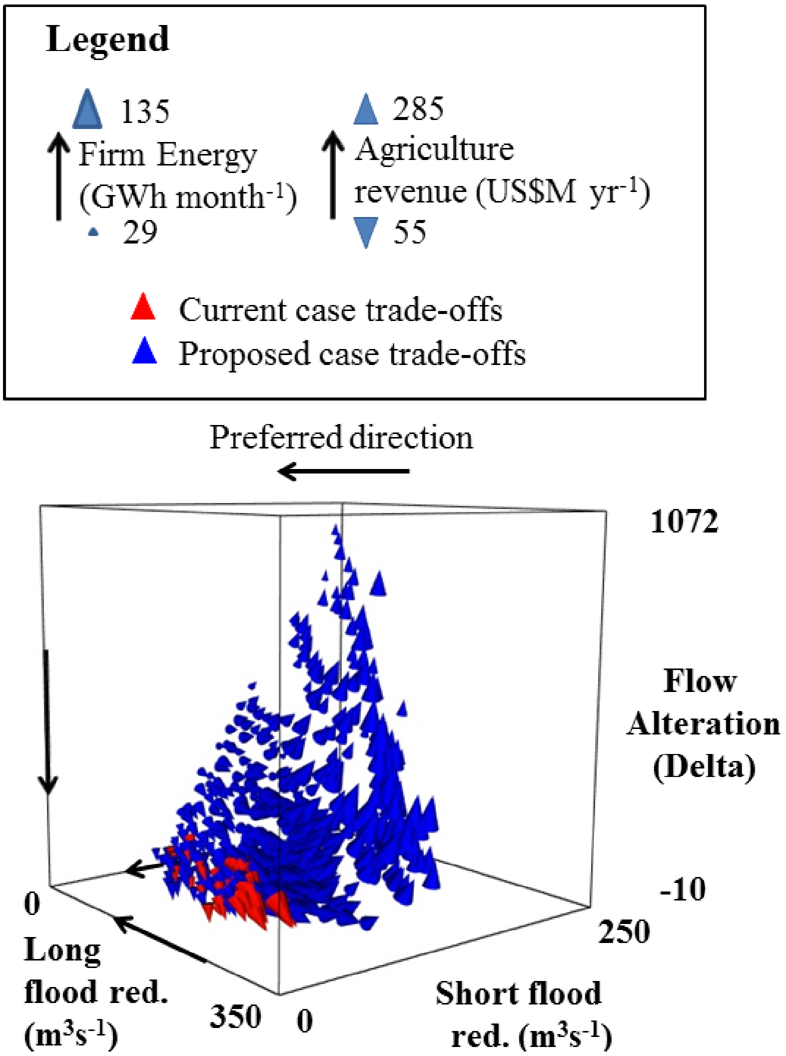

Figure 4.6 Trade-off surface of the combined current and proposed demands cases (blue cones show system performance when irrigation schemes can be expanded). Some proposed demands solutions dominate the current demands solutions reducing their representation on the surface. This figure shows how trade-offs achievable by the best system operating rules change once irrigation investments are considered.

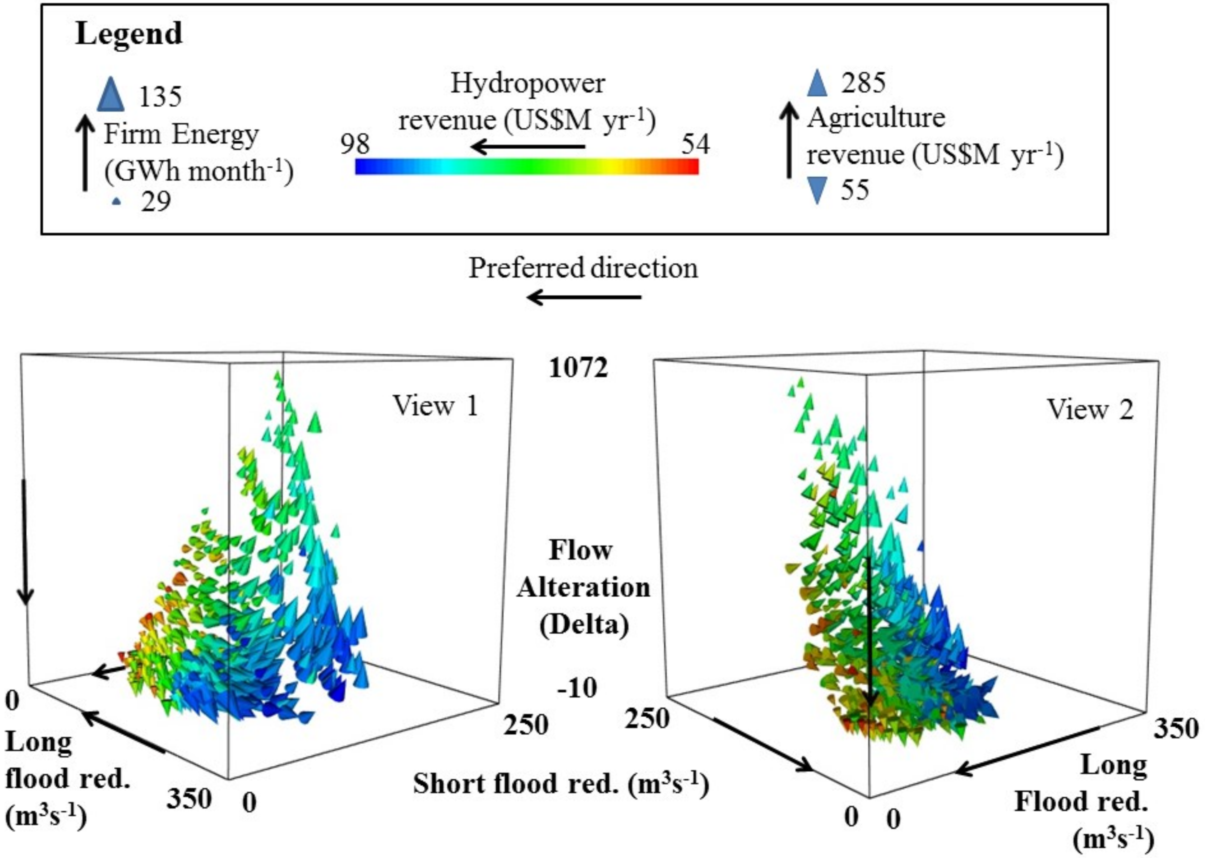

Figure 4.7 The same trade-off surface as Figure 4.5 but with different extents of irrigation scheme implementation. Maximum agricultural revenue more than doubles but maximum flow alteration increases by 5.5 times. Increased agricultural revenue correlates with greater disturbance of the natural water environment.

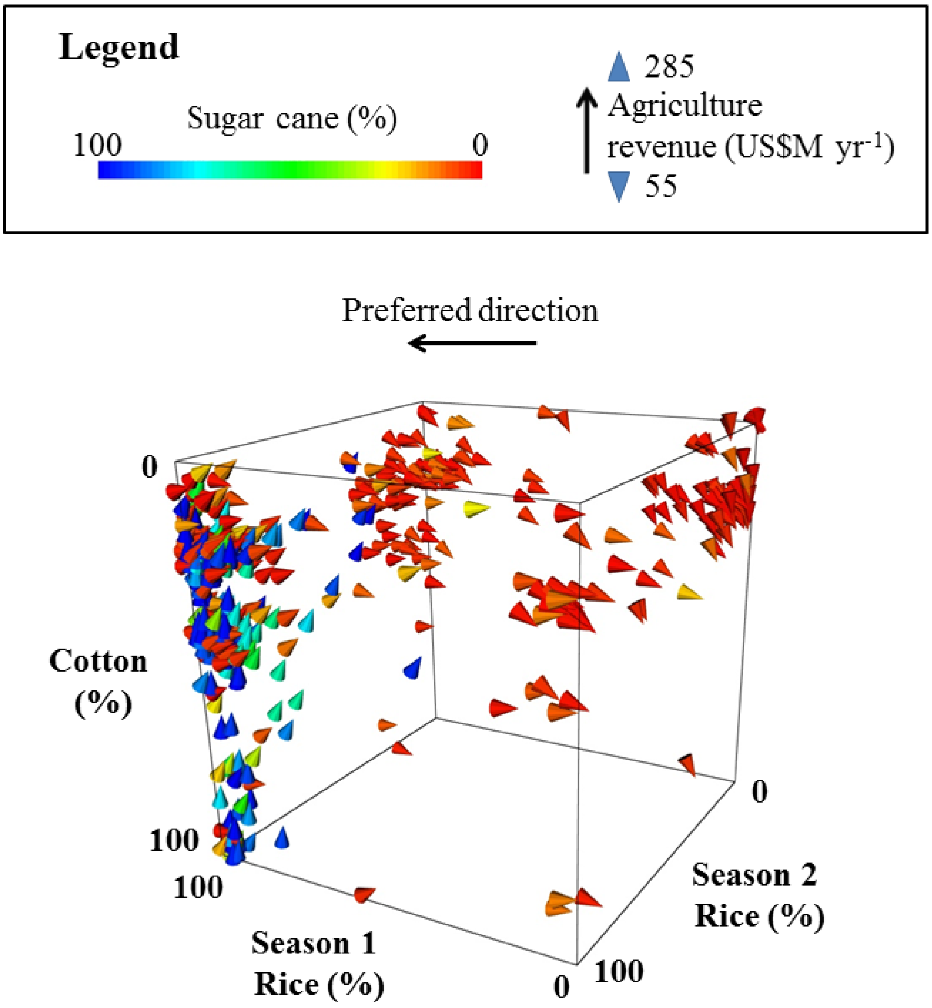

Figure 4.8 3D (non-trade-off) plot showing the relationship between irrigation scheme selection and agricultural revenue. The solution points are the same as those shown in Figure 4.7. High revenues can be achieved with or without the implementation of the cotton scheme. A high proportion of all other schemes must be implemented to achieve maximum revenue however.

4.4.3 How to select a balanced plan?

Exploring trade-offs is insightful, but ultimately the proposed approach is designed to assist with decision-making. This section demonstrates an approach that could help decision-makers settle on a plan – i.e. a set of reservoir operating rules and a portfolio of new irrigation schemes. This involves a) filtering the Pareto-front so that only decision-maker-preferred solutions figure there, b) identifying promising areas of the trade-off curve from which to choose example plans (individual trade-off points) to assess in more detail, and c) for those example plans look at various objective function performances and decision-variables. In this work it was not possible to work with decision-makers; so only a proposed approach is described.

First the Pareto options are filtered to arrive at those of primary interest to decision-makers. For this case-study it was assumed that decision makers would be most interested in solutions that ensure high reliability of municipal supply and therefore the trade-off surface was filtered to only allow plans with no municipal deficit (Figure 4.9a). From this surface, following step b) above three promising policies were selected to demonstrate how resulting benefits vary between them.

Finally, in step c), detailed plots and a table (Table 4.5) were generated that show the performance in detail of the example policies. For example, Figure 4.9b compares the natural with actual flow duration curves resulting from each policy. None of the selected policies are amongst the highest performers in terms of flow alteration, but they deviate from the natural regime in different ways. Policy H generates the most hydropower revenue by favouring release rates close to the turbine capacity of the Kiambere hydropower station. Policy G results in better flow alteration performance at low and high flows, resulting in high firm energy but lower hydropower revenues. Although around 20% of its highest flows are closer to natural than the others, Policy I results in the greatest alteration of the regime to increase agricultural revenue. The delta irrigation schemes are almost fully implemented (Table 4.5). Both policies which implement new irrigation schemes result in the delta receiving no water, except return flows from irrigation schemes, for 1-2% of the time.

Figure 4.9c illustrates the monthly trends in hydropower production for policies G-I. The highest revenue (Policy H) is achieved by generating more power when the bulk energy price is highest. There are four months where Policy G produces more energy than Policy H however.

4.5 Discussion of the application

This application has shown that it is possible to provide information about the trade-offs between diverse interests, in relation to water infrastructure (i.e. irrigation) investments as well as operating rules. Irrigation investments, whether in increasing storage or distributing water to farmers and fields is important for increasing food security. This application was reported on as a proof of concept as work with decision-makers had not yet begun when the work was undertaken. The approach aims to allow decision-makers to visualise the precise trade-offs they face when choosing amongst a subset of ‘best’ (Pareto-optimal) strategies identified by a multi-criteria search algorithm. Analysing trade-offs visually could help foster an intuitive understanding of the relationships between gains and sacrifices intrinsic to the system. The approach can be considered an alternative form of cost benefit analysis (Chakravarty, 1987), with costs expressed not in financial terms but in terms of sacrifice of other benefits.

The decision-making framework involves two steps 1. Settling on a framing of the planning decision that is preferred by decision-makers, then 2. probing the trade-offs (Pareto-optimal strategies) to identify a few alternatives to investigate in detail.

