



Negotiated risk management of transboundary rivers

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PUBLICATIONS

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ABSTRACT

Reaching agreements over water management on transboundary rivers is a complex yet necessary endeavour to assure that humans can live within the limits of available resources. The myriad of challenges is both physical and social in nature; the uncertainty of water availability due to natural hydrologic variability is often increased by the involvement of multiple management institutions. Jurisdictions of control are typically defined by political borders, and thus they represent distinct geographic domains and interests. Increasing scarcity, driven by rapidly expanding populations and our growing awareness of climatic non-stationary, increases the urgency to find agreements among these institutions. Although the need is significant and growing, a lack of available approaches exist that considers the physical, technical and political dynamics to address these complex challenges.

This thesis describes novel analytical methods to engage in the complex political realm of transboundary river management. Building from an engineering systems analysis approach to engage this topic, the main hypotheses of this thesis are: (1) Existing analytical approaches for water resource development are useful but often constrained in a transboundary negotiation context, and (2) cooperation among co-riparian water management institutions can be significantly increased with strategic implementation of analytical tools to jointly manage current and future risks.

To test this hypothesis, this thesis presents an analytical approach that (1) examines previous applications of water resource models to identify their perceived contribution to managing transboundary rivers, (2) develops a new modelling framework that engages with transboundary negotiations, and (3) incorporates methods for risk-based decision making to evaluate the benefits, opportunities and trade-offs of cooperation among co-riparian states. A retrospective analysis is conducted on the Colorado and Murray-Darling River Basins to understand lessons learned from recent applications of analytical modelling tools. New methods are then developed

and applied to the rapidly changing Eastern Nile River Basin. The ongoing construction of the Grand Ethiopian Renaissance Dam (GERD) and the implications on downstream countries of Sudan and Egypt provides the context and a relevant case for testing the methods and evaluating the hypotheses.

Results from this thesis demonstrate the distinct advantages of an early development of system-wide analytical tools within a transboundary context, which is made available to all parties. Conversely, the challenges of reconciling multiple models used by different institutions after full allocation is reached in a basin is a significant barrier to cooperative management. Results also demonstrate the advantages of developing an analytical tool that is sufficiently accurate, transparent and flexible to seek creative solutions, and the need to select an appropriate breadth and depth of model design that conveys its credibility, saliency and legitimacy to support a decision-making process. The appropriate design of tools to consider multiple future hydrologic scenarios can shift a discourse from rigid water allocations to considering the effects of new developments in terms of changes to risks, and to allow stakeholders to decide whether these changes are tolerable when juxtaposed with the benefits that new infrastructure provides. Finally, the results show how risks among multiple stakeholders can be evaluated under expanding uncertainties, and cooperative solutions can be sought to minimise or balance these risks.

The application of the proposed methods to the Eastern Nile Basin indicates that solutions are indeed possible that benefit all three countries. A number of cooperative solutions are identified that suggest operational rules for the new and existing infrastructure. These operations can be responsive to variable climatic conditions and thus encourage dynamic cooperation. In this light, the developments in Ethiopia need not be a risk, but can result in substantial benefits to the downstream countries if agreements can be reached. Embedding highly adaptable analytical tools within a negotiation process can help to overcome the challenges faced at this historic point on the Nile River.

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1 INTRODUCTION

1.1 BACKGROUND

The use of rivers that flow across political borders inherently involves many perspectives on how water should be shared and managed. Approximately 263 river basins span international boundaries (Wolf 2007), and many of the 319 federal rivers of the world cross interstate boundaries (Garrick et al. 2013). Growing global populations resulting in increased demands have caused concerns of increasing water scarcity and highlight the need for improved management and possible redistribution of existing freshwater resources (Gleick 2000). Furthermore the increased awareness of the implications of future global climate changes (Vörösmarty et al. 2000) have called into question whether the natural water supplies of the future will resemble that of the past (Milly et al. 2008). The formation of new transboundary river sharing agreements or adapting existing treaties to allow greater flexibility is seen as an increasingly important task as river basins reach closure (Cooley and Gleick 2011; Falkenmark and Molden 2008).

A wide variety of water sharing arrangements exists that seek to manage and allocate water amongst the national and sub-national stakeholders for variety of consumptive and non-consumptive uses (De Stefano et al. 2010). Many factors such as strong institutional capacity, the drive for economic development and regional integration and physical scarcity have been linked to the emergence of these agreements (Blomquist et al. 2005; Dinar 2009b; Sadoff and Grey 2002). A basin-wide desire to mitigate the risks of flooding and drought can contribute to collective action to minimize harm from extreme events (Hall and Borgomeo 2013). Asymmetric power dynamics and counter-hegemonic manoeuvres have also been shown to play a significant role in generating the political will to find a compromise among co-riparian states (Dinar 2009a; Zeitoun et al. 2017). While a number of theories exist on causal factors for successful treaties, the

negotiation processes by which agreements over international water management and allocations decision are achieved is contextual, seldom replicated, and thus poorly understood.

This thesis addresses this challenge by first examining the recent use of analytical tools to seek water-sharing agreements, and then develops a new analytical framework to demonstrate how these tools can be implemented to better facilitate transboundary negotiations. To enhance multi-stakeholder engagement, Integrated Water Resource Management (IWRM) has emerged as a comprehensive paradigm that strives to be inclusive and promote coordination among uses and across various users (Grigg 2008). More recent frameworks of water diplomacy (Adelphi 2016; Islam and Susskind 2012) uses negotiation theories to seek mutual gains through trades to enhance the benefits that water provides (Sadoff and Grey 2002). Central to the effectiveness of both these paradigms is the sharing of existing knowledge of the current and potential distribution and utilization of water resources across borders. To accomplish this, credible, legitimate and salient information systems seek to produce a common understanding of how rivers could be better managed into the future (Cash et al. 2003). Water resource models are one particularly useful tool for analysing the development of new management strategies.

Models are often used within countries and among relatively amicable co-riparian nations to address management challenges. These tools help to identify efficient allocation schemes and reservoir operations to meet multiple objectives (Loucks 1992; Wurbs 1994; Yeh 1985). Successful uses of models on transboundary rivers such as the Columbia and Rhine demonstrate their utility, but most successful contexts have been shown to have countervailing forces and relatively abundant water (Hensengerth et al. 2012; Song and Whittington 2004). Much has been written on how waters of international rivers *could* be managed in more contentious situations (Guariso and Whittington 1987; Rogers 1969), particularly in the context of international investment planning (GWP 2013). However, the use of models as tools to navigate difficult negotiations over water allocations and dam operations is far less frequent. This gap is primarily a result of

asymmetrical technical capacities among stakeholders to use models, a distrust in models due to the risk of embedded assumptions, and the gravitas implied by relying on such techniques in an internationally binding context (Biswas 2011; Dinar 2009a; Salman 2007). Notable exceptions to this include successful negotiations between the United States and Mexico over the Colorado River (Buono and Eckstein 2014), ongoing planning on the Mekong River for a number of dam construction projects (MRC 2014) and the management of the Toktogul Reservoir on the Syr Darya of the Aral Sea Basin (Cai et al. 2003; Heaven et al. 2002). While a number of best practices have emerged for collaborative modelling (Langsdale et al. 2013), there is a lack of generalized frameworks on how to integrate models within an inherently political decision-making process of transboundary negotiations.

This thesis builds upon the framework of water diplomacy (Islam and Suskind 2012) with the utility of models for water resource planning and management (Brown et al. 2015). While traditional approaches to reach international agreements have relied heavily on historical average hydrologic conditions to determine allocation values, the methods developed in this work utilize risk-based approaches that have increasingly gained acceptance (Hall and Borgomeo 2013). Stochastic methods are developed and used to evaluate the potential for satisfactory outcomes, which are defined as reaching a tolerable level of risk (Grey et al. 2013) or an acceptability criteria of no significant harm (Salman 2007). Managing uncertainties that can be characterised by probabilities, and considering those which cannot be easily predicted, are particularly challenging in transboundary negotiation contexts.

The central question of this research is how cooperative risk management can be incorporated into transboundary water sharing negotiations. Using a case study approach, I explore this topic with three distinct questions:

- 1) To what extent are water resource models useful to facilitate transboundary negotiations?
- 2) How might water resource models be developed to enhance cooperation?
- 3) How can uncertain hydrologic futures be incorporated to transboundary decision making?

1.2 AIMS AND OBJECTIVES

This thesis aims to provide new methods for water resource decision-making in transboundary river contexts and explore how modelling tools can be utilized in negotiations to consider risk-based strategic cooperative solutions. To achieve this aim, the following four objectives were identified: (i) Explore previous examples of the application of water resource models in transboundary contexts using the analytical framework of credibility, saliency and legitimacy; (ii) develop and apply a policy-oriented water resource model to test its value for facilitating cooperation in a transboundary context; (iii) develop a generalized stochastic hydrology generation method to simulate significant uncertainties in future hydrologic conditions; (iv) develop an overarching framework to apply water resource models and multi-objective search methods to explore cooperative management strategies in transboundary basins while considering the deep uncertainty of future hydrologic conditions.

This research first examines the application of water resource models on the Colorado and Murray-Darling River Basins to draw from recent applicable experience. The focus then shifts to the Eastern Nile River Basin where negotiations over the Grand Ethiopian Renaissance Dam (GERD) are currently ongoing. The methodology is applied in the context of building cooperation among the countries of Ethiopia, Sudan and Egypt.

1.3 CHAPTERS OUTLINE

Applying the critical lens of Cash et al. (2003) that characterises the value of knowledge management systems as *boundary objects*, Chapter 2 examines the recent application of water resource models in two river basins including the federal and international transboundary Colorado River and the federal Murray-Darling River Basin. Specifically, this chapter analyses the use of these models during negotiations among the sub-national states or provinces, and within the successful negotiation between the United States and Mexico. These lessons are then compared to the ongoing use of models in the Nile Basin. The focus of this chapter is on analysing multiple technical and non-technical viewpoints to evaluate the role of models as valid boundary objects within the negotiation contexts.

Chapter 3 describes the development and application of a new water resource model constructed for the Eastern Nile River Basin with a similar reservoir operation and policy development focus as the Colorado River case study. This new model is calibrated and demonstrated by simulating a variety of potential cooperative filling policies for the new GERD reservoir, while minimizing impacts to Sudan and Egypt. The chapter demonstrates the flexibility of a 'hydro-policy' model and highlights the value of using these tools for collaborative policy exploration.

Chapter 4 describes a methodology for multi-site stochastic hydrology generation that can reproduce historical statistical characteristics and the correlation structure among basin-wide inflow locations. Furthermore, the parsimonious and generalized procedure can generate outputs with user-modifications to the statistical characteristics to simulate the potential effects of climate changes. The method is applied to develop multiple hydrologic scenarios with varying hydrologic persistence for the Eastern Nile Basin.

Chapter 5 develops a generalized methodology for exploring cooperative management solutions in transboundary basins, and demonstrates this on the Eastern Nile using the model developed in

Chapter 3 and the hydrologic sequences developed in Chapter 4. The method described in this chapter also applies a multi-objective evolutionary algorithm to explore alternative operational policies and integrates deeply uncertain hydrologic futures into the evaluation of the robustness of potential solutions.

2 TRANSBOUNDARY RIVER MODELS: BRIDGING THE BOUNDARIES BETWEEN SCIENCE, PARTICIPATION AND REGIONAL DECISION-MAKING

2.1 INTRODUCTION

Water resource models (WRMs) are frequently used to aid decision-making by capturing, communicating and translating knowledge of complex hydrologic and social systems. Abstract representations of these systems are created using equations and assumptions, along with spatially and temporally simplified data. WRMs are often used in contested situations with multiple interests where the saliency of policy insight they provide must be balanced with scientific credibility and perceived legitimacy of the knowledge from which they are built upon (Cash et al. 2003).

Management of shared water resources across multiple jurisdictions such as federal river basins is particularly complex (Garrick et al. 2014) and challenges are exacerbated in drought-prone regions or fully allocated rivers. Water governance paradigms such as Integrated Water Resource Management (IWRM) (GWP 2000) and water diplomacy (Islam and Susskind 2012) seek to improve dialogue and coordination among multiple scales of government, water users and scientific knowledge through information exchanges across disciplinary, organisational and knowledge boundaries (Jacobs et al. 2016). These frameworks rely on scientifically credible and socially robust knowledge-action systems to exchange information and guide interactions among participants (Robinson et al. 2011).

WRMs have been a core part of regional water resource decision-making and management for many decades (Brown et al. 2015; Jacobs et al. 2016) but have struggled to articulate their value. Growing pressures on water availability, combined with shifting governance and management, has resulted in a need to re-engage with design and application of WRM (van Asselt and Rotmans 2002) to incorporate diverse contributions from multiple stakeholders, communities and interest

groups (Kroon et al. 2009). Varied scales of information across large basins often lead to heterogeneity and knowledge gaps, and poses challenges to perform system-wide analyses, communicate findings and implement regional responses to phenomena such as droughts and climate change.

The growing need for resource managers to learn, experiment and adapt to complex threats and opportunities that are inherent in water decision-making has attracted the attention of a growing field of sustainability science (Clark and Dickson 2003). This field of research draws on the notion of boundary work (Gieryn 1983) that describes efforts of two-way, iterative communication between actors on both sides of the science/decision-making boundary to translate and mediate knowledge into policy decisions. For boundary work to be useful and usable, it needs to not only be scientifically credible but also salient for real-world applications and reflect legitimate information-gathering processes that consider a range of values, interest and concerns (Cash et al. 2003; Clark et al. 2016; Jacobs et al. 2016). In this chapter, the focus is on how federal governance structures utilize WRMs as 'boundary objects' to enable the sharing of knowledge across multiple state and national governments, stakeholder interests and disciplinary perspectives to support river basin planning.

This chapter first draws on responses from WRM designers and users in two fully allocated, drought-prone and contested transboundary river basins: The Colorado River Basin (CRB) in North America and the Murray-Darling Basin (MDB) in southeastern Australia. Both basins are characterized by federal water governance structures and WRMs were recently developed or enhanced in both basins amidst significant water planning and management reforms in response to severe drought. The chapter reviews IWRM as it relates to the development and application of WRMs to enable water managers to link knowledge with actions required to address complex water resource management issues, then draws on the sustainability science literature to describe the key perspectives and attributes of boundary work. Regional water resource planning contexts

within the basins are then reviewed and the survey responses analysed. Finally, this chapter discusses the recent history and ongoing challenges of applying a WRM to facilitate the development and decision making process of the Nile Basin.

The results demonstrate that WRMs act as boundary objects through their management functions, however who has control of, and access to, the WRMs within a multi-jurisdictional context is a critical factor that affects their ability to function in this role. Results also show that the successful use of WRMs is inherently iterative given the political and legal conditions that exist in such a context. Furthermore, results show that enhancing stakeholder participation in modelling is valuable but numerous practical barriers and challenges exist. This chapter concludes with recommendations geared towards contributing knowledge to, and using knowledge from, WRMs more effectively for managing drought risks within federal and international river basins.

2.2 THEORETICAL FRAMEWORK

Much has been written on water governance and the concept of IWRM, including what should be integrated to achieve an inclusive yet practical management framework (Biswas 2004; Gourbesville 2008; GWP 2000). The co-evolution of water institutions – the rules, norms, values and shared knowledge of practitioners – alongside development of governmental authorities, creates challenges that can make water decision-making regimes resistant to change (Pahl-Wostl 2009). One challenge includes the integration of basin-scale technological approaches with increasing contributions from diverse knowledge sources and interests (Raymond et al. 2010). Inherent challenges arise on how such information can be best incorporated into traditional reductionist, yet often relied upon, decision-making frameworks.

The term ‘boundary work’ has been coined to describe and analyse the continuous transfer and integration of knowledge across functional and organisational boundaries and different

knowledge domains (Jasanoff 2004; Lemos and Morehouse 2005). WRMs are key boundary objects to facilitate shared long-term problem solving capacity that respect the domains and differences contained in water governance knowledge-action systems (Jacobs et al. 2016). 'Boundary organisations' - such as government and non-government water management organisations - perform boundary work by acting as intermediaries between different stakeholders (Buizer et al. 2016; Clark et al. 2016), which become particularly relevant when significant knowledge and power imbalances exist (Zeitoun and Warner 2006).

In the context of this paper, a key role for boundary organisations is to build and apply WRMs that are trusted by stakeholders and to ensure that interests and individuals are respected, valued and engaged in a legitimate process (Lemos and Morehouse 2005). However the process by which trust in WRMs is gained among competing actors is less understood beyond notions of stakeholder participation (Olsson and Andersson 2007; Van den Belt 2004). This is particularly relevant in federal river systems that are bound by a common overarching government, but ownership and management of water is maintained at sub-national levels. As a result, local state governments must find ways to co-manage the shared resource. In doing so, WRMs become important 'boundary objects' for organisations to develop and communicate collective knowledge through assimilation of information across multiple sources, time scales, spatial domains and jurisdictions (Liu et al. 2008).

Multi-level and polycentric governance structures (Ostrom 2010) have been shown to increase reliance to environmental shocks and system-wide changes through adaptation (Pahl-Wostl 2009), however coordination among multiple governance institutions is important to avoid fragmented decentralization (Pahl-Wostl et al. 2012). WRMs provide a tangible form of coordination across multiple state actors or between states and an overarching federal or basin-wide government. The application of WRMs for dispute resolution in a multi-jurisdictional river basins is well established (Dinar et al. 2007), and many river basins rely on them for effective

management among competing interests. How WRMs are developed, managed, shared and applied to build consensus among competing actors has received limited attention and provides a point of departure for this research.

2.3 RESEARCH CONTEXT AND METHODS

2.3.1 WRM Contexts

2.3.1.1 *Colorado River Basin*

The CRB covers an area of 637,000 square kilometres and drains portions of seven states before flowing across the international border with Mexico and into the Gulf of California (Figure 2-1). The river originates in the Rocky Mountains and descends more than 4,000 m along its course to the tidal waters of the Gulf. With runoff dominated by seasonal snowmelt, the flows fluctuate widely throughout the year, with high flows occurring in the late spring and low flows during the late autumn and winter months. Total annual runoff varies considerably, ranging from 8 BCM to 32 with an average of 20 BCM. Beginning in the early 1900's, large storage reservoirs were constructed to control this variability from causing catastrophic flood damage to existing downstream irrigation, provide a reliable source of water for new irrigation and municipal development, and harness the river's potential for hydropower development. In 1936 the Hoover Dam was completed which formed Lake Mead. This structure allowed controlled irrigation diversions via the All-America to the Imperial Irrigation District of California. The second large structure, The Glen Canyon Dam, was completed in 1966 and forms Lake Powell upstream of Lake Mead. The combined storage capacity of these major reservoirs, along with a number of others in the Basin provides around 80 BCM of storage capacity, or over the ability to completely capture and control approximately 4 years of average annual runoff.

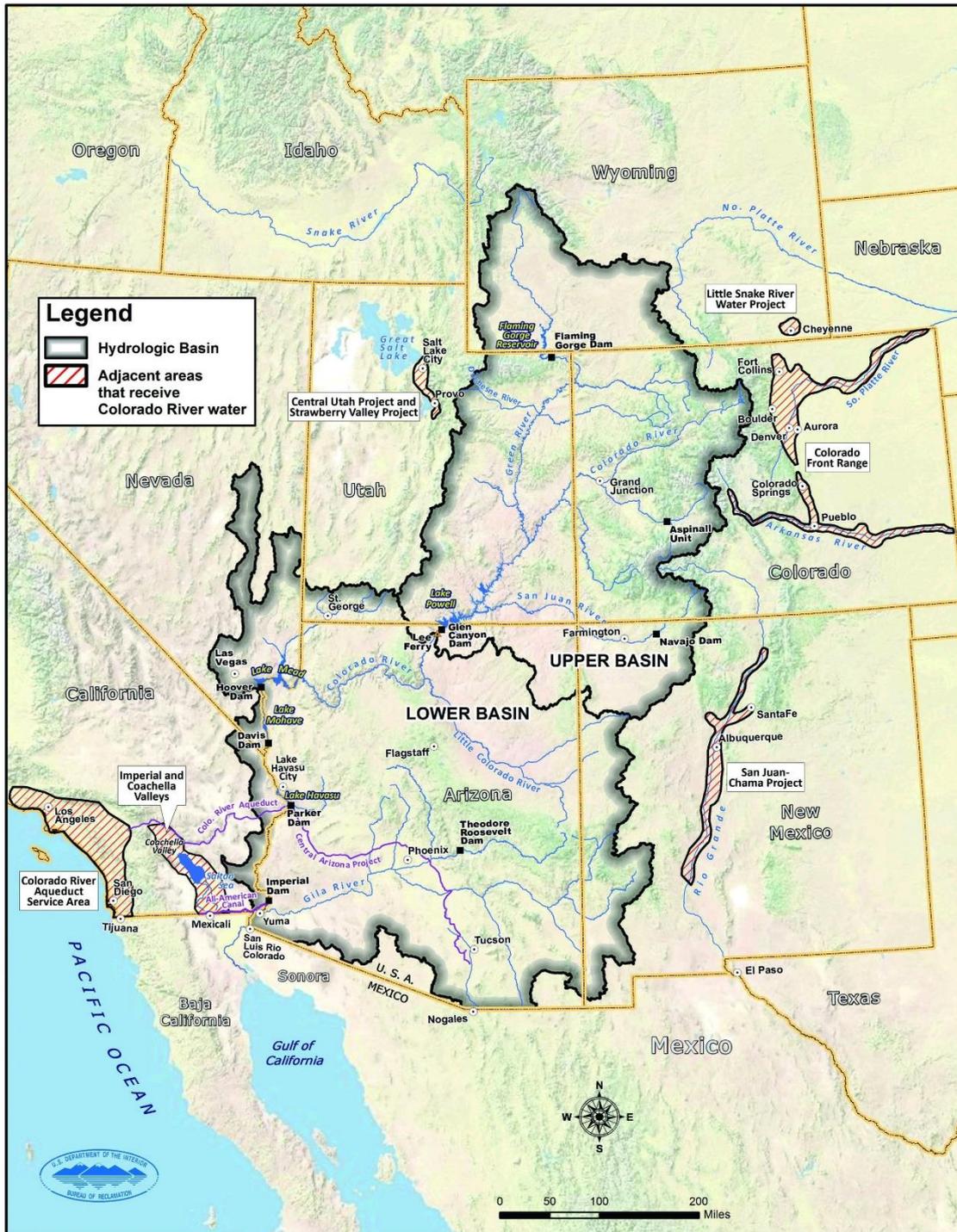


Figure 2-1. Map of the Colorado River Basin
(USBR 2012b)

The river is managed and operated through a complex assemblage of regulations, which are collectively referred to as the *Law of the River* (MacDonnell et al. 1995) that establishes the rules

for sharing between states and nations. Within the U.S., the Bureau of Reclamation (USBR) is the primary authority charged with the operation of the dams and reservoirs, and management of water deliveries. Water sharing arrangements between the U.S. and Mexico are defined in a 1944 Treaty and administered by the joint International Boundary and Water Commission (IBWC).

In 2000 the USBR completed an Environmental Impact Statement (EIS) to develop guidelines for allocation of *surplus* water among the lower basin states (USBR 2000), and in doing so, ushered in a new era of collaborative WRM use in the basin. Responding to a rapid decline in reservoir storage, growing demands and climate change risks, a *Shortage Criteria EIS* (USBR 2007) was conducted soon thereafter to define *shortage* conditions among the lower basin states and improve coordination of reservoirs.

Central to each of these efforts was a WRM known as the Colorado River Simulation System (CRSS) (Garrick et al. 2008; Jerla et al. 2011). Originally designed by USBR as a FORTRAN model (Cowan et al. 1981), the CRSS model was transferred to the RiverWare platform in 1990s with an objective of making the model more adaptable to changing policies and accessible to a wider audience of stakeholders (Zagona et al. 2001). With this development, expertise in the CRSS model began to extend beyond the USBR. New users included lower basin state governments, coalitions of upper basin states, municipalities and water authorities (USBR 2012a). Understanding the role of the CRSS in the policy formulation process, non-governmental organizations (NGOs) and certain Native American Tribes, who hold substantial interests or water rights in the Basin, also sought to build their own expertise through collaboration with universities and externally hired consultants (Westfall and Bliesner 2006; Wheeler et al. 2007).

The USBR made the CRSS model freely available to a *Stakeholder Modelling Workgroup* comprised of technical representatives from the different organizations, and held regular meetings with interested technical and non-technical parties. This allowed the USBR to share outputs from the

model and receive well-informed suggestions for improvements. These efforts were not only to promote understanding of the scenarios developed, but also to encourage stakeholders to evaluate and propose management alternatives that could meet their own objectives. As more stakeholders became familiar with the model, the tool evolved into a platform for exploring, sharing and testing alternative ideas for river management. Technical experts could evaluate proposals presented at a formal policy level and also communicate and scrutinize ideas informally across networks of modellers.

On an international level, the Mexican government recognized the increasing need to engage over future river management decisions and held a RiverWare training session in April 2008 to increase their modelling capacity. Formal bilateral negotiations began in 2011 that used the CRSS as the central analytical platform, and included participation of federal and state governments, municipalities, NGOs and agricultural districts. Minute 319 to the 1944 Treaty was signed in November 2012 that demonstrated a new level of multi-level coordination. (Buono and Eckstein 2014).

2.3.1.2 Murray Darling Basin

The Murray-Darling Basin covers an area of over 1.1 million square kilometres in south-eastern Australia and includes areas across four states as well as the Australian Capital Territory (Figure 2-2). With portions of the headwaters originating from river systems in the highlands of the Great Dividing Range and the Australian Alps, the vast majority of the basin consists of extensive plains with elevations of less than 200 meters above sea level. The 23 river valleys cover a variety of ecosystems ranging from rainforests of the eastern uplands to hot and arid lands of the western plains. Similar to the Colorado River, the annual runoff of the MDB varies widely, ranging from 6.7 BCM to 117.9 BCM, with an average value of 31.8 BCM. A number of reservoirs have been constructed that can store up to 22.6 BCM, or 70% of the average annual runoff. Regardless of

this relatively limited storage volume, the outflows to the ocean near the city of Adelaide are only 5.1 BCM on average due to upstream consumption. While with the vast majority of the runoff is used for agricultural purposes, approximately 3.4 million people live within the basin or within areas that depend on the water from the river system.



Figure 2-2. Map of the Murray-Darling Basin

(MDBA 2010a)

The National Water Initiative is the blueprint for Australian water policy and planning reform and its policy prescriptions and objectives are widely accepted as salient and appropriate for Australia (COAG 2004). Local, state and basin water planning institutions have agreed on a set of key elements within their water planning frameworks such as stakeholder engagement and applying a risk-based approach to water resource management. Its implementation is the responsibility of state jurisdictions or regional multi-state partnerships such as those within the MDB.

WRMs such as IQQM (Simons et al. 1996), REALM (Perera et al. 2005) and MSM-BIGMOD (Close et al. 2004) have been used as decision-support tools to understand, plan and manage MDB water resources over the past four decades, but principally developed at the individual sub-basin level and managed by state agencies. Disparate characteristics, such as temporal resolutions and alternative depictions of water rights systems, exist between the various sub-basin models (MDBA 2012). In the throes of an unprecedented decade-long drought, the Australian Government passed the 2007 Water Act, which directed the formation of the Murray-Darling Basin Authority (MDBA) and its mandate to strategically plan and manage the basin as a whole. From this greater centralized management paradigm, the need to standardize and merge the existing modelling frameworks emerged. There were significant challenges to link the individual historical models within an Integrated River System Modelling Framework (MDBA 2012). With funding from the federal government, the new Source modelling platform was developed by CSIRO, now managed by eWater LLC, with a goal to eventually replicate and replace the individual sub-basin models and provide a common analytical framework (Dutta et al. 2013; Welsh et al. 2013). While the existing models continued to be used during this period of critical drought, the new platform was designed with the intention that multiple state agencies would adopt it for their future planning purposes. The process of adoption of this common platform continues today.

The models strive to simulate the management of water across four states according to parliamentary agreements. Under these regulations the downstream state of South Australia

receives a minimum annual entitlement flow and the balance is shared according to requirements for salinity mitigation, flood storage and environmental flows as well as water user entitlements (Connell and Grafton 2011; MacDonald and Young 2001; Walker et al. 2003).

The 2007 Water Act recognized the risk of environmental degradation resulting from low flows caused by over-abstraction coupled with the persistent drought. An ambitious agenda of water policy reform set to establish Sustainable Diversion Limits (SDL); resulting in more than 20 percent of previous extracted water use recovered for the basin's freshwater and estuarine ecosystems (Bark et al. 2014). This has required the application of integrated water governance frameworks that can negotiate various uses to sustain multiple values and encourage local community input and review of management objectives and priorities (Robinson et al. 2015). A challenge implicit in the resulting Basin Plan 2012 is establishing an approach that provides credible water resource sharing decisions between all water users, including the environment, managing the basin as a single system while being responsive to local values and priorities. In this research, we contend that the process of model development, adaptation and application to meet these multiple needs constitutes an example of boundary work.

2.3.1.3 The Nile River Basin

The Nile Basin encompasses 3.18 million square kilometres of Eastern Africa, including 11 nation-states of Burundi, Democratic Republic of Congo, Egypt, Ethiopia, Eritrea, Kenya, Rwanda, South Sudan, Sudan, Tanzania, and Uganda (Figure 2-3). The river system is formed by two distinct major tributaries, commonly called the Blue Nile and White Nile, which merge in Sudan to form the Main Nile. The Blue Nile flows from Lake Tana in Ethiopia and carves a deep clockwise canyon through the Ethiopian plateau before it passes into Sudan, contributing substantially to its agriculture-based economy (Craig 1991) before joining the White Nile in the capital city of Khartoum. The flows that eventually become the White Nile begin in the complex of lakes, wetlands, and rivers in the Equatorial Lakes region of Burundi, Democratic Republic of Congo, Kenya, Rwanda,

Tanzania, and Uganda, and emerge from Lake Victoria as the Victoria Nile in Uganda. After passing through the Sudd Wetlands of South Sudan as the Bahr el Jebel and joining the Bahr el Ghazal and the outflow of the Baro-Akobo-Sobat tributary sub-basin, the river enters Sudan as the White Nile. Downstream of the confluence of the two major branches of the Nile in Khartoum, the intermittent Atbara River, originating in Ethiopia and Sudan as the Tekeze (called the Setit River in Sudan), joins to form the last major contribution before winding through the Nubian Desert and into Egypt.

While no overarching governance of the Nile exists, various WRMs have been developed to analyse the development potential of the Basin. Until recent years, the majority of these studies have been conducted by external individuals, institutions or consultants working for one or more of the countries. Guariso and Whittington (1987) demonstrated that there is little conflict between the objectives of Ethiopian hydropower and Egyptian and Sudanese agriculture by using a classical multi-objective optimization framework. Block and Strzepek (2010) demonstrated the economic benefits for Ethiopia of large-scale Blue Nile development under historical hydrologic conditions, but also showed the possibility of a reduced degree of benefit using stochastic hydrology influenced by climate changes. Similarly, McCartney and Girma (2012) provide an analysis of multi-use infrastructure development within Ethiopia and the resulting benefits to Ethiopian agriculture and hydropower while considering the risks of climate change and reduced flows. Jeuland (2010) provides a hydro-economic framework for integrating climate change impacts into infrastructure planning and found a high sensitivity of economic benefits to runoff conditions, and furthers this work with a real-options approach for analysing the selection, sizing, sequencing and operation of reservoirs within Ethiopia (Jeuland and Whittington 2014). Arjoon et al. (2014) use a stochastic dual dynamic programming approach within a hydro-economic framework to optimize operations for the benefits of hydropower and agriculture production under various build-out scenarios.

Another class of models developed for the analysis of the Nile Basin is decision support tools, which are generally commissioned by institutions and designed to be used by multiple stakeholders. Models such as the Nile Decision Support Tool (Yao and Georgakakos 2003) integrate with a database to form a Decision Support System (DSS) to bring together vast amounts of spatially and temporally discrete and distributed hydrologic data. More recently the Nile Basin Initiative (NBI), which is envisioned to conduct studies on behalf of member countries, developed the Nile Basin DSS to provide a user-accessible platform that can incorporate a variety of models designed for various purposes (NBI 2014). Water resource planning models using the generalized software platforms of MIKE HYDRO (formerly MIKE BASIN (Jonker et al. 2012)) and WEAP (Yates et al. 2005) have been developed and integrated into the Nile DSS, while another cadre of models developed by the Eastern Nile Regional Technical Office (ENTRO) of NBI including SWAT (Hassan 2012), Ribasim (van der Krogt and Ogink 2013) and RiverWare (Wheeler and Setzer 2012) can potentially be integrated into the Nile Basin DSS. All modelling platforms have their strengths and thus cater to particular applications (Brown et al. 2015) such as the hydrologic focus of SWAT, the river basin planning focus of WEAP, and the reservoir planning and management focus of RiverWare. Similar to the CRSS model of the Colorado River and the basin-wide Source model of the Murray-Darling River Basin, the objective of the Nile-DSS is to provide a shared analytical platform from which decisions among competing stakeholder can be made. However, the use of this platform has thus far been limited to the NBI and a number of stakeholders in the Equatorial Lakes region, and has not been adopted by the current major users of Nile water including Egypt and Sudan for collective decision-making.

2.3.2 Methods

Information on model usage in the CRB and MDB was collected through multiple routes including reviews of government-produced reports, academic literature and from a semi-structured survey. A stratified sample selection was followed augmented with snowballing. In the period January 2016 through February 2017, invitations were sent to national and state level WRM developers, users, as well as individuals representing stakeholder interest groups. The responses collectively represent a variety of backgrounds, interests and perspectives from both sides of the science-policy interface and multiple institutional positions in each the basin. The semi-structured survey asked respondents about their perspectives of WRM design and application. Questions were guided by aspects of boundary work identified by Cash et al. (2003), where, WRM information needs to be *credible* (scientific adequacy), *legitimate* (its development is respectful of divergent stakeholder beliefs and values, fair and unbiased) and *salient* (information is available and relevant for decision-making).

In total, 44 invitations were sent and 21 returned for a 39% response rate. Ten completed questionnaires were returned from the CRB including four from federal level governments in the United States (USBR and IBWC-USA), two from federal level governments in Mexico (CONAGUA and IBWC-Mexico), two from NGOs and two from state-level water authorities. In the MDB, we received seven completed questionnaires including three from federal level researchers (CSIRO), two from the basin authority (MDBA), one from a state government (South Australia) and one from a state-level irrigation district. Table 2-1 demonstrates the distribution of roles of the respondents, with some respondents selecting more than one category. The interview questions are provided in Appendix A.

Table 2-1. Survey Respondent Distribution

	Colorado River Basin			Murray-Darling Basin	
	United States		Mexico		
	Federal	Sub-Federal	Federal	Federal	Sub-Federal
Institutional Manager	3	2	1	2	
Research Scientist/Engineer	1	1	1	3	1
Policy Analyst	1	2			1
Consumer Representative		3			2

The questionnaire responses were coded for themes (Bernard and Ryan, 2010) using a constructivist grounded theory approach that allowed strong themes to emerge (Glaser and Strauss, 1967). These responses were then triangulated with the narratives provided in reports and other available literature, noting the authors’ role and nature of their perspectives. After compiling this information, the primary functions of boundary organizations – convening, translation, collaboration and mediation (Cash et al. 2006) were linked to the model characteristics of credibility, legitimacy and saliency (Cash et al. 2003). Throughout the results and subsequent discussion, respondent-approved quotes are provided to illustrate key findings. In the discussion, these findings are contrasted with the evolving use of WRMs in the Nile Basin.

2.4 RESULTS

Survey results are organised by credibility, legitimacy, saliency attributes of effective boundary work identified by Cash et al. (2003) with attention to both the physical ‘hardware’ (WRM infrastructure and resource commitments) and the institutional ‘software’ (governmental roles and shared knowledge capacities within each Basin) that acted to enable or prevent effective use of WRMs to guide water resource management decisions.

Credibility: The CRSS was widely considered scientifically credible by all respondents across the CRB. Survey respondents noted the modelling software platform, hydrologic data and methods used to evaluate uncertainty are well supported by peer-reviewed literature, and equations

simulating water management are structured as hierarchical rules that can be readily mapped onto the Law of the River. Throughout the basin, water demands were provided by the individual states based on population projections. Assumptions of exaggerated future demands from the upper basin states to safeguard future allocations challenged the credibility of WRM projections. To manage this critique, the USBR documented model assumptions thoroughly in each EIS study so that decisions could be accountable to the collaborative decision-making process.

In the MDB, the tools used to prepare the Basin Plan 2012 can be distinguished from the subsequent platform and model developments. The historical sub-basin models - IQQM, REALM and MSM-BIGMOD - were generally perceived to be scientifically credible due to the regard held for the model developers and the established institutional usage of these models. The credibility of the new Source software and the models actively being developed in this framework was supported by detailed documentation describing guidelines for model development (Black et al. 2014), quality control measures and procedures (MDBA 2012) and the scrutiny during the development of its internal algorithms (Welsh and Black 2010). The development of new models using this platform has however attracted some criticism amongst various non-federal stakeholders. One respondent stated they “have often been frustrated by the lack of evidence to support the modelling of the Murray-Darling Basin Authority.” Perceptions of credibility were influenced by limited access to the models, which are generally owned by individual States.

Legitimacy: According to respondents, the legitimacy of the CRSS was largely attributed to the direct access to the model given to stakeholders and the transparency that the platform provides. The USBR-developed model is freely available to participants through the *Stakeholder Modelling Workgroup*, however users must purchase a RiverWare software licence be able to modify the model or hire external consultants to do so. Survey respondents commented that the ability for stakeholders to analyse, operate, challenge and modify the CRSS helped them gain a sense of ownership during the inter-state negotiations of the EIS and processes, and allowed them to

develop new alternatives to be proposed for consideration. Perceptions of model legitimacy among various non-modelling stakeholders such as some Native American Tribes was not included in this assessment. These groups often rely on USBR to interpret the information that the CRSS produces.

Within the MDB, the legitimacy of historical WRMs was initially established through their relative simplicity at the time of initial development, followed by continuous use and enhancement across state offices. As new models are developed using the Source platform, expert input and algorithms from the legacy models are incorporated, thus their legitimacy is expected to transfer as well. State governments are generally responsible for developing their own local Source models while managing and stakeholder engagement with respect to WRMs and their outputs. The move to the new platform was generally seen as positive, however some non-state respondents expressed concerns. One respondent noted that their opportunity to provide feedback was limited to the results of the models and not the models themselves. Another respondent questioned the accessibility of the model when claiming the “custom approach, along with limited documentation, makes use of the models other than (by) the MDBA very difficult”. The prolonged adoption of the platform and implementation of new models reflects a degree of caution among the States or the constituents they represent. Problems of institutional fragmentation and historical model developments have challenged coordination and boundary work efforts between government and civil society, among state governments and between states and the MDBA.

Saliency: In order to fulfil their respective mandates to sustainably manage water resources into the future, the USBR and MDBA are the primary drivers of new model development. One challenge facing both basins was the evolution of water management concerns that required the function and scope of their WRMs to expand. In the case of the CRB, saliency of the CRSS model remained strong among federal and state government, however NGOs found the narrowness of the design to be a significant limitation when modelling environmental objectives. As one respondent noted,

“The fact that environmental flows are not assessed likely makes it easier for water managers to make decisions, as you are less likely to be concerned if you aren’t getting information that says you should be concerned.” This can raise some information equity issues. As one respondent observed, “Stakeholders could be disadvantaged because the model is not geared/suited towards their needs.”

While inclusion or exclusion of particular aspects in a WRM is subject to debate, respondents agreed that complex management decisions are difficult if not impossible to make without a basin-wide model. Concurrently many respondents recognized that models are not the ultimate arbitrators of water management decisions. This ‘necessary but insufficient’ role of WRMs was exemplified during the EIS negotiations when solutions proposed by one state or coalition would undergo a technical review by other parties using the CRSS. These reviews would occur alongside evaluations from legal and strategic policy-oriented perspectives before acceptance or counterproposals could be offered. This process would iterate until mutually agreeable outcomes could be reached. Throughout the development of Minute 319, similar iterations of proposed solutions followed by legal, political and technical analyses occurred between the two nations.

As experience with WRM development and application in the MDB highlights, issues such as severe drought can put enormous pressure on models to deliver immediate results to support the development of new water management guidelines. The need for integrated models to provide highly relevant decision support for basin-wide policies became increasingly clear. While many respondents highlighted that model saliency became a focus in terms of their capabilities, strengths and limitations, another respondent astutely noted that “A lot of energy can be expended in arguing about the model rather than what its saying.”

Next, key insights are organised to draw on main functions of boundary management: convening, translation, collaboration and mediation.

Convening: is an important initial function of boundary work, but can face numerous logistical challenges such funding to enable stakeholder input, or context specific challenges such as the selection of participants (Glicken 2000). This latter is delicate as excluding certain participants can delegitimize any boundary work before it begins, while including too many voices can render a discussion ineffective. Convening stakeholders in a federal context poses unique challenges of representation. The degree to which interests are adequately represented by sub-national governments depends on the democratic nature and political focus of the government. As an example, non-economic interests may not be on the agenda of the governments, and inclusion of NGOs may be necessary to voice these concerns. Establishing clear objectives at the outset can assist with deciding the composition of a group (Liu et al. 2008), but can also influence the output. This comparative analysis highlights that the capacity of water management institutions to work with WRMs and for stakeholders to engage in WRM information is key to the function of convening.

Development of the CRSS for managing the CRB began in 1970s by the USBR and from 1973 to 1978 it was “given serious scrutiny and many changes were made to solve some of the problems and strengthen some of areas of weakness that had been detected” (Cowan et al. 1981: 11). Participation from the States likely began then, but one respondent to our questionnaire surmised that the “entities least satisfied [today] with Colorado River Management were not at the table: tribes, conservation organizations, Mexico.”

During the inter-state negotiations leading to the recent EISs, the States increased their in-house modelling capacity and began to operate the CRSS independently of the USBR. Shortly thereafter, NGOs also invested in their own modelling expertise, which allowed greater access to, and understanding of, the alternatives under consideration. Within the U.S.A., the USBR facilitates a *Stakeholder Modelling Workgroup* that includes any stakeholder that “actively runs the model or uses its results”, which continues to be a key forum to share model assumptions, structure and

outputs. Through this technical working group, relationships that were developed throughout the negotiations are maintained. Upon commencement of the bi-national negotiations that resulted in Minute 319, the USBR also allowed the Mexican government to access the CRSS. This allowed Mexico to ask informed questions regarding how the U.S.A. administered their treaty allocation and better understand management process of the Colorado River. Throughout the bi-national negotiations, interstate and international committees of technical stakeholder representatives convened regularly to explore mechanisms of cooperation.

In the MDB the need to meet the obligations under the Water Act 2007 and to determine the SDLs became a major impetus to develop a nationally consistent approach to modelling for water management and planning. Significant efforts to were made to engage and inform stakeholders throughout the development of the Basin Plan (MDBA 2009). State water agencies provided the models used to develop the integrated modelling framework and offered comments throughout the process, but convening of technical individuals across the states during the integrated WRM development and application was less apparent than in the CRB (MDBA 2010a; MDBA 2010b; MDBA 2012). With regard to the development of the new Source modelling platform, since its inception significant efforts were made to convene stakeholders. Early workshops were held across the basin to elicit user requirements from eWater CRC partners. A team of senior project staff travelled across Australia to hold meetings with key management organizations in all states and territories with the aim of gaining their engagement (Welsh and Black 2010). In addition, a Technical User Group (TUG) was convened that included individuals from the eWater CRC partner organizations that were actively involved in software development.

Translation: of information and knowledge across language or cultural differences is a primary function of boundary organizations, and can manifest with effective boundary objects developed or applied by those institutions. This can be either through translators, a common spoken language, or in the case of certain endeavours, the nature of the boundary work itself (Robinson

et al. 2014). Models can be the medium for effective communication, even when language or other cultural differences exist, but can also present a barrier to some stakeholder's understanding given uncertainty inherent in such decision-support tools (Weichselgartner and Kaspersen 2010).

The benefits of developing strategies to facilitate structured knowledge translation between multiple actors and water governance organisations were highlighted as key ingredients to effective use of WRMs. In the case of the CRB, one respondent noted the importance of WRMs to not be a 'black box' and many emphasized the advantages of its transparent structure. The USBR believed that "transparency facilitated stakeholders being on relatively equal ground, rather than having an advantage" and one non-governmental stakeholder recognized that a model could create 'a common language' to enable participants from different levels of decision-making to engage in the complex task of policy development. The IBWC emphasized the translational function of the model by stating, "with the aid of the modelling information, the stakeholders were able to visualize the effects of drought and expected water allocations to users in both countries".

Experiences from the MDB highlight that translation requires that participants have sufficient technical expertise to engage in a model-based dialogue. Substantial investments in time and resources are often required, resulting in a "limited community of skilled modellers." Understanding the logic and limitations of models, the rationale behind the assumptions imbedded within them, and the value they provide to the decision making process is often challenging to communicate to a non-technical audience, particularly in the midst of a critical situation such as a severe drought. Perceived limitations to their usage was when "Resources were required to explain modelling results to decision makers (and also explain what models could and couldn't do)" and when complex results are presented with jargon and statistics that users of the

information cannot relate to. Communicating hydrologic uncertainty, particularly in face of unprecedented conditions, was a critical factor in the MDB.

Collaboration: is the process of building consensus for a particular objective (Margerum and Robinson 2015). The co-production of knowledge to underpin water models (Jasanoff 2004) or process of overcoming adversity (Susskind and Cruikshank 1987) are examples of powerful forces that can bond parties together. Such actions require time and effort to achieve success and can be difficult in water management contexts where there are multiple decision-makers, users and values to consider (Islam and Susskind 2012; Linnerooth-Bayer et al. 2001; Robinson et al. 2014). The benefits of collaborative model development for facilitating a broader understanding of trade-offs among stakeholders has been emphasised (van de Belt 2004), however such collaboration can be hindered by time pressure for an outcome, the specialization of knowledge required, or fear of political debates subverting the process or results (Gilfedder et al. 2016).

Collaborative decision making within a federal river context is the main justification for the formation of a river management organization or interstate compacts. A common WRM platform for analysis provides a medium for this collaboration. Agreements reached among individual states are expected to be accepted by the federal government, thus minimizing federal interference or regulations being imposed. The ability to reach such a consensus is facilitated by parties having equal access to the analytical tools and decision-making process, and presumably some capacity to influence them. An iterative exchange of possible solutions during negotiations is accelerated considerably if each party has trust in a common tool to develop and analyse new ideas, thus avoiding the risk of multiple models providing conflicting results.

In the case of the CRB, 'official' modelling is conducted by the USBR, with regular input and review from the states and other stakeholders in the *Stakeholder Modelling Workgroup*. When the CRSS was transferred to the RiverWare software platform, the goal was largely to encourage more

collaborative participation; however, most respondents indicated that it still requires a high level of expertise to understand, operate and modify. Many emphasized the need for a significant amount of time to understand and become comfortable with the model. One respondent stated, “Building trust in the model, model framework and assumptions, takes much longer than the actual time to run the model and produce the results.” Given Mexico’s initial inexperience with the CRSS during Minute 319 negotiations, one Mexican modeller identified a challenge as the “Lack of available resources for problem solving [and] model building and operation apart from model developer [sic].” This was reinforced by responses from the U.S.A acknowledging, “The U.S. agencies had greater knowledge than their Mexican counterparts in terms of experience”, yet “The U.S. worked with Mexico to insure adequate training and knowledge transfer”. While respondents from both sides of border expressed they “worked as a team” with “subgroups of modellers and decision makers [that] we always worked together”, others believed that Mexico was reluctant to “buy into CRSS analysis”.

Success of collaboration is not necessarily measured by the outcome, but by the process itself. The Surplus EIS helped build inter-state cooperation and model acceptance that was leveraged for the subsequent and more contentious Shortage EIS. Similarly, the modelling work during Minute 319 was perceived to form a basis for future collaboration between the U.S.A and Mexico. Process benefits were also realized by the NGOs ability demonstrate a relatively minor impact on other basin users of water dedicated to environmental objectives (Wheeler et al. 2007).

In the MDB, states contributed the their individual sub-basin models to form the Integrated River System Modelling Framework used to develop Basin Plan 2012 (MDBA 2012). The modelling itself was conducted by the MDBA and CSIRO, and comments were provided by the states. Our survey replies and media reports (Kotsios 2017) indicated that various stakeholders continue to hold a deep frustration over a lack of access to the models. Whether development and application of the

MDB WRMs for the Basin Plan could have been more transparent or inclusive is still a subject of debate and speculation.

The technical challenges faced in assembling the disparate models for development the Basin Plan have both demonstrated the need for a unified platform and encouraged members of the eWater CRC to work cooperatively to produce the new analytical tools. The new development of the Source modelling platform benefits from modern approaches to facilitate understanding and cooperation such as object oriented programming, graphical user interfaces, databases and internet communication. Welsh and Black (2010) describe extensive efforts to involve stakeholders during development including solicitation of user requirements, incorporating feedback, holding monthly project update meetings and conducting regular planning meetings. To satisfy the needs of all eWater CRC partners, frequent debates occurred on the appropriate modelling approaches to incorporate. Managing equity in stakeholder influence was often necessary, and when conflicts could not be resolved, multiple methods were incorporated into the software, often prolonging its development.

Mediation: The function of mediation in a trans-boundary river context is not limited to the science-policy interface as proposed in the original framing of the concept of boundary work, but must also include mediation between upstream and downstream jurisdictions, between national and sub-national governments, and between governments and a potential plethora of water users. With a sound design to incorporate and adapt to different types of knowledge, interests and geographical domains, WRMs can facilitate this effort as long as parties establish what knowledge the tool can and cannot support or provide.

With the broad understanding that conflicts over water resources are likely to intensify in both basins, increasing stakeholder engagement in WRM design and application will be useful for mediating those conflicts. One respondent in the CRB noted WRMs provide value to negotiations

by stating “Without models, there would be more speculation about future conditions, and likely more conflict as modelling has helped form the foundations of many important water management decisions.” AN NGO stakeholder believed models add value because “decisions are complex and intertwined even at small scales and are difficult to evaluate in any other way at large scales.” This statement supports a USBR assertion that including various stakeholders in the modelling process would “improve capacity so as to improve understanding regarding negotiations”. The process by which a model becomes a trusted mediation tool relies on its acceptance by conflicting parties. When describing lessons learned in the negotiations, one respondent in the CRB stated “Agreeing to use a particular model in a negotiation setting requires parties’ ‘buy-in’ of the model.” and “Model competition and too many models impedes investment in any one”. Even more fundamental, was the belief that “sound technical data is the foundation of effective/informed negotiation and decision making” and a key component is to “remove ... obstacles by sharing data and working off the same dataset.”

In the MDB this process continues, but even so, most respondents recognised that model outputs are very influential and heavily relied on to reach agreements. With respect to their role as a mediation tool between states during the development of the Basin Plan, one respondent stated that advantages were held by “Upstream states ... because they own and develop models of the tributaries” which they only share with the MDBA not the other states. Issues regarding model ownership were also problematic between the states and the MDBA since the MBDA was only allowed to use the State models under restrictive licenses. The assemblage of models was linked together to form an integrated assessment tool that was sufficient to develop the Basin Plan in response to the immediate need, however it was not distributed among stakeholders and thus limited its ability to serve the function of a common mediation tool. However after initial proposals, States provided comments and a number of model developments occurred to help refine the SDLs (MDBA 2012).

2.5 DISCUSSION

Federal rivers that flow across borders of sub-national states are often forced to reach agreements on how water is allocated, invoking knowledge-action systems that also cross political - as well as conceptual - boundaries to seek consensus among stakeholders. WRMs are tools that are used as platforms for making or justifying such decisions, with vastly different institutional approaches and process designs within a multi-actor environment. The application of WRMs within a federal river context demonstrates a complex form of boundary work, involving many interests and often require iterations of possible solutions (Sarkki et al. 2015).

The CRSS model in the CRB has evolved over five decades as the principal, and hence salient, basin-wide planning tool. Since the modernization of the CRSS into the RiverWare modelling platform in 1993, the capability of the software, general acceptance of the knowledge incorporated into the model, and number of trained model users around the basin has greatly expanded. This has had a profound effect on the credibility and legitimacy of the model among participating stakeholders. Future saliency is being tested as demands on the river evolve while the CRSS is ostensibly a reservoir operations and management model.

In contrast, the basin-wide modelling platform in the MDB is earlier in its evolution and has adopted an arguably more challenging task. Although various models have been used across the MDB for over four decades, the Water Act of 2007 and subsequent CSIRO Sustainable Yields Project (CSIRO 2008) provided the impetus to link the 24 local sub-basin models into an Integrated River System Modelling Framework (MDBA 2012). The advanced state of these sub-basin models and the need to maintain their functionality when replicating them in the newly developed Source software has presented a formidable challenge. Furthermore, the need to include aspects such as rainfall-runoff modelling, environmental criteria and accounting procedures to simulate water trading has led to the modular design of the Source software. The complexity of this scope has

both challenged the model development yet broadened its audience for saliency. Ultimately is expected to result in a multi-faceted modelling tool.

When analysing the development and application of WRM within complex river basins with respect to boundary work, it becomes clear that the classical definition of boundary work on the science-policy interface must be expanded to be applicable. Clark et al. (2016) provides a useful generalized framework that classifies a matrix of one to many sources of knowledge mapped onto the various uses of enlightenment, decision-making and negotiation. Within this framework, both the CRB and MDB are examples of *political bargaining* due to the incorporation of knowledge from multiple experts and the negotiation among multiple users of knowledge. For a tool, such as a model, to be useful, it must be sufficiently trusted by, not only the scientists that contribute data and design the algorithms, but also by policy makers that may use its outputs and stakeholders that must adhere to the decisions they make from it. Stakeholders can help formulate the model assumptions, but there must be a fundamental match between model functionality and what the users can expect. Both case studies described this critical point of managing expectations and this constitutes a significant component of boundary work.

In the case of these complex systems, the sources and users of knowledge are distributed across political as well as social boundaries, thus boundaries exist between the multiple sources of science, the multiple governance structures involved and the multiple stakeholders affected. Figure 2-4 presents a conceptual model of these three broad categories of actors, across multiple political boundaries (states) within a federal state, and WRM types. The role of boundary work between each interface is shown with each group's emphasis of legitimacy, credibility and saliency (Cash et al. 2003). Within this space, we can identify types of models used and their particular emphases. For example, purely scientific fact-finding models may focus on being a credible beacon of truth, yet at the expense of transparency to stakeholders or utility to policy-makers. A decision-support system may be constructed to be policy-relevant, but lack scientific rigor or limit

stakeholder access and understanding. A model focused on stakeholder learning might generate broad understanding of the issues, but lack scientific rigor or the flexibility needed to simulate complex laws, treaties or policies.

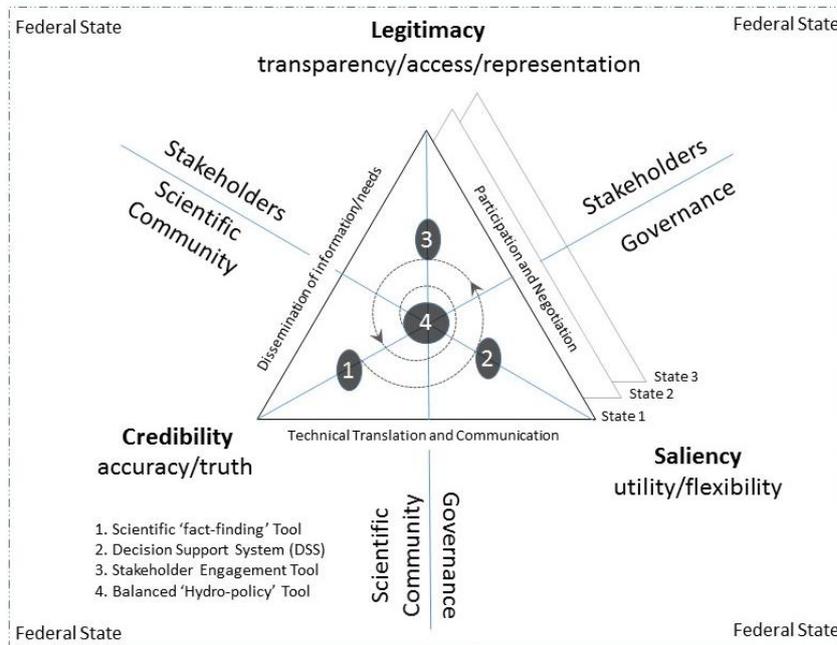


Figure 2-4. Shared water resource models as a boundary objects

The evolution of WRMs emerged as a key theme in this research and is depicted in Figure 2-4. Models were initially developed in both basins, as well as many others in the world, as largely scientific endeavours that sought to be useful decision-making tools (1, 2), but largely inaccessible by others who may wish to challenge their assumptions. As the value of stakeholder participation and decentralized governance emerged, the need for greater access to these influential tools grew (3). The migration of the CRSS into the RiverWare software starting in 1993 and the development of the Source in 2007, were both substantial efforts to increase stakeholder participation and hence find the right balance between legitimacy, credibility and saliency (towards 4). In the context of river basin management, this has been termed a hydro-policy model (Wheeler et al. 2016).

The successes and challenges of using WRMs in the CRB and MDB can provide insight to the obstacles faced in the Nile Basin and provide possible pathways for overcoming them. The Nile-DSS began with a series of consultations led by the NBI of stakeholders and external experts from other river basins to determine what form of analytical framework was needed to manage the future of the Nile (Droogers et al. 2010). Drawing from these experiences, a comprehensive assortment of requirements was developed that could inform decisions, over investments, management alternatives, and future negotiations. Specifically, the requirements prescribed that the Nile-DSS include:

- An information management system that provides a common and shared information basis for the planning and decision making processes, locally, sub-regionally, and basin wide, directly accessible for all stakeholders;
- A modular river basin modelling and economic evaluation system built around a dynamic water budget and allocation model, that helps to design and evaluate possible interventions, strategies and projects in response to the problems and challenges identified and prioritized in the stakeholder consultations;
- Tools for a participatory multi-criteria analysis to rank and select alternative compromise solutions for win-win strategies.

Similar to the case of the CRB and MDB, the Nile-DSS was developed to facilitate basin-wide decision-making. However, the pathways of development differed considerably. The modelling platform in which the Nile-DSS would be developed was based on a contract with the Danish Hydrologic Institute (DHI) using a suite of commercial modelling products. By using a well-established modelling product, the NBI could provide assurance to its stakeholders of the *credibility* of the algorithms used. The database associated with the Nile-DSS would provide a vast repository of information that includes many types of data including information on climate, hydrology, land use, hydraulic characteristics, environmental needs etc., and could include raw,

processed and modelled information. Furthermore, the Nile-DSS was coupled with a Geographic Information System (GIS) that would allow spatially distributed information to be utilized for analysis, displayed, and archived. In principal, the Nile-DSS also incorporates the ability of a number of modelling platforms to access and utilize the information provided in the database, as well as contribute to the archive.

With the use of professional consultants and a wide breadth of capabilities, the NBI sought to demonstrate the *credibility* of the Nile-DSS and worked to expand its *legitimacy* among a wide variety of stakeholders and interests, however the multi-purpose development objective greatly exceeded the narrow scope of the reservoir management objective of the CRSS, and even the drought-driven development of the basin-wide MDB WRM. Regardless of these efforts to gain legitimacy, challenges in building stakeholder acceptance have been observed, particularly driven by arguments of *saliency* in Egypt and Sudan. For Egypt, a lack of uptake has been largely driven by the fear of capitulation of their perceived historical rights and a preference of pre-existing tools that are not shared basin-wide, while the uptake of in Sudan has been attributed to the inability of the modelling tools used in the Nile DSS to simulate complex and detailed reservoir operations. Both countries have expressed concerns over the effort required to learn the complexity of the data intensive modelling system relative to the utility of the tool to meet their pressing needs.

The development of the Nile-DSS did not follow the evolution demonstrated in Figure 2-4. Assumptions of credibility and a focus on expanding its legitimacy subverted its saliency. This was largely driven by the tense political context in which these efforts took place. The product was a generalized tool that sought to address a wide variety of concerns rather than a tool that was aimed on dealing with a particular pressing issue. By the time the critical issue of the Grand Ethiopian Renaissance Dam (GERD) arose in 2014, Egypt had withdrawn from the NBI and the Nile-DSS was not yet adopted by either downstream riparian country. Despite the efforts of the NBI, the four functions of boundary work - convening, translation, collaboration and mediation – could

not be demonstrated on a basin-wide scale without the participation of Egypt. Instead, an additional modelling effort by an external consultant was funded by a tripartite committee comprised of representatives of Egypt, Sudan and Ethiopia. This expert-led effort has thus far not yielded any agreement due to conflicts over the assumptions in which the modelling is based. Only speculations can be made on whether the design and implementation of the Nile-DSS could have been improved, however, a streamlined model that adequately addressed the emerging issue of the GERD and coordination of its operational rules with existing reservoirs could have made the downstream countries more apt to use it. Since this issue of the GERD has not yet been resolved at the time this thesis is being written, the Nile-DSS may still prove to be useful as a negotiation tool for this or future projects, but will likely require an expanded user base and a narrower focus.

Throughout all case studies, it became apparent that the issue of access emerged as critical factor for models to serve as an effective boundary object between multiple stakeholders, policy-makers and scientific sources, Limitations to model access can be a result of many reasons that include, but are not limited to, proper training and understanding, financial resources to invest in the knowledge required to participate, institutional barriers such as intellectual property rights, or concerns regarding the of loss of local control over resources. Each of these barriers have been, and must be, addressed by developers, managers and users of WRMs if they are to serve as effective boundary objects. In the MDB, one respondent claimed, “The models are very complicated and require an intimate knowledge of the model and the system to be able to run and modify the model”. In the CRB, NGOs hired external consultants to support their needs but explained, “There’s usually more useful modelling that could be done than we can afford”. In both basins, there is reluctance by the developers to share models widely outside of technical groups “either for security reasons or fear that others will not have the relevant skills to run the model appropriately”. Although clearly not the arbitrators of truth, WRMs have a significant influence over discourse of water management, and the misuse of models can complicate negotiations or

compromise their function as effective tools for mediation. Developing effective protocols for access and peer review can help to resolve these challenging issues.

2.6 CONCLUSIONS

WRMs in federal and international rivers have emerged as potent examples of boundary objects serving the functions of boundary work to handle the complexities of allocating natural resources in regions experiencing environmental changes. This becomes increasingly critical, as the potential for future conflict exists at multiple levels and between multiple users and uses. Both case studies illustrate how drought and future drought risk initiated, and has sustained, significant advancements of WRM to manage boundary work. WRM are influential tools for supporting the decision-making process and can provide insight into system-wide dynamics however, they are simplifications of reality, imperfect by nature, and by understanding this, consideration of other sources of knowledge is concurrently needed.

Many lessons drawn from this research are potentially transferable to other contested federal or transboundary contexts in which WRM are implemented such as the Nile River, the Mekong River, the Tigris and Euphrates Rivers. Similar to other knowledge information systems seeking to provide viable and sustainable solutions, the challenges for WRM often lies in the tensions between saliency, credibility and legitimacy. Therefore, we provide three key recommendations:

1. A well-structured modelling process should identify what aspects are included and excluded in the framework, resulting in explicit knowledge gaps that stakeholders could help to fill.
2. Stakeholder groups can potentially benefit significantly from investing in their own technical capacity to understand, review and use models collaboratively or independent of the model developers.

3. Model developers must allow WRMs to be available for scrutiny by knowledgeable stakeholders to enhance model acceptance and relevance.

3 COOPERATIVE FILLING APPROACHES FOR THE GRAND ETHIOPIAN RENAISSANCE DAM

3.1 INTRODUCTION

The construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile offers a unique and timely opportunity for cooperation among the Eastern Nile countries of Ethiopia, Sudan, and Egypt. While the potential benefits of the GERD to Ethiopia and surrounding countries are apparent through improved electrification (EDF and Scott Wilson 2007) questions of how the GERD will affect water supply and power generation of downstream countries has been the focus of ongoing debates by numerous stakeholders and institutions both internal and external to the basin. We acknowledge the historically rich and geopolitically complex situation that currently exists in the region. Consequentially, this study explicitly does not attempt to address issues of this larger context, but focuses exclusively on the physical characteristics of the system including the operation of current and planned infrastructure, along with the potential for coordination and collaboration amongst the parties involved.

A review of existing design documents by an International Panel of Experts indicated the need for further analysis of the period during which the 74 billion cubic meter (BCM) storage reservoir behind the GERD will be initially filled (IPoE 2013). A recent Declaration of Principles (DoP) was signed by the leaders of the three countries that exemplifies the willingness of the parties to cooperate on these matters (DoP 2015), however the technical details of how this cooperation would manifest with respect to reservoir filling have yet to be established. While this period could result in the first effects to downstream countries, it also provides the first opportunity to translate the principles of cooperation into tangible actions.

Numerous computer models have been developed that simulate the long-term development of the Eastern Nile Basin (Arjoon et al. 2014; Blackmore and Whittington 2008; Block and Strzepek

2010; Guariso and Whittington 1987; McCartney and Girma 2012; Yao and Georgakakos 2003), and recent efforts have been conducted to analyse possible GERD filling strategies (Bates et al. 2013; King and Block 2014; Mulat and Moges 2014; Zhang et al. 2015). While all the modelling tools listed above have strengths and have provided valuable insight for the basin, the studies concerning GERD filling strategies has either limited the analyses to a handful of hydrologic scenarios resulting in deterministic results (Bates et al. 2013; Mulat and Moges 2014), lacks detail of the current complex operations of existing reservoirs (King and Block 2014; Zhang et al. 2015), or provides limited flexibility to test creative and incremental degrees of coordination among stakeholders.

This paper compares the findings of 224 potential and practical filling strategies that are developed from combinations of 1) various operations of the GERD during filling, 2) modifications to the current operations (reoperation) of the Sudanese and Egyptian Reservoirs, 3) explicit coordination of releases from the GERD to avoid critical downstream impacts, and 4) starting conditions of the High Aswan Dam (HAD). Each management alternative was analysed using 103 sequences of hydrologic inflow data to compare the filling strategies and scenarios with a risk-based framework. This paper demonstrates that the degree to which cooperation takes place on a technical level is a continuum ranging from unilateral operations to truly dynamically cooperative solutions that reflect an awareness of the benefits and risks to others (Sadoff and Grey 2005). As a result, a wide variety of solutions can be identified that can inform a negotiation process, yet the complexities of implementing cooperative strategies must not be underestimated.

Finally, this paper argues that, although an agreement ultimately should not be based solely on technical studies, a successful negotiation can be supported through a well-designed hydro-policy modelling framework. We define such a framework as one that provides sufficient accuracy, transparency, and flexibility for stakeholders to develop and test innovative solutions and explore

the trade-offs and benefits of compromise. Such a framework should provide a sufficient representation of the physical characteristics of a system alongside an accurate representation of the existing and potential operational policies. In this spirit, a particular ‘optimal’ filling solution is intentionally not identified, but a potential pathway of mutual benefit through joint management is identified for further exploration by stakeholders within the basin.

3.2 STUDY AREA

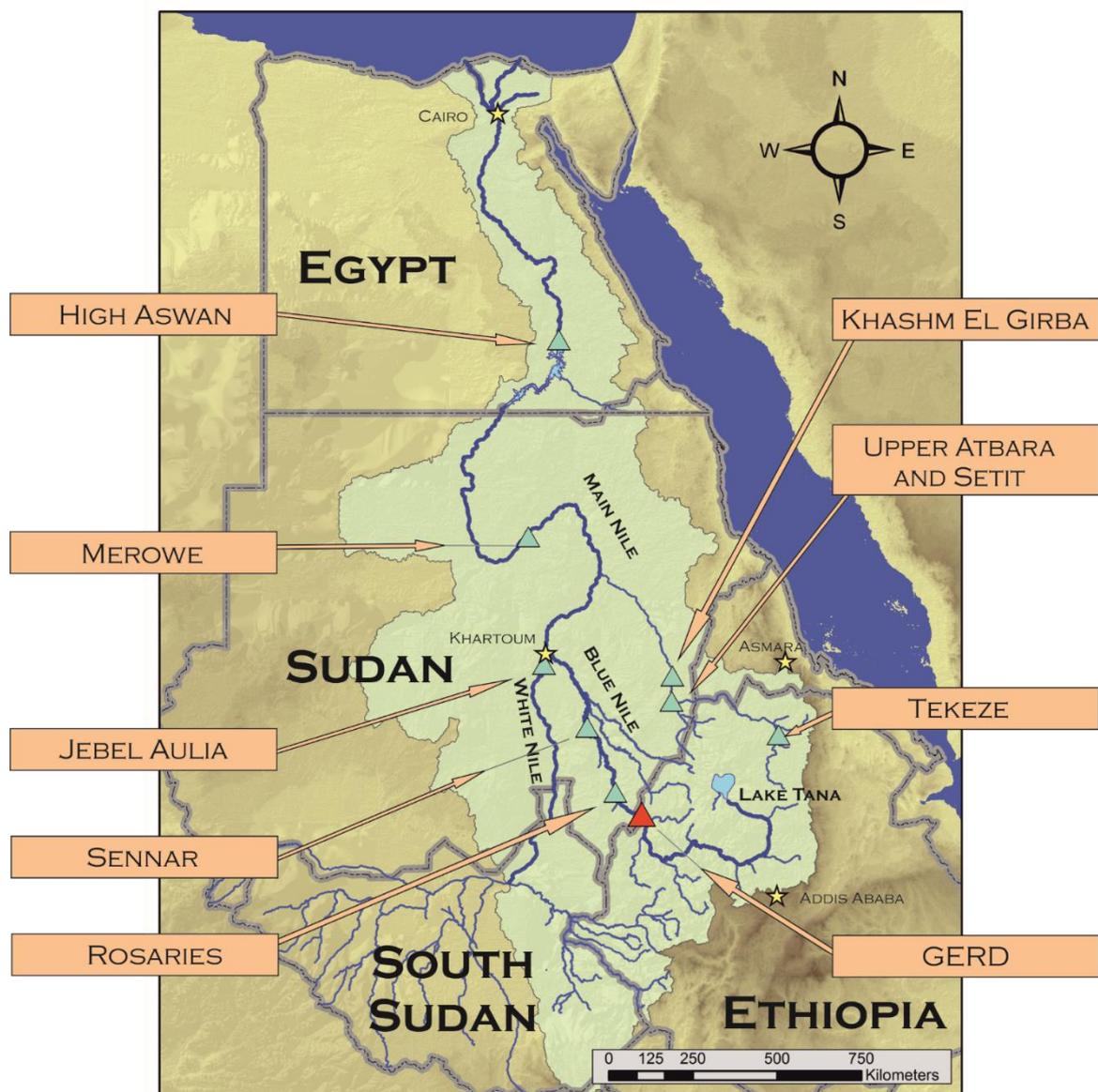


Figure 3-1. Map of Eastern Nile region with reservoir locations

The study area consists of the Eastern Nile region of the Nile Basin (Figure 3-1). This uses a commonly assumed hydrologic division that separates the Equatorial Lakes region from those regions that contribute flows below the Sudd wetlands. The complex and buffering effect of these wetlands and the long-maintained Malakal gage in South Sudan provide the justification for this assumption, particularly relevant when analysing future developments in the Blue Nile tributary that is independent of changes to the inflows around the Equatorial Lakes. The monsoonal rainfall over the highlands of Ethiopia generates the majority of the flow into the system via the Blue Nile, the Tekeze-Setit-Atbara, and the Baro-Akobo-Sobat sub-basins (Sutcliffe and Parks 1999), while only approximately half of the contributions from the Lake Victoria region emerge from wetlands of South Sudan. As a result, the Blue Nile contributes approximately 57% of the total runoff into the Main Nile as measured inflow to Egypt, while the White Nile and the Atbara River contribute 30% and 13%, respectively (Blackmore and Whittington 2008; NBI 2012). Although the majority of precipitation falls in Ethiopia and the Equatorial Lakes region, Egypt and Sudan consume the vast majority of water. This geographic disparity between where the rivers begin and where the water is consumed provides both the potential for conflict and the rationale for cooperation.

3.2.1 Infrastructure

The construction of the GERD is the latest chapter in a substantial history of infrastructure development in the Eastern Nile Basin. Although coordinated planning and operation of infrastructure across international borders has existed briefly in the past, the longevity of this coordination has been limited with respect to actual operations. The Low Aswan Dam (1902), Sennar Dam (1925), and Jebel Aulia Dam (1937) were constructed under British colonial influence with a vision of coordinated management that would extend the availability of seasonal flood waters in Egypt and open up the agricultural potential in Sudan with the Gezira irrigation scheme (Tvedt 2004). After independence of Egypt and Sudan, the Khashim El Girba Dam (1964), Rosaries Dam (1966), and High Aswan Dam (HAD; 1970) were constructed under the auspices of the 1959

treaty between the two countries (Nile Treaty 1959). This agreement established a joint technical committee to oversee data collection and periodic technical assessments; however, joint operations of the reservoirs was not established and the storage volume of the HAD made any previous coordination between the original Aswan Dam and the Sudanese dams irrelevant. The relatively recent development projects of Ethiopia's Tekeze Dam (2009) and Sudan's Merowe Dam (2009) have been effectively independent of international coordination during construction and operation, with hydropower as essentially their only purpose. At the current time, joint management of infrastructure across international boundaries in the Eastern Nile basin is non-existent (see (Salman 2016) and Yihdego (2016) for more detail).

With 169 BCM of storage capacity, Egypt's HAD is the only structure in the basin that creates a storage volume comparable to that of the GERD. Even though the benefits of the HAD have been shown to be substantially positive for the economy of Egypt (Strzepek et al. 2008), the development of additional storage upstream has been met with concern due to uncertainty of what the implications may be for both Sudan and Egypt.

3.2.2 GERD Project

The United States Bureau of Reclamation conducted a study on behalf of the Government of Ethiopia that identified four potential dam sites on the Blue Nile, including one which has now become the location of the GERD (USBR 1964). As described in greater detail in (Yihdego et al. 2016), Ethiopia began the GERD construction project in 2011, which has a planned full supply elevation of 640 m and will create 74 BCM of reservoir storage – equal to approximately 1.5 times the average annual flow at the dam location.

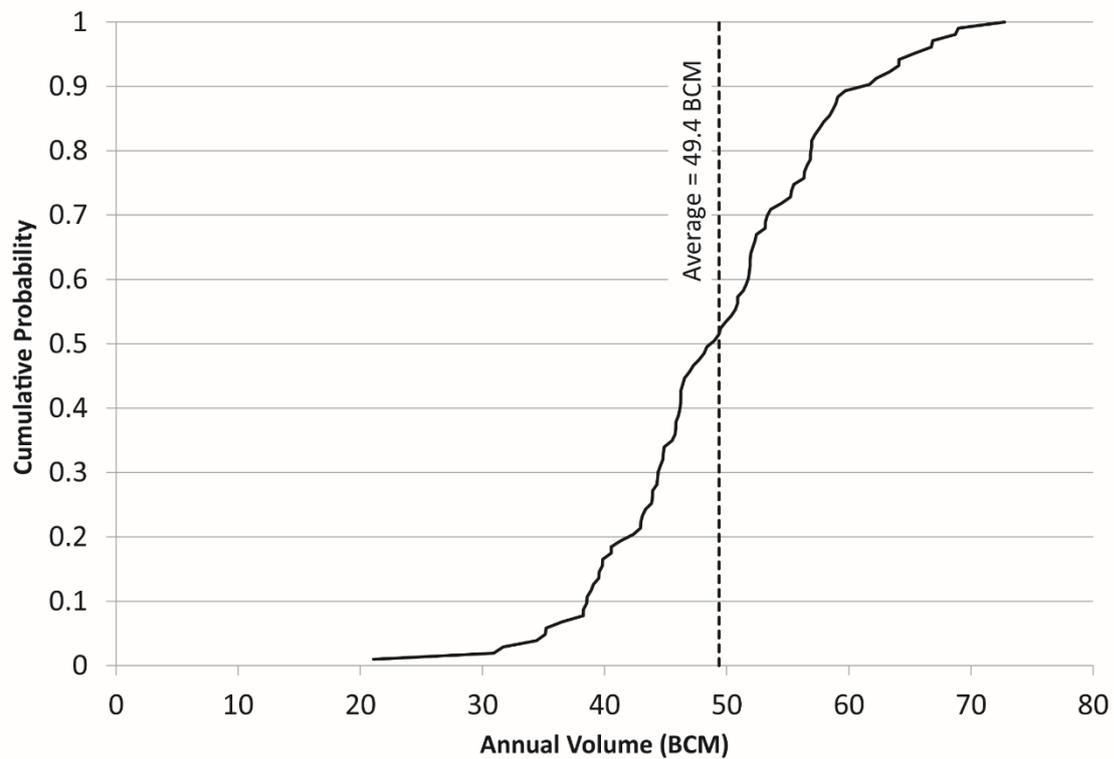


Figure 3-2. Annual flow volume at the GERD site

The addition of 6,000 MW of installed generation capacity to the approximately 6,833 MW that currently exists within the basin (NBI 2012) suggests that the GERD is likely to be a significant step-change for the region as a whole with respect to access to electricity (NBI 2012; Whittington et al. 2014). Furthermore, the additional storage on a river system that produces an average 94.5 BCM of annual runoff into Egypt (Blackmore and Whittington 2008) could potentially allow greater reliability of flows for Sudan and Egypt. In addition to the Ethiopian hydropower benefits, arguments supporting the dam claim that increased control over the natural flow regime will result in reduction of the flooding risk to Sudan, reduction of sediment in the river that currently challenges the management of reservoirs and agricultural schemes, hydropower efficiency benefits for Sudanese reservoirs, improved depth for navigation, and reduced pumping costs for water users (Ethiopian NPoE 2013).

Critics of the dam claim that there are risks of reduced downstream water availability and reduced Egyptian hydropower, the likely loss of recession agriculture in Sudan, losses to the brick production industry that use the sediment deposits, reduced land fertility due to the reduction of nutrient rich sediment, and an unknown environmental impact (Beyene 2013; Egyptian Chronicles 2013). Although these critics claim the reservoir's planned storage and turbine capacity are oversized, the Ethiopian government believes the benefits will be worth the \$4.8 billion construction cost.

Independent assessments note both potential costs and benefits, and have called for more studies to be conducted (Bates et al. 2013; MIT 2014). While Ethiopia seeks to take greater advantage of the benefits the river may provide, it is still unclear how these benefits and costs may be incurred, especially during the reservoir filling period.

3.2.3 Previous Studies

In addition to the more general development studies described in Section 2.3.1.3, three recent analyses have specifically considered the filling of the GERD. Bates et al. (2013) analysed specific fixed monthly release patterns that range from 20.8 to 40.0 BCM/year under three deterministic *average, moderate drought* and *severe drought* scenarios and using three starting elevations of the HAD. A combination of tools was used in this study including MIKE BASIN and the RAPSO model (EDF and Scott Wilson 2007) and separate runs were required to capture the transition of policies from filling to normal operations. Similarly, Mulat and Moges (2014) used MIKE HYDRO to simulate a single historical period of 1973-1978 that represents "average" conditions to analyse a predefined single 6 year filling strategy. This study considers a single hydrologic inflow node on each the Blue and White Nile tributaries, includes the GERD and HAD, but contains no information on Sudanese reservoirs or any intervening flows. King and Block (2014) and Zhang et al. (2015) describe a model to simulate five potential filling policies including retention of 5%, 10% and 25%

of inflows, and retention of flows over the historical annual mean average (HASF) and 90% of the HASF. This study uses stochastically generated inflows from a precipitation-driven hydrologic model and includes the potential effects of climate change, yet the model is simplified with four inflow nodes and considers only the GERD and no other reservoirs.

While the studies that have been published to date provide insight by analysing a number of possible filling strategies, there remains an urgent need for a robust analytical policy-oriented modelling framework that can adequately represent all major infrastructures in the system with their existing operational criteria, simulate the many potential GERD filling arrangements that can be envisaged by the negotiators, and be physically accessible and logically verifiable by parties within the basin. Cash et al. (2003) describe the essential role and criteria of knowledge systems to enhance the credibility, legitimacy and saliency of the information they provide. Olsson and Andersson (2007) emphasise that the acceptance and influence of water resource management models depends on the access and ability of stakeholders to understand and be able to criticise the methods and assumptions embedded in the tools. In essence, the 'hydro-policy' modelling framework needed for this analysis should be robust enough to represent a system with sufficient *accuracy*, be sufficiently *flexible* in its architecture, and be *transparent* enough to be understood and trusted by stakeholders. Furthermore, any study should demonstrate a completeness of sampling hydrology and management strategies.

3.3 METHOD

3.3.1 Modelling Framework

For the purposes of developing and testing various potential filling strategies for the GERD, the RiverWare platform was selected based on its flexible rule-based design (Zagona et al. 2001) and ability to meet the above criteria. This capability has been demonstrated by its recent successful

use in trans-boundary negotiations over international management of the Colorado River (United States of America and United Mexican States 2012).

3.3.1.1 RiverWare Modelling Environment

The RiverWare modelling environment utilizes an object-oriented workspace to represent physical items in the basin such as tributary inflow locations, reservoirs, hydropower generation facilities, water diversions, water users, river reaches, pipelines, etc. Each object is described by a number of data attributes or *slots* such as time series information (e.g. inflows and outflows), descriptive information provided in predefined tables (e.g. elevation-volume relationships for reservoirs, power generation characteristics of turbines as a function of hydraulic head and flow through turbines), or fixed scalar values (e.g. minimum operation levels of reservoirs, roughness coefficient of channels). Engineering algorithms are selected from extensive libraries that compute facets of water management for each object based on the known physical characteristics of the system and information available. A model is executed over a specified time horizon using time steps ranging from hourly (i.e. real-time operations) to yearly (i.e. long-range planning studies). Whenever an object is provided with sufficient information given the selected engineering algorithms for that particular object, the object solves and outputs are produced. These outputs are propagated throughout the model network through links between objects, causing other objects to solve. This solution system frequently results in an under-determined system wherever management decisions must be made, similar to actual water management infrastructure. A prioritized rule-based simulation procedure provides underdetermined model objects with scripted user input, which can characterize the myriad of multi-objective operational policies that govern the management of water including international and intra-national agreements between users, water rights arrangements, legal constraints, and dam management guidelines. This format allows management decisions to be freely coded into the logic of any object to determine its solution independent of other objects in the model. Alternatively,

RiverWare has the capability of solving as classic optimization problem using a linear pre-emptive goal programming technique if and when is desired by the user, but this solution method is not used in the current modelling configuration.

The generalized format allows RiverWare to simulate the movement of water through a river basin while maintaining mass-balance yet not be constrained by pre-determined management algorithms or solutions. Data management interface allows any pieces of data to be imported to or exported or from the model, thereby connecting a model freely to databases, spreadsheets or other modelling tools. Concurrent model executions allow multiple runs to execute in parallel, allowing multiple scenarios such as hydrologic conditions, demand futures, or management policies to be executed for statistical evaluation and policy analyses. RiverWare allows many other capabilities such as salinity simulations and water accounting that are not used in the current Nile model, but provide an extensive platform for expansion of the tool for future analyses.