Table 4.5 Objective values and irrigation scheme implementation percentages for selected operating policies from Figure 4.9

		Operating policy		
Objective	**Units**	**G**	**H**	**I**
Municipal deficit	Mm^3	0.0	0.0	0.0
Hydropower revenue	US$M	88.0	92.7	82.1
Firm energy (90%)	GWh $month^{-1}$	131.1	105.1	79.9
Agricultural revenue	US$M	121.8	241.4	277.2
Flow regime alteration (Forest)	-	36.4	23.2	49.5
Flow regime alteration (Delta)	-	38.3	134.1	568.8
Long flood peak reduction	m^3s^{-1}	177.3	228.1	179.7
Short flood peak reduction	m^3s^{-1}	77.6	151.3	173.4
Delta irrigation implementation				
Rice (season 1)	%	0	86	100
Rice (season 2)	%	0	98	97
Cotton	%	0	69	31
Sugar cane	%	0	30	100

The Tana Delta flow regime would be altered by irrigation schemes which withdraw water upstream. The benefit of the proposed approach is that it is able to show the degree of alteration which would occur with the implementation of different scheme sizes. Revenues from the largest irrigated schemes are Pareto-optimal according to the optimisation, but the sacrifice of other benefits to achieve this is high. A limitation of the application was that irrigation water was assumed to be provided free from source to crop. Had the optimisation included capital and operational costs of supplying irrigation the trade-offs would have been different. Considering further non-water related benefits (e.g. increased local employment) of irrigation schemes could also be included to further elucidate the trade-offs involved. An ensemble analysis considering many

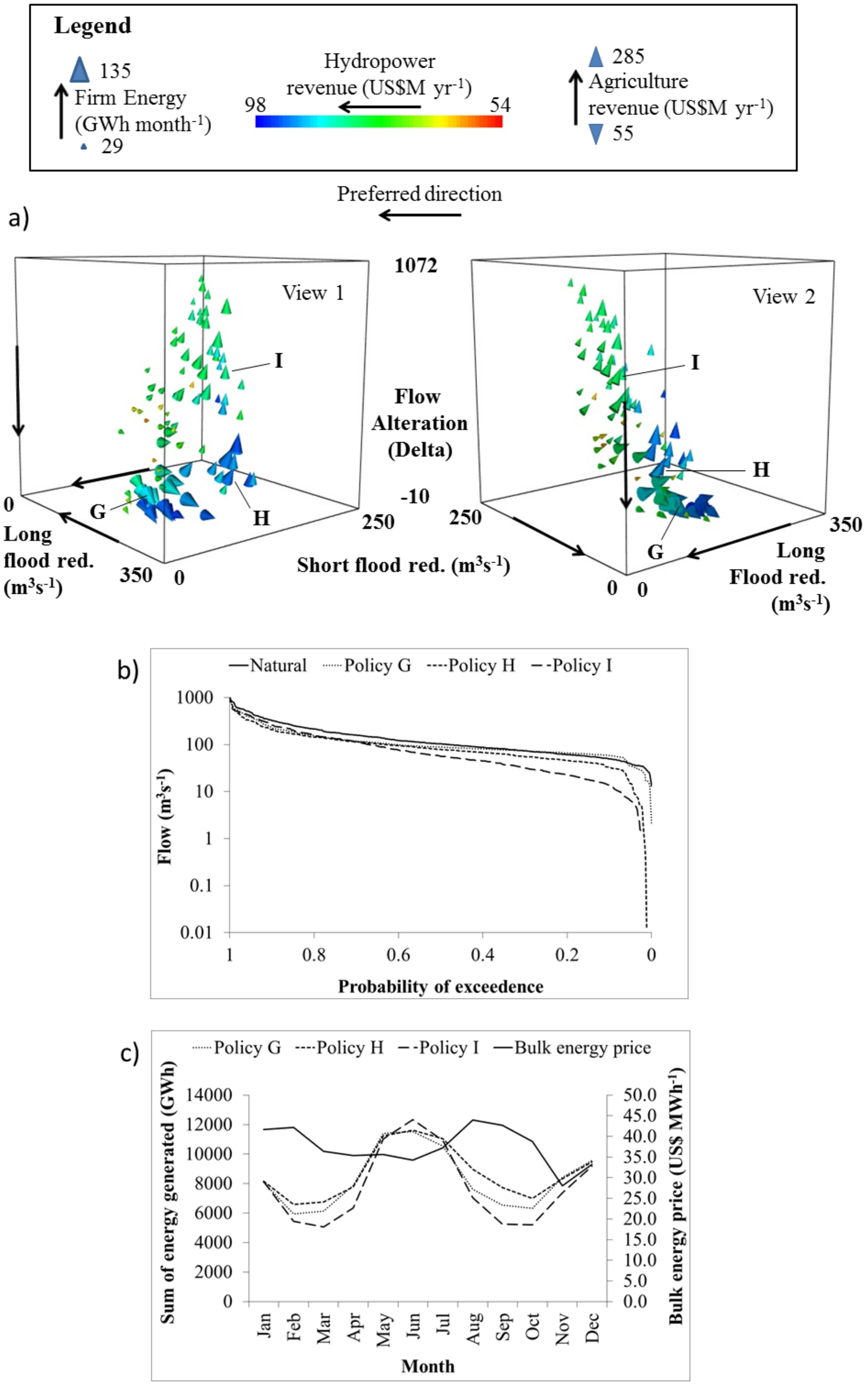

Figure 4.9 a) The same trade-off surface as Figure 4.7 but restricted to reservoir rules which result in no municipal deficits considering historical data. Such 'brushing' of

trade-off plots allow stakeholders to focus on system designs that interest them. Three policies are selected for discussion. b) Comparison of the flow duration curves for the three selected operating policies in a) showing implications of the flow alteration values in Table 4.5. The Policy G flow regime is closest to natural conditions at both low and mid-range flows, but high flows are sacrificed to increase firm energy. Policies H and I result in the river not reaching the ocean for 1-2% of the time. c) Plot of the total energy generation for each of three selected policies from a) alongside the monthly bulk energy price. Higher hydropower revenue (Policy H) is achieved by generating high levels of power in months (Aug-Oct) when the bulk energy price is highest.

plausible future flow series may also alter this assessment if water resources availability changes; uncertainty on future flows and demands was not included in this analysis.

This application sought reservoir operating rules that appropriately meet water manager and/or stakeholder expectations. The rules were designed such that they produce acceptable results over the range of hydrological conditions present in the historical time-series. If the hydrological regime were to change in the future, or a series of new assets were put in that would strongly change the system, the study would have to be redone to adapt to new conditions.

Mean hydropower revenue over the modelled period peaks at around 100 US$M year^{-1}. This is lower than figures of ~US$150M/year stated by Kiptala (2008) whose work used flows from a shorter but wetter period from 1966-90. The hydrological characteristics of this flow time-series were inconsistent with the 1934-1975 record used here, preventing their combination. Inconsistencies in data relating to hydraulic head ranges at hydropower turbines may also contribute to the discrepancy in power production/revenue between studies. Further work will attempt to resolve these discrepancies on the basis of more accurate survey data.

A further limitation of this application was the use of proxy objectives for ecosystem services. Appropriate expertise or further research should be employed to ascertain the significance of different flow regime alterations and advise on thresholds beyond which individual species, ecosystems or ecosystem services would be severely affected. In this way, impacts on local beneficiaries of these services may be clearer. Local farmers and pastoralists are likely to be better able to describe the relationship between river flows and their livelihoods allowing more specific and accurate benefit functions to be included in our model. This could replace or enhance our assumptions that entirely natural flow regimes are best providers of ecosystem services.

Two important impacts of the dams were not considered in this analysis, being barriers to fish migration and sediment trapping. Hydropower by Design (Opperman et al., 2015) emphasises the fragmentation of river reaches by dams as one of their greatest impacts on ecology. These impacts would be possible to incorporate where migratory fish are an important resource and new dams are proposed, but in this case study the operations and the irrigation schemes would not have so much impact. The operations of the dams could impact on sediment trapping within the reservoirs, and therefore the time taken for storage capacity to be depleted. In the Tana sediment trapping is also a significant issue because historically the sediment from the river has nourished the Kenyan coastline – an important and valuable Tourism resource (Emerton, 2005). IRAS-2010 does not currently include a sediment module to allow this impact to be quantified, although this could be an important inclusion in future as sediment issues are leading to significant loss of storage world wide (Wisser et al., 2013).

Opportunities exist to implement further hydropower projects on the river (van Beukering et al., 2015). Further work will seek to define the trade-offs inherent in decisions surrounding two or more new hydropower reservoirs which are proposed for the Tana river. Understanding these trade-offs could help inform both the optimal sizing and combinations of development for balancing system benefits. With infrastructure planning it will also be important to optimise across a range of possible hydrological futures to ensure proposed plans are robust to different plausible future climates.

The method applied appears useful for integrated water resources management of systems with a water-energy-food nexus. Revealing trade-offs between stakeholder-defined metrics helps could help orient planners towards solutions that protect livelihoods and the ecosystem services which support them in addition to obtaining good economic returns. In the case of the Tana Basin, decisions are currently made independently and autonomously by different agencies with mandates for development. This means there is currently no formal setting in which these organisation could input to and consider the outputs from application of the approach. One aim of the WISE-UP to Climate project (IUCN, 2016) is to bring stakeholders together to appreciate the value of more coordinated planning.

5 Selecting efficient and robust hydropower investments under multiple uncertainties

5.1 Introduction

The previous two chapters investigated the use of many-objective trade-off analysis for re-operation of existing reservoirs and investment in new infrastructure, specifically irrigation schemes. Water infrastructure systems need to share the benefits from water resources amongst many stakeholders but also perform adequately under uncertain future conditions. Neither of the previous applications accounted for any uncertainty in future conditions. Considerations of the risks associated with climate change have prompted a wider discourse around decision making under uncertainty – including but not limited to climate change as discussed in Section 2.5.2.

This chapter demonstrates a four-phased approach to water infrastructure portfolio design under deep uncertainty at the river basin scale, building on the applications reported in the previous two chapters. It involves: 1) System characterisation, 2) Vulnerability assessment, 3) Automated search and 4) Stress testing. The approach is demonstrated in Nepal, where installed run-of-river hydropower capacity is impeded by seasonal low flows resulting in severe annual electricity shortages. The implications are investigated for the Koshi Basin water resource system of combining different generating capacity options for run-of-river schemes with storage schemes and their operations to address national electricity deficits. The approach could be applied at basin or national system scale to inform selection of a portfolio of assets for investment, given many objectives and a complex physical system. In this case the application was based on interaction with stakeholders in Nepal by Prof. Julien Harou.

5.2 Case study context

5.2.1 Nepalese context

Because of a reliance on run-of-river hydropower, Nepal's electricity-generating capacity is severely hindered by low river flows in its dry season (Nepal Electricity Authority, 2014). Demand is relatively constant throughout the year, resulting in a mismatch in the seasonality of electricity supply and demand (Figure 5.1). The electricity supply-demand gap was about 410 MW in November 2013, when peak demand reached 1,201 MW, resulting in load shedding of up to 14 hours a day (Nepal Electricity Authority, 2014).

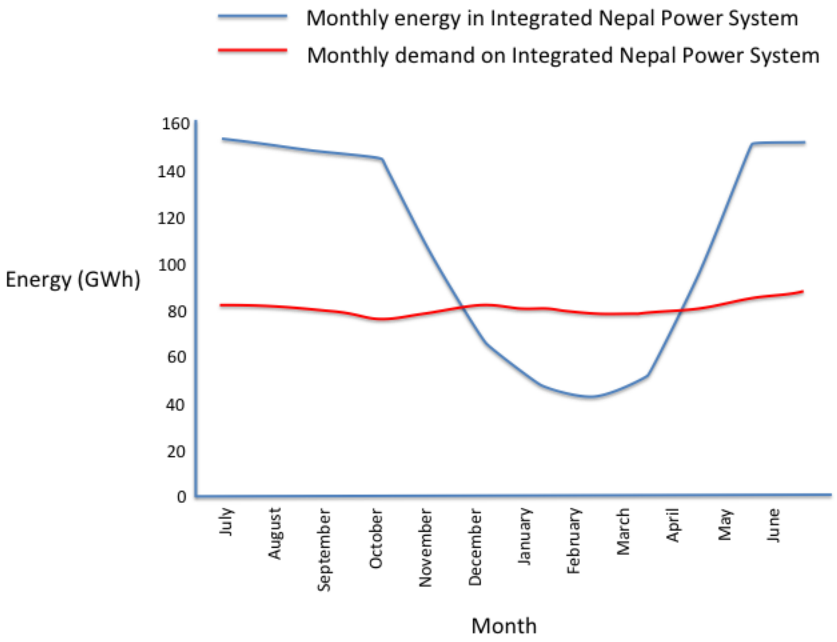

Figure 5.1 Monthly energy balance in the Integrated Nepal Power System (INPS) (Adapted from: Nepal Electricity Authority, 2014)

Lack of grid electricity is a major barrier to improving living standards, raising productivity and incomes, and helping Nepal's youth transit from agricultural to non-agricultural employment. Commercial and industrial consumers compensate by running generators using expensive imported diesel fuel at a high cost, weakening their productivity, competitiveness and ability to expand. The associated lack of job opportunities has pushed more than 5 million Nepali labourers to work overseas (Bonzanigo et al., 2015).

Nepal is actively exploring development of its hydropower resources, which already comprise 97% of its current national electricity generation portfolio. Its economically viable hydropower potential is estimated at approximately 43,000 MW spread across the seven river basins (Bartle, 2002). Hydropower remains the least-cost option for power generation to meet domestic demand and has the potential to make Nepal a powerhouse of the South Asia region, exporting to India and beyond.

Development of storage-type hydropower dams to help address the seasonal deficit is considered by a master planning exercise which prioritised 10 schemes across the country from 67 candidates, on the basis of wide ranging economic, social and environmental criteria but only recommended that climate change impacts be considered at a later stage (NEA, 2014).

Storage dams could also help supply irrigation for agriculture, with only 24% or arable land currently irrigated. There is a perception that better use of the available water resources could provide significant economic growth through the hydropower and agriculture sectors (Bharati et al., 2014)

In South Asia future climate projections are affected by the complex topography, influence of the South Asian Monsoon and uncertainty associated with glacier volumes (Gardelle et al., 2012; Kaab et al., 2012; Lutz et al., 2014; Miller et al., 2012; Rees and Collins, 2006). Historical analysis has shown increasing temperatures and no clear signal on precipitation. Glaciers are growing in some areas and receding in other areas, and more are receding than growing. Streamflow generally seems to be increasing, presenting an opportunity for hydropower generation (Lutz et al., 2014).

5.2.2 Koshi Basin context

5.2.2.1 Physical context

The extent of the Koshi Basin studied here was around 58,000km^{2,} upsteam of Chatara and extending into the Tibetan Autonomous Region, China (Bharati et al., 2014). The elevation range of this are is 140 - 8848m, including Mt. Everest. As a remote mountainous region, with high climatic and geographical variability and few gauging stations, climate and hydrology data are particularly scarce (Karki et al, 2011). It is however estimated that the water resources yield of the basin is around 48 billion m^3 per year (Bharati et al., 2014).

Fifty-two hydropower project sites have been identified within Nepal's Koshi Basin (Figure 5.2), with a total generating potential of 10,909 MW (JICA, 1985). The Basin comprises three main tributaries, the Sun Koshi, Arun and Tamakoshi (Figure 5.2). Little development of any kind has occurred in the basin and it is the location of two priority storage-type hydro-dams in the Nepal Electricity Authority (NEA, 2014) master plan as well as a number of new run-of-river projects. Of the three main tributaries the Arun River in particular has a high average discharge at around 200m^{3}s^{-1}, making it a good prospect for developing run-of-river hydropower with lower seasonal effects.