3.3.2 Nile Basin Model Structure

The RiverWare model of the Eastern Nile developed for this study was structured to contain all the major features in the basin that significantly affect water management and distribution including: Lake Tana with the Tana-Beles Hydropower Project and Tekeze Reservoir in Ethiopia; Rosaries, Sennar, Jebel Aulia, Khashim El Girba, and Merowe reservoirs in Sudan; and Lake Nasser/Lake Nubia formed by the HAD in Egypt. The recently heightened Rosaries Dam, the newly developed Upper Atbara and Setit Dam complex, and the GERD are included in simulations of future conditions. Monthly naturalized hydrologic input locations include 162 inflow nodes within South Sudan, Ethiopia, Sudan and Egypt. Demand locations reflect the major Sudanese diversion structures of the Gezira-Managil, New Halfa and Rahad schemes as well as the minor diversions from the Jebel Aulia reservoir and small aggregated demands between gauged locations.

Consumptive or non-consumptive water uses within Egypt are not modelled beyond expected monthly releases from Aswan and necessary spills into the Toshka diversion works.

3.3.3 Data Requirements

The basin-wide hydrologic inflow data were developed by van der Krogt and Ogink (2013) and provided by the ENTRO office of NBI. This study compiled historical hydrologic data collected from a variety of sources with differing periods of record and filled in missing data using site specific regression and partitioning techniques to reconstruct a complete naturalized dataset - meaning non-depleted and unregulated by anthropogenic effects - of 103 years (1900-2002). Stochastic hydrologic conditions were developed using the index-sequential method (Ouarda et al. 1997), which applies a historical sequence of naturalized hydrologic flows to the future modelled period (2016-2059) with a start date that corresponds to each of the years in the reconstructed historical record. The length of the simulation period was selected to allow the model to reach equilibrium after the effects of filling under all hydrologic conditions. We acknowledge that the selected hydrologic method does not reflect future transient climate change conditions (Milly et al. 2008) or the *Hurst Effect* of persistent behaviour of flows (Hurst et al. 1965), however the approach is considered sufficiently robust for this analysis given the short-term nature of the filling process.

Estimates of current irrigation water use were obtained during the Nile Basin DSS development (Carron et al. 2011). Historical diversions from the Nile Encyclopaedia (Nile Control Staff 1933-Present) were used for calibration when available, and the Nile Basin DSS data was used otherwise recognising that this likely represented an overestimation of historical uses. Diversions for the Gezira/Managil scheme were updated with recent monthly averages from September 2012 to August 2014 (Sudan MoWE 2015). Future target annual diversion volumes were assumed to remain constant throughout the modelled period to isolate the effects solely attributable to the GERD from any further changes to water use that could be partially attributable to the GERD or

future development in the basin. For the purposes of this study, Ethiopia's diversions from the Nile are assumed to remain insignificant, while Sudan's diversions are assumed to remain at the current estimated volume of 16.0 BCM per year using the data sources described above, and Egypt's annual diversions are assumed to be 55.5 BCM, which is equivalent to the allocation specified in the 1959 Treaty with Sudan (Nile Treaty 1959). Although these assumptions have been incorporated into this study to reflect our best understanding of the current reality (see supplemental appendix), variants upon them could be readily explored if new water use estimates become available.

Current reservoir operations were obtained from numerous information sources throughout the basin including the Nile Basin Initiative (ENTRO 2013), water resource agencies (Egypt MWRI 2005; Sudan MoIHP 1968), engineering reports (Lahmeyer International 2005; PB Power 2003; Salini Costruttori 2006; SMEC International 2012) and analysis of various existing models (Jonker et al. 2012; Mulat and Moges 2014; van der Krogt and Ogink 2013; Yao and Georgakakos 2003). In the absence of further information, operations of single purpose hydropower reservoirs were simulated to generate a target power production. Reservoirs with more available information were simulated as being managed for a combination of hydropower production, control of sediment accumulation by seasonal reduction of pool elevations, satisfying irrigation diversions from the reservoir, and meeting downstream flow requirements (Table 3-1). Just as the requirements that govern actual dam operations change throughout the year, prioritized operation rules were written to simulate these changing objectives. The model was made available and refined through seven training workshops conducted between 2012 and 2016 at NBI-ENTRO, Addis Ababa University, University of Khartoum, Cairo University, Sudan's Dams Implementation Unit of the Ministry of Water Resources, Irrigation and Electricity, and Egypt's Water Resources Research Institute of the Ministry of Water Resources and Irrigation. After operational policies were simulated in the rules with the best available information, modifications

were made to explore alternative management policies. All rules in the model were transparently written to allow the technically trained stakeholders to readily understand the operational logic. Participation in these training sessions does not imply endorsement of the model or the results.

Table 3-1. Prioritized operation parameters of existing reservoirs

	Rosaries				Sennar				Jebel Aulia			Khashm El Girba				Merowe			HAD	
Jan	<----->	*	--	<---by-product of other operations--->	<----->	856	421.7	<---by-product of other operations--->	56	377.4	<---by-product of other operations--->	<----->	113	474	<---by-product of other operations--->	<----->	--	470	3510	<---by-product of other operations--->
Feb	<----->	*	--	<---by-product of other operations--->	<----->	794	421.7	<---by-product of other operations--->	60	377.4	<---by-product of other operations--->	<----->	96	474	<---by-product of other operations--->	<----->	--	536	3920	<---by-product of other operations--->
Mar	<----->	*	--	<---by-product of other operations--->	<----->	416	421.7	<---by-product of other operations--->	75	376.9	<---by-product of other operations--->	<----->	74	474	<---by-product of other operations--->	<----->	--	565	4380	<---by-product of other operations--->
Apr	<----->	*	--	<---by-product of other operations--->	<----->	69	421.7	<---by-product of other operations--->	81	375.4	<---by-product of other operations--->	<----->	44	474	<---by-product of other operations--->	<----->	--	639	4120	<---by-product of other operations--->
May	<----->	*	--	<---by-product of other operations--->	<----->	138	417.0	<---by-product of other operations--->	88	373.9	<---by-product of other operations--->	<----->	52	474	<---by-product of other operations--->	<----->	--	699	5080	<---by-product of other operations--->
Jun	<----->		470	<---by-product of other operations--->	<----->	659	417.0	<---by-product of other operations--->	92	372.5	<---by-product of other operations--->	<----->	106	464	<---by-product of other operations--->	<----->	290	861	6320	<---by-product of other operations--->
Jul	<----->		469	<---by-product of other operations--->	<----->	937	417.0	<---by-product of other operations--->	185	376.5	<---by-product of other operations--->	<----->	122	464	<---by-product of other operations--->	<----->	290	860	6760	<---by-product of other operations--->
Aug	<----->		469	<---by-product of other operations--->	<----->	474	417.0	<---by-product of other operations--->	193	376.5	<---by-product of other operations--->	<----->	138	464	<---by-product of other operations--->	<----->	290	740	5900	<---by-product of other operations--->
Sep	<----->		487	<---by-product of other operations--->	<----->	938	418.7	<---by-product of other operations--->	352	377.4	<---by-product of other operations--->	<----->	134	474	<---by-product of other operations--->	<----->	298	861	4150	<---by-product of other operations--->
Oct	<----->		490	<---by-product of other operations--->	<----->	1040	421.7	<---by-product of other operations--->	418	377.4	<---by-product of other operations--->	<----->	148	474	<---by-product of other operations--->	<----->	300	860	3890	<---by-product of other operations--->
Nov	<----->	*	--	<---by-product of other operations--->	<----->	926	421.7	<---by-product of other operations--->	351	377.4	<---by-product of other operations--->	<----->	121	474	<---by-product of other operations--->	<----->	300	625	3840	<---by-product of other operations--->
Dec	<----->	*	--	<---by-product of other operations--->	<----->	922	421.7	<---by-product of other operations--->	99	377.4	<---by-product of other operations--->	<----->	121	474	<---by-product of other operations--->	<----->	300	511	3720	<---by-product of other operations--->
Priority	1	2	3	4	1	2	3	4	1	2	3	1	2	3	4	1	2	3	1	2
	Min Outflow (MCM)	Downstream Demands	Target Elevation (m)	Power Generation (MW)	Min Outflow (MCM)	Direct Diversions (MCM)	Target Elevation (m)	Power Generation (MW)	Direct Withdraws (MCM)	Target Elevation (m)	Power Generation (MW)	Min Outflow (MCM)	Direct Diversions (MCM)	Target Elevation (m)	Power Generation (MW)	Min Outflow (MCM)	Target Elevation (m)	Target Power (MW)	Target Release (MCM)	Power Generation (MW)

* Rosaries release to meet storage proportional % of (Gezira + DS Sennar Demands) + Rosaries to Sennar Demands - Rosaries to Sennar Inflows
 Note: Tekeze Operated for 112 MW constant hydropower, Upper Atbara and Setit Dam complex operated for 43 MW constant hydropower

3.3.4 Model Calibration/Validation

A basin-wide model calibration and validation was performed by simulating historical conditions including hydrologic flows, channel diversions, and dam operations. Actual reservoir pool elevations and historical dam operation policies were used whenever available to drive the simulation, including historical dam construction dates and filling periods. Calibration parameters include travel times using time-lag routing and storage routing, flow and time dependent channel gains/losses, channel evaporation, and evaporation from the swamps. Calibration adjustments were performed over the period of 1951-1970 followed by a validation using the period of 1971-1990. Table 3-2 shows the Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and RMSE-observations standard deviation ratio (RSR) at each gage location. The validation of all metrics were considered *very good* or *good* according to published criteria (Moriasi et al. 2007). The supplemental appendix provides additional calibration results.

Table 3-2. Calibration and validation results

Location	Calibration Period (1951-1970)			Validation Period (1971-1990)		
	Nash-Sutcliffe	PBIAS	RSR	Nash-Sutcliffe	PBIAS	RSR
Blue Nile at Kessie	0.99	-0.73	0.10	0.99	-2.87	0.07
Blue Nile at El Diem	1.00	-0.84	0.05	1.00	-2.9	0.06
Blue Nile at Khartoum Soba	0.98	-5.31	0.16	0.91	-11.62	0.30
Baro at Gambella	0.83	-4.5	0.42	0.93	-1.78	0.26
Sobat at Hillel Doleib	0.85	-1.69	0.39	0.81	-7.03	0.44
Atbara Kilo3	0.89	-1.9	0.33	0.79	-10.58	0.46
White Nile at Malakal	0.89	1.76	0.34	0.85	0.79	0.39
White Nile at Melut	0.89	2.17	0.33	--	--	--
White Nile at Mogren	0.67	1.06	0.57	0.72	1.18	0.53
Nile at Tamaniat	0.97	-2.53	0.17	0.93	-6.59	0.26
Nile at Dongola	--	--	--	0.94	-5.76	0.24

3.3.5 Reservoir Filling Scenarios

3.3.5.1 General Approach

Previous studies have recognised that the effects on downstream users depends on the hydrology during the filling period, the starting conditions of current reservoirs, and the filling policy implemented (Bates et al. 2013; IPoE 2013; King and Block 2014; Zhang et al. 2015). The goals of

this study were to identify and evaluate potential filling and management options, and to test the major dimensions of water distribution to, and energy production from, the three countries during the filling period. Many filling strategies were envisaged and tested throughout this study, and the current paper reflects only a subset of these. Two general paradigms of GERD management during filling emerged: 1) reach an agreement for the GERD to release a minimum flow or volume over time, and 2) adopt a specified or capped filling rate over time. Only the minimum flow paradigm allows the GERD to fill faster during wet years and slower during dry years whilst meeting a minimum water requirement for Sudan and Egypt (MIT 2014), so this paradigm is the focus of the results reported herein.

3.3.5.2 Common Assumptions

Certain characteristics of the GERD filling were assumed for all scenarios based on stated criteria of the chief dam construction engineer (S. Bekele, Personal Communication, 12 June 2015) and known physical characteristics of the GERD (IPoE 2013; MIT 2014). The reservoir is assumed to fill during the initial year (2016) to 560 m (3.58 BCM) to test the first two installed turbines and remain at that elevation until the start of the second year flood period (2017). Additional turbines are assumed to come online every 2 to 3 months. Downstream releases may be passed through the increasing number of installed turbines, through bottom outlets, or over the incrementally raised open spillway (Figure 3-3). Starting in 2017, monthly releases patterns from the GERD during the filling period are assumed to evenly distribute an agreed annual release volume throughout the year to the extent possible (Ethiopian NPoE 2013), while readjusting continuously if shortfalls are encountered. Once the minimum operation level of 590 m (14.7 BCM) is reached, maintaining this level is assumed to take priority over downstream releases. The filling is considered complete when the reservoir level reaches 640 m (74.0 BCM) (Mulat and Moges 2014) at which time a policy of regular energy generation of 1,308 GWh/month begins.¹ All of these assumptions are based on best available knowledge and can be subject to refinement.

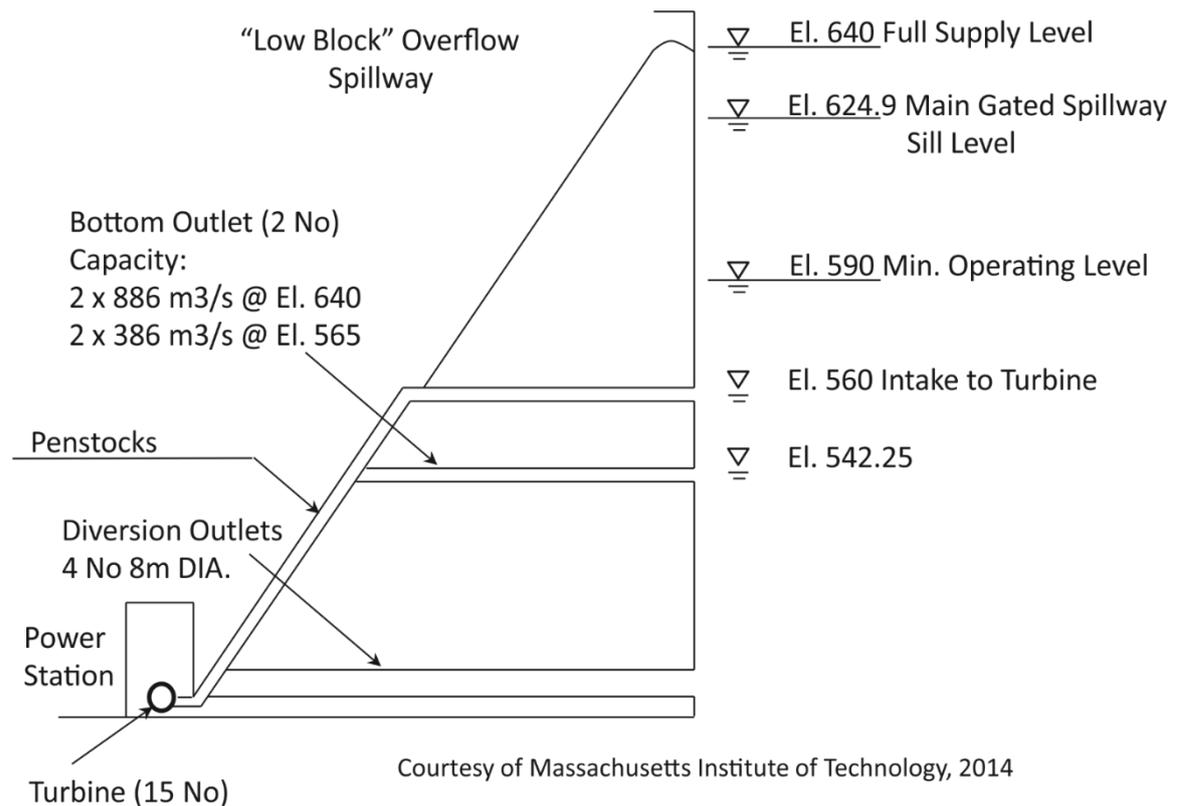


Figure 3-3. Cross section of the GERD with assumed hydraulic capacities

The HAD is assumed to be operated primarily to meet downstream demands that total 55.5 BCM per year. The minimum elevation for power generation and downstream releases is 147 m (31.9 BCM), and the elevation range from 175 to 182 m (121 to 167 BCM) is reserved for emergency storage or flood protection operations. Pool elevations above 178 m are assumed to begin spilling into the Toshka canal (van der Krogt and Ogink 2013). A drought management policy reduces deliveries to downstream water users by 5% as the storage volume in Lake Nasser decreases below 60 BCM (159.4 m), 10% when storage falls below 55 BCM (157.6 m), and 15% when storage falls below 50 BCM (155.7 m) (Egypt MWRI 2005 and Personal Comm. K. Hamed, 2012).

3.3.5.3 Scenarios Analysed

The model was used to study the effects of modifying five factors within the system. Some items are simple numerical changes that represent the sensitivity of a particular parameter, while others

represent conceptual changes to operation policies that respond to the existence of the GERD.

The five factors analysed in this paper are:

1) Total agreed annual release volume from the GERD during the filling period – Five agreed annual release values of 25, 30, 35, 40, 45 and 50 BCM per year were analysed to reflect the range from below the 1984 drought flow (30.9 BCM) to above the average annual flow (49.4 BCM). In addition, a rapid fill scenario (0 BCM) was also analysed for comparative purposes. The GERD will attempt to release this volume every year until the filling is complete using the assumptions provided above.

2) Starting conditions for the HAD - A range of four starting pool elevations of 165, 170, 175 and 180 meters is used to demonstrate the possible effects in Egypt resulting from initial conditions.

3) Sudan Reservoir Operations - Two potential scenarios were simulated including a) all reservoirs use current operation rules and b) reservoirs are operated at the maximum elevation feasible with releases only to meet hydropower demands (Merowe), meet downstream demands (Rosaries and Sennar), and flood control operations, thus forgoing seasonal flushing for sediment.

4) HAD Drought Management Policy - Two potential HAD operation scenarios were simulated including a) no drought management policy implemented and b) the drought management policy implemented that reduces downstream deliveries based on low storage thresholds as described above.

5) GERD-HAD Safeguard Policy - A policy was envisaged that uses the storage in the GERD to ensure that the minimum power pool elevation of the HAD (147 m) is protected. This alternative evaluates whether the pool elevation of the HAD is expected to fall below 150 m (providing a 3 m buffer), and if so, an additional release is made from the GERD to try to maintain this elevation. This additional release is made after any decision to implement the HAD drought management

policy is made and thus reduced HAD releases are maintained. This policy terminates when the GERD reaches 640 m. Two potential scenarios were simulated including a) no GERD support of the HAD and b) with the GERD explicitly supporting the HAD with the above criteria. Additional thresholds and release volumes can be explored.

The five dimensions described above were used to generate 224 combinations of policies and initial conditions, each being subject to 103 hydrologic traces and thus requiring around 23,000 simulations.

3.4 RESULTS

3.4.1 Time to Fill the Reservoir

A key metric across the potential scenarios is how much time would be required to fill the GERD. Figure 3-4 demonstrates the increase in average time to fill and the variance in that time given hydrologic variability with an increasing agreed annual release. Including the first year of fill to 560 m for testing the turbines, the fastest possible time to fill the reservoir to the full supply level of 640 m would be during the flood of the third year (2018). In situations where the agreed annual release exceeds the average annual flow rate of 49.4 BCM, the reservoir on average cannot fill completely.

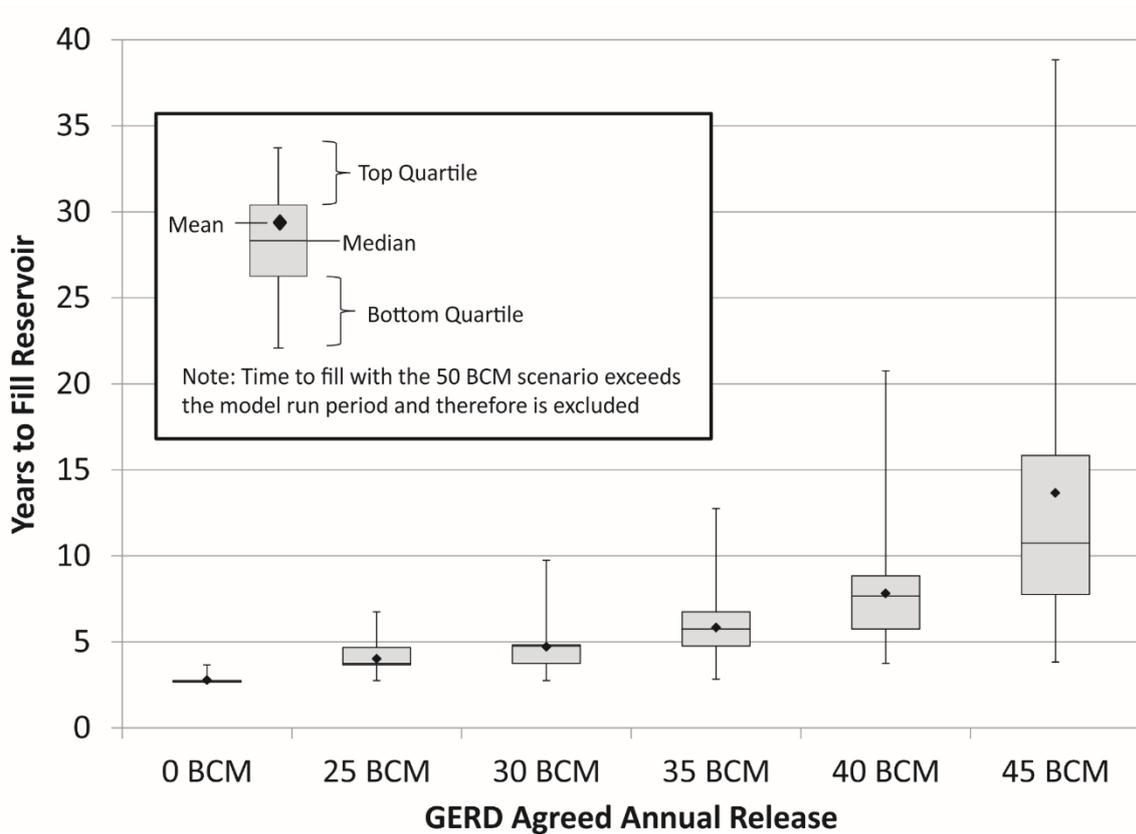


Figure 3-4. Years required to fill the GERD under various agreed annual GERD releases

3.4.2 Effects on Downstream Consumptive Uses

A major concern of downstream countries is whether the GERD will negatively affect the reliability of their water supply. Table 3-3 demonstrates the risk of shortages to Sudan users with and without the GERD, and before and after any reoperation of the Sudanese reservoirs in response to the GERD. The current management practices of the Blue Nile reservoirs in Sudan are designed to operate the reservoirs at a minimum elevation to pass sediment until late September, and then capture the end of the flood flow to retain sufficient storage to meet the needs of the Gezira-Managil diversion. The results show that this current operation plan is not compatible with the assumed constant operation of the GERD during filling. However, by starting the Sudanese reservoirs at the maximum capacity when the filling of the GERD begins and reoperating them to make releases only to meet downstream demands and allow necessary spills during flooding, the risk of shortages to Sudanese irrigated agriculture and municipal uses is essentially eliminated.

This reoperation may be feasible due to sediment capture of the GERD, but warrants further investigation.

Table 3-3. Shortages to Sudan Water Users (2016-2025)

	GERD Agreed Annual Release	Maximum Probability of Shortage		Average Annual Shortage (BCM)	
		Before Dam Reoperations	After Dam Reoperations	Before Dam Reoperations	After Dam Reoperations
		50 BCM	100%	0%	0.3
45 BCM	100%	0%	0.6	0.0	
40 BCM	100%	0%	0.6	0.0	
35 BCM	100%	0%	0.5	0.0	
30 BCM	100%	0%	0.5	0.0	
25 BCM	100%	0%	0.5	0.0	
0 BCM	100%	100%	1.4	0.9	
No GERD		4%		0.008	

Figure 3-5 demonstrates the average volume of shortages to Egyptian water users relative to the 55.5 BCM delivery assumption if there is no HAD drought management policy used, there is no GERD-HAD safeguard policy in place, and Sudanese reservoirs have been reoperated as described above. Although such a lack of adaptation to the construction of the GERD is unlikely, it shows the effects of the initial elevations of the HAD and agreed releases from the GERD. While simplifying the probabilistic distribution of shortages, it demonstrates that agreed annual releases of 35 BCM and greater reduce the average shortage volume, while releases of 30 BCM or less may be insufficient to keep up with the 55.5 BCM annual Egyptian demand. It can also be noted in Figure 3-5 that as the effects of filling subside, the long-term risk of shortages for Egypt decreases relative to the baseline condition due to the benefit of flow regulation that the GERD provides, however this warrants further analysis of future water resource developments and potential operations after filling is complete.

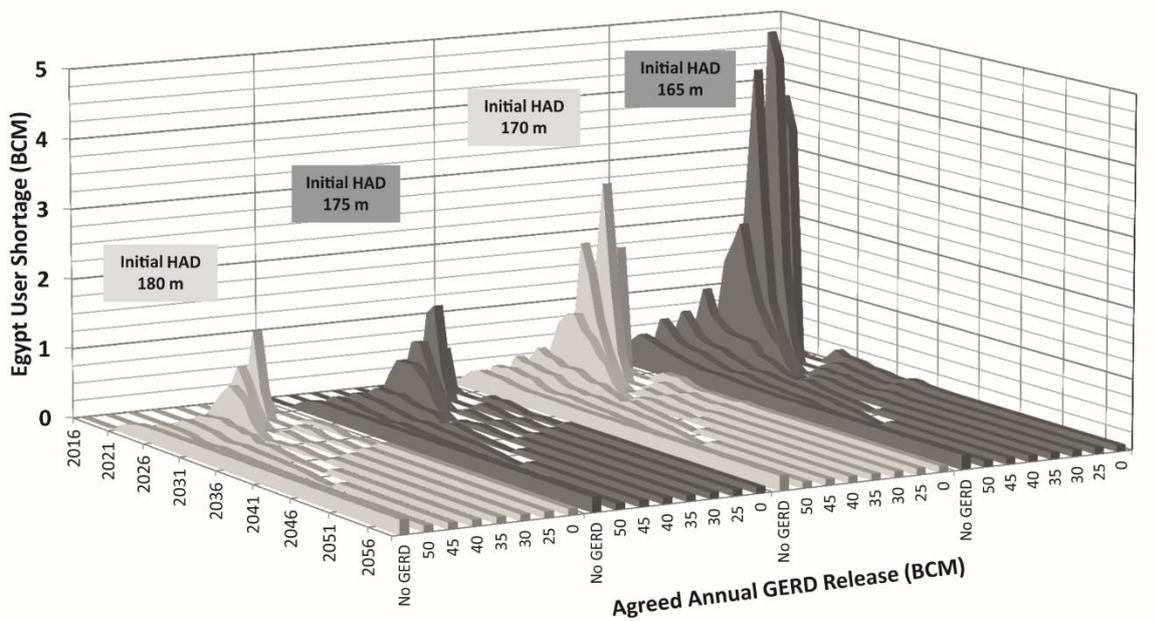


Figure 3-5. Average annual shortages to Egyptian water users without the HAD drought management policy or GERD-HAD safeguard policy

By taking 175 m as the approximate starting pool elevation of the HAD at the start of 2016 (Personal Comm. I. Selah 2016), more specificity within the results can be explored. Figure 3-6 demonstrates the probability of exceedance of shortages to Egypt during the initial 10 years after filling commences and across the various agreed annual releases for all four combinations of inclusion and exclusion of both the HAD drought management policy and the GERD-HAD safeguard policy. While these cumulative plots demonstrate the potential range of shortages across policies and their relative probabilistic distributions over the time period, they do not reflect specific annual risks. Figure 3-6A shows that significant shortages are possible under dry conditions if neither the HAD drought management policy or GERD-HAD safeguard policy are put in place. Figure 3-6B demonstrates the effect of implementing the HAD drought management policy which reduces the risk of severe shortages while increasing the likelihood of proactive reductions to water users, but it also demonstrates that the risk of shortages beyond these planned reductions are not eliminated for agreed annual releases of 30 BCM and less. Figure 3-6C shows that the GERD-HAD safeguard policy by itself does mitigate the vast majority of the risk without the need for proactive reduced deliveries, however the possibility of high magnitude

shortages remain under extreme conditions due to the minimum operation level of 590 m for the GERD and the assumed immediate termination of the policy after filling. In Figure 3-6D, the combination of both the HAD drought management policy and the GERD-HAD safeguard policy is shown to completely eliminate the risk of unplanned shortages to Egyptian water users. Each of these plots demonstrates the paradox that higher agreed annual releases provide a guaranteed delivery downstream during filling, but also prolong the filling process and therefore extend the risk to downstream users.

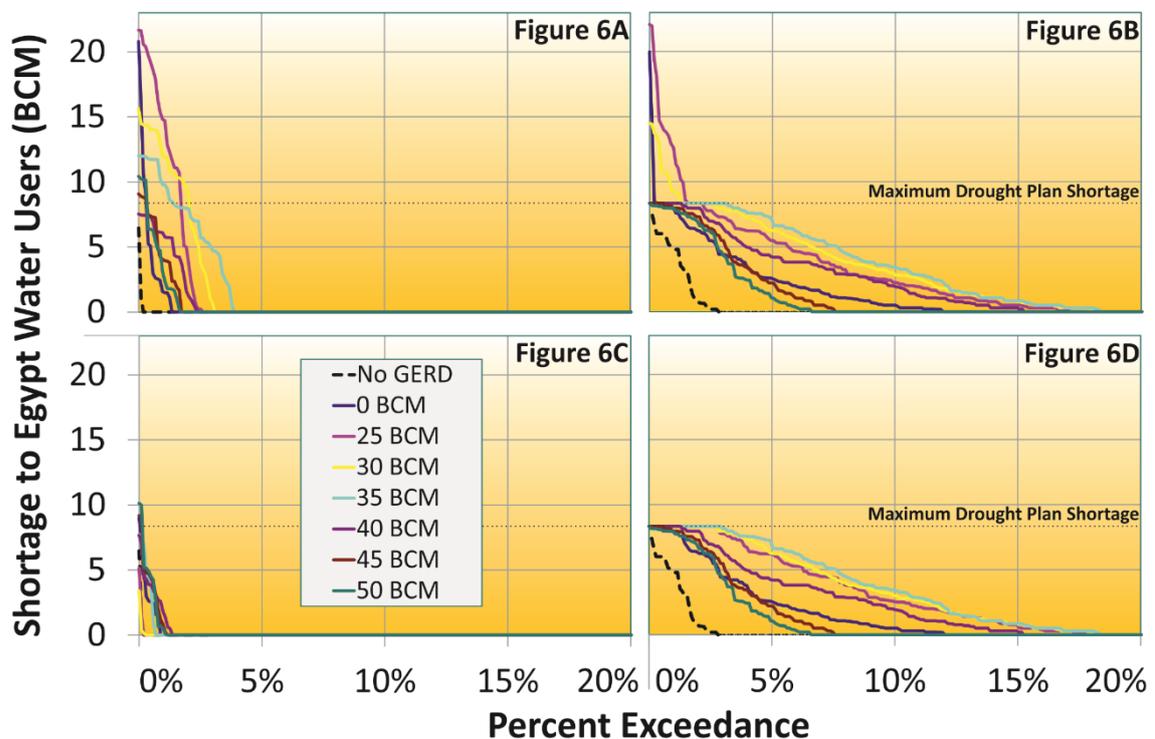


Figure 3-6. Cumulative probability of exceedance of annual shortages to Egypt across 2016-2025 with initial pool elevation of HAD = 175 m.

No GERD-HAD Safeguard Policy; B) With HAD Drought Policy, No GERD-HAD Safeguard Policy; C) No HAD Drought Policy, With GERD-HAD Safeguard Policy; D) With HAD Drought Policy, With GERD-HAD Safeguard Policy

Table 3-4 highlights the differences between the policies in more critical terms by calculating the maximum probability of the HAD reaching 147 m across all points in time throughout the 43-year model run period. Below this elevation power cannot be produced and requested downstream releases cannot be made therefore the model reduces downstream releases to maintain this

elevation. Table 3-4A shows this probability if neither the HAD drought management policy nor the GERD-HAD safeguard policy are used. Table 3-4B shows the degree to which the assumed HAD drought management policy cannot alone protect the minimum pool elevation, and Table 3-4C shows the extent to which the GERD-HAD safeguard policy alone leaves a remaining risk due to limitations of the minimum operating level of the GERD and immediate termination of the policy. When applying either of these policies independently, it can be seen that much of the risk of reaching this critical elevation is reduced, but some risk still remains. Finally Table 3-4D shows that the combination of the HAD drought management policy and the GERD-HAD safeguard policy does provide almost complete protection for the HAD.

Table 3-4. Maximum probability of High Aswan Dam reaching the minimum power production elevation (147 m) under 4 management scenarios across the run period (2016-2059)

		A) No HAD Drought Mgmt. Policy No GERD-HAD Safeguard Policy				B) With HAD Drought Mgmt. Policy No GERD-HAD Safeguard Policy			
		Initial HAD Elevations				Initial HAD Elevations			
		180m	175m	170m	165m	180m	175m	170m	165m
GERD Agreed Annual Release	No GERD	0%	0%	0%	0%	0%	0%	0%	0%
	50 BCM	3%	4%	6%	10%	0%	0%	0%	2%
	45 BCM	3%	4%	6%	11%	0%	0%	0%	3%
	40 BCM	5%	6%	7%	13%	0%	0%	0%	5%
	35 BCM	7%	9%	15%	31%	1%	1%	3%	6%
	30 BCM	7%	9%	21%	45%	4%	5%	6%	11%
	25 BCM	8%	9%	27%	47%	6%	7%	9%	18%
	0 BCM	2%	7%	17%	37%	1%	3%	10%	20%
		C) No HAD Drought Mgmt. Policy With GERD-HAD Safeguard Policy				D) With HAD Drought Mgmt. Policy With GERD-HAD Safeguard Policy			
		Initial HAD Elevations				Initial HAD Elevations			
		180m	175m	170m	165m	180m	175m	170m	165m
GERD Agreed Annual Release	50 BCM	2%	4%	5%	8%	0%	0%	0%	1%
	45 BCM	2%	3%	4%	8%	0%	0%	0%	1%
	40 BCM	2%	3%	3%	7%	0%	0%	0%	2%
	35 BCM	2%	2%	3%	7%	0%	0%	0%	1%
	30 BCM	2%	2%	3%	5%	0%	0%	0%	2%
	25 BCM	2%	3%	4%	7%	0%	0%	1%	1%
	0 BCM	2%	3%	5%	21%	0%	0%	2%	2%

3.4.3 Effects on Hydropower Generation

Table 3-5 reports the average annual change to Ethiopian, Sudanese and Egyptian hydropower generation with the addition of the GERD averaged across two time frames: the initial 10 years starting from the commencement of filling (Short Term) and the following 20 years (Medium Term). The results for Sudan assume no reoperations of Sudanese reservoir management takes place, and the results for Egypt assume Sudan reoperations have taken place, but no HAD drought management policy or GERD-HAD safeguard policy has been implemented. Although this not a likely scenario, this arrangement demonstrates the result of inaction of each country to adapt to the GERD. Table 3-6 presents similar results, but assumes adaptation has taken place by reoperation of the Sudanese reservoirs, and implementation of both the HAD drought management policy and the GERD-HAD safeguard policy. The differences between Table 3-5 and Table 3-6 demonstrate the largely positive effects of these operational changes averaged over the short and medium-term time periods.

Table 3-5. Change of average annual energy generation (GWh/year) due to the GERD without downstream adaptations

		Ethiopia		Sudan: No Reops		Egypt: No Drought Management; No GERD-HAD Safeguard							
		Short Term Effect	Medium Term Effect	Short Term Effect	Medium Term Effect	Short Term Effect				Medium Term Effect			
						Initial HAD Pool Elevation				Initial HAD Pool Elevation			
						180m	175m	170m	165m	180m	175m	170m	165m
GERD Agreed Annual Release	50 BCM	10339	13481	561	1029	-872	-953	-1049	-1094	-386	-417	-482	-536
	45 BCM	10660	14011	376	1076	-1090	-1180	-1289	-1330	-363	-400	-471	-531
	40 BCM	11106	14037	272	1136	-1314	-1408	-1508	-1540	-290	-324	-389	-434
	35 BCM	11441	13815	253	1147	-1405	-1493	-1582	-1599	-200	-228	-282	-310
	30 BCM	11675	13547	282	1144	-1393	-1480	-1559	-1553	-169	-197	-245	-262
	25 BCM	11784	13460	296	1140	-1374	-1455	-1528	-1509	-164	-191	-237	-255
	0 BCM	11890	13306	230	1134	-1135	-1224	-1305	-1299	-140	-164	-210	-235

Table 3-6. Change of average annual energy generation (GWh/year) due to the GERD with downstream adaptations

		Ethiopia		Sudan: With Reops		Egypt: With Drought Management; With GERD-HAD Safeguard							
		Short Term Effect	Medium Term Effect	Short Term Effect	Medium Term Effect	Short Term Effect				Medium Term Effect			
						Initial HAD Pool Elevation				Initial HAD Pool Elevation			
						180m	175m	170m	165m	180m	175m	170m	165m
GERD Agreed Annual Release	50 BCM	10339	13481	1498	2262	-869	-943	-1024	-1030	-342	-369	-425	-456
	45 BCM	10660	14011	1360	2234	-1086	-1167	-1259	-1259	-309	-341	-399	-425
	40 BCM	11106	14037	1216	2244	-1309	-1393	-1469	-1443	-211	-233	-267	-275
	35 BCM	11441	13824	1158	2246	-1384	-1459	-1507	-1460	-139	-158	-188	-194
	30 BCM	11662	13556	1081	2227	-1370	-1440	-1482	-1430	-121	-138	-160	-169
	25 BCM	11780	13477	996	2223	-1356	-1426	-1456	-1403	-118	-131	-155	-162
	0 BCM	11891	13306	952	2206	-1124	-1198	-1233	-1181	-98	-116	-137	-141

Short Term = Average from 2016 - 2025 (10-years), Medium Term = Average from 2026 - 2045 (11-30 Years)

These tables provide direct comparisons of energy gains and losses between the countries and allow contrasts with the risk of shortages to Sudan (Table 3-3) and Egypt (Figure 3-6 A,D). For example, an agreed annual release of 35 BCM would add an average of 11,441 GWh of energy each year for Ethiopia in the short term, and assuming the initial elevation of the HAD of 175 m and no adaptation policies (Table 3-5), would reduce an average of 1,493 GWh each year for Egypt and incur a 3% cumulative risk of shortages of at least 5 BCM throughout the short-term period (Figure 3-6A).

Several general results emerge from examining these two tables. The average annual energy generation in Ethiopia (dominated by the GERD) increases with decreased agreed annual release in the short term, which is largely based on completing the filling early and transitioning to normal operations. Sudanese energy generation is improved by reoperating their reservoirs. In contrast, the combination of the HAD drought management policy and GERD-HAD safeguard policy results in competing factors that result in increases and decreases to energy generation for Egypt. These include reduced HAD turbine flows, additional water made available from the GERD, increased pool elevation, and the reduced likelihood of reaching the minimum power generation elevation.

Various non-linear behaviours can be observed in Table 3-5 and Table 3-6 that are largely based on the timing for which filling is achieved relative to the time periods used for averaging. The maximum energy generation in Ethiopia occurs at the point of transition to normal operations when the GERD is at 640 m; therefore, this peak occurs in the short-term under low agreed annual releases and the medium-term period for higher releases. Similar behaviour of Sudanese and Egyptian power generation can be seen as well. One notable result is the non-linearity from the 50 BCM agreed annual release scenario, which is due to this release exceeding the average annual flow of 49.4 BCM resulting in the GERD not being able to reach full capacity on average and

consequentially less medium-term energy generation for Ethiopia and slightly greater generation for Egypt and Sudan.

While the change to energy generation in Ethiopia is quite small between Table 3-5 and Table 3-6 indicating that minimal concessions are required, Table 3-7 provides another perspective to demonstrate the foregone energy benefit to Ethiopia to provide assurance to Egypt through the GERD-HAD safeguard policy. The exceedance probability of generating the target energy of 1,308 GWh/month is shown as a function of the agreed annual delivery and starting elevation of the HAD. This table again demonstrates that the ability to meet this power generation target is essentially unchanged when protecting the HAD power pool elevation given any additional release from the GERD can be passed through the turbines to generate electricity. Assumptions were made regarding the ability of the GERD to generate energy throughout the filling period while making the necessary releases and the uniform energy demand pattern after the filling is complete, however the demand for energy will depend on factors such as the local market demand, capacity of transmission lines, and timely completion and/or expansion of the regional interconnection projects (Block and Strzeppek 2010; MIT 2014). This highlights the opportunity to match the agreed annual release with these energy demands and the need for flexible energy demands if additional releases are required.

Table 3-7. Change in % reliability of a 1,308 GWh/month firm energy generation of the GERD due to implementation of the GERD-HAD Safeguard Policy

		Short Term: 2016 - 2025					Medium Term: 2026-2045					
		Initial HAD Elevations					Initial HAD Elevations					
		No Safeguard	180 m	175 m	170 m	165 m	No Safeguard	180 m	175 m	170 m	165 m	
GERD Agreed Annual Release	BCM	50	10.1	0.0	0.0	0.0	0.0	34.1	0.0	0.0	0.0	0.0
	45	12.9	0.0	0.0	0.0	0.1	65.6	0.0	0.0	0.0	0.0	
	40	28.4	0.0	0.0	0.0	0.2	79.5	0.0	0.0	0.0	0.0	
	35	42.6	0.0	0.0	-0.1	0.1	80.0	-0.1	-0.1	-0.1	-0.1	
	30	52.6	0.0	0.0	-0.5	-0.7	78.2	0.1	0.1	0.2	0.2	
	25	59.0	-0.2	-0.4	-0.6	-1.2	77.6	0.1	0.1	0.2	0.3	
	0	69.6	0.0	-0.1	-0.3	-0.8	76.5	0.0	0.0	0.0	0.0	

3.5 DISCUSSION

Results indicate that the GERD will indeed provide a substantial amount of hydropower generation once the turbines are installed and the reservoir begins to fill. The study demonstrates that under the assumed hydrologic conditions and non-increasing demands during the filling period, the risks to existing downstream consumptive uses and hydropower generation can be managed with the combination of an agreed annual release from the GERD, proactive reoperation of the Sudanese reservoirs, implementation of a drought management policy for the HAD, and a safeguard release from the GERD if the HAD pool elevation falls below a critical level. Assured protection of Egypt's needs across all hydrologic conditions is only feasible with cooperative management of the upstream infrastructure in Ethiopia and Sudan.

Maintaining reliable water supplies to the large irrigated agricultural areas of Sudan will require modifications to the operations of the Rosaries and Sennar dams to accommodate the intra-annual timing of releases from the GERD. With effective communication and coordination between Ethiopia and Sudan, the supplies to these large diversions can be assured throughout the filling period. This would require the Rosaries and Sennar reservoirs to reach their full capacity during the first year of GERD filling and make releases to only meet direct diversions requirements to the Gezira/Managil canals, satisfy the minimum downstream flow requirements, and pass any flood water while retaining the maximum possible volume of storage. However, without agreed annual GERD releases and proper re-operation of Sudanese reservoirs, up to 28% losses to energy generation in Sudan may occur in the initial years. Once filling is complete, up to 21% increases in energy generation can result due to greater available flows during the non-flood period and reduction of spills during the flooding season. Implications of sediment management during this transitional period were not analysed in this study and we did not attempt to evaluate the impacts to flood recession agriculture in Sudan, either along the river or around the reservoirs due to

revised dam operations. Developing detailed reoperation plans of the Sudanese reservoirs was beyond the scope of this current study, but is a topic for further analysis.

Risks to Egyptian water supplies and energy production are dependent on the initial storage in Lake Nasser when filling begins, the hydrologic conditions that occur during the filling period, an agreed annual release from the GERD, and the operational policies of the HAD and all upstream reservoirs. This study quantifies this risk and demonstrates that it can be significantly reduced with proper planning. Egypt will lose both hydropower generation from the HAD and the ability to fully satisfy downstream demands simultaneously if the HAD pool elevation falls below the intake elevation of 147 m. In this study, management of this risk was analysed across different agreed annual releases and by examining two policies including 1) Egypt proactively reducing releases through the HAD drought management policy and 2) Ethiopia making additional releases when the elevation of the HAD is expected to fall below a pre-specified trigger elevation and Sudan allowing this water to pass downstream to Egypt. By relying only on an agreed annual release, the risk of reaching this minimum elevation ranges from 2% to 47%, depending on the release value and the initial storage of the HAD. The HAD drought management policy can reduce the risk of large shortages by making planned reductions; however, some risk of reaching this elevation remains, particularly if an agreed annual release of less than 35 BCM is used.

In contrast, the GERD-HAD safeguard policy endeavours to maintain the HAD at an elevation of 150 m regardless of an agreed annual release. In this case, the extra volume released is dynamically estimated to assure the 150 m pool elevation is maintained based on the expected incoming hydrology and downstream Egyptian demands. However due to losses, lags, extreme hydrologic conditions and infrastructure limitations, maintaining this level is not always certain. The results indicate that the GERD-HAD safeguard policy alone largely protects the HAD and avoids the need for Egypt to proactively reduce releases downstream of the HAD. However, the minimum power elevation of the GERD can be a limiting factor when providing this supplemental water and

Egypt's risk persists after the GERD reaches maximum elevation. This policy may need to be extended for a period of time after the GERD is filled to assure the risk to Egypt is alleviated.

To eliminate all risks of the HAD reaching the minimum power elevation, a combination of the HAD drought management policy and the GERD-HAD safeguard policy was shown to be effective. While this policy suggests potential proactive reductions to Egypt's deliveries from the HAD, it avoids the risk of unplanned shortages to Egyptian water users. Support from the GERD can be made to maintain the pool elevation of 150 m after assuming planned downstream releases subject to the HAD drought management policy. Any such collaboration between the GERD and the HAD requires an increased level of cooperation that assures particular releases have been made from each reservoir.

The large generation capacity of the GERD would allow Ethiopia to provide the HAD safeguard releases with only small reductions of hydropower production. The foregone benefit depends on Ethiopia's ability to utilize the energy generated when the water is needed downstream. If there is demand and transmission capacity that can absorb the energy generated when these excess flows are required, then protecting the HAD with flows from the GERD can be economically beneficial (Tawfik 2016). In addition to the use of the HAD drought management policy, the three key additional components of this strategy: an agreed annual release, a trigger elevation for protecting the critical HAD power pool elevation, and the calculation of a safeguard release volume, are subjects for negotiation and further analysis.

3.6 CONCLUSIONS

Although much dialogue and analyses have taken place regarding the GERD and its potential downstream benefits and impacts, there remains a need for specific arrangements to manage the process of filling the GERD. In this study, we present some possible arrangements of reservoir

coordination to achieve this goal and demonstrate an analysis framework that quantifies the benefits and risks. We demonstrate that reservoir coordination is a continuum ranging from unilateral management to dynamic operations that reflect current needs. Unilateral actions by Ethiopia may result in both positive and negative externalities such as improved energy generation for Sudan and reduced energy generation for Egypt. An agreed annual release from the GERD demonstrates a greater degree of coordination that results in increased benefits and reduced downstream risks. Further along this continuum is a dynamic awareness of the water security situation between co-riparians. This study demonstrates this concept by analysing safeguard releases from the GERD to support the HAD under critical circumstances which minimises severe risks.

Risks to water supply and hydropower generation have always existed on the Nile, and changes to the system may alter this risk profile either positively or negatively, and either temporarily or permanently. This study, along with others that consider the filling of the GERD, can provide important technical information for the negotiation process. A single correct solution is unlikely from any study, but the analysis allows negotiators to understand how significant the changes of risks might be, whether they are acceptable, how they might be managed, and whether alternative approaches must be pursued. Ultimately, we believe this study demonstrates that a middle ground does indeed exist.

Notes

1. In the absence of future estimated energy demands patterns, 1,308 GWh/month represents the projected 15,692 GWh/year energy generation distributed evenly over the year (IPoE 2013). While the reservoir will have a 6000 MW installed capacity and hence the ability to provide peak power generation and avoid all spills, the assumption used will only require power generation to exceed 2000 MW in less than 2% of all cases.

4 A MULTI-SITE NON-PARAMETRIC METHOD FOR HYDROLOGIC SCENARIO GENERATION IN THE EASTERN NILE BASIN

4.1 INTRODUCTION

Evaluating hydrologic conditions across river basins with multiple tributaries is a challenging yet necessary task to manage water resources at a basin scale. Water resources system models are often used for both planning and operational purposes in river basins (Brown et al. 2015), and typically require estimates of river flow sequences at different locations throughout the basin. Developing synthetic hydrologic sequences to drive these models allows a river system to be studied with a wide variety of potential scenarios and thus allows water managers to understand system dynamics and risks more thoroughly than would otherwise be possible using historical data alone (Thomas and Fiering 1962). To develop a set of synthetic hydrologic sequences across multiple locations, each synthetically derived sequence must not only maintain statistical properties that are consistent with historical flows at that location, but must also maintain the appropriate statistical dependence among the multiple locations. Applications using synthetic hydrology approaches include drought frequency analyses (Salas et al. 2005), drought vulnerability assessments (Borgomeo et al. 2015b), reservoir design and operations (Montaseri and Adeloye 1999), and infrastructure planning studies (Block and Strzepek 2010; Jeuland 2010).

4.2 STOCHASTIC HYDROLOGY

Synthetic streamflow generation methods were initially developed using parametric methods such as a periodic autoregressive models (PAR) (Matalas 1967; Thomas and Fiering 1962) to capture both the first order statistics and the auto-correlation of flows from previous time steps. Variations such as moving averages (ARMA) and various transformations (Hirsch 1979; Salas et al. 1982; Tao and Delleur 1976) were developed that improved performance of these classic methods. A number of temporal disaggregation approaches have been developed to replicate

both annual and monthly statistics (Grygier and Stedinger 1988; Mejia and Rousselle 1976; Santos and Salas 1992; Stedinger et al. 1985; Stedinger and Vogel 1984; Valencia and Schakke 1973). In the context of the Nile River, Montanari et al. (2000) developed a fractional autoregressive integrated moving average model to capture both the short and long-term persistence of the Nile flows. Well known limitations of parametric methods have been demonstrated such as assumptions of underlying functional forms (Prairie et al. 2006), which prompted the development of non-parametric methods that are not subject to these limitations.

Alternative non-parametric methods of synthetic hydrology generation have emerged in recent decades that are considered 'data driven' and do not assume any distribution, thus can reproduce a wide variety of possible density functions. Lall and Sharma (1996) introduce a nearest neighbour approach (NN) that begins with an assumed initial hydrologic condition, identifies a set (K) of similar states within the historical record, and then makes a weighed selection of the subsequent time period based on the degree of similarity, resulting in a bootstrap resampling of historical hydrologic conditions. Prairie et al. (2006) builds upon this K-NN method with a residual resampling that allows generation of values not seen in the historical record. Similar to the K-NN approach, Sharma et al. (1997) introduces a kernel-based resampling method that estimates a kernel (weight) function at each point of interest. Tarboton et al. (1998) describes a temporal disaggregation method based on this kernel density estimate that can be applied to annual resampled values, and suggests that it could be expanded for spatial disaggregation as well. Prairie et al. (2007) answers this suggestion by developing a K-NN based disaggregation method for annual flows at a single site that can be applied both spatially and temporally.

Recently Borgomeo et al. (2015a) introduced a non-parametric approach to synthetic streamflow generation that uses the combinatorial optimization method of simulated annealing (Kirkpatrick et al. 1983), which has previously been applied to a number of optimization problems (Bárdossy 1998; Farmer 1992). This method begins with a series of randomized flow values drawn from a

historical sample set along with a flexible user-defined objective function that describes the statistical characteristics the user wants to preserve or perturb in the synthetic time series. This method was applied to generate synthetic flow sequences on a single site with results superior to a PAR(1) routine. An advantage compared to other non-parametric methods is that both annual and monthly statistics can be maintained, thus temporal disaggregation is not required. Borgomeo et al. (2015a) also demonstrated how the method could be used to perturb statistics of interest (e.g., inter-annual variability) whilst preserving low order moments of the flow distribution. The simulated annealing approach has not yet been developed for multi-site generation of synthetic streamflows, and thus offers a point of departure for this work to expand on this methodology.

4.2.1 Multiple-Site Synthetic Hydrology

Multi-site synthetic streamflow generation is considered initially in and Fiering and Jackson (1971) with an assumption that the statistical dependence among flows at related sites can be adequately characterized among the random components of flows at the sites. In subsequent development of parametric methods, Grygier and Stedinger (1988) describe procedures of spatial disaggregation similar to those of temporal disaggregation, therefore first generating synthetic flows for a particular mainstem downstream site, followed by disaggregation to its upstream tributaries. Santos and Salas (1992) describe a parsimonious method for lag-one multi-site temporal disaggregation of flows using a step-wise procedure to minimize matrix sizes while maintaining the appropriate cross-correlation between sites.

As mentioned above, the non-parametric K-NN method developed by Prairie et al. (2007) is used for both temporal and spatial disaggregation. This method was used to synthesize multi-site inflows across the Colorado River Basin for use in the U.S. Bureau of Reclamation's Colorado River Simulation System (CRSS) model. Combinations of parametric and non-parametric methods have been proposed by Srinivas and Srinivasan (2005) that demonstrate the use of a non-transformed PAR(1) or a transformed PARMA(1,1) (Tasker and Dunne 1997) with block bootstrapping, which

successfully captures multi-site covariance statistics. While this method clearly demonstrates the benefits of both parametric and non-parametric methods to achieve a multi-site and multi-season outcome, it requires multiple steps, a high variable count and commensurate computational burden. Recently, entropy methods (Srivastav and Simonovic 2014) and simulation-optimization approaches (Srivastav et al. 2016) have been successfully applied to multi-site and multi-season flow simulations. Application of these methods has focused on reproducing observed time series without demonstrating their ability to model climate induced changes in streamflow properties, which is the focus of this paper.

Methods for generating synthetic sequences of climate variables across multiple sites have been developed widely and are often referred to as weather generators (Wilks and Wilby 1999). Wilks (1998) uses Markov chains at multiple sites that are driven by a correlated random field, but does not fully capture spatial variability of the generated precipitation fields. This approach was further developed by Brissette et al. (2007), Khalili et al. (2009), and Srikanthan and Pegram (2009). Various non-parametric methods have been developed such as a reshuffling algorithm for daily weather sequences (Clark et al. 2004), K-NN approaches (Buishand and Brandsma 2001; Rajagopalan and Lall 1999) and Neyman-Scott rectangular pulses (Burton et al. 2008). Breinl et al. (2013) proposes a semi-parametric combination of Markov processes and a reshuffling algorithm to generate precipitation values that may exceed historical daily values and proposes its use for risk analysis applications. Whilst weather generators enable simultaneous simulation of multiple weather variables, (i) this represents an even more challenging problem spatially than the streamflow problem, so, as the citations above indicate, experience with spatial weather generators is mixed and (ii) the weather variables then have to be propagated through a hydrological (rainfall-runoff) model, introducing another layer of uncertainty. Direct synthetic streamflow generation offers the potential for a more accurate representation of observed flows, though at the expense of not providing a direct means of testing the effects of specified climatic or catchment changes.

4.2.2 Considering Climate Change

Commonly used “top-down” approaches (Wilby and Dessai 2010) to analysing the hydrological effects of climatic change use stochastic weather generators based on parametric or non-parametric resampling of historical climate data and conditioned on change factors provided by global circulation models (GCMs) (Glenis et al. 2015) or regional climate models (Alemseged and Tom 2015). These approaches result in ensembles of temperature and precipitation that are used as inputs to rainfall-runoff models and subsequently water system models (Borgomeo et al. 2014). These methods have been applied in the context of the Nile (Block and Strzepek 2010; King and Block 2014; Zhang et al. 2015) to assess potential impacts of climate change on infrastructure development, however the results from the GCMs are known to be highly variable in Eastern Africa (Beyene et al. 2010; Conway and Hulme 1996; Strzepek and McCluskey 2007). While these methods provide useful estimates of the potential effects of climate change in addition to the natural variability, uncertainties in these approaches arise due to the selection of climate models, choice of greenhouse gas emissions scenarios, techniques used for weather generation, downscaling procedures, and the parameterization and structure of rainfall-runoff models (Teng et al. 2012).

Alternative “bottom-up” or scenario-neutral approaches have been suggested that consider the effects of climate change by testing plausible ranges of climate related variables and then evaluating the robustness of the management decisions being considered across this spectrum (Brown and Wilby 2012; Groves and Lempert 2007; Herman et al. 2015; Nazemi and Wheeler 2014; Prudhomme et al. 2010). These approaches effectively present the sensitivity of the modelled system to different climatic changes, and climatic variables from global circulation models are used as points of comparison rather than drivers of the analysis. However, the methods still require the stochastically generated weather and rainfall-runoff models to generate stream flows.

Additional approaches to evaluate the impacts of climate change can be made through resampling of historical stream flows with climate-expected modifications incorporated into the resampling process. In this alternative “bottom-up” approach, changes are introduced that encompass the range of modifications which are expected from “top-down” predictions, but can demonstrate a wider variety of potential climate change outcomes. Time series of synthetically generated flows are produced with desired modifications to the statistics that are believed to be most influenced by climate changes. In the case of the Nile, Jeuland (2010) and Jeuland and Whittington (2014) stochastically generated hydrologic flows from a simplified autoregressive model (Fiering and Jackson 1971), then introduce a range of scaled runoff percentages that reflect results from regional climate based analyses. Other applications of synthetic streamflow generation for bottom-up water resources assessments include Nazemi et al. (2013) who analysed the impact of a changing river flow regime on water supply security in the Canadian Prairies, and Herman et al. (2016) generated more severe and frequent drought to test urban water portfolios in the south-eastern United States.

The non-parametric method introduced by Borgomeo et al. (2015a) demonstrated the ability to generate synthetic sequences that reproduce potential climate change effects of increased high frequency persistence of flows (longer duration of intra-annual droughts and extended wet periods), increased inter-annual variability of flows (larger variation of wetter and drier years), and perturbed seasonal flows (lower dry season flows). This method was demonstrated for a single site on the Thames River, but was not expanded to multiple-sites across the river basin.

4.3 MATERIALS AND METHODS

4.3.1 Rationale and general approach

This research presents a method for developing synthetic streamflows at multiple sites across a large river basin, which differs significantly from existing multi-site methods described above that either rely on rainfall-runoff models and/or require sequential steps such as data matrix transformations, principal component analyses and spatial or temporal disaggregation. The approach presented here uses the combinatorial optimization-based method of simulated annealing (Kirkpatrick et al. 1983) to simultaneously generate sequences representing time series of hydrologic inflows across multiple locations. The method seeks to generate outputs that maintain the statistical properties of a set of input time series which are generally based on historical flows but can also introduce user-specified perturbation of these input statistics.

The general approach developed by Borgomeo et al. (2015a) first calculates a set of target statistics from a historical time series (i.e. mean monthly flow, monthly standard deviations, lag correlations, mean annual flows, inter-annual standard deviation, etc.). The historical time series are then randomly resampled to generate an initial synthetic output time series and thus does not initially maintain any of the statistical properties. An objective function is developed that quantifies the difference between the simulated and historical observed statistics. An optimization routine is applied that iteratively rearranges elements of the synthetic outputs by randomized swapping of elements in the time series, followed by a re-evaluation of the objective function. The rearranged sequence is either accepted or rejected based on evolving probabilistic criterion until a user-specified endpoint is reached. The result from the algorithm is a new time series that has statistics which closely match those of the historical sequence.

We describe an enhancement to this method that simulates the statistical characteristics of multiple interdependent time series. While generic in nature and potentially useful in many applications, this modification is demonstrated by simultaneously simulating flows at multiple

locations across a river basin. The method uses the relevant statistics from each individual series along with the cross-correlations (or other characterisation of the spatial dependence) between the time series at the different locations to generate a set of synthetic time series that replicates these historical statistics. To simulate the potential effects of climate change, the target statistics can be perturbed from historical conditions, resulting in time series that demonstrate these changes. The consideration of the relationships between all simulated time series of interest extends the work of Borgomeo et al. (2015a) into the multiple sites. Moreover, the case study on the Eastern Nile (see Section 3) represents very different hydrological conditions to those tested by Borgomeo et al. (2015a) on the Thames, including strong seasonality and intermittent flows at some sites.

4.3.2 Simulated Annealing

The combinatorial optimization algorithm used in the process described above is that of simulated annealing. This algorithm uses the analogy of cooling a melted material into a crystalline structure (Kirkpatrick et al. 1983), whereby the atoms in the resulting complex system are arranged and rearranged while a lower energy level is continuously sought. A heuristic approach is taken that first describes an atomic configuration (state) and the energy of that state relative to some desirable or equilibrium energy level (objective function). Next, a simple alteration to this arrangement is proposed such as the swapping of two atoms (elements), and the new energy level is re-evaluated and any improvement to this outcome is noted. If the objective is better satisfied compared to the original arrangement, the new arrangement is accepted as the current “best” state. Inherent in the progression of this simple algorithm is the discovery of local optimal solutions by which further simple rearrangements are increasingly unlikely to result in improvements even though more optimal solutions may indeed exist. Convergence on local optimal solutions is partially overcome by allowing a certain degree of acceptance of less-optimal rearrangements.

Metropolis et al. (1953) began the formalization of this algorithm by describing a lattice of particles undergoing a perturbation from which the change of energy ΔE of a system is calculated. A $\Delta E < 0$ would bring the system into a state of lower energy and therefore the particle position change would be accepted. If $\Delta E > 0$, the move would be accepted with probability of:

Equation 4-1

$$P(\Delta E) = \exp\left(\frac{-\Delta E}{k_B T}\right)$$

Where T is the temperature of the system and k_B represents a physical constraint of the system that is analogous to the Boltzmann constant in statistical mechanics (Kirkpatrick et al. 1983). In this case, a random number (ξ) is generated between 0 and 1 and compared with the result of equation (1). The change is accepted if $\xi < P(\Delta E)$ and rejected if $\xi > P(\Delta E)$.

4.3.3 Simulated annealing for a single site

Borgomeo et al. (2015a) describe the process by which the simulated annealing algorithm is developed and applied to a single streamflow location on the Thames River. The elements required to invoke the algorithm are (1) an initial configuration of time series, (2) a swapping algorithm capable of rearranging elements in the initial configuration, (3) an objective function describing the desired properties of the final synthetic time series, (4) an annealing schedule that describes the acceptance or rejection of proposed elemental swaps, and (5) a termination criterion for the algorithm.

An initial configuration is developed from resampling the historical record. The method used generates n years of streamflow values x for each month j by random sampling from the historical monthly distribution $f(x_j)$. Initial configurations can resample values from any fitted parametric or non-parametric distribution, or derived directly from empirical data. The objective function is constructed from differences in selected statistical metrics between the historical record and the initially generated sequence:

Equation 4-2

$$O = \frac{1}{O_0} \sum_{k=1}^K w_k (z_k^{\text{obs}} - z_k^{\text{sim}})^2$$

where O_0 is the initial value of the objective function used for normalization, K is the number statistical metrics z that are to be reproduced, and w is an optional weight given to each metric to balance the influence of each parameter or emphasize particular statistics within the objective function. Statistics from the observed historical series (obs) and the simulated series (sim) can include, but are not limited to, monthly mean values, monthly standard deviations, monthly autocorrelation, annual standard deviation and annual autocorrelation.

The effect of climate change can be introduced in a variety of ways to the simulated annealing algorithm. By introducing changes to the target statistics, the objective function is altered and the swapping algorithm will rearrange the simulated series to match the statistics of the modification.

Equation 4-3

$$O = \frac{1}{O_0} \sum_{k=1}^K w_k (z_k^{\text{target}} - z_k^{\text{sim}})^2$$

In the example of the Thames River, Borgomeo et al. (2015a) demonstrates that simple increases of the monthly autocorrelation allows simulation of increased persistence of low and high flows within a single annual cycle. Similarly, increases of the inter-annual standard deviation can introduce changes to the long-term variability resulting in more frequent droughts and wet periods. Furthermore, they also demonstrate the ability to reduce mean values during the low-flow periods through modifications of the objective function, however it should be noted that forced lower mean flows in particular periods result in higher flows during other periods. Global reductions to total annual water flows can happen if both initial resampling and target statistics are modified.

Incremental modification of the target statistics allows generation of hydrologic scenarios to test the robustness of a water resource system. This method is analogous to “bottom-up” approaches suggested by (Brown et al. 2012; Prudhomme et al. 2010), and does not require the use of rainfall-runoff modelling. The selection of statistics within the hydrology-focused multi-site synthetic streamflow generation process may be guided by the expected changes to temperature and precipitation resulting from climate changes. Directly perturbing streamflow characteristics provides a water system-oriented perspective that focuses on addressing critical questions for water supply. Such questions may ask what the impact might be for longer durations of low-flow years triggered by extended droughts or the impact of the failure of expected annual floods that are necessary for replenishing over-year system storage.

4.3.4 Simulated annealing algorithm for multiple sites

4.3.4.1 *Required information*

Generating synthetic hydrologic sequences at multiple locations within a river basin is an extension of the concepts presented in the previous sections. In the simulated annealing algorithm, flows are derived from parametric or non-parametric resampling of historical distributions or values at each location, therefore a historical dataset is required at each location of interest. The relationships between the different time series must be reproduced, therefore the historical datasets must cover a consistent time range. Acquiring a complete dataset of flow gauge data across a large river basin is a non-trivial task and is often done through backfilling of missing values or extrapolation of missing time series, etc. While it is beyond the scope of this article to discuss the statistical methods potentially used to obtain a complete dataset (Hirsch 1982; Hughes and Smakhtin 1996; Rees 2008), it is necessary to say methods used to filling missing data affects the properties used in generating synthetic sequences and care must be taken to obtain a complete and robust historical dataset that accurately demonstrates the variability and statistical relationships.

4.3.4.2 Developing multi-site stream flows

The steps required to develop multiple synthetic series mirror the single site case, with added dimensions of multiple locations and consideration of the correlation between the various time series. The first step is to identify the set of properties (**Z**) or statistical metrics to be reproduced across each set of locations (**G**).

Equation 4-4

$$Z = \{z_1, z_2, \dots, z_k\}$$

To develop the objective function, the differences between observed and simulated values for each z_k are aggregated across each location prior to combining the weighted statistics. The objective function is formulated as:

Equation 4-5

$$O = \frac{1}{O_0} \sum_{k=1}^K w_k \left(\sum_{g=1}^G |z_{k,g}^{\text{obs}} - z_{k,g}^{\text{sim}}| \right)^2$$

where g is the index of gauged sites G to be simulated.

A metric may include one or a combination of statistics such as mean monthly flow, monthly standard deviations, lag correlations, mean annual flows, inter-annual standard deviation, and the Hurst coefficient for long-term memory. To maintain the observed statistics between multiple gauged sites, one objective must contain information that quantifies the cross-correlation between the sites. A simplified cross-correlation metric aggregates the vector product of each pair of gauged locations to create a $G \times G$ matrix:

Equation 4-6

$$Z_{\text{xcorr}} = \left\{ \begin{array}{ccc} \sum \langle x \rangle_1 \langle x \rangle_1 & \dots & \dots \\ \dots & \sum \langle x \rangle_i \langle x \rangle_j & \dots \\ \dots & \dots & \sum \langle x \rangle_G \langle x \rangle_G \end{array} \right\}$$

where each $\langle x \rangle$ is a historical observed time series for each i and j location.

The second step is to generate n years of initial streamflow values x for each month j by random sampling from the historical monthly distribution $f(x_j)$ at each location g . This initial sampling begins each synthetic sequence with historically realistic values, however statistical properties are not initially maintained beyond monthly mean values and standard deviations.

The third step is to invoke the simulated annealing algorithm to rearrange the initial streamflow sequences. The procedure is as follows:

- 1) An initial T_0 is selected, that is analogous to a high temperature state where all time series configurations are accepted
- 2) A random gauge site g is selected for the modification of its time series
- 3) Two randomly selected values for g are selected to be swapped
- 4) The change in the objective function ΔO is calculated
- 5) If $\Delta O < 0$, the new arrangement is accepted as the current simulated result
- 6) If $\Delta O > 0$, the new arrangement is accepted with the probability of:

Equation 4-7

$$P(\Delta O) = \exp\left(\frac{-\Delta O}{T}\right)$$

As described earlier, this is done by generating a random number (ξ) uniformly distributed between 0 and 1 and comparing with the result $P(\Delta O)$. The change is accepted if $\xi < P(\Delta O)$ and rejected if $\xi > P(\Delta O)$.

- 7) Repeat steps 2-6 while periodically updating the value of T after a user-defined number of iterations M is reached. At these updates, lower the value of T by a user-defined increment α such that $T_{M+1} = T_M \alpha$ and $0 \leq \alpha \leq 1$.
- 8) Terminate the algorithm when a user-specified criterion is reached such as a total maximum number of iterations.

Various user-defined criteria are described in the above procedure including the selection of statistics to be reproduced through the set metrics Z , the assignment of T_0 , the number of iterations M between updates to T , the rate of cooling α , and the termination criteria. As mentioned earlier, the set of statistics (Z) to be reproduced reflect both the known characteristics of the system and any specific objectives that are being considered. For example, systems such as the Nile are known to demonstrate long-term 'memory' or persistence of states of wet and dry years (*Hurst 1951*), therefore inclusion of the Hurst coefficient is appropriate. For systems that do not demonstrate such tendencies, the additional computational burden may not be worthwhile. While certain statistical properties may be commonly used such as average flows or standard deviations, the technique is highly customizable to meet the needs of the locations being considered.

The optimization element of this algorithm is contained in the iteration of steps 2 through 6. New arrangements are continuously sampled in a highly randomized manner to while evaluating for improvements to the objective function. The optimization objective simply minimizes the difference between a set of desired properties and the properties of a particular arrangement of elements. After each exchange of elements, an evaluation of the objective function is conducted and if improvements are found, the exchange is accepted and the form prior to the exchange of elements is maintained. However, if the exchange is not found to improve the outcome with respect to the objective function, the exchange is increasingly rejected over time. While rejecting a less desirable configuration is intuitive, accepting a less-desirable configuration is also permitted in an attempt to avoid potential sub-optimal outcomes. Maintaining this level of 'doubt' in the best outcome allows for constant re-exploration of the decision space. The further the negative deviation is from the state prior to the exchange however, the less probable the acceptance of that state will be. As a result, the algorithm attempts to hone in on an optimal outcome while maintaining a level of doubt that increases with multi-parameter 'distance' and decreases with 'time'.

The algorithm described above requires some form of cooling schedule. Various forms of this schedule have been developed (Hajek 1988; Kirkpatrick et al. 1983), compared (Yaghout and Bjarne 1998) and optimized (Hoffmann and Salamon 1990) for a number of applications, however there are no standardized guidelines yet for developing synthetic hydrologies. Kirkpatrick et al. (1983) suggests that the simulation should proceed long enough at each temperature to reach a steady state and then proposes a simple exponential cooling that allows essentially all changes to be accepted at the initial temperature state (T_0) and 10 potential swaps for each element allowed at each temperature. Bárdossy (1998) suggests that the number of iterations should be proportional to the length of the time series (N) and $M = N$ or $M = 2N$ should allow each element a high probability for being involved in a possible swap. In the case of multi-site annealing, the total number of elements is the length of the time series multiplied by the number of rivers to be simulated, therefore this would suggest a requirement of $M = 2NG$. However, due to the interdependence between the multiple rivers introduced through the cross correlations, a higher number of iterations would be recommended. This research avoids solving this mathematical question by applying a large number of iterations at each temperature step ($M=4NG$) throughout 92 exponentially decaying temperature increments. Methods of optimizing annealing schedules can lower energy results significantly compared to linear and exponential cooling (Hoffmann and Salamon 1990), therefore strategic methods of annealing schedules can be sought if computational resources are limited.

The simulated annealing procedure is generic in nature and can be applied in many contexts and for many practical applications. The method effectively rearranges the elements that comprise a complex system until the desired properties are sufficiently achieved. The optimization itself is not particularly advanced or efficient in mathematical terms, but instead leverages computational resources that are becoming increasingly powerful in terms of processing speed, and more widely available in the form of multi-core processors on desktop and laptop computers, computational clusters often available in universities and research facilities, and commercial cloud computing

that can make use of many processors simultaneously for extended periods of time. In other words, simulated annealing is appropriate for any context with increasing computational resources.

4.3.5 Model Verification and Validation

Verification and validation of multi-site simulated annealing is necessary to demonstrate whether the individual site statistics, correlations between sites, and aggregate characteristics are reproduced from the observed hydrologic inputs. Evaluating the statistical properties that are incorporated into the objective function demonstrates the ability of the algorithm to replicate these target statistics. Evaluating additional metrics that are not incorporated in the objective function demonstrates how well the set of selected statistics describes the characteristics of the time series.

Verification and validation can be accomplished by three general approaches including: 1) a gauge-by-gauge evaluation, 2) comparing aggregate statistics derived from the combination of multiple gauges (i.e. basin-wide runoff), or 3) applying the synthetic results through a basin simulation model and comparing the results to a known downstream gauge (i.e. basin-wide outflows).

A gauge-by-gauge verification and validation provides the best assessment of the performance of the algorithm itself, yet is lengthy to report for many sites. Stream flows should demonstrate the ability to preserve the monthly mean and variance of each historical time series. Annual average flows and inter-annual standard deviations should also be preserved at each gauge site, particularly for systems with significant inter-annual variability. Inter-annual and intra-annual temporal correlations should verify whether monthly flow patterns and year-to-year persistence of flow conditions are reproduced. Cross-correlations between sites should also be verified to evaluate how well relationships between various sites have been maintained.

Verification and validation using multi-site aggregate runoff or basin outflows allows a more condensed yet less robust reporting. Basin-wide monthly or annual flows helps to communicate how well the simulated annealing algorithm performs, however the resolution among the sites is obscured. The ability of the algorithm to replicate these statistics is particularly relevant for river basin managers. Validation of basin-wide outflows using a water resource model incorporates multiple uncertainties including those in the hydrology data, lags, losses and any modelled management decisions, and can provide a cumulative process assessment. A combination of individual gauge and basin-wide evaluation metrics should be taken when using multi-site simulated annealing in a decision-making process. Other statistics of particular interest to water managers which are not necessarily incorporated into the objective function may include the magnitude and duration of droughts and floods at specific gauges or at a basin-wide scale.

4.4 APPLICATION

The Eastern Nile River Basin is used to demonstrate the proposed method using a reconstruction of naturalized historical flows from 1900 until 2002. The Eastern Nile region covers an area of approximately 2.7 million km² which is 85% of the total Nile Basin and includes the drainage areas of Ethiopia, Sudan, South Sudan and Egypt. The major sub-basins include the Blue Nile originating near Lake Tana in Ethiopia and ending in Khartoum, Sudan; the White Nile emerging from the Sudd Wetlands in South Sudan and merging with the Blue Nile in Khartoum; the Baro-Akobo-Sobat sub-basin starting in the southern Ethiopian Highlands and draining into the White Nile near the town of Malakal, South Sudan; the Tekeze-Setit-Atbara sub-basin originating in the Northern region of Ethiopia and flowing into the Nile near the town of Atbara, Sudan; and the Main Nile flowing from the confluence of the Blue and White Niles in Khartoum and flowing northward through the Nubian desert of Sudan and into Egypt. The upstream-most gauge considered on the White Nile is that near Mongalla South Sudan, which drains the Equatorial Lakes region of the Nile.

4.4.1 Data

The historical data set of naturalized flows was developed by van der Krogt and Ogink (2013) as part of a study for the Eastern Nile Technical Regional Office (ENTRO) of the Nile Basin Initiative. A primary output was a complete suite of time series at different locations throughout the Eastern Nile Basin that could be used to evaluate future development projects. This effort compiled over 40 gauged streamflow records covering different locations and time periods throughout the basin. This study divided the basin into 162 hydrologic inflow locations (catchments) that were delineated geographically by topography, location of streamflow gauges, and locations of existing and proposed reservoir and irrigation developments. Some of these catchments can be considered headwater contributions while others describe local inflows along a reach. All locations are non-depleted and unregulated flows. The report by van der Krogt and Ogink (2013) describes how a number of site specific regressions between gauged locations were used to fill in missing data across the multiple but often temporally fragmented sets of historical data, and spatial disaggregation techniques were used to populate multiple inflow locations above gauges. The result was a complete dataset of monthly flow time series from 1900 to 2002 for all 162 catchment sites, which is referred to as the *assumed historical flows*.

For this study, this dataset was analysed to reveal that the sites could be grouped into 18 sets of catchments in which each member of a set was linearly dependent on the other members. In Figure 4-1, catchments with like colours represent linearly correlated groupings and representative or *key* sub-basins are labelled with Roman numerals. In this dataset, 24 catchments showed no contributing inflow (shown in grey), although we note that some of these catchments may indeed regenerate net runoff, particularly in areas of the hydrologically complex Sudd wetlands. The effects of these net contributions are incorporated in water resource models (van der Krogt and Ogink 2013; Wheeler et al. 2016) when calibrated at the downstream Makalal gauge. In addition, three catchments between the Rosaries and Sennar Dams (shown in white) had repeating monthly patterns that when combined contribute less than 1% of the total basin

inflow. With knowledge of one “key” catchment in each of the 18 sets and the cross-correlations between all 162 catchments, estimates of flows for all sites can be determined.

The focus of our research was not to critique the methods used to develop this naturalized dataset, but to develop a multi-site simulated annealing methodology that can (i) generate synthetic monthly streamflow sequences that replicate the statistics of this dataset and (ii) demonstrate the ability of this technique to introduce perturbations to these statistics that represent potential impacts to stream flows as a result of climate changes at the basin scale. The method is therefore intended to be useful for supporting risk-based decision making and analyses of potential development pathways for the Eastern Nile Basin.

4.4.2 Historical Streamflow

The multi-site simulated annealing algorithm was used to generate 100 realizations of monthly time series for 18 of the key catchment sites that are each 50 years in length. The catchments with no contributing flows or continuously repeating monthly flow patterns were assumed to remain unchanged, and all other sites could be recreated using the known correlations among the 18 sets. To begin the algorithm, the initial sequences for these 18 key sites were developed by random sampling of the monthly flows from the reconstructed naturalized historical data from 1900-2002, with the exception of the inflows from the Equatorial Lakes through the Bahr El Jebel (Upper White Nile) at Mongalla (XVII) and a small catchment immediately above the Malakal (XIII). A well-known historical step increase in precipitation over the Equatorial Lakes occurred starting in 1960 resulting in higher outflows (Tate et al. 2001), therefore data sampling at these locations was limited from 1966 to 2002 to replicate the recent statistics at this location. While the XVII site represents the gauged runoff into the Bahr El Jebel, the smaller catchment (XIII) represents the ungauged inflows to Malakal and also demonstrates this notable shift. Cross-correlations between each of these two sites with the other locations were less than 0.3, therefore were considered independent with respect to the other 16 sites.

The initial historical sampling produced 100 ensemble sequences representing randomized monthly flows at the 18 sites across 600 months, totalling 10,800 elements in each sequence. After this initial step, no statistical properties other than average monthly flows would be expected to be well preserved. The annealing process would then transform the sequences to match other important statistical properties.



Figure 4-1. Sub-basins of the Eastern Nile Basin

4.4.2.1 Annealing Formulation

The objective function was configured to combine metrics that compare matrices of mean monthly flow ($\bar{\mathbf{m}}$), monthly standard deviations (\mathbf{s}) monthly lag auto-correlations up to 11 months (ρ), inter-annual standard deviations (σ), inter-annual lag-1 auto-correlation (\mathbf{d}), the Hurst coefficient for long-term memory (\mathbf{H}), and cross correlations between gauges (\mathbf{x}).

Equation 4-8

$$\begin{aligned}
 O = & w_1 \left(\sum_{g=1}^G \sum_{m=1}^{12} \frac{|\bar{\mathbf{m}}_{g,m}^{obs} - \bar{\mathbf{m}}_{g,m}^{sim}|}{|\bar{\mathbf{m}}_{g,m}^{obs} - \bar{\mathbf{m}}_{g,m}^0|} \right)^2 + w_2 \left(\sum_{g=1}^G \sum_{m=1}^{12} \frac{|\mathbf{s}_{g,m}^{obs} - \mathbf{s}_{g,m}^{sim}|}{|\mathbf{s}_{g,m}^{obs} - \mathbf{s}_{g,m}^0|} \right)^2 \\
 & + w_3 \left(\sum_{g=1}^G \sum_{c=0}^{11} \frac{|\rho_{g,c}^{obs} - \rho_{g,c}^{sim}|}{|\rho_{g,c}^{obs} - \rho_{g,c}^0|} \right)^2 + w_4 \left(\sum_{g=1}^G \frac{|\sigma_g^{obs} - \sigma_g^{sim}|}{|\sigma_g^{obs} - \sigma_g^0|} \right)^2 \\
 & + w_5 \left(\sum_{g=1}^G \frac{|\mathbf{d}_g^{obs} - \mathbf{d}_g^{sim}|}{|\mathbf{d}_g^{obs} - \mathbf{d}_g^0|} \right)^2 + w_6 \left(\sum_{g=1}^G \frac{|\mathbf{H}_g^{obs} - \mathbf{H}_g^{sim}|}{|\mathbf{H}_g^{obs} - \mathbf{H}_g^0|} \right)^2 \\
 & + w_7 \left(\sum_{i=1}^G \sum_{j=0}^G \frac{|\mathbf{x}_{i,j}^{obs} - \mathbf{x}_{i,j}^{sim}|}{|\mathbf{x}_{i,j}^{obs} - \mathbf{x}_{i,j}^0|} \right)^2
 \end{aligned}$$

Terms describing the monthly mean and standard deviations were included in the objective function to preserve the high seasonal variation of the Nile. The monthly autocorrelation up to lag-11 was included to capture the correct form of the seasonal variation. To capture multi-year persistence of droughts and wet periods, one-year inter-annual lag coefficients and the Hurst coefficient are included as terms in the objective function, while the inter-annual standard deviations are included to replicate the frequency of these droughts and wet periods. The computationally intensive method originally introduced in Hurst (1951) was adapted using a rescaling range technique (Lenskiy and Seol 2012) that computes the changing ratio of required storage to standard deviation of annual flows using multiple scales of adjacent sub-windows of time series data. Finally, the term aggregating the cross-correlations between gauges maintains the temporal relationships between the time series.

Each term is normalized relative to its initial state (0) before any annealing begins therefore all terms in the objective function begin with a value of 1. The result of the equation decreases when a configuration is found to result in a lower value of the objective function or increases if a higher objective function value is accepted. Each term was weighted equally in the example provided ($w_1 \dots w_7 = 1$), but unequal weights could be easily added.