5.2.2.2 Stakeholder and institutional context

According to the 2001 census, the larger Koshi Basin is home to around 5 million people, although the area studied for this application only comprises around 80% of the full Koshi Basin within Nepal including the most sparsely populated parts. Around 75% of the population are involved in smallholder agriculture (ICIMOD, Undated). There is some existing irrigated agriculture and nearly 500,000ha of irrigable land (GoN-WECS, 1999). Table 5.1 lists the various stakeholders in the Koshi Basin's water resources. Conflicts are not common in relation to water resources use owing to their abundance, but new hydropower projects in particular have proved highly controversial in the past, (e.g. Mahat, Undated) in relation to Arun-III dam.

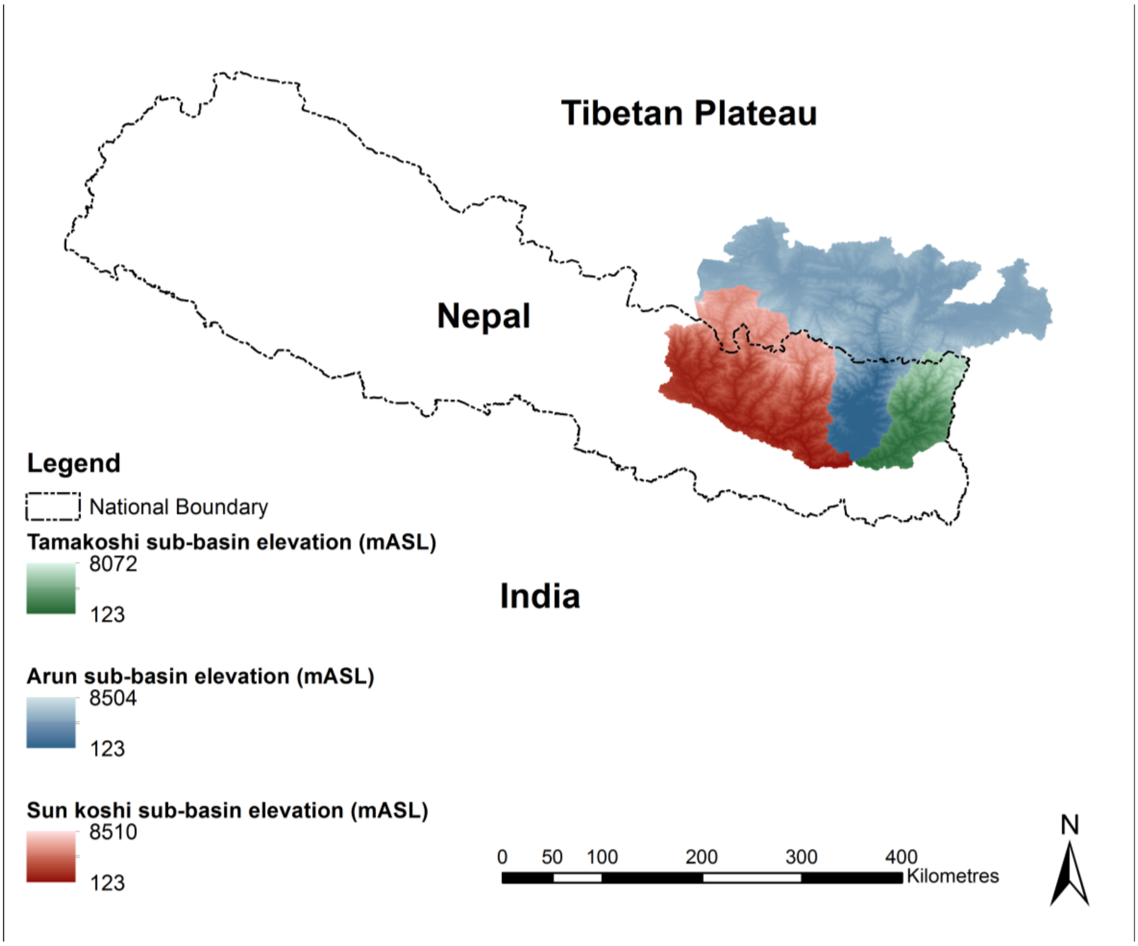

Figure 5.2 Location and elevation of the three sub-basins comprising the Koshi Basin modelled for this study, extending beyond Nepal's national boundary and flowing generally south towards its confluence with the Ganges within India.

This case study application was informed by stakeholder engagement events held in Kathmandu in September 2014. Stakeholders present included NEA, WECS, Department of Electricity Development (DOED), Department of Hydrology and Meteorology, Investment Board Nepal, Ministry of Agriculture Development. It was also informed by stakeholder engagement work undertaken by the author reported in Hurford et al., 2014. These processes helped to define the key performance issues for consideration through performance metrics in the system model and the uncertainties to be addressed.

5.3 A four-phased approach to efficient and robust decision-making

This section introduces the four-phased approach being demonstrated and its

Table 5.1 Stakeholders in the Koshi Basin water resources system

Stakeholder	Interests
Nepal Electricity Authority (NEA)	The basin has substantial undeveloped hydropower potential, which could help to address the national shortfall in dry season electricity. NEA is responsible for awarding concessions for hydropower development and purchasing the power generated
Water and Energy Commission Secretariat (WECS)	The primary responsibility of WECS is to assist the Government of Nepal's different ministries relating to Water Resources and other related agencies in the formulation of policies and planning of projects in the water and energy resources sector (WECS, 2016)
Municipalities within the basin	Abstraction of water from the river for piped supply
Irrigators within the basin	Abstraction of water from the river for piped supply
District Water Resources Committee	Licensing uses of water to which people are not entitled through the Water Resources Act (1992), maintaining environmental flows.
Hydropower developers	Private entities wanting to develop projects on the river to generate hydroelectricity

application to this case study. The methodology draws on developments reported in the previous two chapters to construct a more advanced approach which also considers a range of uncertainties.

The performance of hydropower assets is primarily dependent on environmental factors (river flows, water management rules, upstream and downstream water use, etc.), so this system scale analysis applies an integrated water resource management approach. A river basin simulation model is used to evaluate the performance of the system given various conditions and decisions. The simulation model tracks flows and storages throughout the river network over time and outputs performance metrics, providing decision-relevant information about the system's performance to the user at the end of a simulation. To address the multi-criteria (conflicting stakeholder objectives) and uncertainty-related aspects of the hydropower investment problem, a four-phased approach:

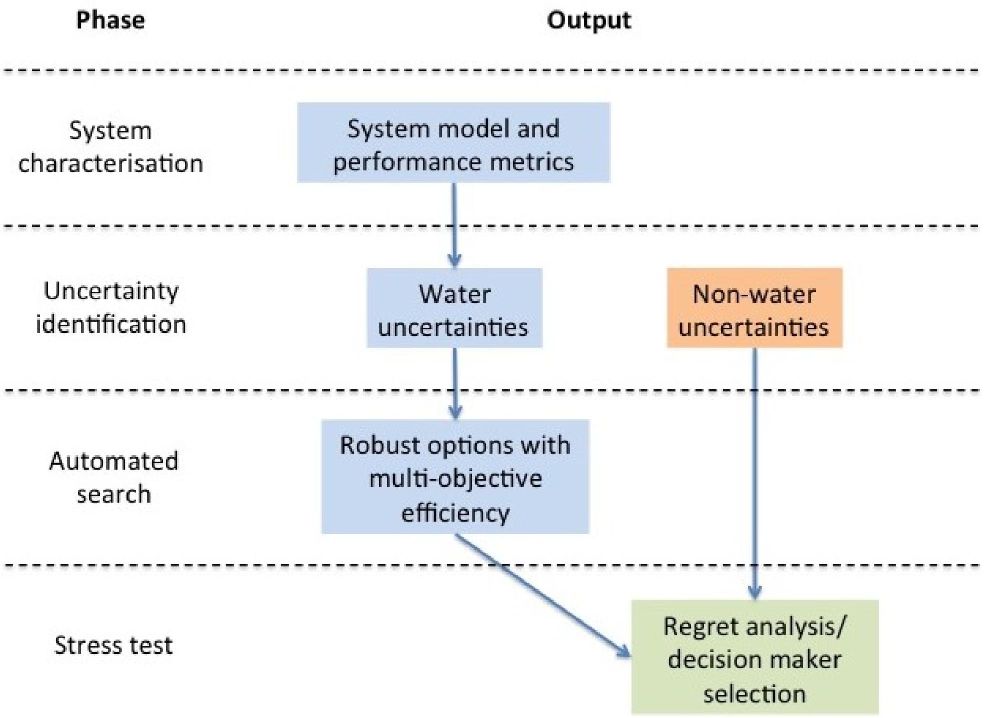

Figure 5.3 Four-phased approach to efficient and robust decision making

5.3.1 Phase 1 – System characterisation

5.3.1.1 Summary

Over an extended period, stakeholders from relevant organisations collaborate to develop a system simulator, including: 1) the system's most salient features, including non-linearities in system function and 2) agreed metrics of system performance most relevant to evaluating the success of proposed interventions (portfolios of assets and their operations). Metrics can be iteratively refined using a water resource system simulator as information provided by the analysis raises new questions about the system's function. Stakeholders must agree that the resulting simulator provides a sufficiently accurate assessment of impacts, and constitutes an agreed and trusted evaluation tool.

5.3.1.2 Application

An IRAS-2010 (Matrosov et al., 2011) Koshi River basin model was refined in consultation with stakeholders, based on topology, abstraction demand and flow data included in SWAT and WEAP models developed by Bharati et al. (2014). Table 5.2 summarises the features of the model and input data sources.

Table 5.2 Summary of model features and data inputs

Modelling software	**IRAS-2010**
No. of system model nodes	105
No. of system model links	112
Inflows	5 x 30-year inflow series based on different percentage change perturbations of the baseline flow series of Bharati et al. (2014)
Transmission losses	Assume none
Return flows	Assume none
Reservoir evaporation	Monthly mean daily evaporation assuming potential evapotranspiration (PET) from Lambert and Chitrakar (1989)
Reservoir rating curves (storage-elevation)	From JICA (1985)
River evaporation	Assume none
Model time-step	30 days
Flow routing	No routing - assumes all flows reach storage or exit system within 30 day time-step
Water demands	From Bharati et al. (2014)

The model includes abstraction demands, sub-catchment inflows and hydropower dams, existing and proposed (Figure 5.4). **Error! Reference source not found.** shows the generating capacities of existing schemes and capacity plus other characteristics of five of the most favoured of those proposed, included as options in the model. The dams are most favoured according to interaction with stakeholders and in the case of the storage-type dams according to NEA & JICA (2014). Where a storage dam is included, its operating rules are represented by a piece-wise linear storage-dependent release curve (Figure 5.5). Interpolation between the 3 labelled points dictates dam release at each model time step. Points are moved in the directions indicated by arrows to vary operation. The search algorithm coupled to the model in Phase 3 finds the best set of point coordinates for each storage dam, guided by resulting system performance metric values. We assume fixed operating rules throughout a simulation.

The modelled storage volume of proposed storage dams follows NEA & JICA (2014). In the case of the Upper Arun run-of-river project (UAHP), five mutually exclusive generating capacity options are included. This leads to 9 individual dam options and 95 possible combinations thereof.

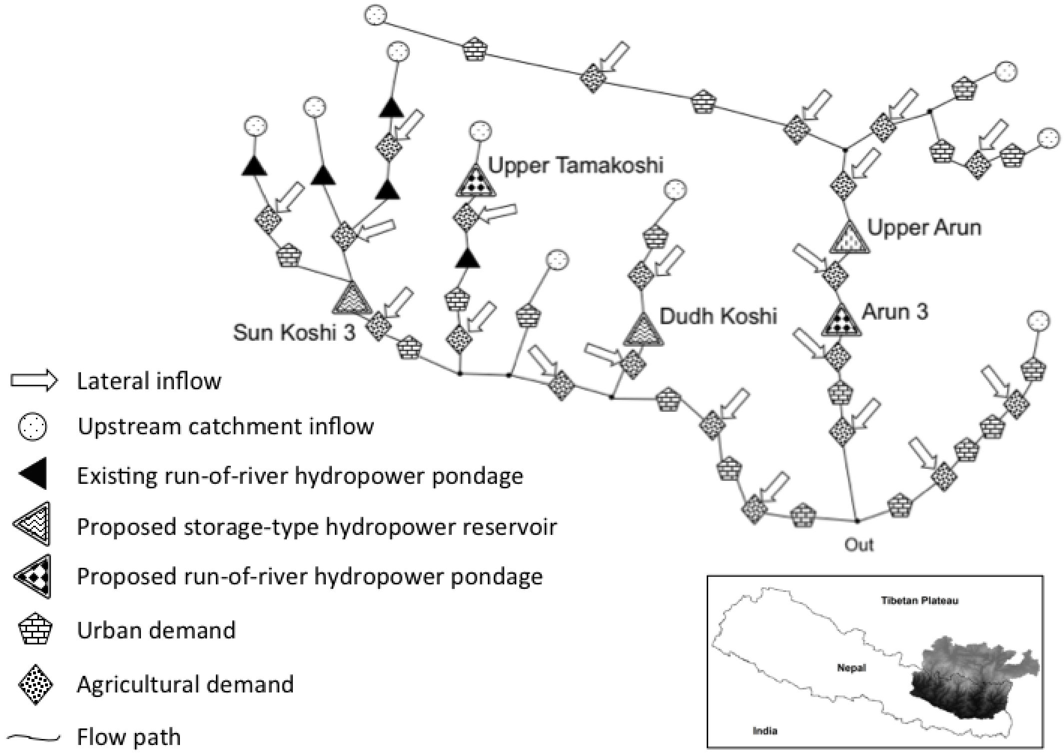

Figure 5.4 Schematic of the IRAS-2010 Koshi Basin model showing the 5 new hydropower dam locations being considered in this hydropower investment assessment. Existing dams are also displayed

Table 5.3 Existing and proposed hydropower projects included in the IRAS-2010 model

	Project name	Type of scheme	Generating capacity (MW)	Capital cost (US$M)
Existing	Sunkoshi HEP	Run-of-river	2.5	N/A
	Baramchi HEP	Run-of-river	4.2	N/A
	Indrawati III	Run-of-river	7.5	N/A
	Khimti	Run-of-river	60	N/A
	Bhote Koshi	Run-of-river	45	N/A
Proposed	Sun Koshi 3	Storage	536	1690.5
	Dudh Koshi	Storage	300	1144
	Upper Tamakoshi	Run-of-river	456	441
	Upper Arun	Run-of-river	335, 750, 1000, 1355 or 2000	446 – 2600 depending on gen. capacity
	Arun-3	Run-of-river	900	423.2

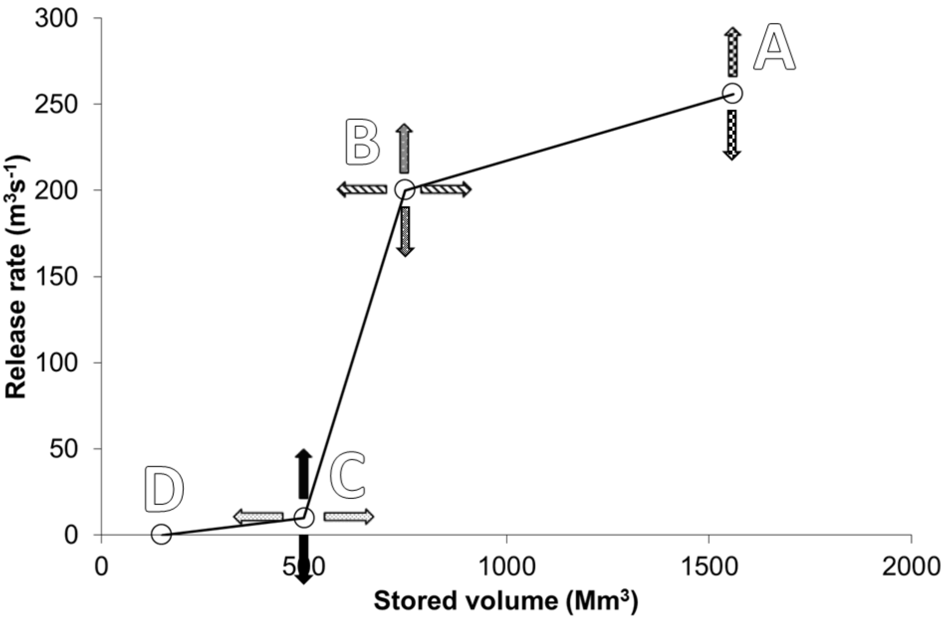

Figure 5.5 Example of a storage dependent release rule curve. Coordinates of the 3 labelled points control dam release at each model timestep. Arrows show directions of possible alteration. The search algorithm finds the best set of coordinates for each storage dam according to the resulting system performance metric values.

The following performance metrics were defined based on discussions with stakeholders in September 2014 in Nepal and issues identified by Hurford et al. (2014):

1) capital expenditure (capex) (US$M)
2) dry season electricity generation (Dec-April, GWh)
3) total annual electricity generation (GWh)
4) firm electricity generation (99.5% reliability)
5) urban water deficit (Mm^3/year)
6) irrigation deficit (Mm^3/year)
7) flood peak at the basin outlet (m^3/s)
8) number of environmental flow failures downstream of dams (occurrences)

Net present value (NPV) of investments was recognised as an important metric in selecting between them, but relies on a number of socio-economic factors not represented in the model. NPV was therefore addressed in Phase 4 analysis, accounting for discount rate, electricity price and asset lifetime, as well as total capex.

Associated with NPV, the maximum regret of implementing any investment is of interest to decision makers. Maximum regret, measured in terms of NPV, is a metric for the financial robustness of a portfolio. It represents the worst performance of a portfolio across a range of socio-economic scenarios, relative to the performance of the other portfolios for each given scenario. Lower maximum regret is more desirable. Because maximum regret evaluation requires cross-referencing all portfolio NPV performances this was also addressed under Phase 4 analysis. Regret is further defined in Appendix A.

This phase produced a basin model providing a sufficiently accurate assessment of the impacts of different interventions and additional metrics to consider by linking to socio-economic factors in Phase 4. The model completes a simulation of 30 years at monthly time step in less than a second. This facilitates the completion of hundreds of thousands of simulations each with different combinations of interventions in a reasonable timescale, to define those which perform best. High performance computing (HPC) clusters provide multiple processors to further reduce computation time.

5.3.2 Phase 2 – Uncertainty identification

5.3.2.1 Summary

Quantitative sensitivity analysis using a system model or qualitative stakeholder consultation aimed at identifying, describing and quantifying the relevant sources of uncertainty for system performance. If quantitative, this amounts to a multi-factor sensitivity analysis of the existing system and/or proposed plan under hundreds of combinations of future conditions, aimed at evaluating the system’s sensitivity to future stresses. The outputs are 1) a description of current or proposed assets’ vulnerabilities to certain future conditions or combinations of realizations of uncertain factors and 2) appropriate scenarios agreed with stakeholder for phases 3 and 4. As with performance metrics, scenarios may be defined iteratively based on the outputs of the approach.

5.3.2.2 Application

Preliminary assessment of uncertainties was completed through workshop exercises in September 2014 in Nepal and subsequent contacts with Nepal Electricity Authority (NEA) and other stakeholders. Uncertainties were assumed to relate to infrastructure in place in the 2050s on the basis that this would affect interventions implemented by 2020 with a 30-year expected lifetime. Sources of uncertainties considered significant in relation to water availability for hydropower generation were river flows, abstraction demands and environmental flow releases. Further socio-economic sources of uncertainty were construction cost, discount rate, plant lifetime and seasonal wholesale electricity price. Uncertainties and their bounds are detailed individually below. Quantitative analysis confirmed the sensitivity of generation to environmental flow releases while other uncertainty identification was done qualitatively through workshop facilitation and consultation.

5.3.2.2.1 Water availability

Water-related uncertainties were accounted for in the automated search in Phase 3. Each uncertainty is detailed below.

5.3.2.2.1.1 River flows

Hydropower generation depends on river discharge, which varies both seasonally and inter-annually. Climate change presents an additional layer of uncertainty. Model input climate change flow scenarios were generated in two stages: 1) a bottom-up analysis of temperature and precipitation change impacts on Arun River flows to the site of the proposed Upper Arun hydropower project (UAHP) dam was undertaken[1] as part of a broader research project (Figure 5.6, Bonzanigo et al., 2015), 2) five percentage change factors (-10, +7.5, +25, +42.5 and +60%) were drawn from the UAHP flow data, extending the range of changes implied by Coupled Model Intercomparison Project Phase 5 (CMIP5) global circulation model (GCM) outputs. These were then applied to baseline (1971-2000) flows from Bharati et al. (2014) for inflow locations across the basin.

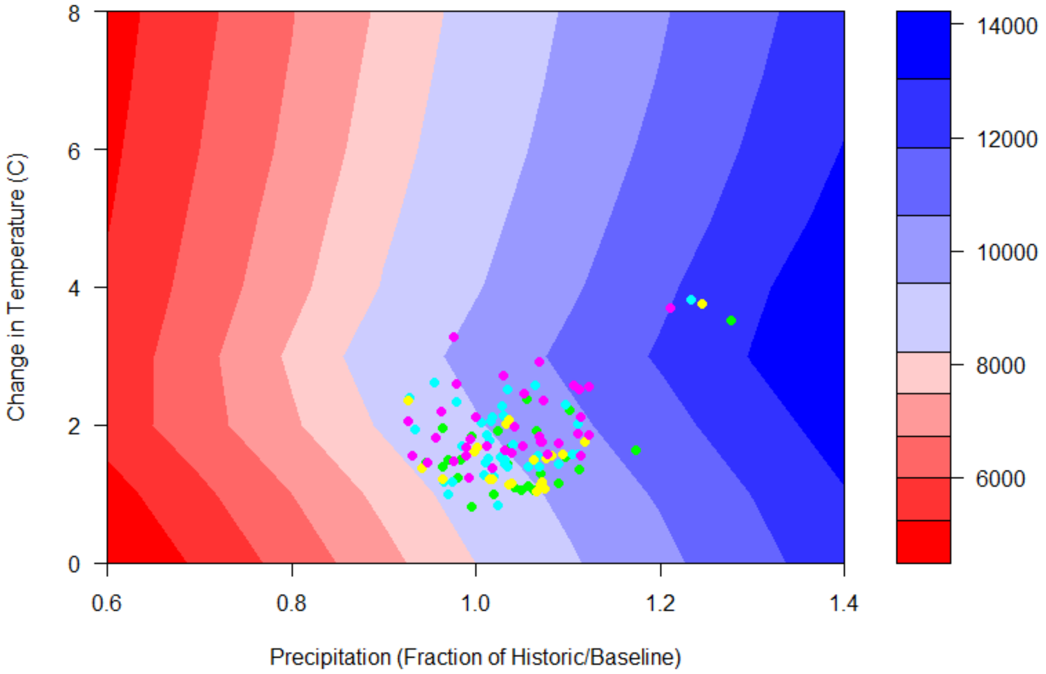

Figure 5.6 Total annual streamflow response surface (in millions of cubic metres) for the catchment upstream of the Upper Arun hydropower project (UAHP). Each coloured point

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[1] Temperature and precipitation inputs to a hydrological model of the upstream catchment, including glacier influences, were systematically varied to produce a response surface relating potential climatic changes to streamflows

is the streamflow response produced by the same hydrological model using a downscaled CMIP5 global circulation model (GCM) projection centred on 2050. (Source: University of Massachusetts)

5.3.2.2.1.2 *Abstraction demands*

Abstractions for agricultural and urban demands can both affect and be affected by hydropower dams depending on whether they take place upstream or downstream respectively. We use present day demands from Bharati et al. (2014) and also increase these by 50% in line with future population projections for Nepal by 2050 (IDS-Nepal et al., 2014). These two demand scenarios can be considered extremes of abstraction demand uncertainty. No behavioural changes were included – it was assumed that irrigators acted as they do now.

5.3.2.2.1.3 *Environmental flow releases*

Nepal’s Hydropower Development Policy (MoWR, 2001) states that environmental flow releases from dams should constitute the “higher of either ten per cent of the minimum monthly average discharge of the river/stream or the minimum required quantum as identified in the environmental impact assessment study report.” However, the feasibility study for the Upper Arun dam states that the expected level of generation takes no account of environmental flow releases and Hurford et al. (2014) report that environmental flow release requirements are not always adhered to, indicating there is a degree of uncertainty around the amount of water available for generation. A scheme designed for a certain level of flow without any requirement for an environmental flow release which is later subjected to such a requirement, will suffer from a reduction in generation and therefore revenue and profitability. We applied two scenarios representing release requirement (ten per cent of the minimum monthly average discharge), or no requirement.

5.3.2.2.2 Socio-economic uncertainties

Socio-economic uncertainties are considered in the Phase 4 stress test. Table 5.4 shows the bounding values for each uncertainty detailed below.

It should be noted that the uncertainty ranges defined are not an attempt to bound the plausible range of each variable as this is the type of limitation which can lead to protracted debate over what is plausible. The ranges are intended to extend into the implausible in order to capture any plausible conditions, even at the extremes of the plausibility range. The values’ ranges were informed by the literature and historical data, and from consultations with energy experts (Bonzanigo et al., 2015).

Table 5.4 Socio-economic uncertainty ranges utilized in this application's Phase 4 stress test.

Uncertainty	**min**	**max**
Wholesale price of electricity (US$/kWh)[a]		
Wet Season (May-Nov)	0.045	0.135
Dry Season (Dec-Apr)	0.084	0.252
Discount Rate	0.03	0.12
Estimated Lifetime of the Plant (years)	15	36
Capital Costs (2013 US$)	Expected (various)	*Expected x3*

5.3.2.2.2.1 Construction cost

Delays in the implementation of hydropower investments can lead to extreme increases in cost. Final capital costs for Nepal's Marshyangdi Dam were three-times higher than expected and considered particularly high, so experts in the Nepal hydropower sector suggested we consider a range of capital costs from a lower bound of the expected costs, to an upper bound of 300% of the expected costs.

5.3.2.2.2.2 Discount rate

The discount rate is a political choice and often highly-contested (Arrow et al., 2013). It shapes how we allocate resources between the present and the future (Gollier, 2011). A higher discount rate prioritises present needs, whereas a lower discount rate takes greater account of long-term effects of an investment. The World Bank typically uses discount rates of 10-12%, but no single rate is appropriate for all projects so stakeholders can struggle to reach a consensus (Hoekstra, 1985; Oxera, 2011). A high discount rate would reduce the importance of optimal plant maintenance as after 25 years, any income generated becomes almost zero after discounting. Consultations with NEA and World Bank experts suggested a range from 3 to 12% be tested to explore both longer-term considerations of sustainability and short-term objectives of significantly increasing grid electricity supply.

5.3.2.2.2.3 Plant lifetime

The lifetime range takes accounts of the potential for varying levels of maintenance or poor management leading to damage from heavy sediment loads in rivers. With good sediment management a plant's lifetime may increase but conversely, poor management could decrease it significantly. The possibility of seismic events leading to irreparable damage or failure is also accounted for in this uncertainty variable.

5.3.2.2.2.4 Seasonal wholesale electricity price

The electricity price currently varies between the wet and dry seasons by a factor of 2, necessitating that price uncertainties be considered at a seasonal resolution. The price may vary further if the Nepal were to begin exporting electricity to India, under which conditions local experts believe it could increase significantly, perhaps up to 0.15 US$/kWh (Bonzanigo et al., 2015).

5.3.3 Phase 3 – Automated search

5.3.3.1 Summary

When multiple definitions of success co-exist in real-world engineered systems, there is no single best solution to a portfolio investment problem. Rather, there are multiple trade-offs available whereby the degree to which each objective is achieved impacts on the achievement of all the objectives with which it conflicts. In this case decision makers need to select a balance between the benefits perceived by different stakeholders. Phase 3 couples a many-objective search algorithm to the stakeholder-approved system simulation model (output from Phase 1) to automatically search for interventions. The output of the many-objective search is not a single optimal solution, but a set of options which perform Pareto-approximately, i.e. those for which any further improvement towards one objective (benefit) would require deterioration in at least one other objective. The range of futures across which a portfolio maintains efficient performance indicates its robustness. With the system simulator and metrics of performance agreed upon, the set of best intervention options will be of interest to stakeholders who then select one or more alternatives to be stress tested in the final phase.

5.3.3.2 Application

In the Koshi Basin there are a large number of possible combinations of assets built and operations ($>10^{20}$) but the efficient search algorithm requires only a relatively small number of trials using the fast-running system model on a high performance computing cluster (e.g. 2 million trials in 24 hours) to converge on the best options. The search algorithm used here was the Epsilon Dominance Nondominated Sorted Genetic Algorithm-II (ε-NSGAII) (Kollat and Reed, 2006) as in the previous two applications. The algorithm was parameterized according to recommendations of Kasprzyk et al. (2009).