The annealing algorithm was applied as described above, iterating between calculations of the objective function and swapping of two random elements within a randomized selection of one of the 18 sites. The initial annealing temperature T_0 is set to 0.2 which allowed 85% of swaps to be accepted (Figure 4-2) while rejecting swaps that would cause extreme increases in the objective function. After allowing the opportunity for 4 potential swaps of each of the 10,800 elements at the initial temperature T_0 , the temperature was decreased incrementally by 17%. This was repeated for 92 temperature reductions and the algorithm was terminated after 4 million iterations were complete.

Allowing a large number of swaps allows the system to initially 'melt' at a high temperature thus increasing the value of the objective function before cooling begins (Kirkpatrick et al. 1983). The components of the objective function that were most sensitive to the random rearrangement of elements changes were those related to monthly statistics (Figure 4-3). This was because the initial sequence configurations were selected from historical monthly observed samples and thus random swapping is likely to make these statistics initially worse before improving. As the temperature decreases, fewer numbers of swaps are allowed that increase the objective function. After approximately 2 million iterations, the objective function elements of all components were below their initial values.

The computational requirements to simultaneously generate a set of sequences for each of the 18 sites took approximately 18 hours of processing time using an HPC cluster consisting of Dual Haswell CPU nodes which have 16 cores per node, a minimum of 64Gb of memory, and between

2.6GHz (standard) to 3.4GHz (turbo-boost maximum) clock speed. To generate the required 100 synthetic traces, 7 nodes of the cluster were simultaneously invoked so all traces could be completed simultaneously.

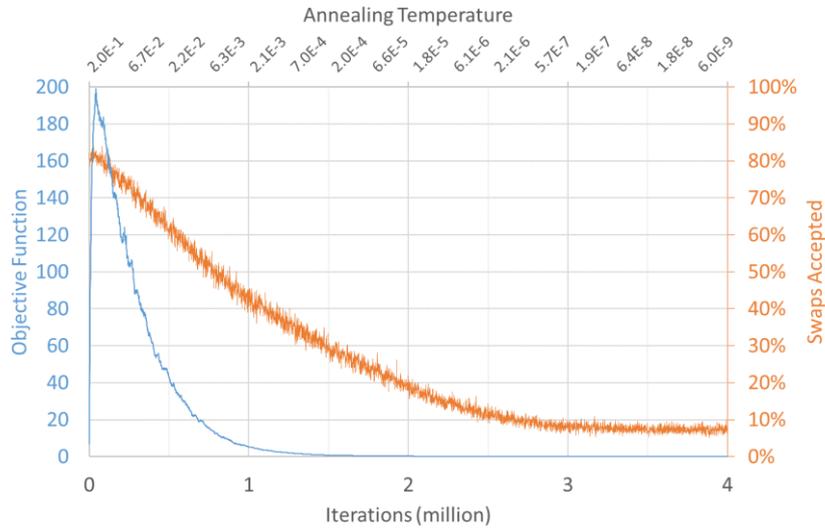


Figure 4-2. Value of cumulative objective function and percentage of accepted swaps against iterations in the simulated annealing algorithm

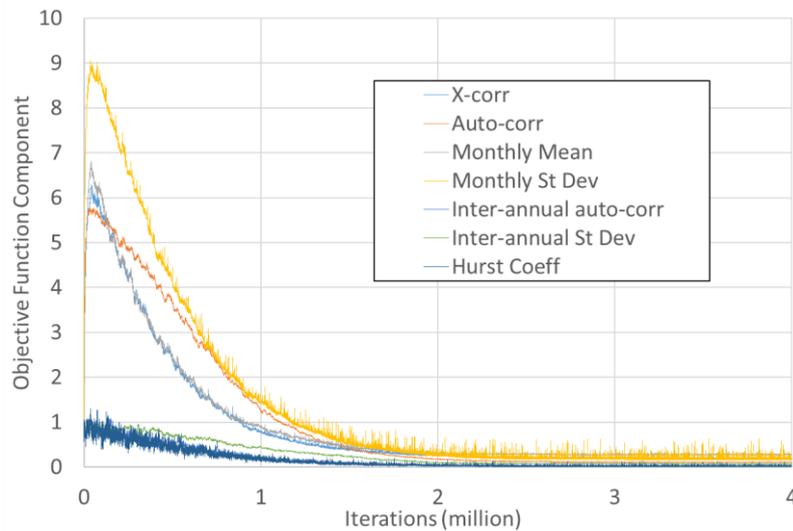


Figure 4-3. Value of objective function components against iterations in the simulated annealing algorithm

4.4.2.2 Validation of Method

A variety of metrics were evaluated to verify the ability of the multi-site simulated annealing method to reproduce historical values. The results were also compared to synthetically generated

sequences using the K-NN resampling technique of the summed flows across all 162 sites, (Prairie et al. 2006) followed by K-NN spatial and temporal disaggregation (Prairie et al. 2007). Monthly flow values from each of the 18 annealed sites were compared to the assumed historical flows and the results from the K-NN method at these locations.

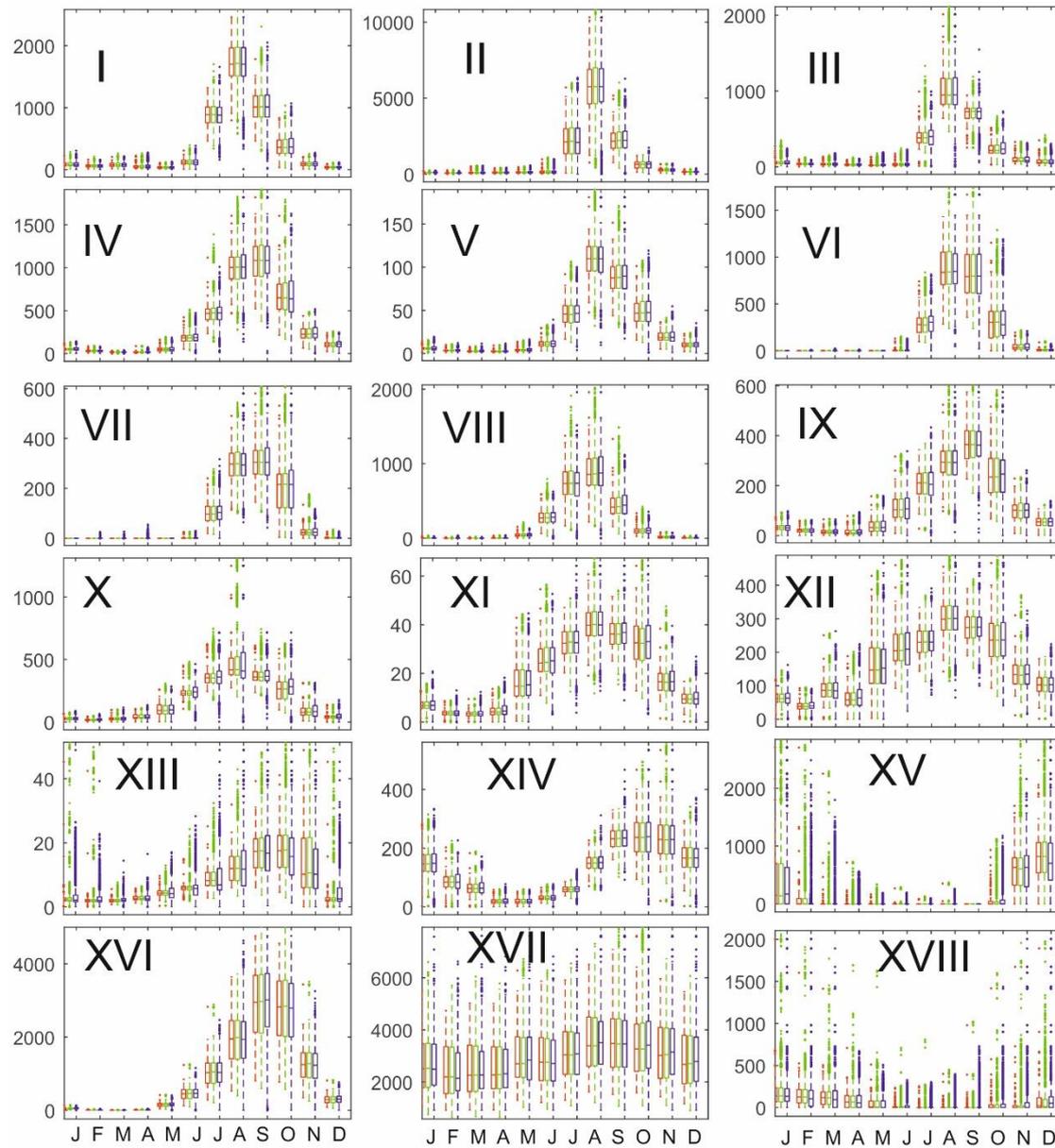


Figure 4-4. Boxplots of synthetic vs. historical monthly flows

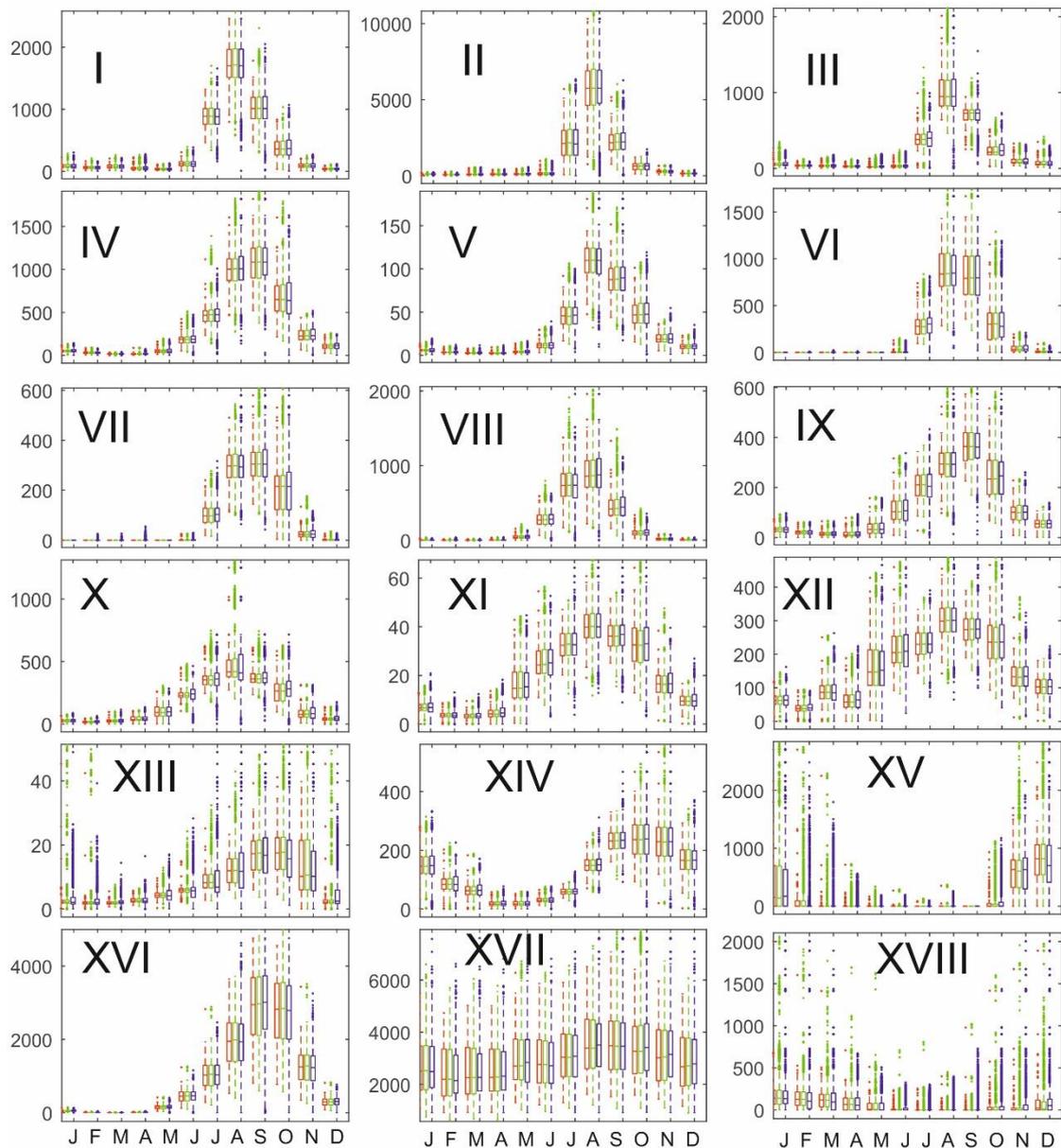


Figure 4-4 demonstrates the ability of the multi-site simulated annealing method to reproduce historical monthly flow values. This shows monthly historical flows (red) compared to 100 realizations of synthetic time series developed by K-NN (green) and simulated annealing (blue). Outliers are defined as beyond 1.5 times the shaded inter-quartile range. Roman numerals correspond to the map in Figure 4-1.

The synthetic time series matched historical monthly flows well in the vast majority of cases, however wider ranges of the outer quartiles were not uncommon. This is due to the flexibility of

the algorithm to swap values across any two months, and as long as the composite objective function improves or the deviation is small while the system is not completely cooled, a swap is more likely to be accepted. Increased outliers in the synthetic scenarios were more common in low flow locations where the effect of a deviation was also less influential on the objective function (e.g. site XIII). Figure 4-5 illustrates how the simulated results typically fall between the historical minimum and maximum monthly values, but it is always possible for some values to fall outside of this historical range.

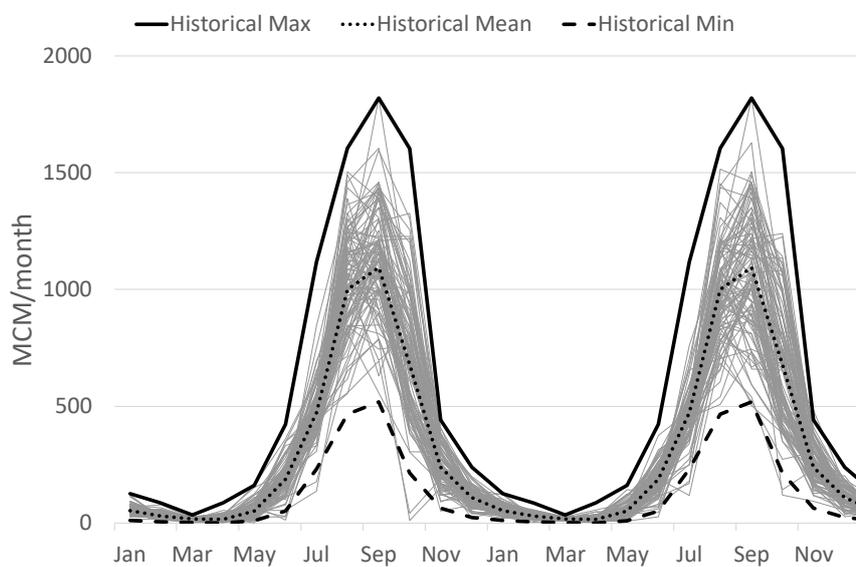


Figure 4-5. Example of multiple hydrologic scenario generation with historical monthly statistics

As seen in Figure 4-6, a summation of the 18 annealed sequences demonstrates how both the inner and outer quartiles distributions match well, but outliers can extend beyond the historical values because of the larger sample size of the simulated dataset compared to the historical values.

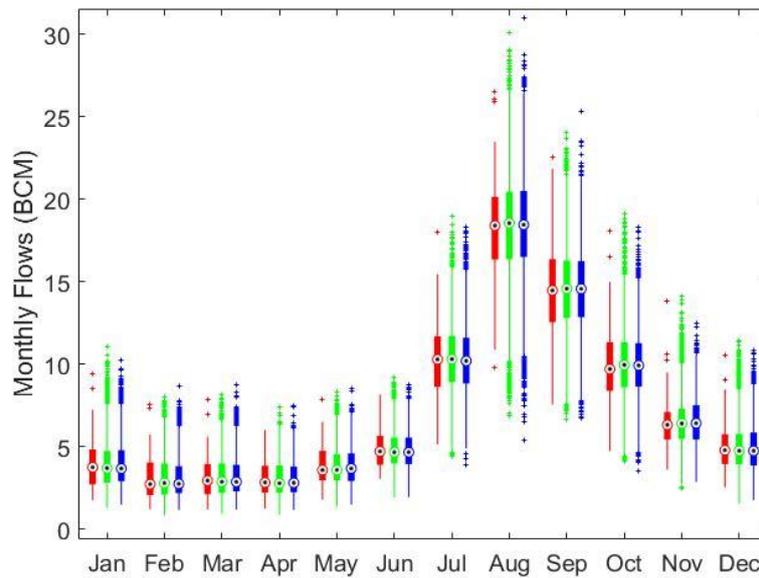


Figure 4-6. Monthly distribution of the cumulative flows for all 18 annealed catchments

The ability of the simulated annealing method to be used to simulate multiple sites relies on maintaining the spatial dependence relationships between the sites. Validation was performed by comparing the correlations resulting from the historical and synthetic sequences between the 18 annealed sites. As shown in Figure 4-7, the average cross-correlations of the 100 synthetically generated traces are well maintained in all pairs with some dispersion occurring particularly in correlations including the lowest correlated site of Equatorial Lakes inflow (XVII). Minor losses of average correlation (< 0.17) occurred infrequently, unidirectional and among some of the highest correlated pairs, indicating marginal improvements to the cross-correlation term in Equation 4-8 becoming dominated by deterioration of the other terms. In Figure 4-7, the cross-correlations of the historical flows are shown by the lines and the cross-correlation of the simulated annealing results are shown by the boxplots. Roman numerals correspond to the map in Figure 4-1.

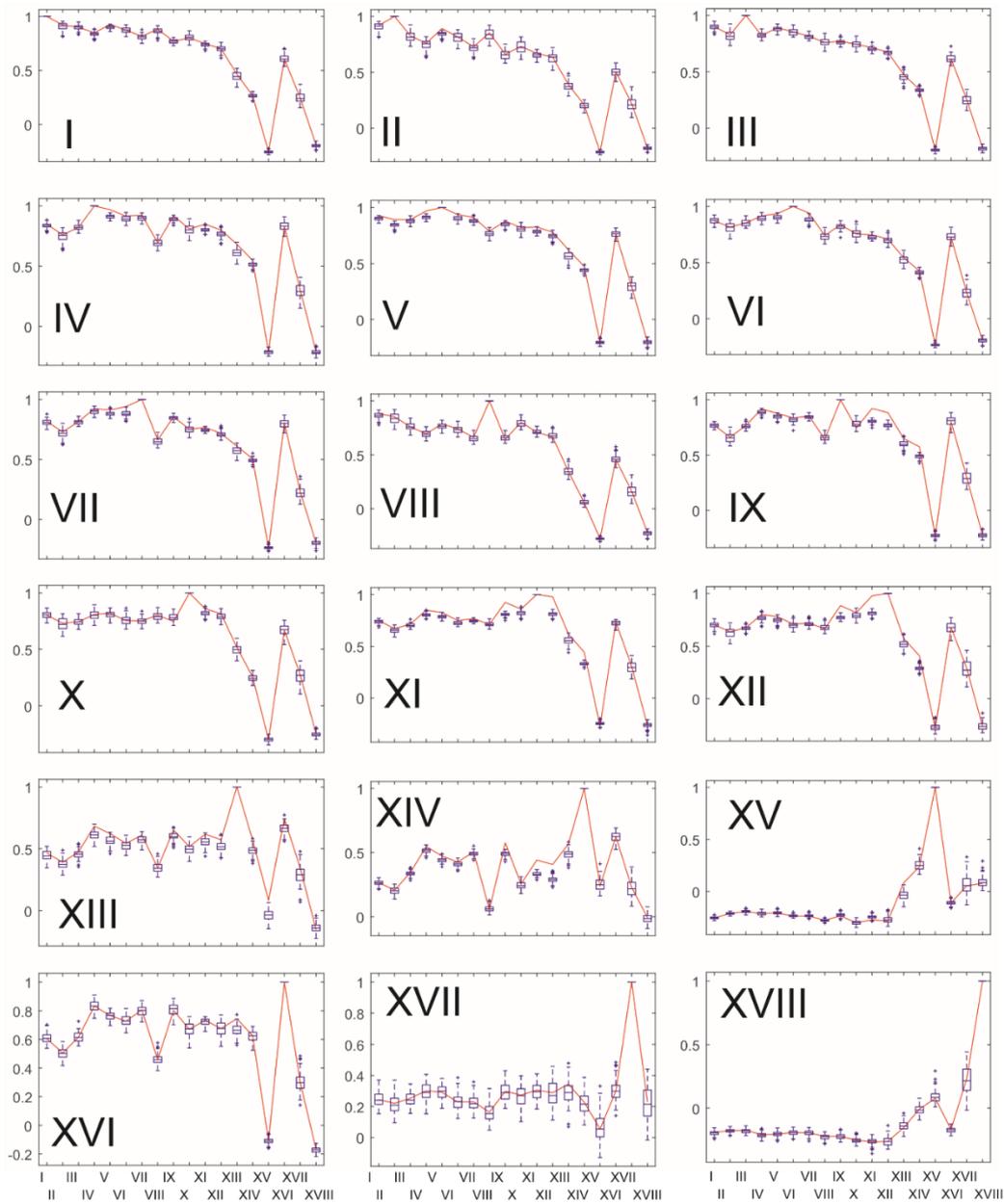


Figure 4-7. Reproduction of cross-correlation between sites

Additional evaluations were performed to determine the ability of the annealing method to generate periods of regional high and low flows. Pairs of sites that had significant cross correlations in the assumed historical record were examined to determine the extent that these relationships were replicated in the synthetically generated results. Figure 4-8 demonstrates the historical monthly flow volumes (red) between Site IV and Site V (correlation = 0.97) and Figure 4-9 between Site VI and Site VII (correlation = 0.94) alongside the reproductions using the K-NN

(green) and simulated annealing methods (blue). Annual flow volumes from the same sites are shown in Figure 4-10 and Figure 4-11 respectively. Both the K-NN and simulated annealing methods performed poorly in maintaining correlations between the sites during the dry months, but had greater success in doing so for the wetter months of July through October. Relative annual flows between the sites were more accurately simulated using the K-NN technique compared to the simulated annealing due to its explicit use of spatial and temporal disaggregation from a single time series. Although the simulated annealing method resulted in a lower degree of correlation among the sites relative to the K-NN method, the general patterns matching the historical flows typically occurred between highly correlated sites (i.e. Figure 4-12). Sites that demonstrate a lower degree of historical correlation would naturally have lower correlations in synthetically generated flows.

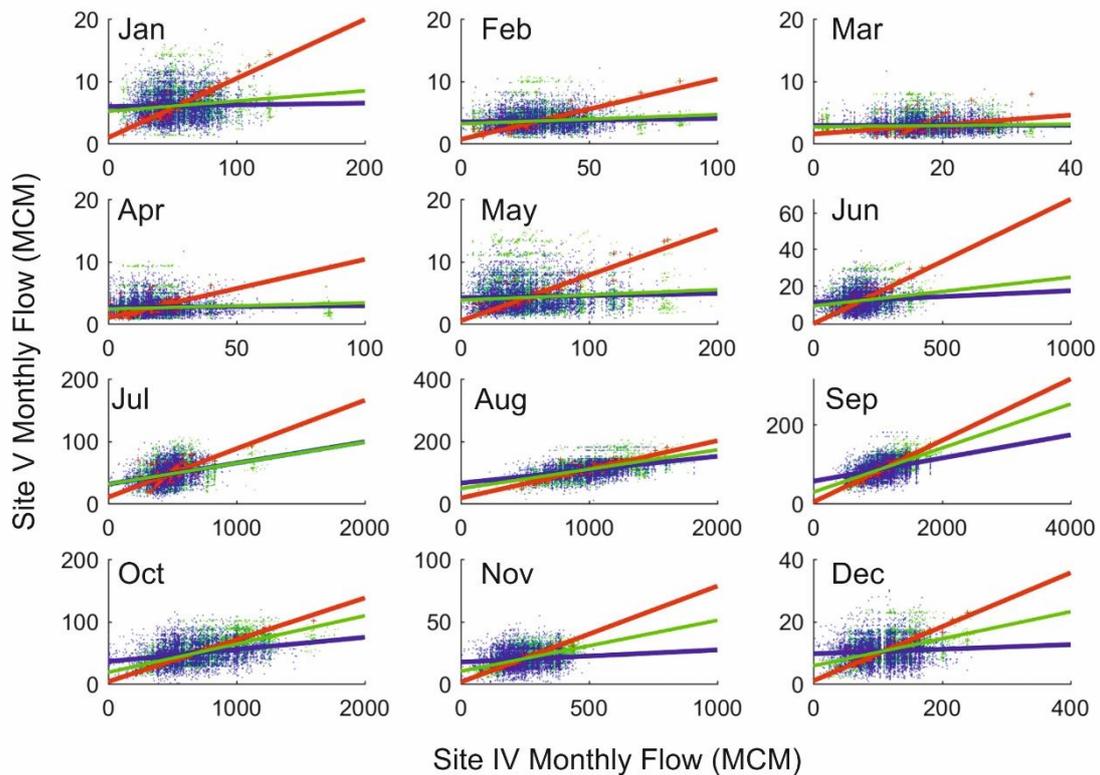


Figure 4-8. Reproduction of monthly flows between highly correlated sites (IV and V)
 Historical (red), K-NN (green), simulated annealing (blue)

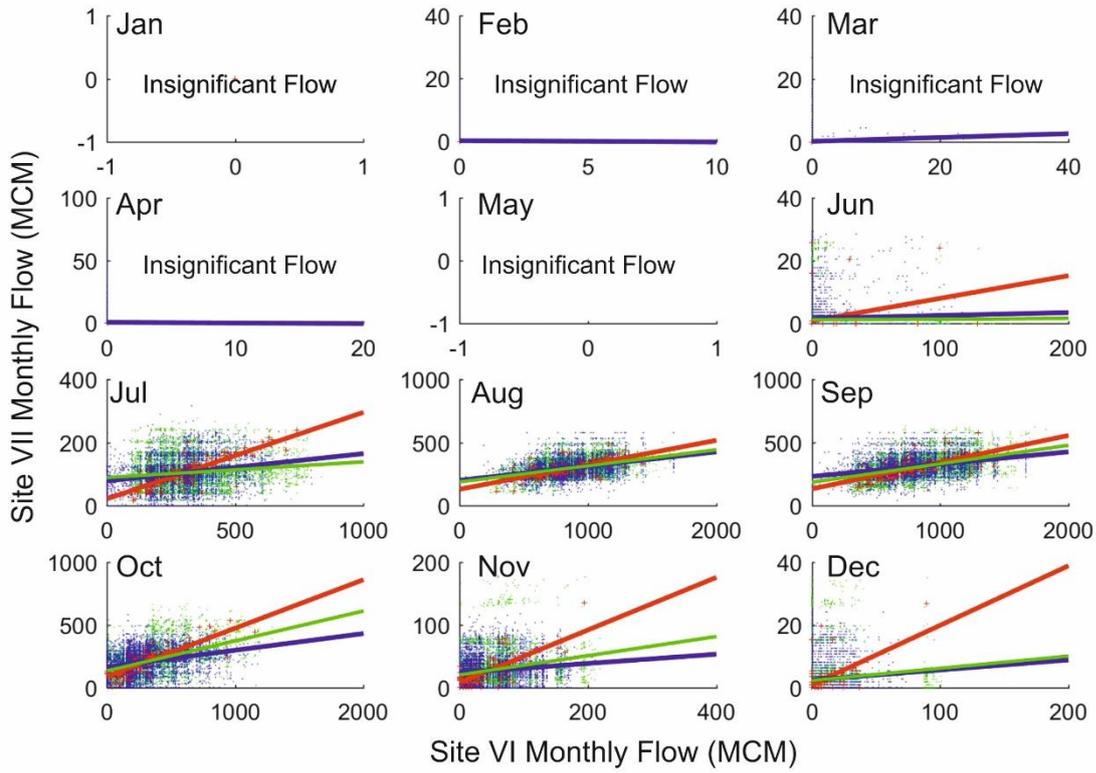


Figure 4-9. Reproduction of monthly flows between highly correlated sites (VI and VII)

Historical (red), K-NN (green), simulated annealing (blue)

Note - January-May flows are typically dry in these sub-basins.

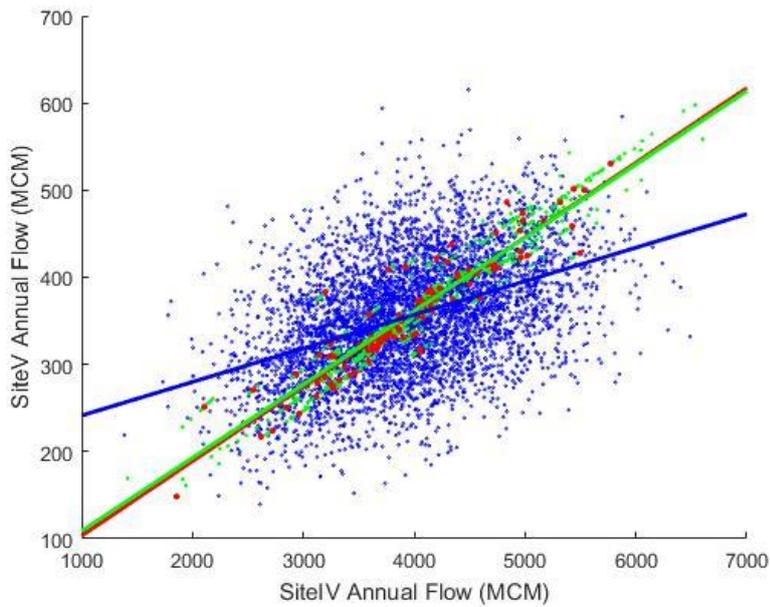


Figure 4-10. Reproduction of annual flows between highly correlated sites (IV and V)

Historical (red), K-NN (green), simulated annealing (blue)

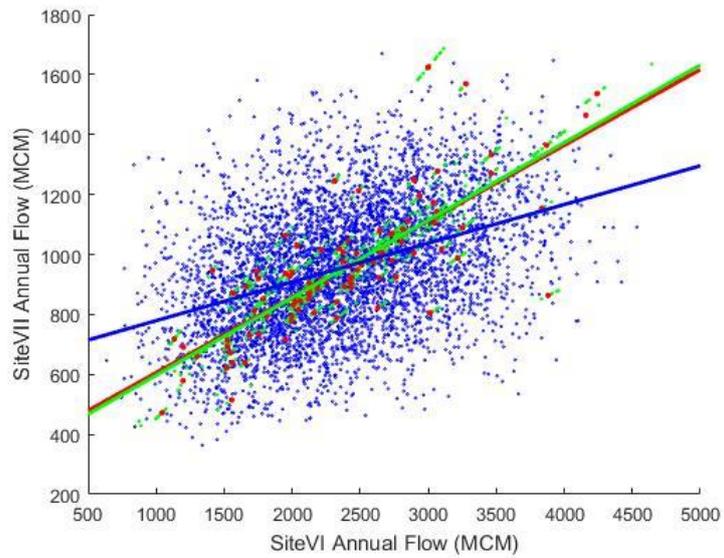


Figure 4-11. Reproduction of annual flows between highly correlated sites (VI and VII)

Historical (red), K-NN (green), simulated annealing (blue)

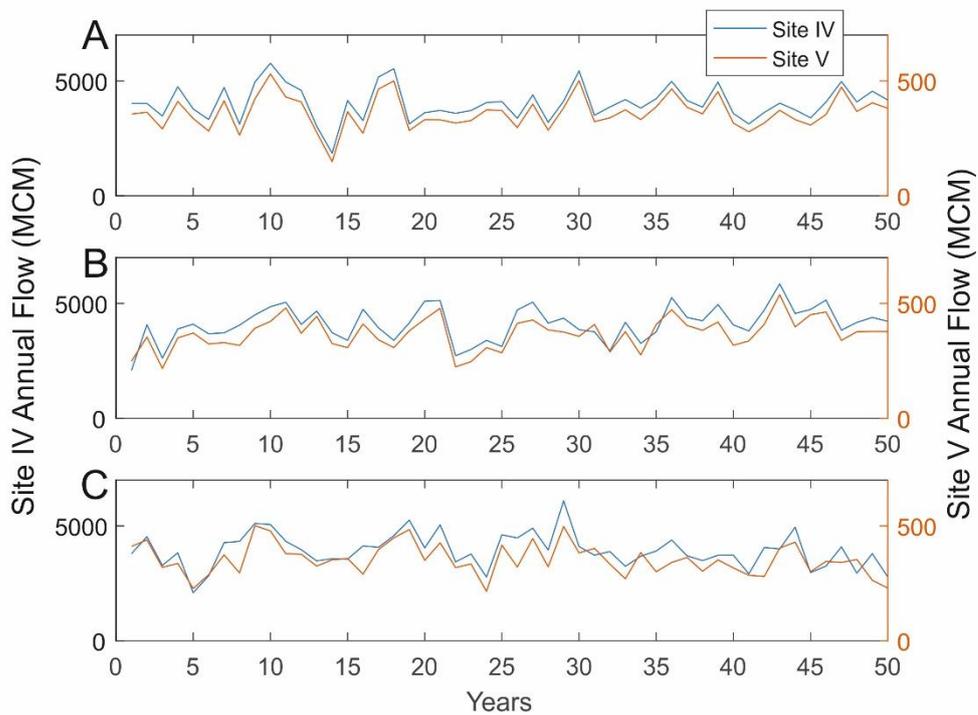


Figure 4-12. Example time series of annual flows for two highly correlated sites (IV and V)

Historical flows (A), K-NN generated synthetic sequence (B) and simulated annealing synthetic sequence (C).

An additional evaluation of the simulated annealing technique was performed by comparing the sum of the basin-wide synthetically generated flows to the basin-wide assumed historical runoff derived from van der Krogt and Ogink (2013). The outputs from the 18 annealed locations were used to estimate flows across all 162 catchment sites by replicating the relationships of the perfectly correlated catchments in the distributed historical data set. A first order polynomial was fitted between the key sites and their perfectly correlated constituents within the original dataset, then the same coefficients were used to map each of the 18 synthetic series to the new sequences. The three minor catchments with simple repeating patterns were duplicated in the synthetically generated series to complete the full suite of sequences for 162 sites. Figure 4-13 shows the ability of the simulated annealing technique to replicate the historical basin-wide runoff while generating of a large number of samples. Red line is the mean, pink box is the standard deviation, and blue box is the 95% confidence interval. Points show all years of each trace.

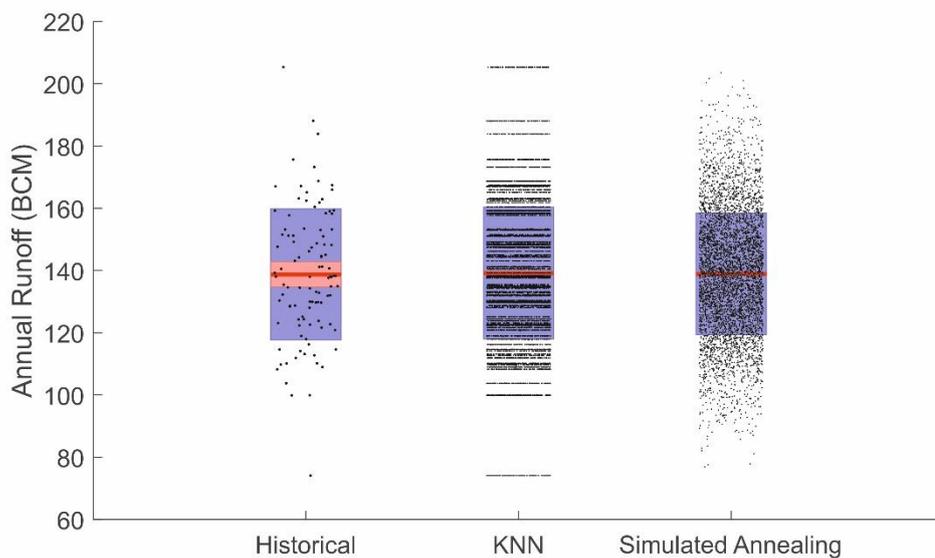


Figure 4-13. Annual total basin runoff from assumed historical flows and simulated annealed

4.4.3 Climate Modified Streamflow

A primary rationale for developing the multi-site simulated annealing algorithm was to explore its ability to generate synthetic sequences that reflect runoff from potential future climate changes.

Borgomeo et al. (2015a) demonstrated that for a single hydrology on the Thames River, perturbations to the objective function can drive the algorithm to generate sequences with desired modified statistical characteristics while leaving other characteristics unchanged. Whether such objectives can be achieved in a complex basin with multiple runoff locations such as the Eastern Nile is the question that is addressed here.

In the case of the Eastern Nile Basin, three targeted perturbations were performed: modifications to the inter-annual standard deviation of flows (ias), modifications to the one-year inter-annual autocorrelation of flows (iaac), and modifications to the Hurst coefficient (Hurst). For this study, the success of each perturbation depended on whether the algorithm indeed generated streamflow sequences with the desired modified statistical characteristics, whether other desired characteristics remained sufficiently close to the statistics of the historical data, and whether the synthetically generated sequences resulted in expected basin-wide changes to drought characteristics as we describe below.

In the first example, we attempt to generate hydrologic sequences with modified ias to produce greater or fewer occurrences of annual flows. This was accomplished by introducing a perturbation factor p_1 in the objective function as a multiplier to the observed ias, and assigning it to each of the desired levels 0.5, 0.75, 1.25 and 1.5. With each value assigned, 100 synthetic traces were generated, each of which are 50 years in length. The resulting sequences are denoted as *ias 0.5*, *ias 0.75*, *ias 1.0*, *ias 1.25* and *ias 1.5* in the following analyses.

In the second example, similar modifications to the iaac were introduced. By doing so, we tested the ability to generate sequences with longer or shorter persistence of flows, hence increasing (or decreasing) the likelihood that a drought year is followed by another drought year or a wet year is followed by another wet year. Within the algorithm, this is accomplished by introducing a perturbation factor p_2 in the objective function as a multiplier to the observed iaac, and assigning

it to each of the desired levels of 0.5 and 1.5. The synthetically generated sequences resulting from these factors were denoted as *iaac 0.5*, *iaac 1.0*, and *iaac 1.5*.

The third modification performed was alterations of the Hurst coefficient at each stream flow location. By modifying this parameter, we tested the ability of the annealing algorithm to generate sequences with changes to the long-term persistence of droughts and wet years. We introduced a perturbation factor p_3 in the objective function as a multiplier to the historical Hurst coefficient and varied this from 0.8 and 1.2 times. Since the Hurst coefficient is bound between 0.5 and 1.0 by definition, each element in the array of objective Hurst coefficients were also bounded within this range. Synthetically generated sequences with modified Hurst coefficients are denoted as *Hurst 0.8*, *Hurst 1.0*, and *Hurst 1.2*.

Equation 9 presents the objective function with the three perturbation factors introduced.

Equation 4-9

$$\begin{aligned}
O = & w_1 \left(\sum_{g=1}^G \sum_{m=1}^{12} \frac{|\bar{m}_{g,m}^{obs} - \bar{m}_{g,m}^{sim}|}{|\bar{m}_{g,m}^{obs} - \bar{m}_{g,m}^0|} \right)^2 + w_2 \left(\sum_{g=1}^G \sum_{m=1}^{12} \frac{|s_{g,m}^{obs} - s_{g,m}^{sim}|}{|s_{g,m}^{obs} - s_{g,m}^0|} \right)^2 \\
& + w_3 \left(\sum_{g=1}^G \sum_{c=0}^{11} \frac{|\rho_{g,c}^{obs} - \rho_{g,c}^{sim}|}{|\rho_{g,c}^{obs} - \rho_{g,c}^0|} \right)^2 + w_4 \left(\sum_{g=1}^G \frac{|p_1 \sigma_g^{obs} - \sigma_g^{sim}|}{|p_1 \sigma_g^{obs} - \sigma_g^0|} \right)^2 \\
& + w_5 \left(\sum_{g=1}^G \frac{|p_2 d_g^{obs} - d_g^{sim}|}{|p_2 d_g^{obs} - d_g^0|} \right)^2 + w_6 \left(\sum_{g=1}^G \frac{|p_3 H_g^{obs} - H_g^{sim}|}{|p_3 H_g^{obs} - H_g^0|} \right)^2 \\
& + w_7 \left(\sum_{i=1}^G \sum_{j=0}^G \frac{|x_{i,j}^{obs} - x_{i,j}^{sim}|}{|x_{i,j}^{obs} - x_{i,j}^0|} \right)^2
\end{aligned}$$

Each factor p_1 , p_2 and p_3 was individually varied while holding the others at constant value of 1 to identify the effects of their respective changes. As described earlier term $p_3 H_g^{obs}$ was bound from [0.5,1]. The results of each of perturbation were analysed by first measuring the ability of the changes to the objective function to meet the intended objective in the outputs. If this was

indeed the case, the degree to which the other desired statistics changed was checked. Finally, the effects of the changes on to the frequency and persistence of droughts and wet periods was evaluated.

4.4.3.1 Variation of inter-annual standard deviation

Synthetically generated sequences that were produced using modifications to the ias term in the objective function demonstrated inconsistencies between the annealed locations. Figure 4-14 shows the ratio of the ias for the annealed outputs to the ias of the assumed historical flows at each of the 18 key locations. Results for each of the 5 perturbations to the ias are shown, each of which are derived from the results for 100 synthetic sequences to generate the box plots shown.