This section describes the problem formulation for the search process, the decision variables i.e. options/levers for acting to change the system's performance and the uncertainty cases used to assess robustness of portfolios.

5.3.3.2.1 Problem formulation

Based on literature review and stakeholder consultation, the optimization problem was formulated as follows: given conflicts between some of the following objectives, what combinations of assets and operating rules best:

- minimize urban water supply deficits,
- minimize capital costs,
- minimize agricultural water supply deficit,
- minimize maximum flood peak at the basin outlet,
- maximize dry season electricity generation,
- maximize total annual electricity generation,
- maximize firm electricity generation, and
- minimize environmental flow failures downstream of dams

5.3.3.2.2 Decision Variables

In total there were 31 decision variables in the Koshi Basin model:

- Build/no build of each of 9 proposed dam options for which sufficient information was available for modelling (**Error! Reference source not found.**).
- Five storage dependent release rule co-ordinates, for each of two seasons and each of two storage dams (Figure 5.4).
- Two dates controlling timing of two storage dam release rule seasons.

Although not considered here, the approach could identify the best storage capacity behind dams or other design characteristics as additional components of each Pareto-optimal portfolio.

A random seed trial was carried out as in previous applications to ensure the results were not sensitive to initial conditions used to generate decision variables within the search algorithm.

5.3.3.2.3 Water availability scenario groupings

To facilitate the assessment and interpretation of investment portfolio robustness, three scenario groupings were searched (Table 5.5). There are five river flow scenarios, 2 environmental flow release scenarios and 2 abstraction demand scenarios from which 20 unique combinations can be created. The 'best case' grouping includes scenarios which are most favourable to hydropower generation owing to greater availability of water resources (assuming environmental flow releases wouldn't be required and abstraction by consumptive uses would not increase). The best case search found those portfolios of new hydropower dams which were best able to capitalize on such futures. The ‘worst case’ search identified portfolios that did best under less favourable conditions for hydropower generation (environmental releases were required and abstractions increase). The average case search was for portfolios that perform best on average, across all scenarios.

Table 5.5 Three scenario groupings used in the search process and the circumstances under which performance for all metrics is evaluated

Uncertainties	Best case	Average case	Worst case
5 Flows (-10% to +60%	X	X	X
No Environmental flow	X	X	
Environmental flow release		X	X
No abstraction demand	X	X	
Abstraction demand		X	X

For each scenario grouping a different optimization problem was solved to identify promising portfolios of assets under expected, favourable or worst case conditions.

5.3.3.2.4 Screening for robustness

Portfolios were classed as robust if they performed efficiently in all three scenario groupings. In case no interventions performed efficiently across the full range of water availability scenarios, other robustness criteria would need to be informed by consultation with stakeholders, analysis of the scenarios to which portfolio performance was vulnerable and assessment of the probabilities of problematic water availability scenarios manifesting.

5.3.4 Phase 4 – Stress Testing

5.3.4.1 Summary

The performance and vulnerabilities of interventions from Phase 3 are tested under a wider uncertainty analysis inspired by Lempert et al.’s (2003) ‘Robust Decision Making’. Multiple combinations of socio-economic uncertainties are statistically generated and applied as inputs to calculate net present value (NPV) and quantify the maximum regret (in terms of NPV) associated with each intervention. Interventions of potential interest to decision makers are then analysed using a scenario discovery method for the conditions which caused their performance to meet or fail a specified performance threshold. Failure scenarios are compared with available evidence to determine if they are sufficiently plausible to hedge against. If they are, other portfolios need to considered and compared (Lempert, 2013). Otherwise the selection of an efficient and robust hydropower investment portfolio is complete.

5.3.4.2 Application

Uncertainty ranges shown in Table 5.4 were sampled using Latin Hypercube Sampling to statistically generate 150 futures covering the uncertainty space efficiently (Saltelli et al, 2000). Probabilities were not assigned to values within each range - the ranges were sampled to explore and identify vulnerabilities.

The NPV and maximum regret were calculated for each efficient and robust intervention identified in Phase 3. This helped identify promising interventions for vulnerability identification. A scenario discovery method called Patient Rule Induction Method (PRIM) (Friedman & Fisher, 1998) was used to identify potential failure scenarios.

5.4 Results of Phase 3 and Phase 4

5.4.1 Phase 3 – Automated search

5.4.1.1 Search for options with multi-objective efficiency

Increasing dry season electricity generation is Nepal’s most pertinent challenge, so the first objective analysed. Figure 5.7 shows the Pareto-approximate (i.e. most efficient) options for increasing dry season energy generation by building new portfolios of dams under the three scenario groupings. These represent least cost options for increasing supply of dry season electricity generation under different scenarios, the aim of traditional hydropower infrastructure selection. Each point represents a portfolio of dams and their operating rules and is colour coded for the generating capacity of the Upper Arun Hydropower Project (UAHP) as a simple indication of differences in portfolio composition. Options requiring equal capital expenditure comprise identical assets as each has a unique estimated construction cost. Water availability, represented by the scenario groupings, impacts on the generating potential of the basin. Portfolios which provide the best average performance across the 20 water availability scenarios (average case) (Table 5.5) do not necessarily perform most efficiently under extreme conditions, i.e. they may not appear in the Pareto-approximate set of results under the best and worst cases. Dry season generation correlates with firm energy and total annual energy generation, so these results represent capital expenditure for energy generation more broadly.

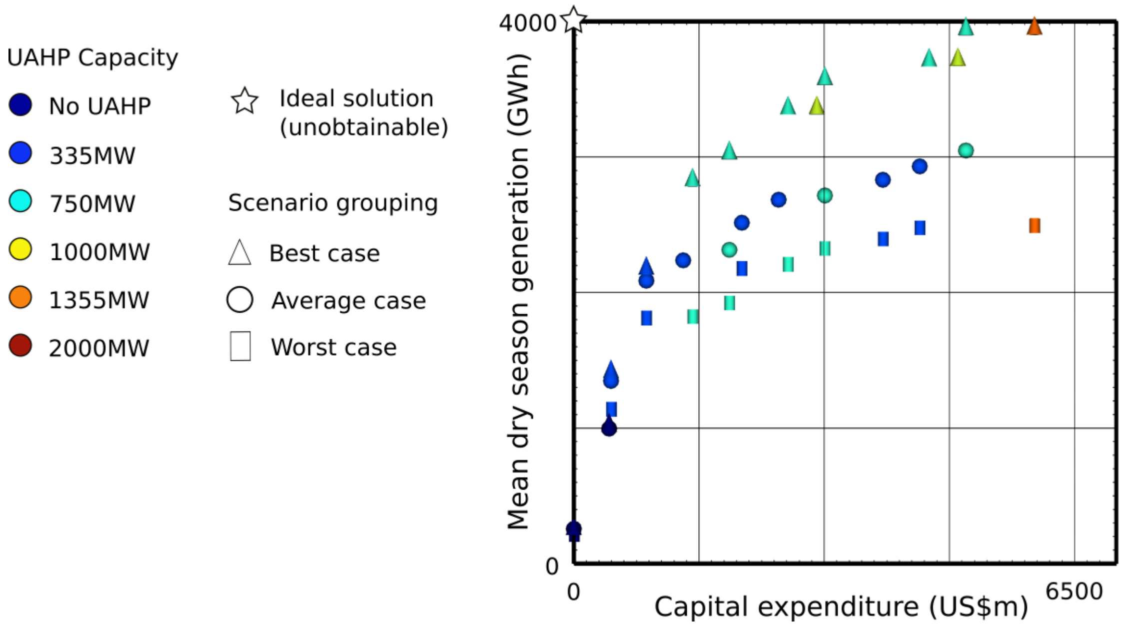

Figure 5.7 Efficient options for increasing dry season electricity supply under three scenario groupings. Each point is colour-coded for the UAHP option it includes, as an indication of the variations in portfolio compositions.

Sets of Pareto-approximate options are generated by the search process between all eight of the performance metrics defined for the system. Least-cost based planning would focus on the three energy generation metrics and seek an option which appears good financial value for increasing supply of electricity, accounting for the options available in other river basins (not assessed here) and assuming power generated outside the dry season is saleable.

5.4.1.2 Filtering for Robustness

Following the efficiency analysis above we considered robust options for least-cost generation capacity expansion to constitute those portfolios which are least-cost for all generation metrics (dry season, annual and firm) under all three scenario groupings. However, in selecting from these portfolios decision makers may be interested to know more about how each option would affect other stakeholder interests in the basin, e.g. environmental flows. Figure 5.8a shows how the robust options for least cost capacity expansion would impact on environmental flow failures on average across the 20 scenarios. By contrast Figure 5.8b shows the performance of robust portfolios which are identified evaluating efficiency for all objectives, rather than only those relating to energy generation. Figure 5.8b presents an increased range and variety of options which trade-off some of the energy generation performance from Figure 5.8a to increase other benefits from the system, such as maintaining environmental flows.

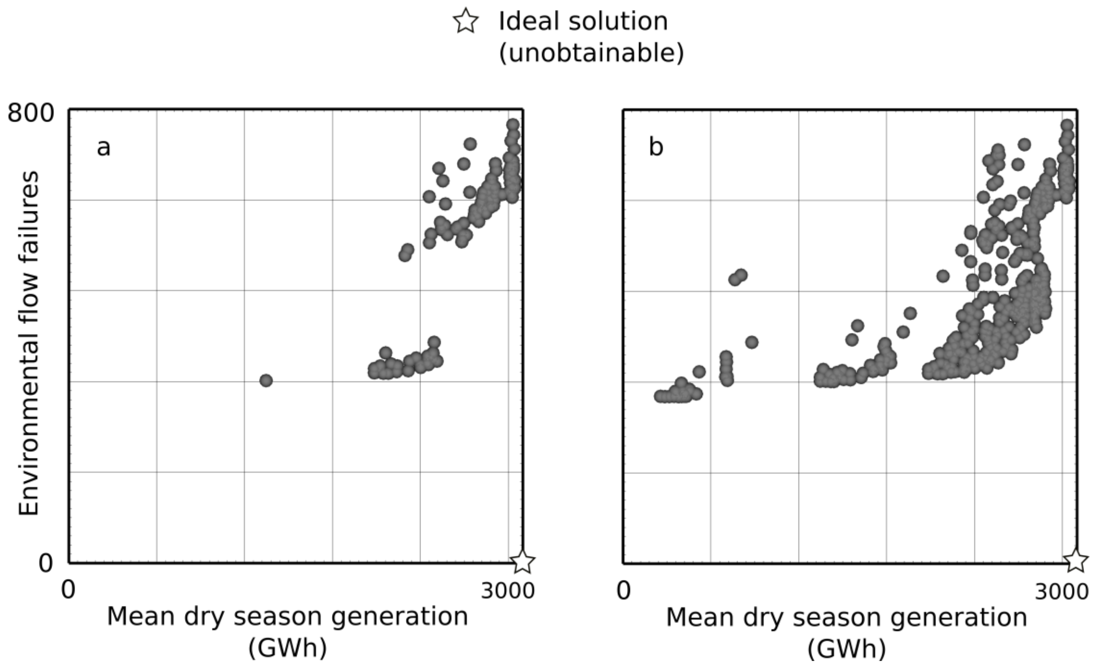

Figure 5.8 Robust and efficient portfolio performances for a) energy generation and capital investment only, b) all eight objectives

Presented with the range of options for infrastructure development and operation in Figure 5.8b, decision makers may wish to understand more about the portfolios employed. Figure 5.9a classifies these portfolios by composition type, focussing on the balance between run-of-river (ROR) and storage type dams. Use of storage type dams increases the range and variety of performance available, with two storage dams (green points) maximising these benefits.

5.4.2 Phase 4 – Stress test

The maximum regret associated with each of the efficient and robust interventions identified in Phase 3 is shown in Figure 5.9b & c. The maximum regret associated with the current situation (i.e. no further development) is high, indicating that an opportunity exists to generate returns on investment. Some interventions utilising only storage dams have higher maximum regret than the ‘do nothing’ option, making them unattractive. The class of interventions which include both storage dams combined with ROR dams has greatest operational flexibility. However, the lowest maximum regret achievable with this class of investment is twice as large as the lowest overall maximum regret option.

To illustrate the scenario discovery analysis the lowest maximum regret portfolio was selected as it also provides a good balance between dry season generation and environmental flows. It lies on the lower gradient part of the trade-off curve between the latter two metrics. It comprises Dudh Koshi storage dam and the Upper Arun (335MW)

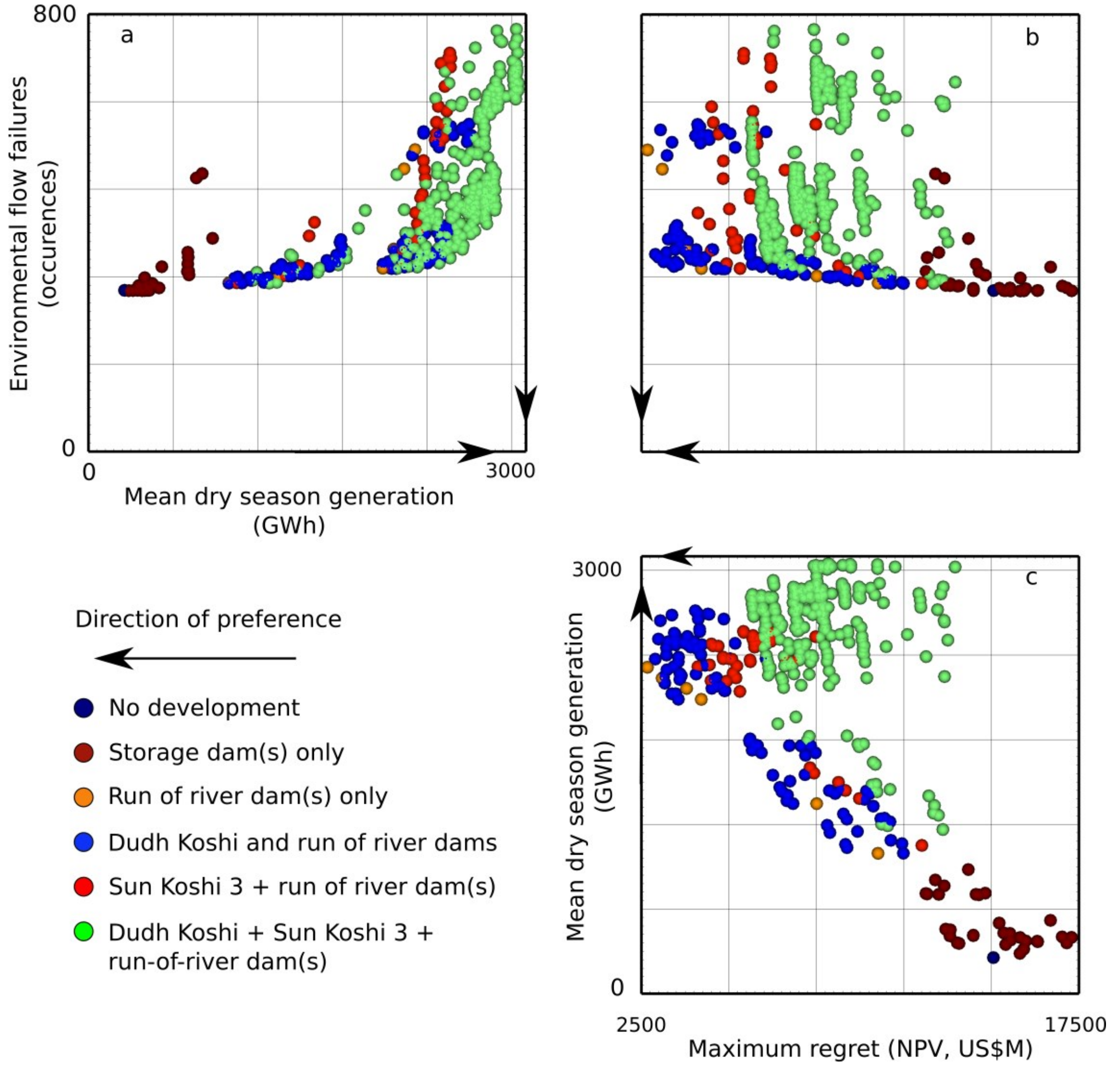

Figure 5.9 a) Robust and efficient interventions for all eight objectives, plotted for performance in environmental flow and dry season generation. Infrastructure portfolio composition is classified to illustrate how composition affects operational flexibility, b) & c) maximum regret associated with each intervention in terms of NPV (according to the Phase 4 stress test), and its relationship with environmental flow (b) and dry season generation performance (c). Direction of preference is shown in place of the ideal solution as maximum regret was not minimized by many-objective search.

and Arun-3 ROR dams. Four ways of operating this portfolio, to favour different benefits, were analysed for their vulnerabilities (Figure 5.10). The performance threshold for defining success or failure was defined as zero NPV.

Figure 5.11 illustrates the performance of Intervention A, for two of the main uncertainties: capex increase and electricity price increase. Scenario discovery analysis revealed that three conditions together (with different critical thresholds) describe scenarios in which the five portfolios' NPV is negative (Table 5.6). For instance, for Intervention A the three conditions and thresholds identified are a statistically strong predictor of when its NPV would be negative. Of the 19 futures with these conditions, the NPV is negative in 18 (i.e. density = 95%). However, it is not a complete predictor: this condition only exists in 18 of the total 27 futures (i.e. coverage=67%) in which the portfolio is not profitable. Further scenario discovery analysis, beyond the scope of this demonstration, would reveal additional sets of conditions that explain the remaining 33%, which policy makers could weigh against additional evidence. Nevertheless, this single condition offers useful information for a policy dialogue on the potential vulnerabilities of Intervention A or its asset portfolio. Assumptions about the discount rate and the plant load factor are less important predictors for determining whether the portfolios are economically sound. Table 5.6 reports coverage and density for each intervention.

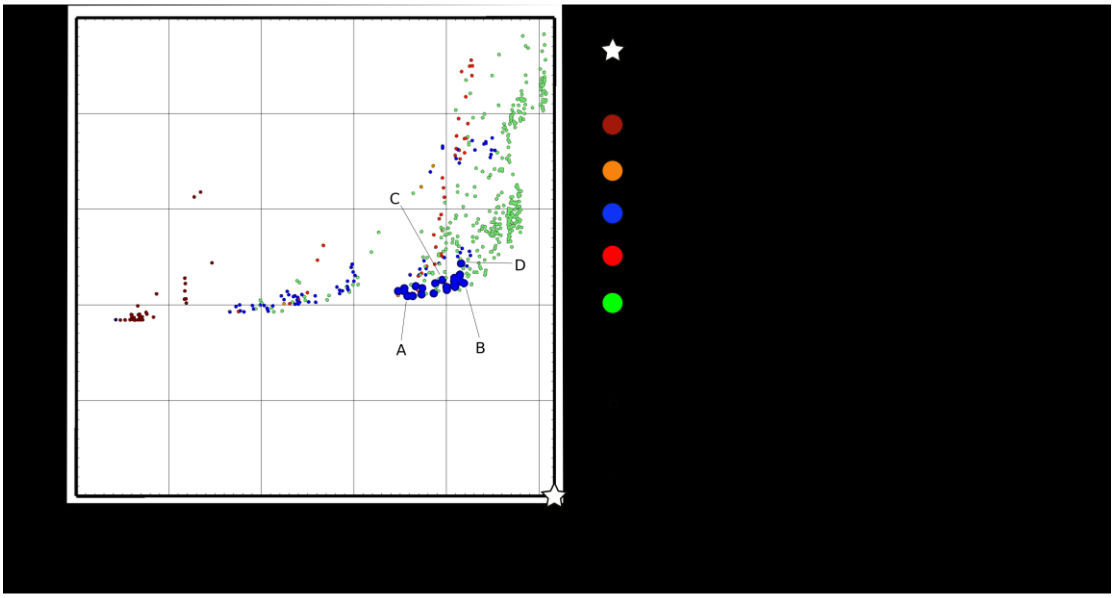

Figure 5.10 The selected low regret portfolio of assets and four ways of operating it (labelled A-D) to maximise different benefits available from it. A minimises environmental flow failures and water supply deficits, B maximises dry season generation, C maximises annual generation and minimises downstream flooding, and D maximises firm energy. The four labelled interventions were analysed for their vulnerabilities for return on the investment, i.e. conditions which could cause negative NPV.

The co-occurrence of these conditions causes the project to have a negative NPV. Although probabilities are difficult to assign, these conditions would generally be considered not likely based on the available evidence. Figure 5.12 summarises the two main uncertainty thresholds and some evidence relating to their plausibility. Intuitively, if capex increased more than average, only a much higher electricity price than the current one could justify the investments. This price increase could potentially be achieved by signing an agreement with India to export electricity in the wet season (when Nepal already has excess), which the two Governments have been negotiating for years.

Note also intervention options A-D are different operations for the same portfolio of assets. This explains the similar vulnerability thresholds. However, it also shows that changing operational rules impacts on robustness to poor economic performance. Scenario discovery quantifies the potential range of vulnerabilities of the investment.

Table 5.6 Combined scenario values to which selected interventions are vulnerable

Intervention	Capital expenditure increases more than	Wet season electricity price less than ($/kWh)	Lifetime (months) less than	PRIM Box Description (Coverage/Density)
A	61%	0.087	300	67%/95%
B	36%	0.088	300	65%/85%
C	36%	0.088	300	65%85%
D	36%	0.088	300	72%/87%

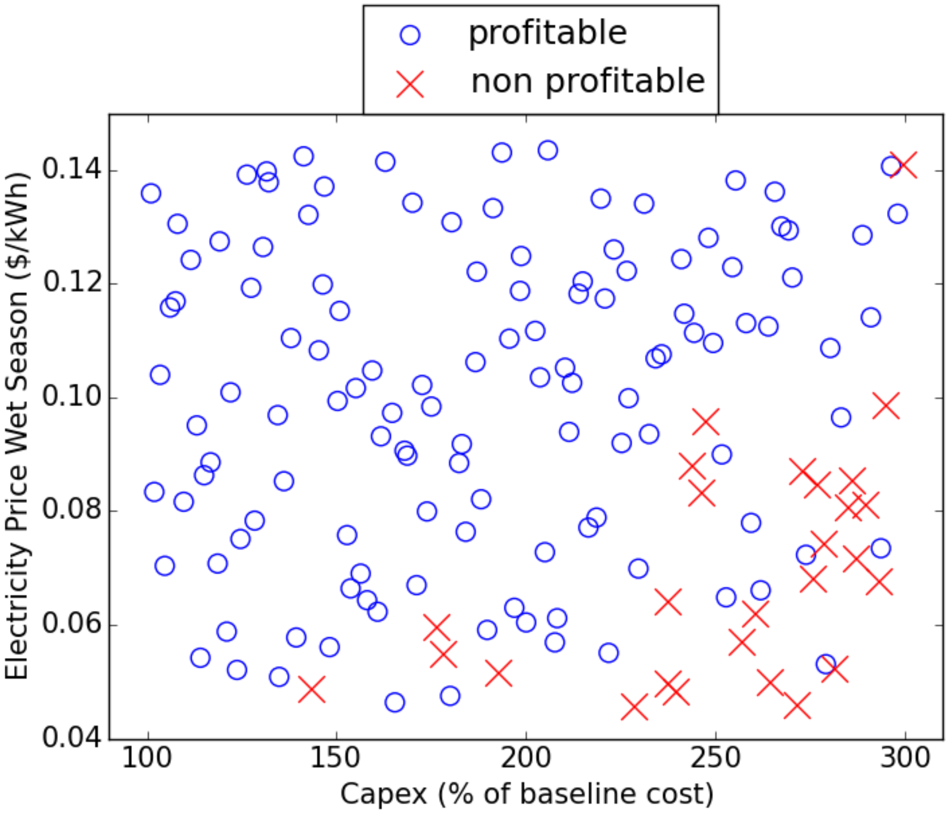

Figure 5.11 Performance of Intervention A across the 150 scenarios plotted for capex increase and wet season electricity price change

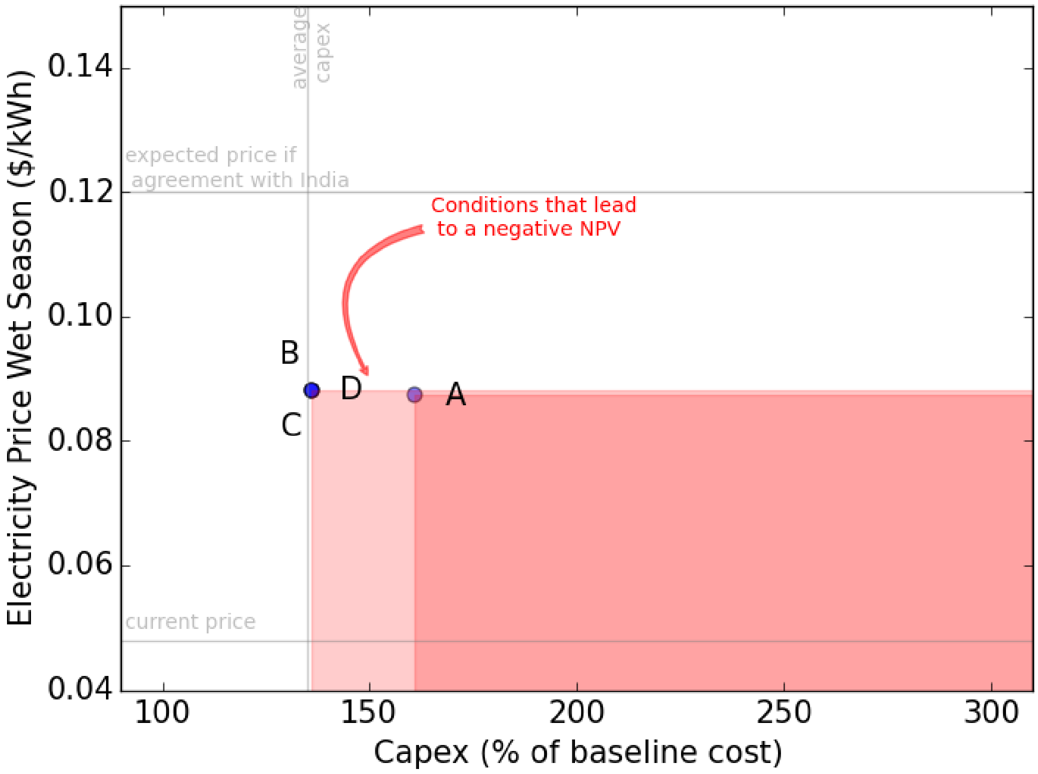

Figure 5.12 Vulnerability thresholds for each of the four interventions, against available evidence

5.5 Discussion of the application

This third application has demonstrated that many-objective trade-off analysis can also provide information to support the identification of water infrastructure portfolios which are robust to future uncertainties. Infrastructure portfolio selection is the primary factor influencing system robustness as operating rules can be altered according to prevailing conditions or preferences. Portfolios of assets, which perform efficiently and robustly do so with varying degrees of operational flexibility. Storage dams are necessary for any flexibility in portfolio operation to be demonstrated in this study as ROR dams have no flexibility at the model time step. Resolution would need to be hourly for operational differences of ROR dams to impact on performance. At the monthly time step applied here no interaction occurs between dams in series, although there is potential for Upper Arun and Arun-3 dams to impact each other's generation at their operational timescales. Water retained behind the Upper Arun dam for generation at peak load times of day may not be able support generation at Arun-3 during the same peak load times owing to flow times between dams and hydraulic head requirements. Hourly resolution modelling could better account for this interaction to ensure the performance of these dams in series is maximised. Addressing this type of issue is one aim of cumulative impact assessments and strategic planning exercises which are beginning to be undertaken (e.g. ICFRE, 2014).

Operational ranges should be accounted for in asset selection to understand options for asset substitution while achieving similar performance, i.e. to identify Pareto-approximate options. Portfolios offering a wider variety of Pareto-approximate performance, may be attractive to decision makers owing to their greater flexibility to adapt to changing preferences or needs. In the case study presented here however, increasing flexibility also increases the range of maximum regret as revenue depends on power generation alone and costs are greater with more storage dams. Maximum regret must be balanced with other considerations in decision-making.

Using NPV as the sole indicator of returns on investment favours revenue earning generation (i.e., power generation) over all other metrics. Environmental and flood control benefits, which could also be considered returns on an investment, do not figure in NPV calculations. Their prioritisation increases maximum regret as less revenue is generated to balance capital expenditure. If the maximum generation from a portfolio traded off heavily in favour of other benefits, then alternative portfolios with lower capex may help reduce maximum regret. Trade-off analysis could indicate the opportunity cost to hydropower generation of maintaining environmental flows or vice versa. Equally, trade-offs between all objectives in the system could be useful in informing compensation arrangements where a particular balance of water-related benefits is preferred. Co-benefits (i.e. multiple uses) which could be associated with storage dams, such as irrigation schemes were not modelled here, but could add significant co-benefits to such schemes thereby increasing their NPV and decreasing maximum regret.