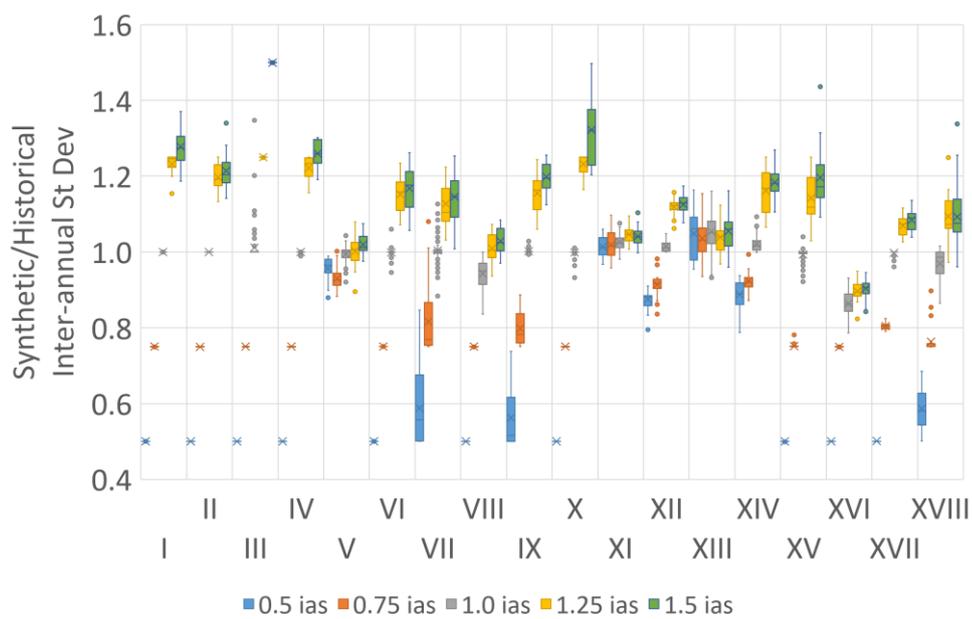


Figure 4-14. Response of changes to inter-annual standard deviation in the simulated annealing algorithm

Reducing the targeted ias within the objective function by $p_1 = 0.75$ and 0.5 resulted in commensurate reductions in the synthetically generated flows in 13 of the 18 key sites. Increases in ias were less frequent with only 5 of the 18 sites able to produce appropriate sequences when $p_1 = 1.25$ was introduced. Only one site could achieve the appropriate increase when $p_1 = 1.5$. The limited ability to deviate from the historical ranges was most pronounced at the sites with lowest

flows (Sites V, XI, XIII) while the sites with both higher flows and seasonal variation allowed for larger deviations from historical values. The values used in the developing the sequences are sampled directly from the assumed historical monthly data, therefore the inconsistent ability to re-arrange the elements in a way that increases the probability of annual low and high flows is attributed to effects on deviations from the assumed historical monthly means, which are also parameters within the objective function. It is likely that both the annual and monthly targets and possibly the initial sampling pool of values must be concurrently modified for the simulated annealing algorithm to reliably generate higher and lower annual flows.

4.4.3.2 Variation of inter-annual auto-correlation

The simulated annealing algorithm was significantly more successful in producing synthetic traces with variations in iaac. Figure 4-15 shows that essentially 17 of the 18 key sites were responsive to changes in the p_2 term in equation 8. The only site for which the algorithm was not successful in scaling the iaac was the inflows to the Eastern Nile from Lake Victoria (XVII). This location has the highest auto-correlation (0.58), the lowest cross correlations with other key sites in the basin, and the highest overall magnitude of flow for a single site in the assumed historical set, therefore deviations in the iaac as suggested by this intended perturbation would result in large penalties incurred by deviations the other variables in the objective function. This site is the exception though and overall the perturbation can be considered successful.

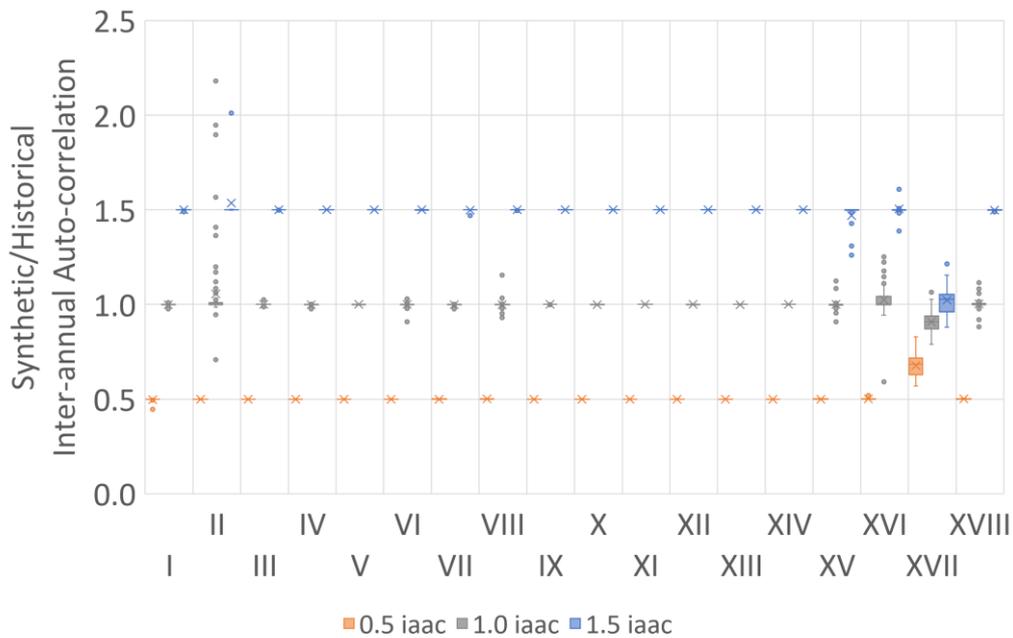


Figure 4-15. Response of changes to inter-annual autocorrelation in the simulated annealing algorithm

The monthly distributions, cross-correlations, and Hurst coefficients were also verified for each of the iaac scenarios and did not deviate significantly from the baseline annealed case ($p_1 = 1$, $p_2 = 1$, $p_3 = 1$)

Drought characteristics from the synthetically generated flows were evaluated to quantify the practical effects to the changes of the iaac values. We arbitrarily selected the annual Q75 as the threshold for drought occurrence. The duration of drought was defined as the number of consecutive years below this threshold and the drought severity is defined as the cumulative multi-year deficit below this threshold (Mishra and Singh 2010). For each iaac scenario and across each of the 100 synthetically generated sequences, the total basin runoff was derived as described above and the duration and severity of droughts evaluated as shown in Figure 4-16. In the assumed historical hydrology, 20 droughts occur using this definition, allowing statistically small yet replicable distribution. The cumulative deficit and duration of severe droughts increases steadily with increasing inter-annual autocorrelations, thus demonstrating that modifications to

the iaac targets within the simulated annealing algorithm is indeed a useful for evaluating the increased risk of drought.

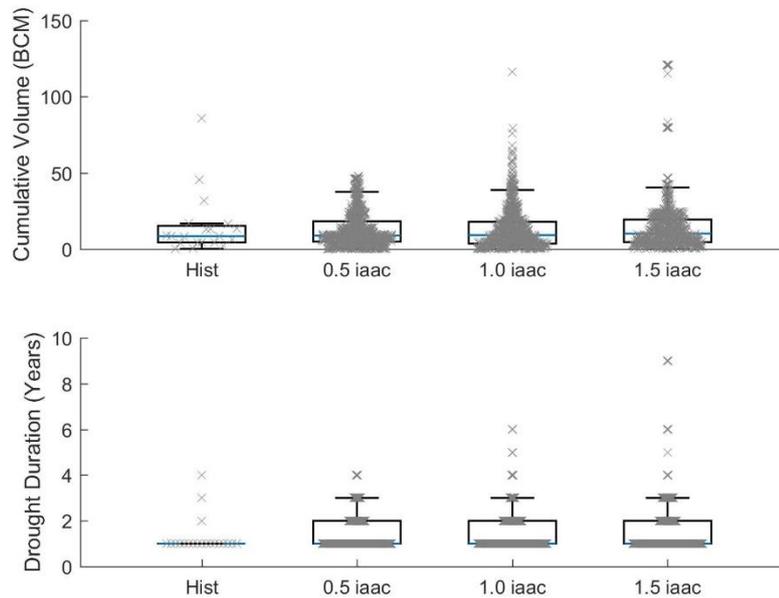


Figure 4-16. Drought duration and cumulative deficit (time and volume below Q75) from various changes to the inter-annual autocorrelation

4.4.3.3 Variation of Hurst coefficient

The third climate perturbation was modification of the Hurst coefficient to alter the long-term ‘memory’ of the system, or effectively altering the persistence of droughts and wet periods (Hurst 1951). Although the limits of the Hurst coefficient are occasionally reached and some dispersion occurs, Figure 4-17 demonstrates that modifications to p_3 in the objective function almost always scales the Hurst coefficient appropriately when compared to the non-perturbed case (1.0 Hurst). This also demonstrates how well the Hurst coefficient of the assumed historical hydrology is replicated in this non-perturbed simulated annealing case.

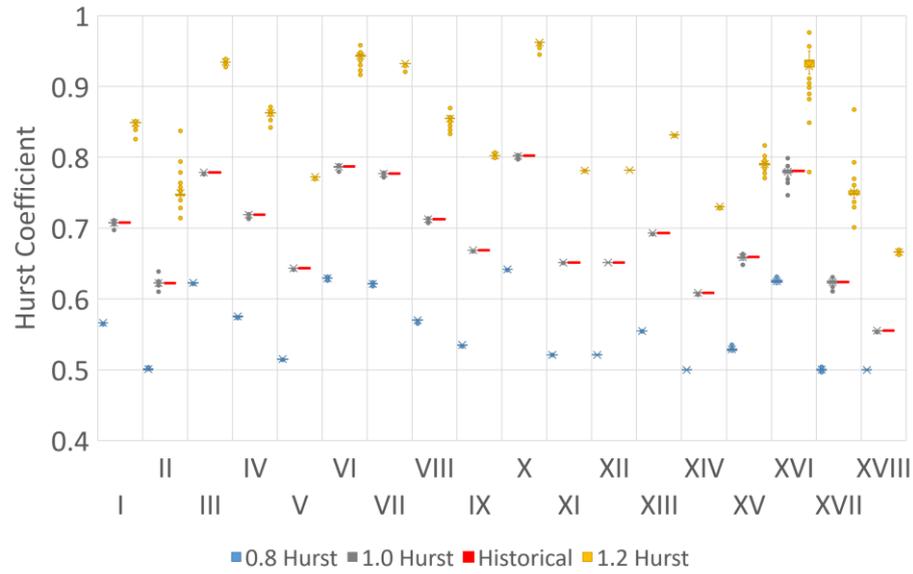


Figure 4-17. Response of changes to Hurst Coefficient in simulated annealing algorithm

Basin-wide drought characteristics of the scenarios that adjusted the Hurst coefficient were also evaluated. Figure 4-18 shows that increasing the Hurst coefficient of the flow series (whilst keeping the other statistics constant) increases the duration of severe droughts and resulting cumulative drought volumes, as would be expected by its original functional definition of an indicator.

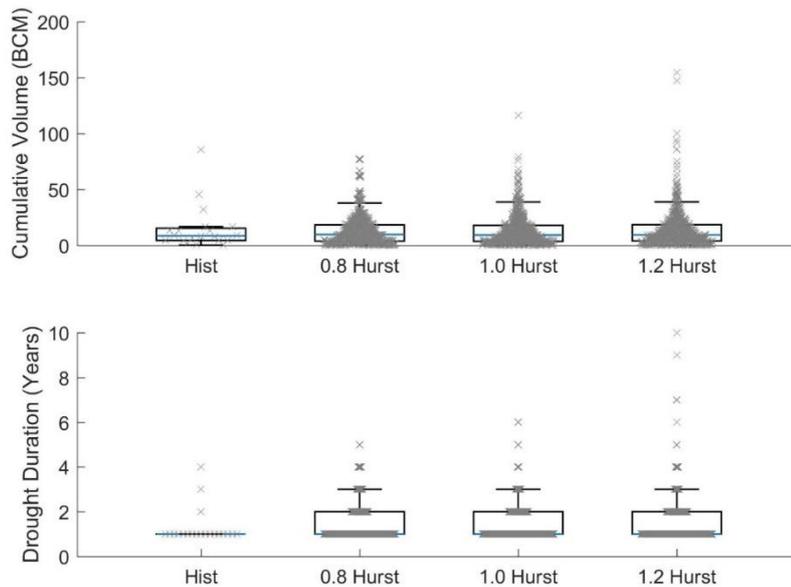


Figure 4-18. Drought duration and cumulative deficit (time and volume below Q75) from various changes to the Hurst coefficient

4.5 CONCLUSIONS

This paper presents a method for multi-site synthetic hydrology generation to reproduce historical sequences and generate perturbed sequences for water resources vulnerability assessments in large river basins. The non-parametric method resamples observed data, using a simulated annealing algorithm to optimize the fit between the statistics of the simulated and observed series. This method is particularly useful for water management at a basin scale, and can provide planners with an important tool for risk-based planning. An application of the method is presented here for the Eastern Nile Basin, with 18 primary flow locations simulated which is expanded to all 162 catchments of the Basin. It has been shown to successfully replicate assumed historical runoff at multiple locations while maintaining correlations between the sites and total runoff volumes across the basin. The river-flow driven method provides distinct advantages over methods that rely on generation of synthetic weather sequences and propagating the outputs through traditional rainfall-runoff models. This bottom-up method requires minimal assumptions,

yet is capable of incorporating essentially any characteristic of historical flows that is desired to capture.

The algorithm also enables perturbation of the flow series to enable testing of the possible effects of climate change on water resource systems. There is inevitably a limit to which some statistics of the time series can be modified whilst preserving others. The results indicate that sequences with desired alterations to the inter-annual autocorrelation and Hurst coefficient can be readily simulated. The modified sequences do indeed demonstrate changes to drought duration and severity. Results also indicate that changes to inter-annual standard deviations cannot be achieved through simple modifications of the objective function, however possible approaches are suggested by this research that statistically alter the input sample data before resampling. Additional modifications to the algorithm are easily incorporated such as sampling from alternative distributions, including additional statistics in the objective function, and applying perturbations of statistics due to the potential effect of climate changes.

The method described here allows water resource systems, including their infrastructure and operational policies, to be evaluated by “stress-testing” them with shifts in variables that are subject to potential natural or anthropogenic changes, thereby quantifying their robustness to future changes in runoff conditions. Management of shared resources in increasingly stressed river basins will require broad understanding of these potential futures. We believe this provides a useful tool to support these types of analyses.

5 EXPLORING COOPERATIVE TRANSBOUNDARY RIVER MANAGEMENT STRATEGIES: A CASE STUDY OF THE EASTERN NILE BASIN

5.1 INTRODUCTION

When limited water resources are unable to meet all demands in a river basin, strategic decisions must be made among uses or de facto management occurs. Planning based on notions of economic or technically optimal efficiency is complicated in the context of transboundary rivers where water allocation is highly politicised and decisions of exploitation and management are often based on ambitious national development plans. These competing interests are an obstacle to cooperative decision-making, a situation that is often exacerbated by rapidly growing demands and uncertainties regarding future supplies. Finding acceptable arrangements for development and management of infrastructure within international rivers requires a negotiation process that seeks to meet the interests of each country, and the region as a whole. Computer models can lend support both as an analytical tool and as a process of collaborative decision-making (Langsdale et al. 2013; Thiessen and Loucks 1992).

This research develops a conceptual framework for seeking cooperative management strategies in transboundary rivers through an iterative and exploratory systems analysis approach. The process developed in this study draws from policy-oriented water-resource modelling (Loucks 1992), advances in optimization techniques (Reed et al. 2013), data visualization (Woodruff et al. 2013) and water diplomacy (Islam and Susskind 2012) to construct a framework that is applicable in a transboundary negotiation context. The focus of this framework is upon the outcomes for various actors under a range of different development and allocation scenarios, which allows solutions to be tested and refined to reach acceptability by the parties involved.

The context for which this method is applicable is a proposed water resource development in one riparian country that may have an effect on other co-riparian countries. Developments such as

these are common and thus our insights can be widely applied in many situations. We demonstrate this framework in the context the Eastern Nile River Basin to consider the Grand Ethiopian Renaissance Dam (GERD), which is currently under construction. Agreements regarding its operations among Ethiopia and the downstream countries of Sudan and Egypt have yet to be reached.

5.1.1 Transboundary negotiations and water resource modelling

Reaching consensus over transboundary water management requires the ability to demonstrate what is possible through effective cooperation. Developing a common understanding among competing stakeholders regarding the availability of a resource and the implications of its various uses can be achieved through a 'joint fact-finding' process (Islam and Susskind 2012) that invokes the use of knowledge systems that seek to enhance the credibility, saliency and legitimacy of the knowledge they produce (Cash et al. 2003). Water resource models can be particularly useful tools to demonstrate how sources of water can be used to meet various demands while capturing the inherent uncertainties of hydrologic systems (Loucks et al. 2005). While many algorithms exist that demonstrate efficient operation of reservoirs (Sheer et al. 2014; Wurbs 1993) and incorporate risk-based strategies for managing flooding and avoiding shortages to water users (Beard 1963; Loucks and Sigvaldason 1981; You and Cai 2008), integrating the complex social and political factors that determine which parties benefit from management decisions is inherently more complex (Barrow 1998). Hydro-policy models that accurately represent operational logic are applicable in transboundary context.

Multi-objective analyses demonstrate and quantify the degree of compatibility and trade-offs that are made when seeking to achieve a variety of interests (Haimes and Hall 1974; Vemuri 1974), which is particularly relevant for transboundary rivers where the desire for development in one country may or may not conflict with the interests of a co-riparian country. Multi-objective evolutionary algorithms (MOEAs) (Reed et al. 2013) can be coupled with hydro-policy models to

explore a wide variety of ways to manage a system that meet many objectives simultaneously. However, our approach is not one of seeking an elusive optimum. Rather, we use optimisation to search for solutions along the Pareto frontier for different actors. We emphasise satisficing rather than optimising behaviour amongst negotiators, in particular in the pursuit of developments that imply *no significant harm* for downstream countries.

Increasing applications of MOEAs have emerged in recent years (Herman et al. 2014; Kasprzyk et al. 2013; Smith et al. 2016; Watson and Kasprzyk 2017). However only small number of examples within transboundary contexts can be found in the literature. Geressu and Harou (2015) apply the ϵ -NSGAII MOEA algorithm (Kollat and Reed 2006) to identify development and management options for the Blue Nile. They conclude that multiple reservoirs of lower capacity are a preferable in terms of overall efficiency. Giuliani et al. (2016a) applies the BORG MOEA (Hadka and Reed 2013) to assess trade-offs between hydropower production, water supply and flood damages for the transboundary Red River Basin that includes parts of China, Laos and Vietnam. In their study, solutions discovered through the MOEA use both current and future hydrologic projections to consider implications of climate changes on the decision-making process. While these examples demonstrate the potential for MOEAs to provide a set of alternatives that narrow a complex decision space, the use of MOEAs have not been yet placed into a practical context of transboundary negotiations over integrating new water resource developments with operations of existing reservoirs.

5.1.2 Methodological Framework

A model-supported process for seeking cooperative water management strategies for new developments in transboundary rivers is presented in Figure 5-1. The framework addresses the scenario of a proposed new infrastructure development. The configuration of decision rules (“the formulation”) describe the operation and allocation guidelines for the new and existing infrastructure on the river system.

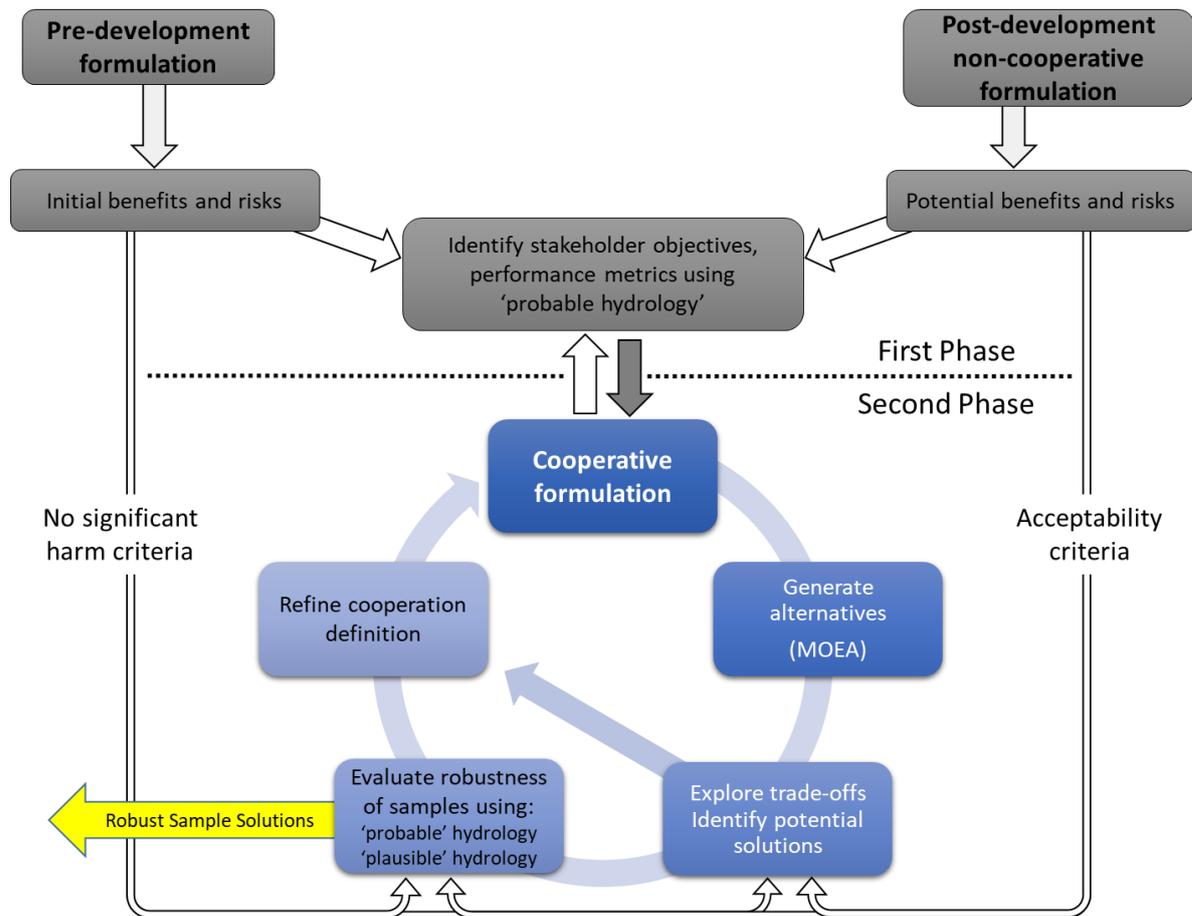


Figure 5-1. Model supported negotiation framework for transboundary river developments

The process is separated into an initial phase that focuses on identifying the interests and objectives of stakeholders, and the second phase focuses on finding ways to meet those objectives. The pre-development formulation represents the status quo situation without any additional infrastructure development, while a post-development formulation represents a scenario after a proposed change has been made to the system. The non-cooperative formulation explores the scenario in which the new infrastructure is operated in a unilateral way that maximises the benefits to those that control it. In the second phase, iterative testing of cooperative formulations explores arrangements in which the new infrastructure would be operated in some manner that considers the needs of co-riparian stakeholders, so its operation is coordinated with existing infrastructure in the basin to achieve this.

Different stakeholders or countries may take different initial positions. A country that is not party to the new infrastructure may prefer the status quo, while the country that controls the new infrastructure prefers to have absolute control of its operation to maximise their own objectives. While both perspectives may be valid, their compatibility is uncertain without further analysis. The pre-development formulation is used to determine current benefits and risks, while the non-cooperative post-development formulation identifies the potential benefits and risks to all stakeholders in the absence of cooperation. Based on these varying perspectives, initial objectives can be established and threshold values may be defined based on stakeholder consultations and notions of tolerable risk (Hall and Borgomeo 2013), or legal principles such as *no significant harm* (Salman 2007). These threshold criteria are to some extent subjective and may be negotiable. The modelling process helps stakeholders to understand and externalise these criteria in terms that are relevant to system operation.

System performance under initial conditions is tested in a wide range of hydrological conditions that are consistent with today's climate, using stochastic simulation of streamflow, calibrated using observed flow series. By simulating the outcomes for different actors in a wide range of hydrological conditions, we are able to estimate risk, i.e. the probability that given (undesirable) outcomes may materialise for different actors. This first layer of simulation addresses hydrological variability, which is reflected in estimates of risk.

However, our estimates of hydrological variability are uncertain, in particular due to the possible effects of non-stationarity. This is addressed in our framework by also considering plausible ways in which the hydrology may change, for example due to changes in the persistence of prolonged dry spells, which may be critical in determining risk. This is relevant to the new infrastructure, which may operate in changed climatic conditions.

Model formulations of cooperative arrangements are unique for individual river basins and based on factors such as physiography of the basin, political dynamics, and historical arrangements.

Sadoff and Grey (2005) describe a continuum of cooperation among co-riparian nations of transboundary rivers, which can be applied to reservoir operations. An acknowledgement of minimum cross-border flow requirements, coordinated flood or drought management planning, or decisions based on sharing benefits (Sadoff and Grey 2002) represent different points along this continuum.

Each cooperative formulation is parameterised according to a set of variables that define how the system would be operated (e.g. reservoir releases, trigger levels). For a given formulation, an MOEA is used to generate a set of parameterisations, each one of which represents a possible solution to the negotiation. A subset of possible solutions can be filtered by the initial criteria. In the context of a transboundary river negotiation, identifying an acceptable solution is unlikely to be a purely mathematical decision and political factors are likely to have significant influence on the outcome. A negotiation however can be informed by identifying scientifically sound and non-dominated alternatives, and then further filtering out combinations of decision variables that demonstrate politically unacceptable outcomes.

If solutions do exist that can meet all assumed stakeholder criteria, it is likely that many solutions will emerge that can be considered potentially feasible. Several sample solutions are then selected to consider their 'robustness' under a wider range of uncertainties or across many plausible states of the world (Hall et al. 2012). This can include expanded hydrologic conditions or any other deeply uncertain parameter.

Rather than seeking an optimal solution that relies on agreement of overall system performance, the notion of *satisficing* seeks to maximize the probability of achieving acceptable or satisfactory outcomes (Hall and Borgomeo 2013). Robust satisficing proposes that decisions made under severe or deep uncertainties should seek to satisfy minimum performance requirements under the widest range of future conditions (Ben-Haim 2006). Herman et al. (2015) describes a practical approach to measure robustness as calculating the fraction of scenarios in which the solution

satisfies one or more of the performance thresholds. Decisions can also be sought by considering a wider range of uncertainties initially, and the cost of doing so evaluated ex post facto (Giuliani et al. 2016a; Watson and Kasprzyk 2017). From a multi-stakeholder negotiation standpoint, the primary question to be asked is whether all parties can live with the proposed solution (Islam and Susskind 2012). If this is not the case, changes can be made to the problem formulation. If no feasible solutions are found to exist that can meet the criteria of all stakeholders, increasing, decreasing or altering the methods of cooperation can be considered or the satisficing criteria need to be adjusted.

5.1.3 Simulation with Multi-Objective Optimization

The outcome of a multi-stakeholder negotiation is seldom optimal from any stakeholder's perspective, because parties rarely agree on the definition of what optimal means. Numerous basin-wide optimisation algorithms exist that provide a global solution based on maximising or minimising an objective function comprised of individual elements that are of interest to various stakeholders, however this approach often requires decisions on how the elements are weighed against each other. The procedure shown in Figure 5-1 is not expected to result in an optimal outcome, but instead provide a set of possible outcomes that could be considered acceptable by all parties. With each formulation of the model-MOEA combination, the MOEAs generate sets of 'decision variables' values (X_i) that represent quantitative management decisions that are used as inputs into a simulation model. The model then produces one or more outputs or evaluation metrics (Y_j) that represent the primary interests of stakeholders or countries in a transboundary context. These objective values are passed into the MOEA, which then provides a new set of suggested input variables. This cyclical routine allows multiple objectives to be simultaneously optimized without indicating a preference. The product is not a single best solution, but a multi-dimensional set of 'non-dominated' solutions that approximates a Pareto-front in which improvements to one objective comes at the expense of another objective (Figure 5-2).

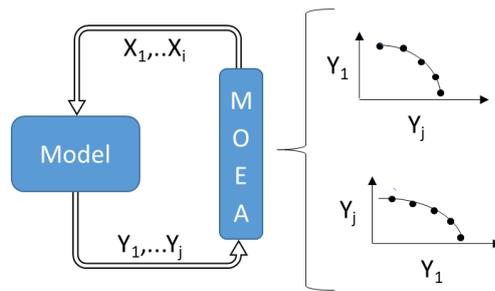


Figure 5-2. Simulation model - MOEA iteration schematic

A variety of MOEAs have been developed in recent years. The goal of each is to explore the often-complex decision space of a problem in the most efficient way possible. These outcomes attempt to describe the trade-offs between evaluation metrics (Y_j) when choosing between the values of the input 'decision variables' values (X_i). BORG is one such MOEA that has demonstrated performance metrics that are superior to other similar algorithms (Hadka and Reed 2013).

BORG builds upon the success of the previous methods and combines them into a set of algorithms. By creating a continuous archive of solutions with a window of user-specified ϵ -dominance describing a 'box' of resolution (Laumanns et al. 2002), BORG approximates and updates Pareto-fronts so to guarantee convergence and diversity throughout the search. Continuous improvements and avoiding stagnation of results are captured by a ϵ -progress criterion that mandates a continuous threshold (ϵ) for improvement, or the search is restarted or abandoned. Such restarts include adaptation of population sizes relative to the archive size, adaptation of the tournament size (a fixed percentage of the population size after each restart), and periodic injection of randomly generated solutions alongside members of the archive (Kollat and Reed 2006). BORG also invokes an auto-adaptive multiple recombination of operators to produce more offspring from the operators that produce successful offspring. As a result, the BORG is considered to be a grouping of algorithms whose operators are adaptively selected based on the problem and the decision variable rather than a single algorithm in itself (Hadka and Reed 2013).

5.2 CASE STUDY

5.2.1 Study Area

The Nile Basin includes portions of 11 countries including Burundi, Democratic Republic of Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda and spans an area of 3.18 million km². One major branch of the Nile begins in the Equatorial Lakes region and flows from Uganda into the Sudd wetlands of South Sudan, and then continues as the White Nile into the Sudanese capital city of Khartoum. The Blue Nile begins in Ethiopia and flows into Sudan where it joins the White Nile in Khartoum. Downstream of this confluence, the combined waters flow as the main Nile from Sudan into Egypt and northward to the Mediterranean Sea. The Sudd wetlands provide a natural hydrologic buffer resulting in relatively steady average monthly flows of the White Nile ranging from 1500 to 3400 cms, while the seasonal fluctuations of the Blue Nile are pronounced with average monthly flows ranging from 150 to 5600 cms. Given the hydrologically distinct Equatorial Lakes region and buffering effect of the Sudd wetland, the Eastern Nile Basin is often delineated to exclude the area upstream of the Uganda-South Sudan border and thus encompasses the countries of South Sudan, Sudan, Ethiopia and Egypt. This area forms the domain of our study to assess cooperative management of the GERD. (Figure 5-3).

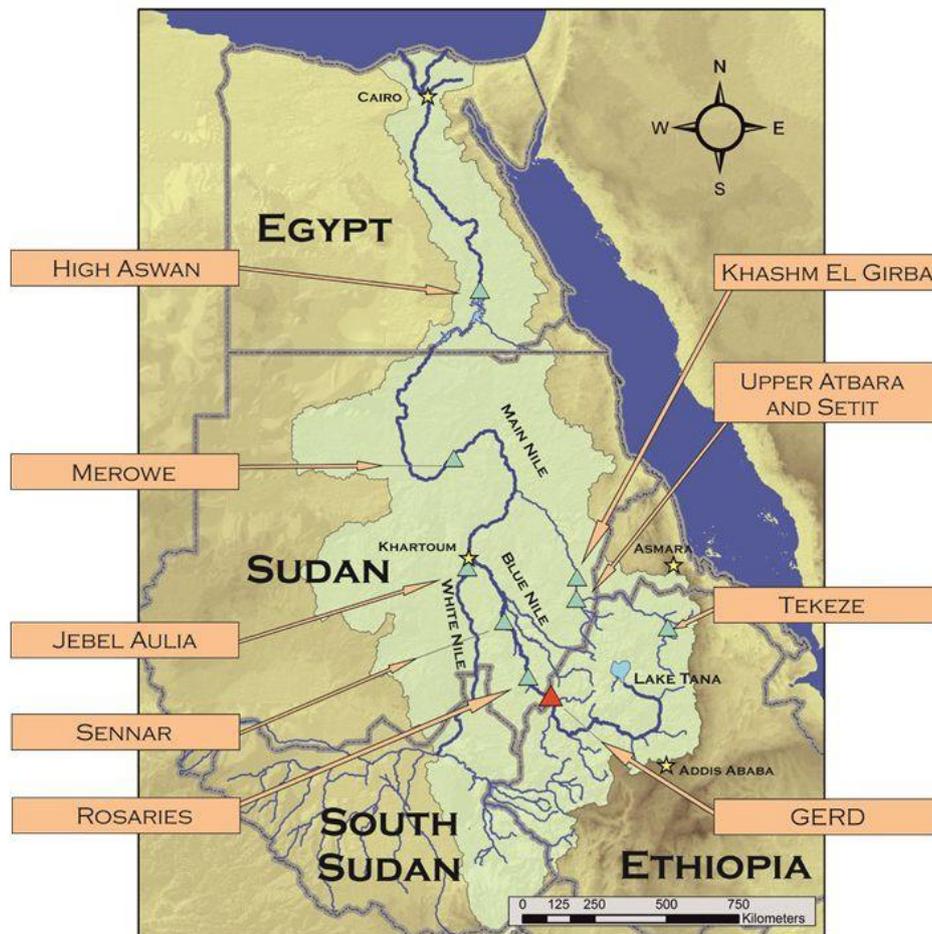


Figure 5-3. The Eastern Nile River Basin with Major Infrastructure Projects

The completion of the GERD will be the latest water management infrastructure in a long history of efforts to engineer the flows of the Nile to meet the needs of a growing population. The Low Aswan Dam (1902) in Egypt, and the Sennar Dam (1925) and Jebel Aulia Dam (1937) in Sudan were the first modern attempts to construct barriers across the Main Nile, Blue Nile and White Nile respectively. The 1959 agreement between Egypt and Sudan initiated the construction of the Roseries Dam (1966) and Khashm El Girba Dam (1964) in Sudan, and the High Aswan Dam (HAD; 1970) in Egypt. The Merowe Dam (2009), the Upper Atbara and Setit Dam complex (2016), and efforts to heighten the Roseries Dam (2013) demonstrate Sudan's modern expansion of water management infrastructure. The Finchaa (1973, expanded in 2012), Tekeze Dam (2009), the Tana-Beles hydropower generation station (2010) are Ethiopia's major endeavours to date.

Ethiopia has long considered large hydropower development of the Blue Nile as an important part of its pathway to improve the economic condition of the country (MOFED 2010; USBR 1964). The construction of the GERD was announced in 2011 and Ethiopian leadership have often stated that it will not cause significant harm to downstream countries of Sudan and Egypt (Gebreluel 2014). While the newly created storage could pose a risk if water is withheld during critical periods, it may also serve as a benefit to these downstream countries in times of extended drought (Whittington et al. 2014). At the current time, no agreements have been reached to coordinate the GERD with the existing infrastructure in Sudan or Egypt, creating a globally unique and potentially precarious situation.

5.2.2 Previous Nile Cooperation Studies

Numerous studies have been conducted that analyse the cooperative development potential of the Nile. Dating back to colonial era, proposals were considered to expand storage capacity high in the two major tributaries to provide more reliable flows for irrigation in Egypt (Hurst et al. 1947). This need was largely met when Egypt constructed the HAD, which effectively postponed the need for cooperative decision making with upstream nations yet at the expense of substantial evaporation losses from Lake Nasser.

Analysis of cooperative arrangements has continued throughout the decades. Using a classical optimization approach, Guariso and Whittington (1987) demonstrated that upstream hydropower development was compatible, and even beneficial, to downstream agricultural production in Sudan and to a lesser extent in Egypt. The economic value of basin-wide cooperation was further demonstrated by Whittington et al. (2005) using a deterministic Nile Economic Optimization Model (NOEM), which Wu and Whittington (2006) coupled with a game theory approach to compare the economic benefits of various coalitions with non-cooperative developments. More recently, Jeuland et al. (2017) reapplied the NEOM in the context of the GERD to examine the economic benefits of system-wide optimization compared to forms of constrained non-

cooperative development including varied adherence to the legal principle of *no significant harm* and the 1959 treaty between Egypt and Sudan.

Block and Strzepek (2010) applied stochastically generated hydrologic scenarios influenced by potential effects of climate change to conduct a risk-based analysis of the cost-benefit ratios of multiple developments in Ethiopia. While downstream flow requirements into Sudan and coordination among potential Ethiopian Reservoirs systems was inherent in the systems optimization approach, cooperative management with the downstream reservoirs was not considered. Goor et al. (2010) developed a stochastic dual dynamic programming model (SDDP) for the Eastern Nile Basin and used 30 synthetically generated hydrologic scenarios to demonstrate the benefits of cooperative operations potential development in the Blue Nile with downstream reservoirs. Arjoon et al. (2014) reapplied this framework specifically considering the GERD, showing strong economic benefits of cooperation. This framework assumes optimized reservoir management across borders, which effectively replaces existing management for an ideally coordinated system.

Jeuland and Whittington (2014) examine a wide variety of Blue Nile development scenarios under different deep uncertainties including multiple multi-reservoir configurations, sequencing and timing of their construction, sizing of the reservoirs, and operating rules. This work introduces one explicit coordination strategy suggesting a minimum release from Ethiopian reservoirs if the storage of the HAD falls below 60 BCM. King and Block (2014) and Zhang et al. (2015) consider various GERD reservoir filling strategies and evaluate the resulting impacts on the Gezira irrigation diversion in Sudan and inflows into Egypt. Finally Wheeler et al. (2016) evaluates potential GERD filling policies that reference dynamic pool elevations of the HAD to demonstrate different degrees of transboundary cooperation. This provides a point of departure for new research to evaluate the potential coordination of reservoirs after the GERD filling is complete and how that decision process might take place.

5.2.3 Droughts and climate changes on the Nile

Records have been kept since ancient times on the flooding and droughts of the Nile (Hassan 2007) and has been a topic of scientific study for well over a century (Waite 1904). In north Africa, droughts are directly linked to the economic well-being of the countries (Block and Rajagopalan 2007; Strzepek and McCluskey 2007), and thus numerous scientific endeavours have been made to understand and predict their frequency and severity (Block and Strzepek 2010; Conway and Hulme 1993; Conway and Hulme 1996; Eltahir and Wang 1999; Siam and Eltahir 2015).

The tendency for flows to remain above and below average annual volumes over sequential years was noticed during early studies to determine the storage required to control the flows of the Nile (Hurst 1951). The ratio of the required storage (R) to the standard deviation of annual flow (σ) were shown to have similar non-dimensional values that increased with record length (N).

Equation 5-1

$$R/\sigma = (N/2)^K$$

Mathematically formalized by Mandelbrot and Wallis (1968), the exponent K has become known as the Hurst Exponent or Hurst Coefficient, a metric of the *persistence* of flows ranging from 0.5 to 1.0 (Sutcliffe et al. 2016). Connections between ENSO signals and the occurrence of flooding and drought conditions have been made (Zaroug et al. 2014) and wavelet analyses have sought to understand the cyclical nature of such events and their implications for water management (Elsanabary and Gan 2014; Melesse et al. 2010; Zhang et al. 2016). Koutsoyiannis (2003) suggests that multiple-scale variability of a time series can explain the Hurst phenomenon.

Projecting the effects of global climate changes in the Nile Basin is an evolving area of research with significant implications with respect to impacts and economic investments. According to studies using general circulation models (GCMs), temperatures are generally expected to increase across the basin. Changes in the direction and magnitude of precipitation are far less certain (Beyene et al. 2010; Conway and Hulme 1996; Di Baldassarre et al. 2011; Yates and Strzepek 1998),

and as a result, projections to runoff and water availability vary significantly. Studies evaluating the climate impacts on the Eastern Nile development potential often focus on analysing the effects of deviations to potential changes in flows (Jeuland 2010; Jeuland and Whittington 2014) or increases in the frequencies of El Niño and La Niña effects (Block and Strzepek 2010). Combining observational evidence and GCM projections, Siam and Eltahir (2017) recently demonstrated that hydrologic variability of flows in the Nile has been increasing and is expected to continue to do so into the future due to increased frequency of El Niño and La Niña events, thus increasing the risk of flooding and extended droughts.

While increased frequency of these extreme events is alarming, the risk of droughts occurring in sequential years would acutely test whether there is sufficient storage volume in the Nile system to maintain a reliable supply to Egypt. Siam and Eltahir (2017) noted an increased Hurst coefficient in over half of their bias corrected GCM projections, and the assessment by Hurst (1951) emphasized that greater hydrologic persistence would require greater storage basin storage. Mitigating potential impacts through costly infrastructure investments is one approach to managing climate risks (Jeuland et al. 2017), however improved operation of existing reservoirs (Goor et al. 2010) and reaching transboundary agreements to cooperatively manage infrastructure in the Nile Basin is another approach with longer-term mutual benefits (Sadoff and Grey 2002; Tilmant and Kinzelbach 2012; Whittington et al. 2005).