Fixed operating rules were used throughout the simulation and moving towards changes in operation within a simulation could utilise a dynamic adaptive pathways (Haasnoot et al., 2013) type approach. This presents technical challenges in terms of coding dynamic operating rules and recording all changes as part of a strategy, which is left to future work. Similarly, the application here at the river basin scale necessarily neglects investment options located outside the basin. Future work will seek to expand the scope of the analysis to ‘natural’ scales for each of the systems involved. For electricity this will be the national grid system requiring representation of a much wider range of hydropower dam options and potentially alternative energy sources such as solar and wind. Such a system scale analysis better facilitates a dynamic adaptive pathways approach as supply-demand imbalance triggers for action are not relevant at smaller scale.

Twenty water availability scenarios were used in this case study, but more complex and extensive arrays of possible conditions could be used, informed by plausible ranges of uncertainties. This would increase the computational burden of the analysis. Although not applied in this case, seasonal variations in flow could be represented within water availability scenarios to explore this aspect of robustness. The scenario discovery analysis here was also based on the average scenario grouping results for simplicity, but could be expanded to the results from each of the 20 scenarios.

Increased computing resources would allow socio-economic scenarios to be included as uncertainties in Phase 3 rather than Phase 4. At present the combinatorial effect is too great, making the problem intractable in reasonable timescales with available resources. Maximum regret could also be minimised as an automated search objective, although this would increase the complexity of the problem and is left to future work. Searching for different statistical properties related to the same benefits could potentially decrease the number of benefits which can be considered simultaneously owing to the practical limit of 10 objectives to which MOEAs are currently bound (Reed et al., 2013). It may be better in some cases to maximise the minimum benefit among a group of stakeholders than aggregating their benefits by averaging.

In terms of the current institutional and stakeholder setting in Nepal, there is a clear case for NEA and DOED to use the information provided by this type of analysis to inform their prioritisation of hydropower infrastructure development and the concessions which are granted. It is unclear to the author what role the District Water Resources Committees play in decision-making about hydropower development site selection, but there may be a need to bring them into the process of system model and metric development to help inform national level decisions. The World Bank is currently funding a project to be managed by WECS in Nepal focussed on river basin planning and hydropower master planning – this type of project could utilise analysis similar to that presented here to support a coherent and balanced plan for increasing electricity generation in the context of maintaining broader benefits from Nepal’s rivers.

6 Discussion and conclusions

6.1 Summary

Various political pressures described in the literature review are driving a change in the way water infrastructure is selected and operated in developing countries. There is growing recognition of the need to implement the principles of sustainable development to maintain ecosystem services which underpin local and national economies. Climate change has opened up the discourse to the uncertainty it brings and the wider related and unrelated uncertainties which were not previously afforded sufficient consideration. The increasing focus on interactions between the activities of different sectors (i.e. water, energy and food) in system scale analyses, involving a broad range of stakeholders with different knowledge, perspectives and preferences requires a new type of analysis to which traditional tools are poorly suited (Lempert, 2002; Hall et al., 2012; Lempert and Collins, 2007).

This thesis investigated the potential for cutting edge analytical approaches to provide a foundation for balancing benefits of infrastructure investment and operation between stakeholders in developing country river basins in the context of uncertainty. Many-objective trade-off analysis was then identified as the most promising approach for application. The first objective was to apply this technology to a developing country basin with a relatively simple decision-making problem about how the existing dams could be re-operated to alter the balance of benefits received by different stakeholders. This involved developing a model of the river basin and benefit functions to evaluate performance metrics which represented the interests of a range of stakeholders. The approach was able to reveal diverse trade-offs between stakeholder interests in the basin which could better inform the existing stakeholder consultation process which currently relies on a limited set of modelled release options. Many-objective trade-offs analysis provides much greater resolution of choice and extensive information about the impacts of each option on each stakeholder group. It was necessary to understand how these benefit functions affect the trade-offs and the appropriate scale at which to assess benefits. This work was reported in Chapter 3.

In Chapter 4 many-objective trade-off analysis was applied to a more complex decision-making problem involving the selection and sizing of large new irrigation schemes with potential impacts on a wide range of other water users, in additiona to re-operation of existing dams. This again required the development of a context-specific model and benefit functions to represent different interests. Rich information was produced by the visual analysis to support infrastructure investment decision-making which could be further expanded with better access to stakeholders and data.

Chapter 5 built on the work reported in Chapters 3 and 4. A four-phased approach was developed drawing on bottom-up climate analysis and Robust Decision Making approaches to take account of a range of water-related and socio-economic uncertainties. This was demonstrated in collaboration with Nepalese stakeholders, illustrating its potential for application in other contexts. A greater and more robust range of options were provided to decision-makers than would have been provided by conventional least cost planning for hydropower development, including information about climate robustness and the socio-economic risks to achieving a financial return on selected investments.

6.2 Benefits and limitations of the approach applied

6.2.1 Benefits

One of the major benefits of many-objective trade-off analysis is that it provides decision makers with a practical and objective method of considering multiple criteria and quantifying impacts on disparate stakeholders in water resources infrastructure decision-making. Decision makers are coming under increasing pressure to do this without an established method in place (Bonzanigo et al., 2015). Similarly they are coming under pressure to consider how their decisions might be affected by a broad range of uncertainties. This thesis has applied an approach using many-objective trade-off analysis and visual analysis to identify sets of decisions which display both multi-objective efficiency (i.e. approximate Pareto-optimality) and robustness to uncertain future conditions. Conventional cost benefit analysis aims to ensure efficient use of capital, but does not disaggregate the impacts on different groups or represent the different values different groups assign to the same monetary quantity. The approach applied here could be considered an advanced or enhanced form of cost benefit analysis because it facilitates this disaggregation while also allowing non-commensurate measures of performance to be considered simultaneously. This helps represent the non-market ecosystem services on which the most vulnerable people often rely in developing countries and avoids often controversial, costly and time-consuming valuation exercises. Many-objective trade-off analysis could be carried out with benefit functions elicited from experts or stakeholders initially (not intending to imply stakeholders can’t also be considered experts) and improved as better information becomes available, if this helps to expedite decision-making.

Considering 10 objectives in water infrastructure decision-making facilitates a much richer understanding of the interactions between stakeholder interests and the impacts of particular decisions. However, in real world decision-making contexts it is easy to identify more than 10 potential interests to represent. This is especially so when thinking about disaggregating benefits received by similar groups who are spatially distributed. Chapter 3 for example, showed trade-offs between the interests of fishers in reservoirs and near the coast, although these are likely to represent relatively similar social groups. Likewise where the agricultural deficit was disaggregated between different regions within the basin it was clear how easily disparities could be overlooked by the lumping of a benefit function in much the same way as traditional cost benefit analysis hides trade-offs through aggregation. It is necessary therefore to carefully apply the approach to ensure that benefit functions take into account the distribution of benefits as well as their aggregated magnitude. As discussed in Chapter 5, it may be better to develop a function which looks at or accounts in some way for the performance of the worst affected group rather than an aggregated total or an average.

In practice, a benefit function might evaluate an average across a group of interests, but apply an extreme penalty where the inequality is too great between them. This would avoid adding additional metrics to represent different aspects of the same concerns. Concurring with Reed and Kasprzyk (2009), this highlights the importance of problem formulation - providing a solution which in reality adversely affects a particular group only creates more unforeseen problems. Another option to remediate this problem is that benefit functions and performance metrics can be employed which do not steer the optimisation (i.e. are not objective functions), but are ‘monitored’ to facilitate analysis of how they’re affected. These types of performance metrics should be correlated with at least one of the objective functions however, to ensure that they are benefitted by some of the decision sets generated.

6.2.2 Limitations

This study faced a number of limitations, in many cases owing to the nature of work in developing countries and the scarcity of data. In all three applications it was not possible to obtain direct observation data of historical system performance. This made it difficult to calibrate the models to ensure that its representation of hydropower generation for example was realistic. It would have been preferable if the approach could have better compared historic with proposed performance as this could have more clearly highlighted win-wins, where gains are achieved without any party becoming worse off. It is anticipated that in real decision-making contexts data would be available to compare performance and indeed this has been confirmed by further work extending the application reported in Chapter 4 as part of the WISE-UP to Climate project (IUCN, 2016), engaging with a wide range of stakeholders.

Another limitation was the lack of information around environmental flow requirements meaning proxy measures were necessary. It would be more meaningful if threshold value were available relating variations in the flow regime to impacts on species richness or ecosystem service provision. Similarly, the costs of developing new irrigation schemes were not available to trade-off cost with other benefits in the Tana Basin application, nor was information about possible co-benefits in terms of employment for local people. Again, experience of extending the work reported in Chapter 4 with stakeholder in Kenya has shown the information to be available to improve representation of environmental flow requirements.

Problem formulation, i.e. the definition of the goals sought in the application of the multi-criteria search algorithm, is a critical and time-consuming component of the approach investigated in this thesis. Its importance for accurately and fairly representing stakeholder interests means it is best carried out in collaboration with stakeholder groups. Opportunities for stakeholder interaction were limited during the research reported here, but experience gained through the research presented suggests an iterative approach will often be necessary to ensure the goals sought are appropriate, give the modelling representation of the system and interactions between performance metrics.

Computational capacity limited the possibilities for including socio-economic uncertainties in the many-objective trade-off analysis. Each additional uncertainty factor must be combined with all others to provide unique uncertainty scenarios for which portfolios are simulated. The 20 scenarios used in Chapter 5 would become 40 if 2 different electricity prices were introduced, and 80 if 2 different asset lifetimes also were introduced. Run times would multiply in direct proportion unless the number of processors on a High Performance Computing (HPC) cluster could be multiplied up simultaneously. It is generally more difficult to gain access to greater number of processors, meaning wait times must then be factored in to any analysis.

The climate change flows used for the Nepal application were rather crudely generated owing to a lack of capacity for extended hydrological modelling. Ideally flows would have been able to vary more between sub-basins as a result of climate change to investigate the impacts of different hydropower dams being built in different sub-basins. Because it was only practical to scale the flows on the basis of change factors modelled for the Upper Arun project, this spatial uncertainty in future water availability could not be represented. Furthermore, the lack of hydrological modelling for the whole basin meant that historical fluctuations in flow and seasonality was preserved where in reality this is likely to become modified (Bharati et al., 2014; Miller et al., 2012; Rees and Collins, 2006). Seasonal shifts could be of particular importance for hydropower generation in the basin and the national supply-demand balance but as time and resources were restricted for this study, investigating these factors is left to future work.

The number of dams for which information was available meant that it was not possible to include dams in series for the Nepal application. This would have revealed greater complexity in the system as operations of storage-type dams would then have influenced other dams downstream. One example of such an ‘in series’ dam was the Saptakoshi dam, which is proposed for the location used here as the outlet for the Nepal Koshi Basin. This dam is large and controversial with multiple potential uses, but was not one of those recommended by NEA & JICA (2014) so it seemed unreasonable to include it if already ruled out by that study and no details of the design or potential uses were available.

One drawback of considering up to 10 objectives is that the results generated are extremely complex and require substantial time and effort to interpret and communicate effectively. There are currently only a limited range of tools available for communicating such data sets –two examples are used visual analytic (i.e. trade-off) plots (used here) and parallel coordinate plots (not used here). The latter are better able to represent large numbers of objectives simultaneously as it is difficult to represent 10 dimensions through visual analytic plots, but only facilitate pairwise direct comparisons between objectives. Customisable approaches such as Matlab and R graphing tools are also available for creating communicative plots but were not used here. Much of this communication relies on the skill of the analyst however. Partly as a result of this complexity, the approach demonstrated in Chapter 5 is intended to be an iterative and long-term process, best suited to strategic planning. It is likely to be necessary for the various parties involved to take their time to digest and understand the implications, formulating new questions about and ways of measuring performance in the system as their understanding develops.

6.3 Future research

The application of many-objective trade-off analysis to the Tana Basin in Chapter 4 has been developed extensively since the work reported was undertaken. This development is part of the Water Infrastructure Solutions from Ecosystem Services underpinning Climate Resilient Policies and Programmes (WISE-UP) project (IUCN, 2016) funded by the German government’s International Climate Initiative (IKI). The model reported here has been developed on the basis of consultations with a wide-range of stakeholders in the Basin and in Nairobi and a process of ongoing engagement is underway known as Action Learning. This process brings decision-makers and stakeholders together separately, every 6 months of the 4-year project, to discuss the issues surrounding development of the basin and interact with the information provided by the project. This has facilitated the presentation of an initial set of trade-offs to both groups, who had not seen this type of information before. The trade-off plots were well received and requests were made to investigate particular aspects of the basin's performance to report back to the groups on the next occasion.

Thus far the analysis has been deterministic in that it has relied on a historical time series of flows as was the case in the applications reported in Chapters 3 and 4 of this thesis. This project will be able to look in more detail at the relationships between changes in the flow regime and ecosystem service provision. The intention is to use climate change time series produced by one of the other project partners (International Water Management Institute) to move towards defining efficient and robust portfolios of infrastructure for the basin as was demonstrated for the Koshi Basin in Chapter 5 of this thesis.

The potential exists to extend the capability of the analysis to schedule investments within a portfolio on the basis of fixed time periods or particular performance level triggers. This would be complex in this context for two reasons: 1) when considering multiple objectives across water, energy and food sectors, the different systems within which each of these sectors functions needs to be represented or bounded in some way for the modelling. For example, in the Koshi Basin application reported here, it was not possible to consider which investments could best address the national electricity shortage without carrying out a national study including all the available options. Electricity generation is not in reality the sole preserve of hydropower, so in order to consider the best investment options, it would be necessary to trade-off hydropower investment options (including all their impacts and robustness) with other options such as solar, wind, geothermal, nuclear or thermal power generation. Likewise in terms of agricultural revenue or food security, it is difficult to confine a meaningful system extent for analysis. 2) Performance levels are not so clearly defined for developing countries where the current situation is less than desirable, i.e. shortages are pre-existing, so the incentives are to build as soon as possible rather than schedule future investments. This contrasts with the applications of other authors (e.g. Matrosov et al., 2015) to water resources systems such as the Thames Basin in the UK, which has more clearly defined and established performance levels and less interactions with overlaid systems as it is not generating hydropower, for example.