5.3 APPLICATION OF METHODOLOGY

This study applies the model-supported transboundary negotiation framework to identify water management strategies that the countries may choose to follow. We analyse potential operations of the GERD and the HAD while considering the risks of increased hydrological persistence as an example of testing robustness to climatic uncertainties. The Eastern Nile RiverWare Model (ENRM) (Wheeler et al. 2016) is coupled with the BORG multi-objective evolutionary algorithm (Hadka and Reed 2013) to explore the ability of the reservoirs to meet the objectives of all three

countries. The BORG MOEA has been shown to effectively handle complex, non-linear, non-concave problems with superior performance efficiency (Hadka and Reed 2012) when searching for non-dominated solutions (Giuliani et al. 2016b; Herman et al. 2014). Potential cooperative arrangements are sought to maximize the individual and collective benefits of the GERD while adhering to the principal of *no significant harm* relative to a condition prior to the GERD.

5.3.1 Simulation

The ENRM simulation model was configured to study long-term management strategies after the GERD has completed the filling process. The monthly model operates for 44 years and includes 162 inflow nodes and 19 water demands representing major or aggregate water diversions. In addition to the management of the GERD, the model simulates reservoir operations of the HAD and Merowe dams on the Main Nile; Lake Tana, Tana-Beles hydropower diversion, Finchaa, Sennar and Roseries dams in the Blue Nile sub-basin; the Jebel Aulia dam on the White Nile; and the Khashm El Girba, Upper Atbara and Setit complex and Tekeze dams in the Tekeze-Setit-Atbara sub-basin.

A naturalized hydrology for the Eastern Nile Basin from 1900-2002 (van der Krogt and Ogink 2013) was used to generate ensembles of 100 stochastic synthetic flow time series across 162 inflow locations using a simulated annealing algorithm (Wheeler et al. In Review). The first set of 100 synthetic time series match the statistical properties of the naturalized hydrology including the Hurst coefficient for hydrologic persistence (Current Conditions). Furthermore, four variations were also generated that increase the Hurst coefficient at each inflow location by 5%, 10%, 15% and 20%, herein referred as H105, H110, H115, and H120 respectively. For each variation, 100 synthetic time series were generated. We use these four scenarios to test the robustness of a given formulation to one version of climatic uncertainty. Many other plausible variations to the flow series could be tested within the same framework.

The High Aswan Dam is assumed to release 55.5 BCM per year into the future for use in Egypt, including 4 BCM pumped directly from the Toskha Pumping Project. The diversions for Sudan are limited the 1959 treaty value of 18.5 BCM and evaporative losses from the Sudanese reservoirs are dynamically modelled in the analysis. Ethiopia is assumed to increase their consumptive use to 2.5 BCM from the Lower Beles River (Blackmore and Whittington 2008). These estimates of diversion requests are not intended to be endorsements of any allocation, but necessary modelling assumptions.

Operations of the HAD include the current drought management plan that reduces releases by 5%, 10%, and 15% when storage volumes fall below 60 BCM, 55 BCM and 50 BCM respectively. The minimum operating level due to hydraulic characteristics of the dam structure is 147m. Maintaining this level may require highly disruptive restrictions on downstream users during severe drought conditions. Flood prevention measures also exist that require proactive releases to lower the pool elevation below 175 m prior to August 1st, which assures sufficient empty space in the reservoir before the onset of the flood season (Egypt MWRI 2005). Dam operators must also respect a 260 MCM/day maximum release to avoid inundation of the islands downstream in Aswan. Assumed reservoir operations in Sudan are described in Wheeler et al. (2016) and shortages to Sudanese water users occur when insufficient water is available at a point of diversion. Calibrating to historical gage data, good to very good metrics are shown in Table 5-1 (Moriasi et al. 2007).

The GERD is operated primarily for steady hydropower purposes, with the ability to generate up to 6000 MW. A minimum operating level of 590 m is assumed and flood releases are made to maintain a maximum elevation of 640 m. All flows are discharged through the turbines up to the maximum generation capacity and the remainder are assumed to pass over the spillway.

Initial conditions for all reservoirs are assumed to be full with the exception of the HAD, which is assumed to begin with an elevation of 170 m based on approximations of an equilibrium elevation from modelled trial runs.

Table 5-1. Model calibration and validation results

Location	Calibration Period (1951-1970)			Validation Period (1971-1990)		
	Nash-Sutcliffe	PBIAS	RSR	Nash-Sutcliffe	PBIAS	RSR
Blue Nile at Kessie	0.99	0.62	0.10	1.00	-1.37	0.04
Blue Nile at El Diem	1.00	-0.41	0.05	1.00	-2.09	0.05
Blue Nile at Khartoum Soba	0.98	0.02	0.13	0.94	-0.62	0.25
Baro at Gambella	0.83	-4.50	0.42	0.93	-1.78	0.26
Sobat at Hillel Doleib	0.85	-1.69	0.39	0.81	-7.03	0.44
Atbara Kilo3	0.89	-1.42	0.33	0.78	-9.97	0.46
White Nile at Malakal	0.89	1.76	0.34	0.85	0.79	0.39
White Nile at Melut	0.89	1.16	0.32	--	--	--
White Nile at Mogren	0.66	-0.97	0.59	0.71	3.96	0.53
Nile at Tamaniat	0.98	0.14	0.14	0.95	0.94	0.23
Nile at Dongola	--	--	--	0.94	-2.61	0.24

5.3.2 Problem Formulations

In addition to the pre-development case, post-development non-cooperative and cooperative formulations are considered that represent steps and sequential iterations of the process shown on Figure 5-1. In all formulations, Ethiopia seeks to maximise average annual energy generation while maintaining a 90% reliable target power production from the GERD. Sudan's objectives are to maximise average annual energy production and minimise the risk of shortages to water users. Egypt's objectives are to also maximise average annual energy generation and minimise the risk of shortages to water users, as well as minimise the risk of the HAD reaching the minimum operation level (MOL) of 147 m where severe and highly disruptive shortages could occur. Minimising system losses by downstream and into the Toshka spillway is also considered as an objective.

Table 5-2. Problem objectives by country

Ethiopia	Sudan	Egypt
Maximise Energy	Maximise Energy	Maximise Energy
	Minimise Shortages	Minimise Shortages
		Minimise Probability of reaching MOL
		Minimise Spills from HAD (Toshka + downstream)

A **pre-development formulation (No GERD)** considers a scenario before the GERD is operational or does not exist in future scenarios. Current operations for Sudanese and Egyptian reservoirs are assumed to continue into the future. This formulation provides the basis for estimating the current risks of shortages in Sudan and Egypt.

A **non-cooperative formulation (No Coop)** assumes that Ethiopia acts independently to maximise hydropower generation. Furthermore, no information is released on intended operational rules, so downstream nations cannot predict the how the GERD will be operated. Assuming the objective of the GERD is to provide a power baseload to Ethiopia and adjacent countries with power purchase agreements (Degefu et al. 2015; DoP 2015), the primary operation is a turbine release for a regular target hydropower generation rate:

Equation 5-2

$$R = \min(\max(R_{HP}, R_{FC}), R_A)$$

Equation 5-3

$$R_{HP} = \frac{P_T}{H_{Net} \times \gamma}$$

Equation 5-4

$$\gamma = f(H_{Net})$$

In these equations, R is the monthly release from the GERD; R_{HP} is the turbine release required to meet the target hydropower objective P_T ; R_{FC} is the release that does not allow the maximum flood elevation to be exceeded; R_A is the maximum release possible without falling below the minimum power pool elevation of 590 m; H_{net} is the net head; and γ is the power plant efficiency.

While this provides a rational choice for Ethiopia, the downstream countries have no certainty that this operation will occur, and no basis on which to adapt their own management policies. As

a result, all potential target power generation levels are assumed possible. No adaptation to Sudanese or Egyptian reservoirs are incorporated into this formulation.

A **basic cooperative formulation (Basic Coop)** is based on an agreed annual release (AAR) from the GERD and adaptation of the HAD operation to minimise risk based on this AAR, including adaptations to current drought and flood management policies. Reductions to HAD releases at low storage levels are explored, with a maximum planned reduction of 15% based on current operations. Modification of the current 175 m flood space elevation is also explored.

This formulation assumes the Sennar, Roseries and Merowe dams will maintain a maximum elevation whenever possible. This simple assumption might not be practical due to sediment management concerns, however it provides a conservative estimate of evaporation losses.

The releases from the GERD seek to achieve target power generation, subject to an agreed annual release (AAR) that the countries may negotiate.

Equation 5-5

$$R = \min \left(\max \left(R_{HP}, \frac{\max(AAR - \sum_{T1}^{t-1} R, 0)}{T2 - t + 1}, R_{FC} \right), R_A \right)$$

T1 is the starting month of the water year and T2 is the final month of the water year. The target hydropower is assumed to remain constant, and the equation above attempts to distribute any volumes of agreed annual release in excess of that which is required for power generation evenly throughout the water year. In this formulation, all downstream parties are assumed to have continuous knowledge of the intended release and can plan their operations accordingly. An AAR must be feasible under all hydrologic scenarios, therefore any agreements that would deplete the GERD below a minimum power elevation (590 m) would not be viable due to insufficient water available to meet such an agreement. The drought management and flood control assumptions for the HAD are adapted to minimize risks of shortages and unnecessary spills in Egypt, and the Sudanese reservoirs downstream of the dam are maintained at the highest level possible.

A **continuous cooperative formulation (Cont Coop)** combines the Agreed Annual Release (AAR) and adaptations to the flood and drought operations of the HAD with a Safeguard Release (SR) from the GERD, which is triggered if the HAD pool elevation is predicted to go below a threshold level. The SR water is allowed to bypass the intervening Sudanese reservoirs. The formulation requires forecasting of inflows into Lake Nasser and assumes that all the information that is necessary to implement the formulation is shared among the countries. A range of HAD trigger levels for the SR is tested in this formulation, ranging from the minimum HAD operation level of 147 m to a higher trigger level of 175 m. Variations of the percentage reductions for drought operations are simultaneously tested. This allows combinations of policies including an upper SG trigger level and low drought percentages reductions, which would result in fewer drought management restrictions on water use and be beneficial to Egypt at the cost of more frequent SG releases from the GERD. This formulation also considers combinations of lower SG trigger levels and higher drought percentage reductions that would invoke more drought management restrictions on Egyptian water use and while still retaining water in the GERD. All possibilities between these extremes are evaluated within this formulation.

Table 5-3. Management variables by countries and formulation

	No Coop	Basic Coop	Cont Coop	Range	Increment
GERD Target Power (MW)	X	X	X	800 - 1800	50
GERD Agreed Annual Release (BCM)		X	X	0 - 50	1
HAD Drought Reductions (%)					
Storage < 35 BCM		X	X	0-15%	1%
Storage < 40 BCM		X	X	0-15%	1%
Storage < 45 BCM		X	X	0-15%	1%
Storage < 50 BCM		X	X	0-15%	1%
HAD Flood Space Elevation (m)		X	X	175 - 180	1
GERD-HAD Safeguard Release Elev (m)			X	147-175	1

5.3.3 Approximating stakeholder criteria

We assume the downstream users expect that the GERD should not cause any *significant harm* (Salman 2016), which is interpreted as avoiding any significant changes to current consumptive uses or energy production. Figure 5-4 demonstrates the current distribution of annual shortages

to downstream water users, where shortages are defined relative to the expected uses of 55.5 BCM for Egypt and 18.5 BCM for Sudan. These shortages can be the result of current operational policies (i.e. drought management restrictions) or physical limitations. Average annual shortages of 714 MCM and 1.6 MCM are expected for Egyptian and Sudanese users respectively. Maximum annual shortage volumes of 19,500 MCM and 400 MCM for Egypt and Sudan respectively are currently possible, but are only associated with the rarest droughts in our stochastic flow simulations.

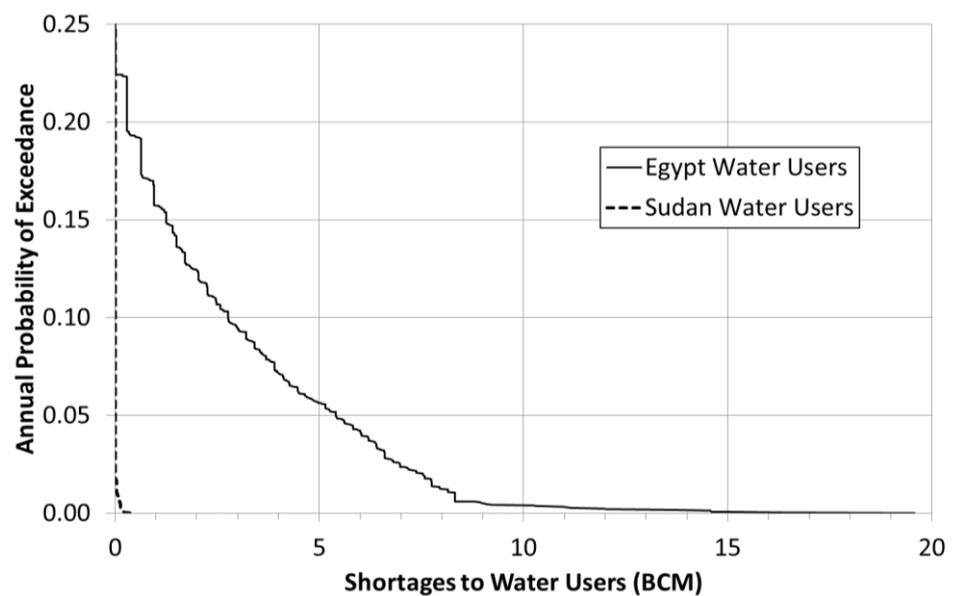


Figure 5-4. Annual probability of exceedance of shortages to Egyptian and Sudanese water users. The pre-development formulation is also used to derive the current average annual energy generation of 7.13 TWh and 9.48 TWh derived from the all Egyptian and Sudanese dams respectively.

In the non-cooperative formulation, we examine a range of target power generation levels for the GERD to determine average annual energy generation that the GERD could deliver, while noting reliability of meeting the target power specified. Figure 5-5 demonstrates that the GERD can provide slightly over 15 TWh/year on average, with 100% reliable power generation when producing 1400 MW. This represents one rational choice (OptEnergy) for Ethiopia’s management of the GERD. The reliability decreases when the dam is operated for power generation above 1400

MW. A reliability of 90% is often used for firm energy generation (Ramachandra et al. 2000), which can be achieved with a target power of approximately 1600 MW. At this power generation rate (OptPower), only 13.7 TWh of average annual energy can be produced. Both the generation levels were considered as potential starting negotiation positions for Ethiopia, so anything less would be considered a cost to Ethiopia.

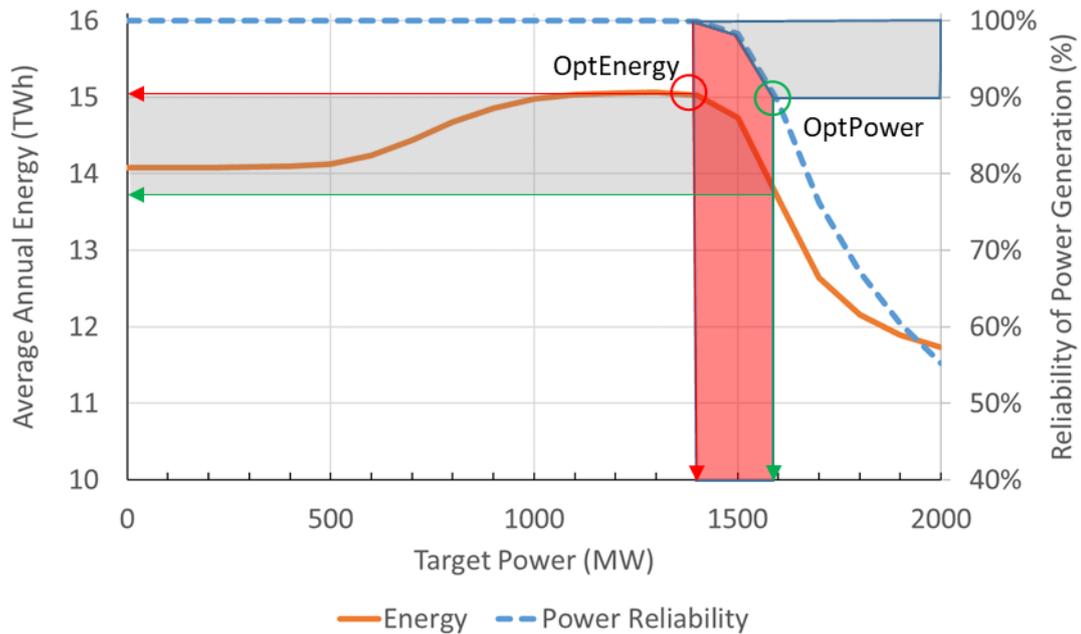


Figure 5-5. Energy production and hydropower reliability at different GERD operations

Given the analysed performance of the pre-development formulation, we propose succinct definitions for the requirements of the GERD to avoid causing significant downstream harm. For Egypt, we include the following three components: 1) the GERD would not cause the average annual shortages to Egypt to exceed the value expected without the presence of the GERD (714 MCM/year), 2) the probability of the HAD reaching the minimum operating level of 147m would not exceed the risk that exists without the presence of the GERD (currently 0.2%), and 3) the average annual energy generation from the HAD would not be less than the value without the GERD (7.13 TWh/year).

The criteria for Sudan would follow a similar logic. To cause *no significant harm*, 1) the GERD would not cause the average annual shortages to Sudan to exceed the expected value without the

presence of the GERD (1.6 MCM/year), and 2) the average annual energy generation in Sudan would not be less than the value without the GERD (9.48 TWh/year). The Sudanese reservoirs are not over-year storage facilities, therefore minimum operating level criteria is not applicable.

The initial criteria for each stakeholder are summarized in Table 5-4. For Ethiopia, the two rational operations to either maximise the energy generation (OptEnergy) or to maximise the power generation with 90% reliability (OptPower). The criteria for Sudan and Egypt are based on the pre-development formulation and thus without the GERD.

Table 5-4. The initial assumed ‘acceptable’ positions for each stakeholder with current hydrologic conditions and increased persistence

	Current	Hurst105	Hurst110	Hurst115	Hurst120
Ethiopia Criteria (assumes with GERD)					
OptEnergy: Max Avg. Energy (TWh/year)	15.06	15.04	15.07	15.07	15.10
OptPower: Max 90% Reliable Power (MW)	1594	1589	1598	1590	1599
Sudan Criteria (assumes without GERD)					
Avg. Energy (TWh/year)	9.48	9.47	9.49	9.48	9.49
Avg. Shortage (MCM/year)	1.6	2.4	1.4	1.7	1.3
Egypt Criteria (assumes without GERD)					
Avg. Energy (TWh/year)	7.13	7.12	7.16	7.14	7.18
Avg. Shortage (MCM/year)	714	800	848	875	865
Probability of MOL	0.18%	0.25%	0.21%	0.23%	0.20%

Table 5-4 also demonstrates how the initial positions would change given scenarios of changes to hydrologic persistence. While not explicitly used in until the second phase of the framework in Figure 5-1, information is presented here to understand the sensitivity of the initial positions to these uncertainties. The only significant change that can be seen is an increased in the average shortages to Egypt with increased persistence. This demonstrates a possible increase of risk regardless of the presence of the GERD, and furthermore demonstrates the benefits that the GERD might provide to mitigate this risk.

5.4 RESULTS

5.4.1 Non-Cooperation

To quantify the risks of non-cooperation among the countries with respect to the GERD operations, we assume the OptEnergy or the OptPower positions for Ethiopia described above and initially assume the downstream reservoirs are not able to adapt to the GERD due to a lack of information. While this scenario may be unlikely, it estimates the implications of not reaching an agreement regarding GERD operations.

The combined effect of changed timing of flows, increased evaporation losses from the GERD, and decreases in evaporation losses from Lake Nasser is shown in Figure 5-6. The average elevations resulting from both the OptEnergy and OptPower operations falls below the no-GERD operations, resulting in a 0.30 and 0.14 TWh decrease in average annual energy generated from the HAD respectively. The relatively steady releases from the GERD results in less frequent occurrences of the HAD reaching high elevations, suggesting the current flood management policy could be adapted to decrease proactive releases and thus conserve water, but at an elevated risk of emergency releases to manage unexpected large inflows. The probability of the HAD reaching low elevations that can trigger drought management operations differ between the two GERD management policies. The OptEnergy policy makes comparatively lower hydropower releases from the GERD, therefore increases the probability of the HAD falling to lower elevations. The higher monthly GERD power output in the OptPower policy results steadier flows and higher HAD elevations being higher than the pre-GERD behaviour, resulting in fewer reductions to Egyptian water users. Without guarantees of how the GERD will be operated however, Egypt is unable to adapt their shortage management strategies to benefit from the GERD.

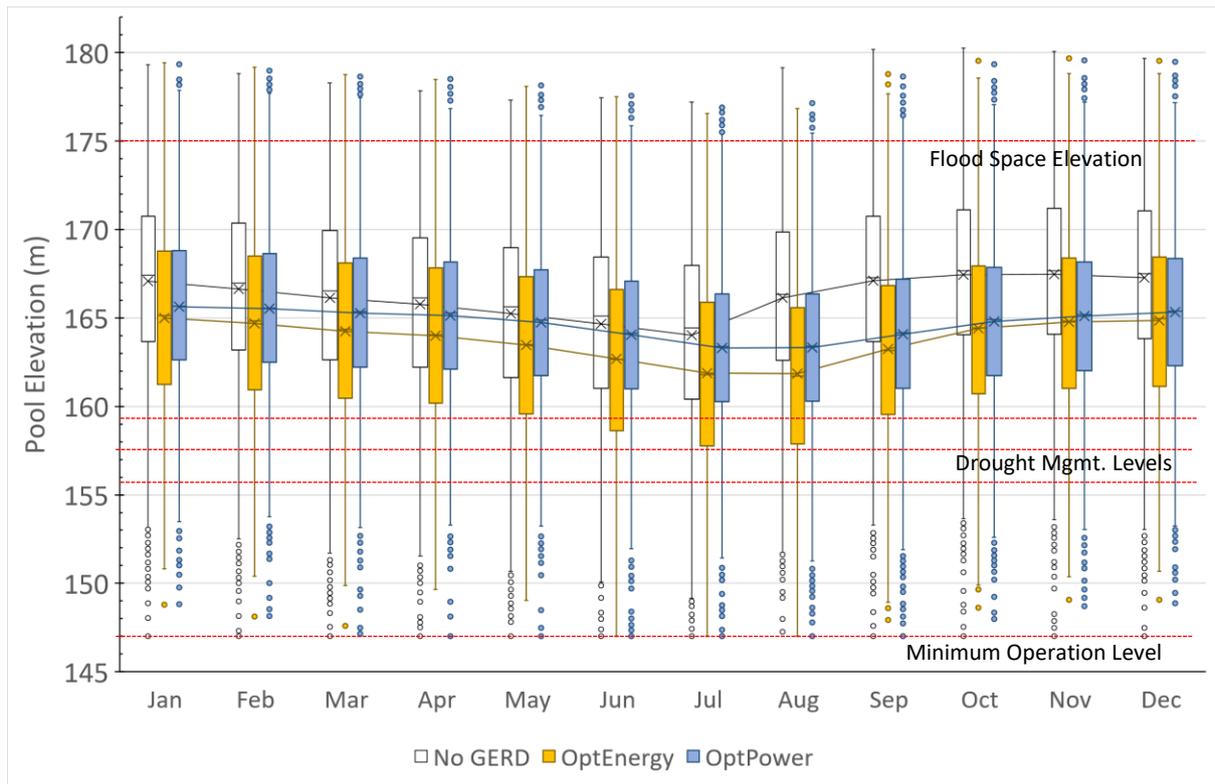


Figure 5-6. Monthly HAD pool elevations with two GERD operations and no downstream adaptations

Figure 5-7 expands on this analysis by demonstrating the change to shortages for Egyptian water users assuming no adaptation of the HAD operations due to a lack of predictability. The flat lines are reference levels of shortages prior to the GERD. The step change between the 1400 MW and 1600 MW aligns with the switch from OptEnergy to OptPower (Figure 5-5). In this transition zone the costs and benefits to Egypt are the most sensitive and demonstrate where negotiations may be the most effective.

We also note that without adaptation of the Roseries and Sennar reservoirs to the operations of the GERD, average shortages to Sudanese water users increases by 200 to 1000%, demonstrating a clear need to for adaptation. If releases from the GERD are known in advance, elevating the Sudanese reservoirs throughout the year provides a logical adaptation response.

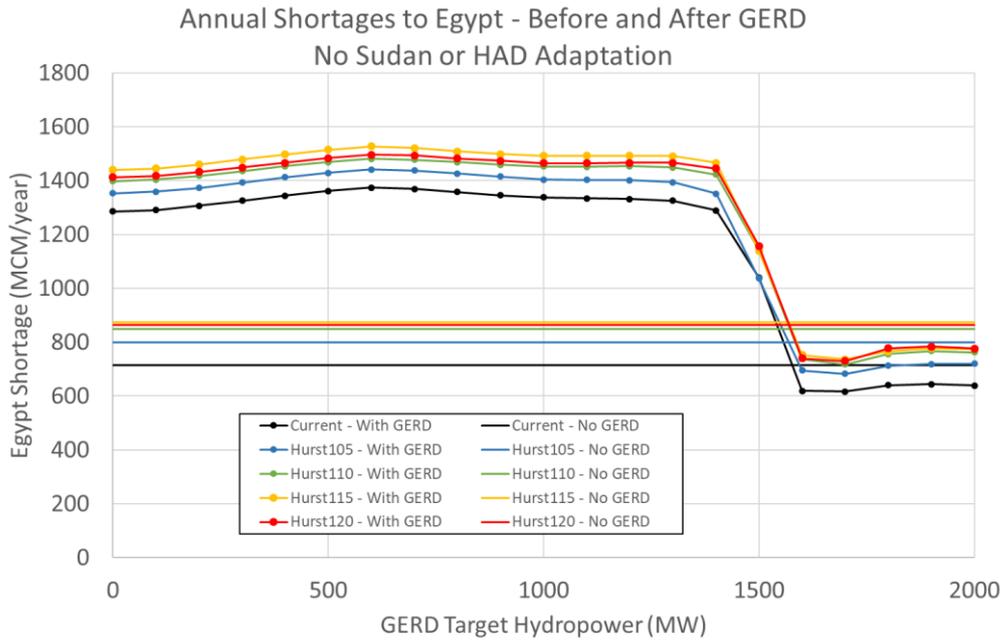


Figure 5-7. Annual shortages to Egypt as a function of GERD target power releases

5.4.2 Cooperative GERD-HAD Management

5.4.2.1 Basic Cooperation Alternatives

Applying the ENRM with the MOEA, basic cooperation arrangements are explored by concurrently sampling the management decisions outlined in Table 5-3 and evaluating the ability to meet the objectives outlined in Table 5-2. The seven objectives in Table 5-2 can be visualized using parallel plots (Inselberg 1985). Figure 5-8 only shows the non-dominated solutions, using a convention of the upward direction on each axis to be desirable. The condition prior to the GERD is shown in blue (No GERD), and the red and green lines demonstrate solutions that decrease and increase the shortages to Egypt respectively. The two non-cooperative operations (OptPower and Opt Energy), are overlain on the parallel plot assuming no adaptation of the downstream reservoirs.

In this formulation, no solutions were identified that both reduce the shortages to Egypt and reduce the probability of the HAD reaching the minimum operation level. Energy gains for Sudanese reservoirs were achieved in all solutions and changes to energy generation for Egypt mirror the shortages to Egypt, as both are driven by the effects of pool elevations.

As noted earlier, the OptEnergy solution with no adaptation performs worse with respect to Egyptian shortages, but decreases the risk of the HAD reaching the MOL, while the OptPower performs relatively well on both these metrics. This solution appears satisfactory from the Egyptian perspective but produces low levels of energy relative to other solutions and therefore was not identified by the MOEA as non-dominated.

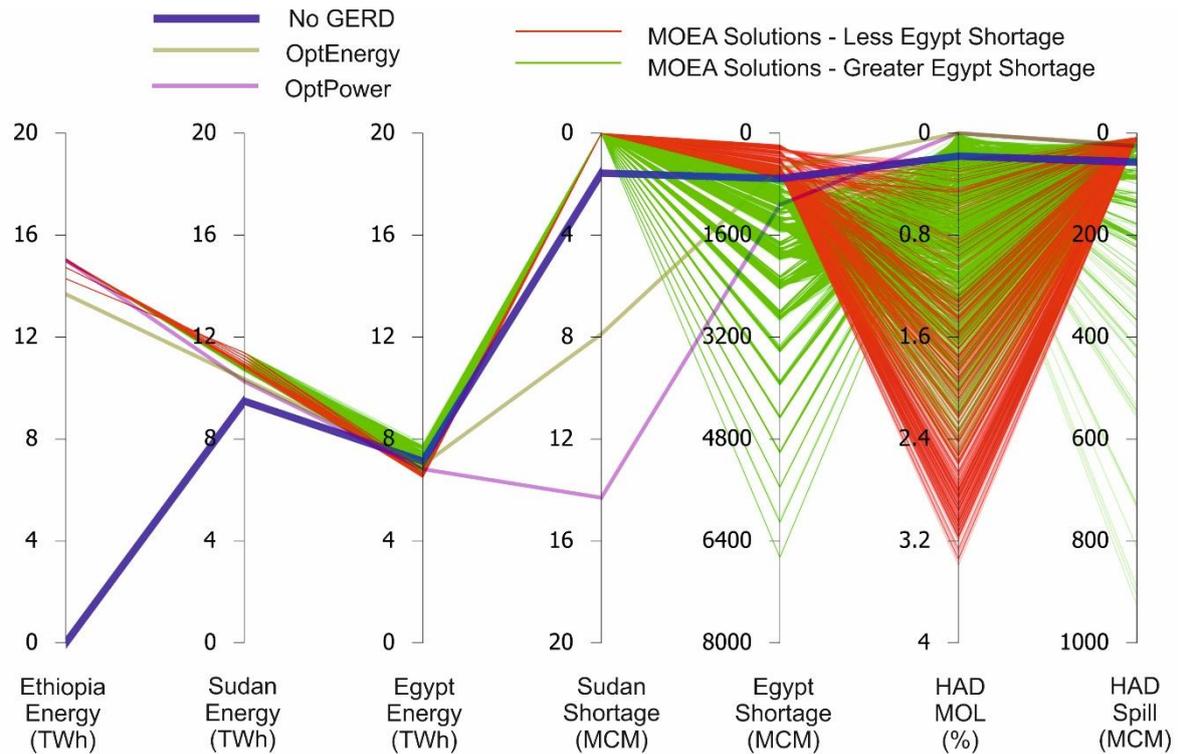


Figure 5-8. Parallel plot of multiple objectives with scenarios discovered under Basic Cooperation
 Figure 5-9 shows the average shortages to Egypt and probability of the HAD reaching the MOL for the basic cooperation solutions with the colours representing the average annual energy to Ethiopia. The Pareto front of these two variables are shown on the left side. None of the discovered solutions is strictly better with respect to both variables and thus this basic cooperation formulation cannot assure the assumed criteria of *no significant harm* can be met. However clearly reductions to the average annual shortages to Egypt are possible with minor increases in the risk of the HAD reaching the MOL.

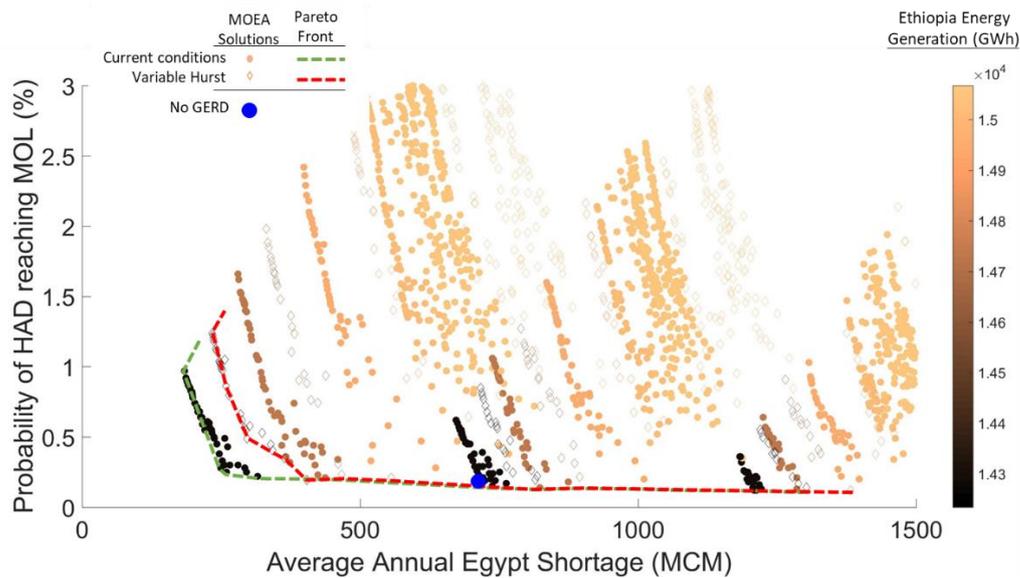


Figure 5-9. Risks to Egypt with scenarios discovered under Basic Cooperation

Figure 5-9 also demonstrates the effect of searching for solutions under the wider variety of hydrologic conditions including scenarios of increased persistence. In this search, 500 synthetic time series were concurrently used, including those from the current conditions, H105, H110, H115, and H120 ensembles. The shift to the right of the Pareto front indicates that alternatives become less protective for Egypt if hydrologic persistence in the basin increases.

Because the basic formulation did not meet the *no significant harm* criteria for Egypt with respect to one of the variables in Figure 5-9, the cycle in Figure 5-1 is repeated to reformulate to a new form of cooperation that may be more acceptable.

5.4.2.2 Continuous Cooperation Alternatives

In addition to an AAR, providing a Safeguard Release (SR) from the GERD if the HAD reaches a critically low pool elevation would help to further mitigate risks to Egypt. It represents a closer form of cooperation as it implies sharing of information and adaptation of operations on the basis that information by all three countries is shared in order to achieve mutually acceptable outcomes. Figure 5-10 demonstrates the seven objectives under the continuous cooperation formulation. In this arrangement, several alternatives can be identified that meet both the average annual shortage criteria for Egypt, and the criteria of not exceeding the current

probability of reaching the MOL. None of these alternatives meets the criteria not having significant impacts to the energy generation to Egypt, with energy shortfalls of between 0.25 and 0.65 TWh relative to current output. On the other hand, adopting a SR does not necessarily influence energy output for Ethiopia if energy can be generated with the releases.

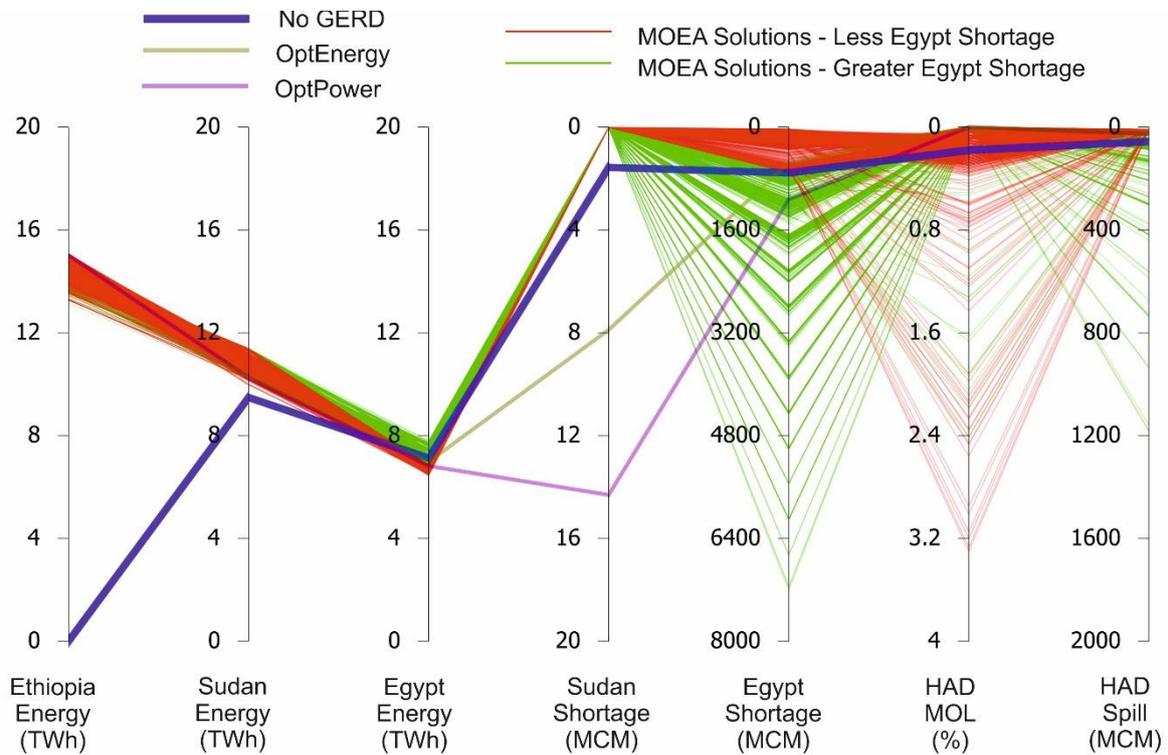


Figure 5-10. Parallel plots of multiple objectives with scenarios discovered under Continuous Cooperation

Figure 5-11 confirms that substantial improvements for Egypt can be made with respect to the two criteria when seeking solutions under current hydrologic conditions, yet also shows that eliminating these risks completely may not be possible under increased hydrologic persistence. Regardless, the results demonstrate possible solutions that warrant further exploration.

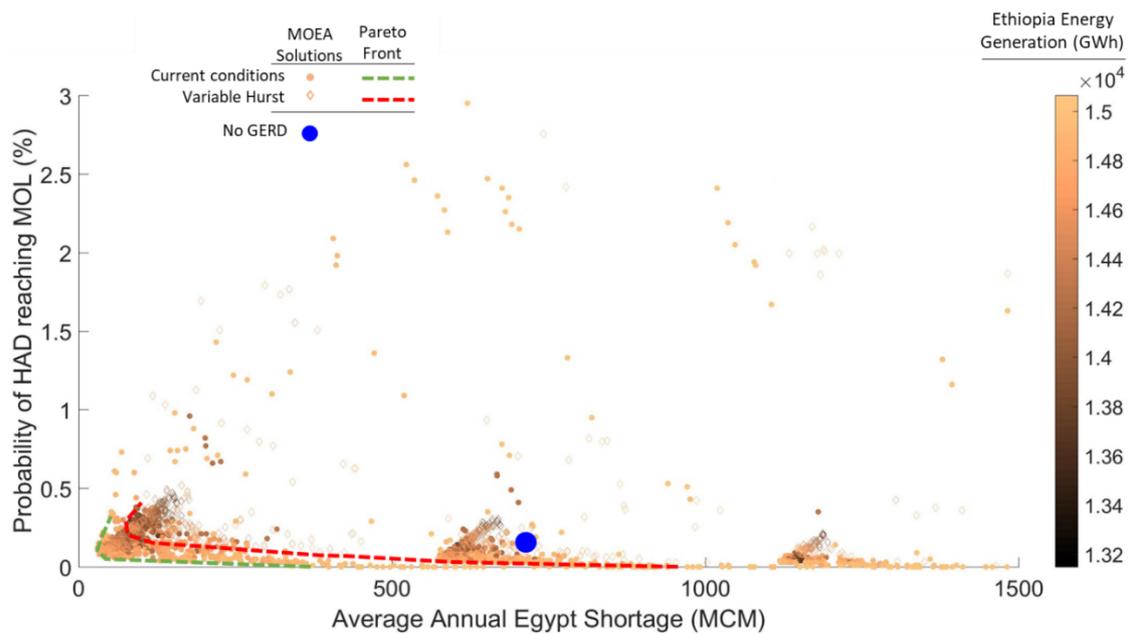


Figure 5-11. Risks to Egypt with scenarios discovered under Continuous Cooperation

Figure 5-12 shows the trade-off of costs with the average annual energy generation for Ethiopia and Egypt. All solutions meet our definition of *no significant harm* to downstream water users with respect to the criteria of no additional average annual shortages (less than 714 MCM/year) and no increased risk of reaching the MOL for the HAD (probability less than 0.18%), but not with respect to losses of average annual energy generation from the HAD (7.13 TWh/year). The bimodal shape is a result of the MOEA searching for solutions along the multi-objective Pareto fronts that seeks to minimise energy shortages to Egypt on one side and maximise Egyptian energy generation on the other. The preferred solutions are shown, demonstrating that the SG releases can result in higher energy generation from the GERD if energy can be generated from them.