The WISE-UP to Climate project (IUCN, 2016) will generate new information and tools around the use of trade-off analysis for infrastructure investment planning in developing countries. This is also an area of interest for research in developed countries. The forthcoming Water Resources East Anglia project in the UK will apply shared vision planning using many-objective trade-off analysis to regional water resources planning.

This will involve a broad range of stakeholders including multiple water supply companies, farmers and power companies requiring cooling water.

It may be possible to develop the algorithm codes used in the analyses reported to better address the socio-economic uncertainties, but this would require an intensive coding exercise to achieve the required outputs. This could allow maximum regret to be minimised as an objective in itself, indicating socio-economic robustness.

Sedimentation and other water quality issues could also usefully be included in the modelling for this type of analysis as these issues are of great concern alongside those of water quantity and timing in developing countries. Water quality issues are generally investigated using different software to that used for water resources, so some development of tools is likely to be necessary to conduct MOEA trade-off analysis incorporating both.

It is possible to envision the approach developed and applied in this thesis being applied to assist with defining appropriate environmental flow levels. This could be the case either where an existing regime is in place, or where environmental flows have yet to be defined. The approach could be used to optimise and balance various factors relating to impacts of flow on the environment and abstraction demands.

6.4 Experience of and recommendations for practical application of the approach

Since the work carried out for this thesis, the author has been involved in further work applying this approach in Kenya. The first presentation of trade-off plots to stakeholders in Kenya took place in September 2015. On the basis of previous presentations only two-dimensional plots and combinations thereof were shown to avoid challenging stakeholders' comprehension. Comprehension appeared to be high and the information was well received by groups of both decision makers from government agencies and representatives of stakeholder organisations. This positive experience motivated a second presentation of further developed trade-off results and three hypothetical decision-making exercises, of increasing complexity, based on these results. In this case workshop participants were divided into groups of four or five to consider and come to an agreement on their preferred options for development considering two conflicting objectives. Participants were enthusiastic and engaged, but the exercises showed that more time would be necessary to allow discussions to evolve based on constantly improving understanding of the results. Nevertheless, groups identified similar options as their preferences and generally options which balanced the two objectives. Participants were provided with a laptop to explore the results, but use of the visualisation software presented a barrier to some. It is important therefore to ensure that a substantial amount of time is available for people to use any new tools intended to help them absorb and explore information. Ideally people would be able to explore results from their own institutions, perhaps using a web-based viewer linked to the results on a server.

The greatest challenge for comprehension of participants in the exercises described above came with considering uncertainties associated with climate change. A two-dimensional plot was provided with only two objectives but options associated with three different climate scenarios. Again, given more time, this information could have been introduced more slowly and explained in more depth so that participants were clear what they were seeing.

In relation to the scarcity of data which is common in developing countries, the approach developed here could be used with existing data to demonstrate the type of information produced and raise awareness of the trade-offs involved in water infrastructure decision making. This could help to focus decision makers on the information needed to assess the trade-offs properly, and thereby inform investments in data gathering. As noted in the benefits above, the analysis could evolve as data become available.

Ideally this type of analysis could be undertaken by people in developing countries, rather than requiring external consultants to be hired. This presents a challenge in terms of capacity building as the approach is technically advanced, currently requiring a range of computer programming skills, water resources and hydrology expertise, data visualisation skills and conceptual understanding of the trade-off options generated. The availability of high performance computers which can utilise multiple processors is a distinct advantage for the analysis, when hundreds of thousands or millions of simulations are undertaken, but such services are available through the internet where hardware is not available. As technology advances, it should be possible to develop user interfaces to automate much of the analytical procedure, link the model to the many-objective optimisation algorithm and visualisation of results.

A great challenge in some countries is likely to be development of institutions and processes to feed social and environmental information in to the analysis. This is likely to require extensive efforts.

7 Appendix A – Problem formulation for Jaguaribe Basin application

This appendix details the mathematical formulation and objective functions used for optimisation.

7.1 Optimisation formulation

$$\boldsymbol{F(x) = \left(f_{losses}, f_{hydro}, f_{fish}, f_{land}, f_{agr}^{j}, f_{flow}^{s}\right)} \quad \textbf{Equation 7.1}$$

$$\forall x \in \Omega$$

$$x = (X_i^s)$$

where *j* is a supply region and $j \in \{Orós, Castanhão, Banabuiú, Lower\ Jaguaribe\}$, *s* is a season and $s \in \{wet\ season, dry\ season\}$, *i* is a reservoir and $i \in \{Orós, Castanhão, Banabuiú\}$.

X_i^s represents a reservoir *i*'s release rule during season *s*

The decision variables being optimised were individual reservoir release rules, where X_i^s represents reservoir *i*'s release rule during season *s* for each of the 3 large regional reservoirs.

7.2 Losses

$$\boldsymbol{Minimise\ f_{losses} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_j Spill_y^j + \sum_i Evap_y^i\right)} \quad \textbf{Equation 7.2}$$

$$i \in \{Orós, Castanhão, Banabuiú\}.$$

$$j \in \{Castanhão, Banabuiú\}.$$

where *y* is the year in the time horizon, *Y* is the total number of simulated years, *i* and *j* are reservoirs, $Evap_y^i$ represents the evaporative losses from reservoir *i* in year *y*, and $Spill_y^j$ represents spills from reservoir *j* during year *y*.

7.3 Hydropower deficit

$$\boldsymbol{Minimize\ f_{hydro} = \frac{1}{Y}\sum_{y=1}^{Y} HDM_y} \quad \textbf{Equation 7.3}$$

where HDM_y is the number of months in year *y* when there is the hydropower deficit.

7.4 Fisheries deficit

$$\boldsymbol{Minimize\ f_{fish} = \frac{1}{Y}\sum_{y=1}^{Y} FUM_y} \quad \textbf{Equation 7.4}$$

where FUM_y is the number of months in year *y* when the fisheries underperform.

7.5 Land availability

$$\boldsymbol{Maximize}\ f_{land} = \frac{1}{Y}\sum_{y=1}^{Y}\sum_{i} AL_{y}^{i}$$ **Equation 7.5**

where AL_y^i is the available land in the floodplain of reservoir *i* in year *y*.

7.6 Agricultural deficit

$$\boldsymbol{Minimize}\ f_{agr}^{j} = \frac{1}{Y}\sum_{y=1}^{Y} AD_{y}^{j}$$ **Equation 7.6**

where AD_y^j is the deficit in supply region *j* in year *y*. An additional aggregated metric – the sum of regional agricultural deficits at each timestep - was not itself optimised, but was used for analysis unless explicitly stated otherwise.

7.7 Flow alteration

$$\boldsymbol{Minimize}\ f_{flow}^{s} = -\sum_{d}\left(1 - \frac{\sum_{t=1}^{TD}(FFC_t^u - FFC_t^r)^2}{\sum_{t=1}^{TD}\left(FFC_t^u - \overline{FFC_d^u}\right)^2}\right)_d^s$$ **Equation 7.7**

$$d = \{1,2,3,4,5,6,7,8,9,10\}$$

where d is a decile of the flow frequency curve, *t* is a timestep, *TD* is the total number of timesteps within decile d, FFC_t^u represents the unregulated flow frequency curve value for timestep t, FFC_t^r represents the regulated flow frequency curve value for timestep *t* and $\overline{FFC_d^u}$ is the mean value of unregulated flow frequency curve in d. *s* represents a season, i.e. the flow alteration is calculated separately for each season. An additional aggregated metric – the sum of seasonal flow alteration at each timestep - was not itself optimised, but was used for analysis unless explicitly stated otherwise.

8 Appendix B – Tana Basin objective function details

This appendix presents the mathematical formulation of objective functions used for optimisation. Table 8.1 details the objectives as they relate to the optimisation before mathematical formulations are presented for each.

Table 8.1 Objective function goals, results precision, units and comments

Objective	Function	Goal	Results precision & units	Comments
Municipal deficit	f_{mun}	Minimise	0.25 Mm^3	Evaluated as the sum of deficits during the simulation divided by the number of years to give a mean annual value.
Hydropower revenue	f_{hydro}	Maximise	US$ 1mil	Total revenue from the five stations according to 2007 bulk energy prices from Kiptala (2008), divided by the years simulated to give mean annual revenue.
Firm energy	f_{firm}	Maximise	1GWh	10th percentile value of monthly total energy generation during the 42 year simulation
Total agricultural revenue	f_{agric}^{total}	Maximise	US$ 1mil	Crop yield responses to water deficit (Doorenbos and Kassam, 1979) used to calculate yields. Yields converted to revenues using commodity prices in Kiptala (2008). Objective evaluates whole system for both cases.

Delta Flow alteration	$f_{flowDEL}$	Minimise	10 -	Evaluated as negative sum of Nash-Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for ten corresponding deciles of natural and regulated flow duration curves. Negative sum was used to make objective more intuitive, i.e. ecosystem benefits are preserved by minimising, rather than maximising flow regime alteration. Theoretical range of objective was -10 to ∞, although physical limits mean value unlikely to approach ∞.
Forest Flow alteration	$f_{flowFOR}$	Minimise	10 -	
Long flood peak reduction	f_{flood}^{long}	Minimise	10 m^3s^{-1}	Flooding results from controlled releases through dam gates and uncontrolled releases over the dam spillways. Objectives were affected by the operation of the downstream most dam, Kiambere although upstream dam operations affect water available at Kiambere. Evaluated as absolute sum of differences between flows for the whole simulation.
Short flood peak reduction	f_{flood}^{short}	Minimise	10 m^3s^{-1}	

8.1 B1. Municipal deficit

$$Minimise\ f_{mun} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_i Deficit_y^i\right)$$ Equation 8.1

$i \in \{Nairobi, Kitui, Downstream\}$.

where *y* is the year in the time horizon, *Y* is the total number of simulated years, *i* is a municipal demand and $Deficit_y^i$ represents deficit experienced by municipal demand *i* during year *y*.

8.2 B2. Hydropower revenue

$$Maximise\ f_{hydro} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_i Revenue_y^i\right)$$

Equation 8.2

$i \in \{Masinga, Kiamburu, Gitaru, Kindaruma, Kiambere\}.$

where *y* is the year in the time horizon, *Y* is the total number of simulated years and $Revenue_y^i$ is the revenue generated by the hydropower plant at reservoir/pondage *i* in year *y*.

8.3 B3. Firm energy

$$Maximise\ f_{firm} = LowGen$$

Equation 8.3

where *LowGen* is the 10th percentile value of monthly total energy generation during the 42 year simulation

8.4 B4. Agricultural revenue

$$Maximize\ f_{agric} = \frac{1}{Y}\sum_{y=1}^{Y}\left(\sum_i AgRevenue_y^i\right)$$

Equation 8.4

$i \in \{Masinga, Kiambere, Delta\}.$

where $AgRevenue_y^i$ is the agricultural revenue associated with irrigation demands in supply region *i* in year *y*.

8.5 B5. Flow alteration

Two flow alteration objectives are evaluated, but as these share a common formulation a generic form is presented here to avoid duplication.

$$Minimize\ f_{flow} = -\sum_d \left(1 - \frac{\sum_{t=1}^{TD}\left(FFC_t^u - FFC_t^r\right)^2}{\sum_{t=1}^{TD}\left(FFC_t^u - \overline{FFC_d^u}\right)^2}\right)_d$$

Equation 8.5

$d = \{1,2,3,4,5,6,7,8,9,10\}$

where d is a decile of the flow duration curve at the objective evaluation site, *t* is a timestep, *TD* is the total number of timesteps within decile d, FFC_t^u represents the unregulated flow frequency curve value for timestep *t*, FFC_t^r represents the regulated flow frequency curve value for timestep *t* and $\overline{FFC_d^u}$ is the mean value of unregulated flow frequency curve in d.

8.6 B6. Long flood peak reduction

$$Maximize\ f_{flood}^{long} = \sum_{y=1}^{Y}\left(\sum_i \left|NatFlow_y^i - ModFlow_y^i\right|\right) \qquad \text{Equation 8.6}$$

$i \in \{April, May, June\}$.

where $NatFlow_y^i$ is the natural (observed) flow rate and $ModFlow_y^i$ is the modified (modelled) flow rate for month i in year y.

8.7 B7. Short flood peak reduction

$$Maximize\ f_{flood}^{short} = \sum_{y=1}^{Y}\left(\sum_i \left|NatFlow_y^i - ModFlow_y^i\right|\right) \qquad \text{Equation 8.7}$$

$i \in \{October, November, December\}$.

where $NatFlow_y^i$ is the natural (observed) flow rate and $ModFlow_y^i$ is the modified (modelled) flow rate for month i in year y.

9 Appendix C - Formulation and parameterisation of the crop yield module added to IRAS-2010

This appendix gives details of the crop yield calculation module added to IRAS-2010 in order to evaluate agricultural revenue. The module added was based on work by Doorenbos and Kassam (1979) on crop yield response to water.

Doorenbos and Kassam (1979) developed an equation (C1) relating crop yields to maximum possible yields, actual and maximum evapotranspiration. In order to simplify the calculation the ratio of irrigation supplied to irrigation demand was used as a proxy for the ratio of actual to potential evapotranspiration. This was justified on the basis of the statement in Doorenbos and Kassam (1979)(p8) that available water supply to the crop controls actual evapotranspiration. In order to validate this assumption was necessary to assume that the only water received by crops in this region is irrigation. This was considered reasonable under the semi-arid climate.

$$\left(1-\frac{Y_a}{Y_x}\right)=K_y\left(1-\frac{ET_a}{ET_x}\right) \qquad \text{Equation 9.1}$$

where Y_x and Y_a are the maximum and actual yields, ET_x and ET_a are the maximum and actual evapotranspiration, and K_y is a yield response factor representing the effect of a reduction in evapotranspiration on yield losses.

Yield response factors used to calculate yields in the IRAS-2010 module are shown in Table 9.1. No response factor for rice was given by Doorenbos and Kassam so it was assumed that yield was directly proportional to water deficit. This was simpler than trying to judge a factor without evidence to support its value.

Table 9.1 Yield response factors for crops proposed for delta irrigation schemes (based on Doorenbos and Kassam (1979))

Crop	Yield response factor
Rice	1.0
Maize	1.25
Cotton	0.85
Sugar cane	1.2

10 Publications arising from this thesis

Hurford, A.P & Harou, J.J.: Balancing ecosystem services with energy and food security - Assessing trade-offs from reservoir operation and irrigation investments in Kenya's Tana Basin, Hydrol. Earth Syst. Sci., 18, 3259–3277, 2014

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