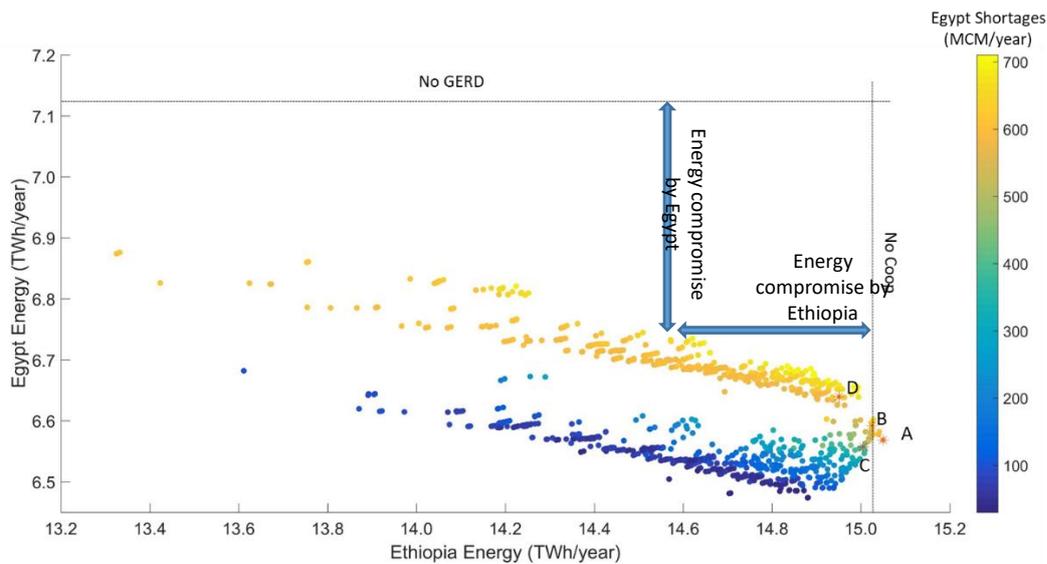


Figure 5-12. GERD-HAD Energy and trade-offs with Egyptian shortages under Continuous Cooperation

5.4.3 Sensitivity to hydrological persistence

A more specific analysis of the potential alternatives was performed considering increased hydrologic persistence. A set of four sample solutions were selected from the potentially viable solutions in Figure 5-12, which are based on current hydrologic conditions. These samples had little or no cost to Ethiopia in terms of lost energy production (Table 5-4). While these selections represent a variety of combinations of management decisions that yielded positive outcomes, others could be considered as well with a negotiation context.

To evaluate robustness, each of the four sample solutions were re-evaluated under the combination of the current conditions and the four ensembles of flow series with increased Hurst coefficient. Figure 5-13 demonstrates the exceedance curves of annual shortages to Egypt using all these scenarios compared to the equivalent result for the No GERD case. Sample solutions that have a lower exceedance compared to the No GERD case demonstrates less harm at any given exceedance level. Sample solutions that performed well across all exceedance levels can be considered robust to increased persistence and cause no harm in all circumstances.

Table 5-5. Potentially viable samples of high cooperation management alternatives

Decisions	No GERD	Sample Solution A	Sample Solution B	Sample Solution C	Sample Solution D
Target Power (MW)	--	1250	1100	1250	1300
AAR (BCM)	--	7	38	20	0
GERD-HAD Safeguard Elev (m)	--	148	150	150	150
HAD Flood Elevation (m)	--	176	178	177	178
Egypt Drought Reduction below:					
60 BCM	5%	0%	0%	0%	0%
55 BCM	10%	0%	0%	0%	0%
50 BCM	15%	0%	0%	0%	1%
45 BCM	15%	3%	7%	1%	1%
40 BCM	15%	10%	13%	7%	2%
35 BCM	15%	11%	15%	8%	3%
Objectives					
Avg Egypt Shortage (MCM/yr)	714	593	678	421	626
Avg Sudan Shortage (MCM/yr)	2	0	0	0	0
Avg GERD Energy (TWh/yr)	--	15.05	15.03	15.00	14.95
Avg Sudan Energy (TWh/yr)	9.48	10.77	10.71	10.80	10.91
Avg Egypt Energy (TWh/yr)	7.13	6.57	6.59	6.56	6.64
HAD Probability of MOL (%)	0.18%	0.17%	0.00%	0.01%	0.07%

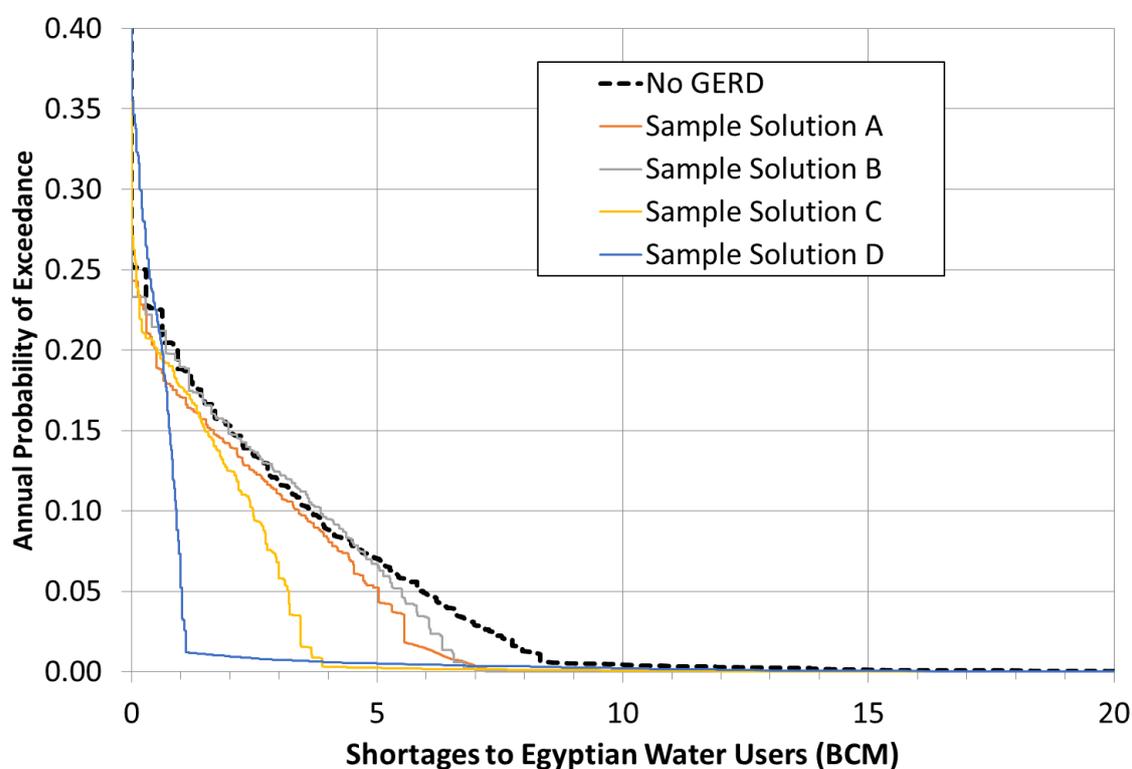


Figure 5-13. Annual probability of exceedance of shortages to Egyptian water users for sample solutions and across uncertain hydrologic persistence

Figure 5-14 is derived from Figure 5-13 and shows the difference (in exceedance probability) between the four sample solutions and the No GERD case. Formulations A and C improve upon the No GERD case under practically all conditions, therefore these two potential solutions would be preferred to B and D.

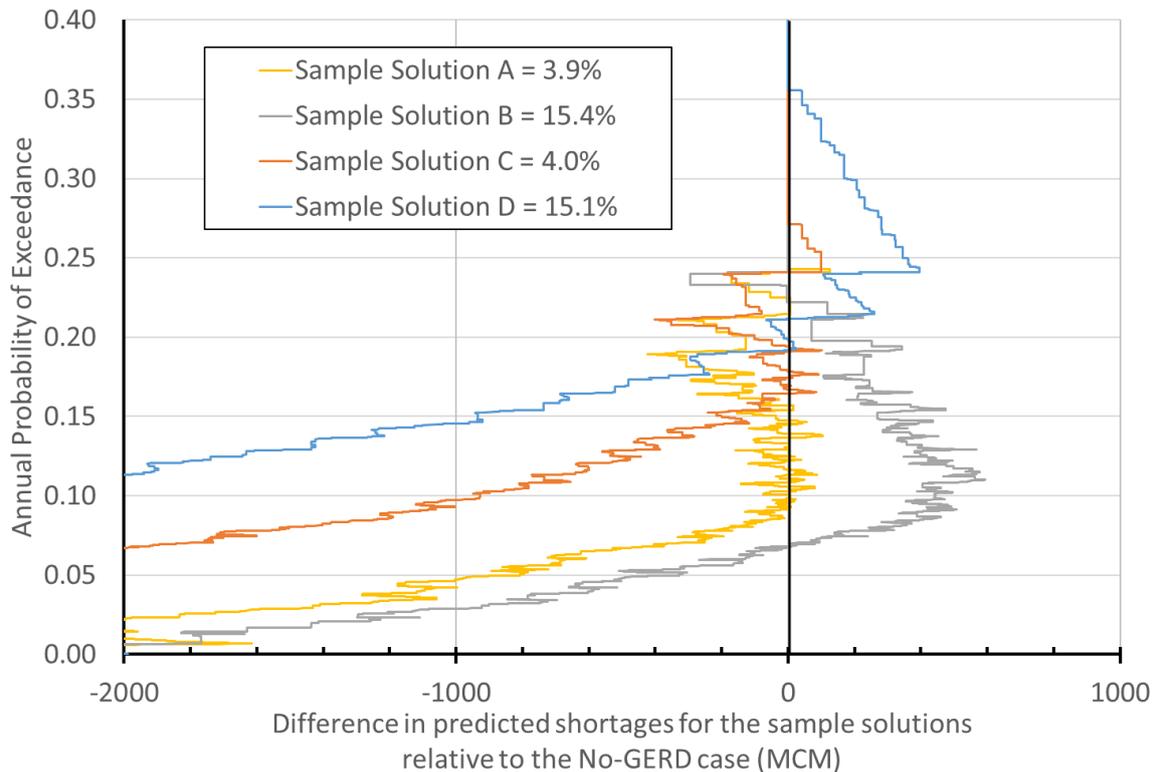


Figure 5-14. Probability of shortages in Egypt relative to the No GERD case

5.5 IMPLICATIONS FOR INFRASTRUCTURE OPERATION ON THE BLUE NILE

Non-cooperative operation of the GERD to maximise hydropower benefits for Ethiopia would not provide assurance against negative impacts for downstream users. If explicit assurances of expected releases from the GERD can be made, and knowledge about planned releases provided well in advance, the operations of the HAD could be adjusted to a certain extent to minimize the additional risks incurred by Egypt. Existing flood management policies could be adapted to allow a smaller flood storage space, but this may not be advisable for safety reasons in the occurrence of unexpected inflows. Existing drought management policies of the HAD can be adapted to

minimise the need to reduce releases to downstream users. Such an adaptation would result in Lake Nasser maintaining a lower elevation and thus a decreased the margin of safety for Egypt. This suggests that close cooperation with Ethiopia would be advantageous, if not necessary, to eliminate any additional risks to Egypt.

Provision of Safeguard Releases from the GERD if the pool elevation of the HAD is projected to fall to a pre-specified safeguard level would enhance the outcomes. Allowing the HAD to operate lower, with a guaranteed back-up from the GERD, minimizes evaporation losses but requires a higher degree of trust and coordination. Simultaneously specifying the GERD release requirements, the drought management characteristics of the HAD, and the GERD-HAD safeguard policy allows the GERD to become beneficial to Egypt's water supply.

While the energy benefits from the GERD are substantial for Ethiopia (around 15 TWh/year), they imply a relatively small reduction in hydropower production in Egypt. All solutions that were considered otherwise viable resulted in 0.25 to 0.65 TWh/year of less energy generation from the HAD. The cost to Ethiopia to operate the GERD in a way that would not cause significant harm to Egypt can range from no reductions in energy to 1.70 TWh/year or alternatively with a power reduction between 100 to 950 MW. If no safeguard policy is in place, it is to the advantage of Egypt for the GERD to operate at a maximum target power generation (Figure 5-7). However, if a safeguard policy is agreed upon, then conserving water behind the GERD would be preferred. If Ethiopia is able to generate electricity when additional releases are needed to meet the safeguard elevation of the HAD, then no energy losses need to be incurred by Ethiopia to provide this water. However, if there is not an energy demand at the time of the needed release, then water used to meet these downstream needs would must be bypassed around the turbines. This emphasizes the advantage of the GERD being connected to a power pool capable of absorbing the energy produced whenever the water is needed downstream.

Analysis of a range of possible scenarios of hydrological persistence has helped to further analyse various cooperative strategies in order to identify combinations that are robust to possibly changes in drought persistence. Two of the solutions sampled are predicted to decrease shortages to Egypt in 96% of the hydrologic conditions considered, whilst maintaining the same or less risk of the HAD reaching the MOL, effectively eliminating the risk of shortages to Sudan, adding approximately 1.3 TWh/year of energy gain for Sudan, and providing 15 TWh/year of energy generation from the GERD. To adopt these scenarios would not significantly reduce the average annual energy production of the GERD, but would limit the power generation to 1250 MW, which could be produced with 100% reliability.

5.6 CONCLUSIONS

Analysing water resource problems with modelling tools to find an economically 'optimal' solution is common, however the processes by which tools are used to support negotiations over transboundary river development is less systematic, in part because of the highly political circumstances. The emergence of the field of water diplomacy highlights these processes and the need to combine multi-stakeholder engagement with analytical tools in a way that contributes new knowledge and offers collaborative solutions to help resolve complex water related disputes.

The framework and example presented in this paper is intended to inform negotiations regarding operation of new upstream dam infrastructure. Our proposed process begins with analysis of the hydrological risks and benefits to all riparian states before the upstream dam construction. In the next step, non-cooperative operation of the infrastructure is simulated in order to establish the maximum possible benefits to the upstream state. These two extreme cases help to identify the objectives for each state and the criteria for *no significant harm* to downstream states. A multi-objective search process is then embedded within an iterative cycle to explore potential cooperative operation strategies, which avoid significant harm downstream, ideally whilst only incurring small sacrifices in upstream benefit. Once a set of acceptable strategies is identified,

these are subjected to sensitivity analysis in order to identify solutions that are robust to hydrological uncertainty. In this study, we used variants in the persistence characteristics of the flow series as an example of this sensitivity/robustness analysis. Future research will explore a wider range of variants on flow conditions that are consistent with possible climatic changes in the Nile Basin. Future research on the GERD will more fully explore how optimization of GERD operation could account for future changes in energy/power demand and the role of new transboundary power interconnections.

6 CONCLUDING REMARKS

6.1 CONCLUSIONS

Reaching agreements on the management of world's transboundary rivers is arguably one of the most challenging tasks that humanity will face in the coming decades and centuries. Increasing demands due to expanding populations and economic growth, coupled with uncertain supplies due to the implications global climate changes, create formidable challenges for water managers to allocate or reallocate freshwater to meet these growing and changing needs. Classic engineering and economic approaches that strive to maximise efficiency or to achieve the greatest overall benefit are helpful to demonstrate what is possible, however the solutions they provide are unlikely to be adopted when institutional barriers and political realities dominate the decision making process. This is particularly relevant in river basins where the historical cooperation has been minimal or relationships are acrimonious. Although popular notions of 'water wars' have been largely debunked through retrospective analyses (Wolf 2007), regions with rapidly increasing water scarcity and little history of cooperation over resources are precisely where agreements are most needed to avoid water becoming a trigger or agitator for conflict (Mirumachi 2015). The paradigms of IWRM and water diplomacy offer pathways to seek cooperative arrangements through an inclusive discourse that considers the complex multi-objective landscape of water allocation. To facilitate constructive dialogue among sovereign states or institutions, there remains a critical need for shared knowledge of the resources to achieve an equitable or sustainable outcome. Technical approaches and innovative solutions are needed, but they must be able to adapt to these complex realities if they are to offer politically palatable solutions. In other words, the challenges are not only technical, but deeply political as well.

This thesis set out with three research questions. The first was to evaluate utility of water resource models to facilitate transboundary negotiations. Chapter 2 explored this question through the

lens of boundary work to manage the science-policy interface. The outcomes highlight the distinct pathways that two water resource models have taken to support basin-wide planning. Most notably this compares and contrasts the relative broad acceptance of the basin-wide water resource model used in the Colorado River Basin with the challenges faced in the Murray-Darling Basin to develop broad acceptance of a model as a common knowledge-sharing platform. Highlighted through various technical and non-technical perspectives, both cases reinforce the potential for models to influence the discourses over transboundary water management. By tracking the evolution of models, the notion of a hydro-policy model was developed that emphasizes the need for sufficient accuracy, transparency and flexibility to allow such a tool to be useful in a transboundary context. These findings are then compared to the relatively new development of shared models for the Nile River Basin, and the challenges that have been faced in the basin-wide acceptance of these tools to date.

The second question builds directly from the first to consider how water resource models might be developed and applied more effectively for use in a transboundary context. Chapter 3 operationalises the notion of a hydro-policy modelling framework by demonstrating a cooperative formulation and application of a modelling tool to address the critical situation of ongoing hydropower development in Ethiopia on the Blue Nile. The tool was applied to explore cooperative solutions among Ethiopia and the downstream countries of Sudan and Egypt when the filling GERD reservoir. The application of the method demonstrates its utility by highlighting practical and incremental steps for cooperation. This research has not only demonstrated the value of model flexibility when exploring potential solutions, but it has also captured the interest of the water ministries in all three countries as offering potentially viable solutions to the current impasse over the filling of the GERD reservoir.

The third research question was to explore how significant climate uncertainties could be incorporated into transboundary decision making. To accomplish this, Chapter 4 develops a

flexible algorithm that is used to generate stochastic synthetic hydrologic sequences over large river basins. The method is used to first produce *plausible* futures based on historical conditions and then produce a wider range of *possible* future hydrologic conditions that demonstrates changes to hydrologic persistence. Chapter 5 then applies these alternative future scenarios within the modelling tool developed in Chapter 3. Through this process, a generalized framework is developed that applies modelling tools and search algorithms to explore viable cooperative management solutions within a negotiation context. This approach is applicable to the situation of new infrastructure development or re-operation of existing dams on transboundary rivers. This is again demonstrated for the case of the Eastern Nile Basin.

The focus of this thesis is not to propose a best solution for any particular context, but instead to assess and demonstrate approaches and tools that can be used to facilitate transboundary negotiations. The experiences on the Colorado River highlight the advantage of developing a common basin-wide analytical tool early in the development of a river system, while the Murray-Darling case demonstrates the challenges of attempting to find consensus after a fragmented analytical environment develops. The context of the Nile and the Grand Ethiopian Renaissance Dam provides a highly salient and critical test case for seeking cooperative solutions. The tools and framework described in this work can be applied in similar contexts where a development project in one sovereign nation is likely to have impacts on co-riparian nations. Although this study uses the possibility of increased hydrologic persistence for demonstrative purposes, there is clearly a need to consider a variety of potential climate change effects or other potential deep uncertainties within a transboundary negotiation context.

To develop an analytical approach to resolve transboundary water disputes, it is important to recognize the advantages that seemingly disparate disciplines offer, and to develop methods that incorporate them in a practical way that can be used by parties involved in negotiations. Advances in computing methods such as MOEAs provide the ability to generate solutions that seek to

maximise the multiple objectives simultaneously, but their utility depends on the capabilities of water resource models to accurately represent the complexity of real-world problems and effectively communicate their outcomes to stakeholders. While the technical focus of models can offer engineering or economic solutions, they can only be considered within the political process of negotiating over the benefits and risks that the outcomes suggest. This fits well into a joint fact-finding stages of negotiation theory, but the users of the information must recognize that the knowledge that models provide is neither absolute nor certain, but still potentially useful to facilitate discussions and identify possible solutions. Exploratory modelling is an iterative process that cannot be seen as a single stage, but instead conducted interactively with decision-makers throughout a negotiation.

6.2 CONTRIBUTION TO WATER DIPLOMACY

A major contribution of this work is a theoretical and practical pathway to resolving water management disputes. The emergence of the field of water diplomacy has sought to blend technical issues of water management with the interactive discourse among competing uses and institutions to reach agreements on how water resources can be sustainably used for mutual benefits. While the emerging frameworks have brought forth extensive knowledge and expertise of system complexity and negotiation (Adelphi 2016; Islam and Susskind 2012), the research developed throughout this thesis fills a gap in this framework of how models have been – and can be used better – to facilitate negotiations over water resources. WRMs have already been used extensively for decades to provide technical solutions within unilaterally managed basins, and to a lesser extent, within shared river basins. Their application and utility in multi-stakeholder contexts of transboundary river basins is likely to increase. As WRMs are applied in these more challenging basins, concerns regarding their credibility, legitimacy and saliency can be expected to emerge. Efforts to reject or delegitimise models based on arguments of bias, over-simplicity, over-complexity, a lack of understanding or trust of algorithms, power dynamics of model

development and management, challenges to knowledge validity, etc. should be planned for throughout the phases of model design and implementation. If these often-valid concerns are properly addressed through transparent, well-informed and participatory processes, the ability of models to develop and exchange knowledge of complex systems becomes clear. Furthermore, a lack of understanding of these tools among stakeholders can offer opportunities for joint learning among competing objectives.

Improvements in the accessibility of models to a wider variety of users, driven through financial and educational resources that expands knowledge of both quantitative and qualitative aspects of water management, will inevitably will result in a better understanding of what models can – and cannot – do to improve shared water management and facilitate negotiations. Algorithms such as simulated annealing and multi-objective decision making provide WRMs with capabilities that greatly exceed those of previous decades, however these advances only provide better tools that decision makers may choose to use to expand their own knowledge base or contribute to a shared pool of knowledge.

This research develops not only new technical tools, but also offers new pathways to leverage these technological advances to facilitate complex multi-stakeholder negotiations. This comes at a time when river basins around the world are facing enormous population growth rates and rapid economic development resulting in significant pressures on limited resources, alongside globally changing precipitation patterns and increasingly uncertain water availability. While contemporary research has shown that cooperation over water resources is historically more common than conflict (Wolf 2007), the pressures - and thus potential for conflict - is also non-stationary. Reaching agreements that avoid such conflicts will continue to depend on finding sound solutions.

6.3 PRACTICAL RECOMMENDATIONS

This research has immediate and direct relevancy to the primary case study on the Eastern Nile River, and to other transboundary river basins undergoing infrastructure developments. In the case of the Grand Ethiopian Renaissance Dam, this research can provide both analytical tools and possible approaches for the ongoing analyses being conducted by consulting firms on behalf of the three countries. Furthermore, this work also can be used to support the trilateral dialogue with an exploratory tool that is readily available for the three countries to use.

The uptake of this research in contexts outside of the case study from which it was developed and tested would require a significant investment in identifying, informing and training stakeholders on multiple sides of a transboundary conflict. The advantages of a model-supported negotiation process become clear as all sides develop trust in a common modelling approach. The process of collaborative development of a model requires a substantial amount of time and effort to gather data and understand the current management of a river system. Extended visits to conduct technical training sessions was an indispensable part of building relationships and confidence in the modelling tools and techniques developed through this research (Olsson and Andersson 2007; Van den Belt 2004). The methodology described in this thesis is to encourage dialogue through the use of models in a multi-stakeholder context by seeking to understand the risks and opportunities of cooperation.

6.4 FUTURE RESEARCH

As the field of water diplomacy develops, the possibilities to extend this research will expand. The methods and framework developed in this thesis can and should be augmented with new experiences from different river basins such as the Mekong, Jordan, Amu Darya and Zambezi, as well as extending the current work to include the existing and proposed developments of the Equatorial Lakes region of the Nile Basin. All these regions have or will undertake significant

infrastructure developments, and various models have been developed and applied to analyse these changes. Adding experiences from these basins provides an obvious path for new research.

A second direction is an expansion of the methods used to analyse the effects of climate change. While this thesis demonstrated one particular aspect of potential changes, there is a need to consider the evolving and improving science of global circulation models along with other deeply uncertain changes that may occur. Further developments in stochastic hydrology generation techniques that represent increasing hydrologic variability and oscillations on decadal scales can be integrated. In addition, dynamic modelling of evapotranspiration and likely changes to cropping patterns and consumptive demands due to increasing temperature is an obvious enhancement. For the context of the Nile, this would require exploring changes to existing demands and restructuring basin-wide treaties with adaptive allocations that reflect the potential for upstream development.

Exploration of emerging and potential power sharing agreements is another important direction for this work. Optimising systems within and across borders for both water supply and hydropower generation can highlight new methods for coordinated management. Incorporating the possibility of linking issues such as compensation for harm, environmental flows, transportation, and explicit flood management policies across all reservoirs is of significant interest for enhancing the general method and consideration within the Nile context.

Finally, a suggested direction of research is further exploration and integration of various emerging techniques for robust decision-making, particularly in contentious and often adversarial contexts as addressed in this thesis. Expanding methods to balance optimisation and satisficing to consider both incremental developments of new infrastructure along with operational decisions would be a valuable extension of this work. Methods such as MORDM (Kasprzyk et al. 2013), Info-Gap (Hipel and Ben-Haim 1999) and decision-scaling (Brown et al. 2012) offer such pathways for future work.

APPENDIX A: CHAPTER 2 SURVEY QUESTIONNAIRE

Dear participant,

The purpose of this brief survey is to learn from your experiences regarding water allocation models as a decision-support tool in trans-boundary river basins. This is not a survey about the quality of any particular model, nor about any particular decision that might have been made after using a model. Rather, it's about how models are developed and then applied in decision-making. We are asking these questions of people at various levels of government in the Murray-Darling Basin (Australia), and the Colorado River Basin (United States and Mexico). This research will form part of my DPhil (PhD) studies at the University of Oxford, England.

I estimate that this survey will take between 20-40 minutes. The survey consists of three main sections, with two to five subsidiary questions within each section and some space for open-ended thoughts at the end. Your name will not be used in reporting or analysing the results of this survey. Either now or at the end of the survey, you may also ask to remove your specific affiliation as well. Quotes will not be used without your consent.

1. Do I have your consent to continue? YES/ NO (circle one)

2. Please write your name:

3. What agency or organization do you work for?

4. What is your job title?

5. Circle the one the best describes your role:

- a. Research Scientist/Engineer
- b. Hands-on Engineer/Water System Operator
- c. Institutional (Governmental/Non-Governmental) Manager
- d. Policy Analyst
- e. Water end-user or consumer representative (agriculture, municipality, etc.)

6. How long have you worked at that job?

7. How long have you worked in that organization?

Questions regarding model saliency

Saliency: The relevance to the needs of decision-makers

- 1. In your experience, where and how have models concerning trans-boundary water allocation been applied (crossing international or interstate boundaries)?**
- 2. Is there any particular application that has proven especially useful for informing policy decisions on trans-boundary waters? Can you provide an example or two and describe why the models were useful?**
- 3. What characteristics of the model would have made them more useful for helping come to decisions?**
- 4. What technical or non-technical issues have restricted the use of these models?**

Data description and Assumptions of Model #1:

Note, this page is an alternate way of listing the items on the previous page

<u>Data Source or Assumption</u>	<u>Credibility of this Data Source?</u>	<u>Basis of this conclusion</u>

*

APPENDIX B: EASTERN NILE RIVERWARE MODEL ASSUMPTIONS

Elev. (m)	Storage (MCM)	Area (Mm2)	Elev. (m)	Storage (MCM)	Area (Mm2)	Elev. (m)	Storage (MCM)	Area (Mm2)
Lake Tana			Rosaries			Sennar		
1783.0	0	2959.2	465.0	0	5	411.0	0.0	0.0
1783.8	2348.1	2982.1	466.0	12	6	411.9	0.8	0.9
1784.5	4540.6	3010.9	467.0	27	10	412.0	0.9	0.9
1785.3	6733.1	3047.0	467.7	46	13	412.3	1.1	1.4
1786.0	8925.6	3090.3	468.0	56	15	412.6	1.5	2.1
1786.7	11118.1	3140.8	468.5	75	19	413.0	2.3	3.2
1787.6	13858.7	3214.1	469.0	98	23	413.3	3.3	4.3
1789.0	18438.6	3361.9	470.0	156	33	413.6	4.6	5.7
Source: Deltares			471.0	230	44	414.0	7.0	7.8
			472.0	321	58	414.3	9.5	9.6
GERD			473.0	429	74	414.6	12.6	11.7
500	0	3	474.0	555	92	415.0	17.6	15.6
510	10	11	475.0	699	111	415.3	22.4	17.8
520	20	29	476.0	862	133	415.6	27.9	20.8
530	50	61	477.0	1044	156	416.0	36.9	25.3
540	750	111	478.0	1246	181	416.3	44.8	28.9
550	2000	180	478.5	1354	195	416.6	53.9	33.0
560	3000	272	479.0	1467	209	417.0	67.9	38.8
570	6000	387	479.5	1585	223	417.3	80.1	43.5
580	9800	531	480.0	1708	238	417.6	93.7	48.6
590	15000	703	480.5	1836	253	418.0	114.2	55.8
600	21500	905	481.0	1970	269	418.3	131.7	61.7
610	31000	1133	482.0	2290	302	418.6	150.9	67.8
620	42500	1380	483.0	2645	335	419.0	179.5	76.6
630	57000	1638	484.0	3035	369	419.3	203.3	83.5
640	74000	1904	485.0	3461	403	419.6	229.3	96.9
650	94000	2189	486.0	3922	434	420.0	267.6	101.3
660	117500	2529	487.0	4415	466	420.3	299.0	109.4
Source:NBI			488.0	4941	498	420.6	340.0	117.9
			489.0	5500	532	421.0	382.5	129.9
			490.0	6095	567	421.3	422.9	139.4
			Source:NBI			421.7	481.2	152.6
						422.4	579.9	175.3
						Source:NBI		

Elev. (m)	Storage (MCM)	Area (Mm2)	Elev. (m)	Storage (MCM)	Area (Mm2)	Elev. (m)	Storage (MCM)	Area (Mm2)
Tekeze			Upper Atbara and Setit			Khashm El Girba		
974	0	0.0	500.0	0	0.0	440.0	0.0	0.0
975	1	0.4	509.0	1180	16.5	445.0	5.0	1.5
1000	69	5.0	510.0	1311	33.0	450.0	12.5	2.0
1010	134	8.1	511.0	1482	49.5	455.0	22.5	3.0
1020	245	14.0	512.0	1653	66.0	460.0	37.5	4.0
1030	423	21.6	513.0	1823	82.5	461.0	42.5	6.0
1040	678	29.5	514.0	1994	99.0	462.0	50.0	7.0
1050	1023	39.6	515.0	2165	115.5	463.0	60.0	8.0
1060	1474	50.6	516.0	2404	132.0	463.5	65.0	9.4
1070	2036	61.8	517.0	2642	148.5	464.0	70.0	10.8
1080	2707	72.6	518.0	2881	165.0	465.0	90.0	19.0
1090	3480	81.9	519.0	3119	181.5	467.5	165.0	35.0
1100	4354	92.9	520.0	3358	198.0	470.0	308.0	63.0
1110	5353	106.9	521.0	3688	214.5	473.6	580.0	95.0
1120	6499	122.7	521.5	3853	231.0	474.0	657.0	100.0
1130	7810	139.7	522.0	4018	247.5	Source:NBI		
1140	9293	156.9	522.5	4183	264.0	Merowe (El. Co)		
1150	10958	176.1	523.0	4347	280.5	244	0.0	0.0
Source:NBI			523.5	4512	297.0	246	0.5	0.6
			Source: U ok Khartoum			248	4.9	4.1
Jebel Aulia			High Aswan			250	17.1	8.9
360.0	0.0	0.0		0	0	252	36.2	10.1
366.0	75.0	50.0	110	5200	450	254	59.8	13.4
370.0	100.0	80.0	120	7800	600	256	89.6	16.5
373.3	305.0	131.0	125	11300	749	258	127.8	22.4
373.7	501.0	216.0	130	15600	988	260	184.3	34.2
374.7	803.0	319.0	135	21200	1242	262	263.8	45.4
375.4	1424.0	560.0	140	28300	1589	264	367.3	58.5
376.0	1925.0	820.0	145	31860	1738	266	501.3	76.2
376.3	2125.0	888.0	147	37200	1962	268	673.8	95.4
376.8	2702.0	1060.0	150	48100	2414	270	884.9	116.6
377.3	3125.0	1220.0	155	61500	2950	272	1140.6	139.7
377.3	3178.0	1225.0	160	77900	3581	274	1446.3	165.9
377.5	3377.0	1326.3	165	97600	4308	276	1803.4	193.3
378.0	3903.5	1494.8	170	121300	5168	278	2220.7	224.3
378.5	4430.0	1663.3	175	149500	6118	280	2697.8	254.4
379.0	4956.5	1831.8	180	169420	6752	282	3240.8	290.6
Source:NBI			183	175700	6962	284	3868.3	335.9
			184	182700	7174	286	4578.2	374.8
			Source:NBI			288	5373.8	420.8
						290	6260.9	468.0
						292	7247.4	520.9
						294	8344.7	577.4
						296	9560.4	638.8
						298	10904.9	707.5
						300	12395.5	784.7
						302	14051.0	872.9
						304	15892.6	970.4

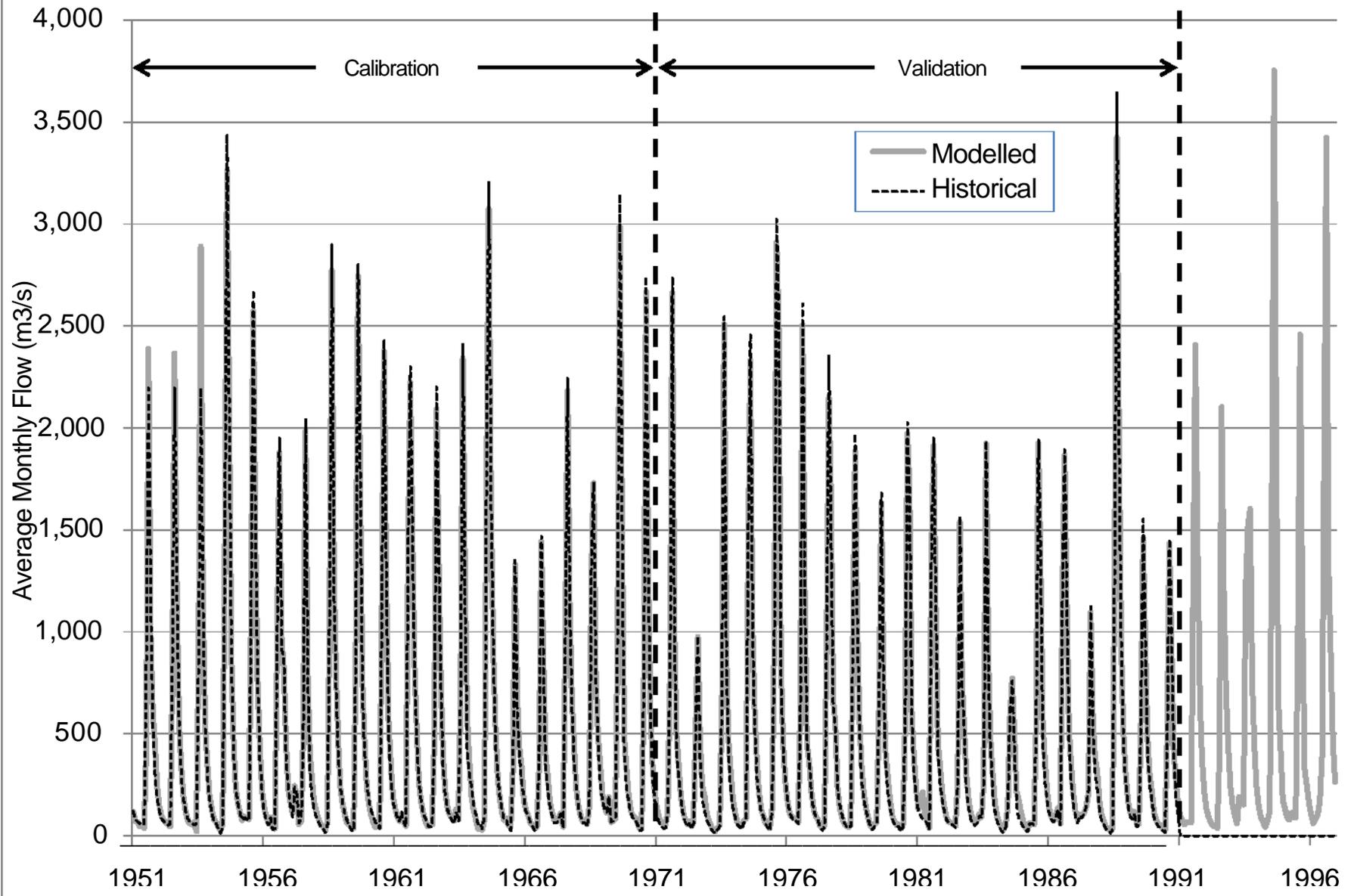
Evaporation Rate Inputs (cm)

	Lake Tana	GERD	Rosaries	Sennar	Tekeze	Upper Atbara & Setit	Khashm El Girba	Jebel Aulia	Merowe	High Aswan
Jan	13.40	13.50	17.98	17.98	13.40	17.36	17.36	18.91	17.36	10.38
Feb	14.39	13.60	18.48	18.48	14.39	20.44	20.44	23.52	17.92	13.00
Mar	9.90	17.10	22.66	22.66	9.90	24.18	24.18	23.25	23.25	20.30
Apr	7.96	15.70	22.11	22.11	7.96	24.80	24.80	22.20	25.50	25.20
May	7.90	10.60	18.91	18.91	7.90	25.78	25.78	22.94	29.45	31.71
Jun	0.21	4.20	6.27	6.27	0.21	23.80	23.80	22.50	29.10	32.49
Jul	-15.40	-0.40	-2.79	-2.79	-15.40	12.58	12.58	11.78	28.83	32.40
Aug	-18.30	0.10	-2.60	-2.60	-18.30	8.09	8.09	11.47	28.52	31.50
Sep	-3.82	1.40	1.95	1.95	-3.82	16.20	16.20	13.50	27.00	27.00
Oct	11.30	9.10	12.49	12.49	11.30	18.25	18.25	15.19	25.11	21.51
Nov	14.67	11.40	15.69	15.69	14.67	18.80	18.80	17.40	19.80	14.01
Dec	14.70	11.50	16.74	16.74	14.70	18.29	18.29	17.05	19.74	10.60
Annual	56.91	107.80	147.89	147.89	56.91	228.57	228.57	219.71	291.58	270.10
Source:	NBI	NBI	NBI	NBI	NBI	NBI	NBI	NBI	Merowe Dam Elect. Co	Deltares

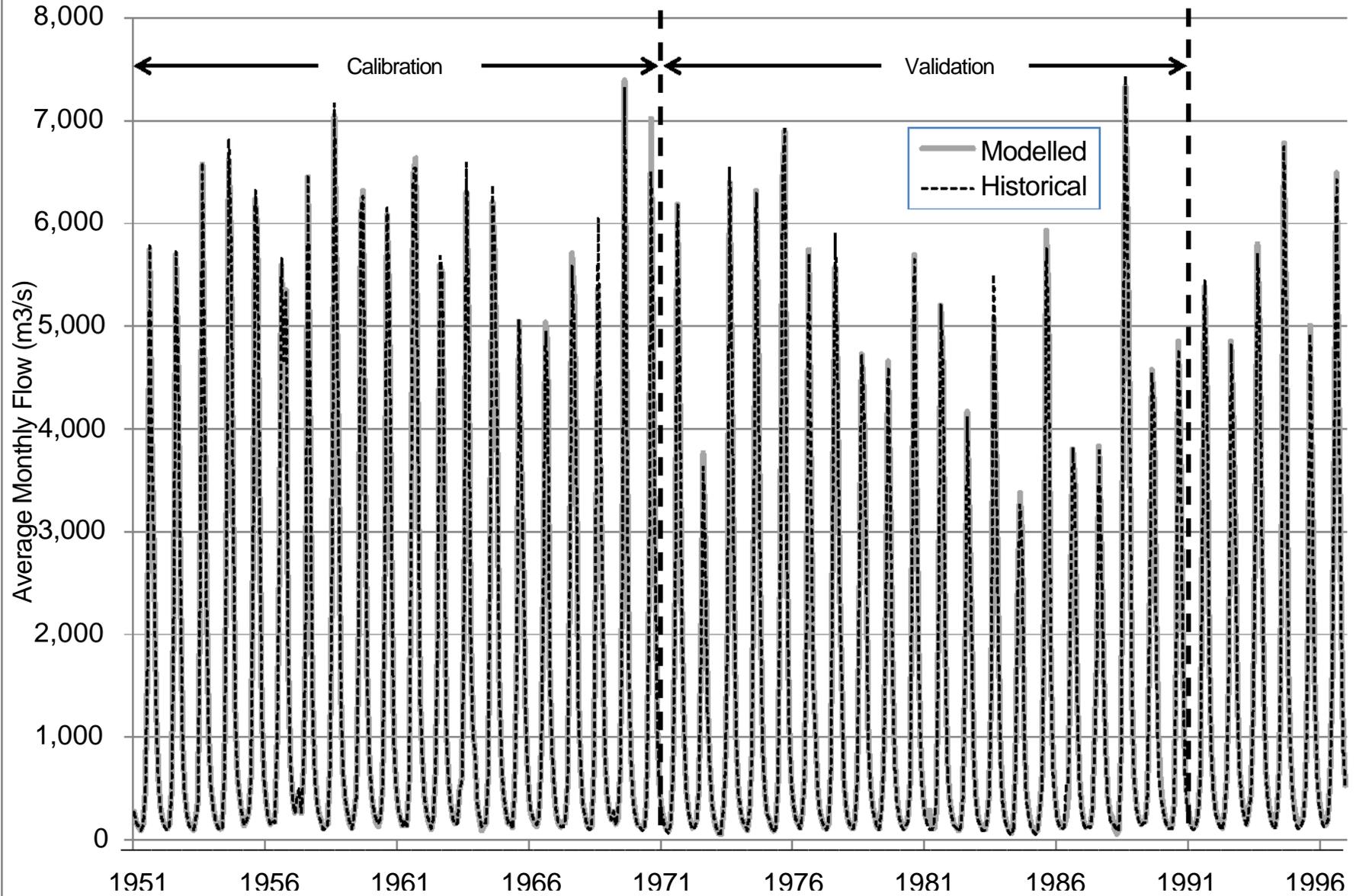
Calibration Results - Channel and Wetland Swamp Losses (MCM)

	Blue Nile: Upstream of Kessie	Sobat: Upstream of Hillel Doleib	Main Nile: Khartoum to Atbara	Main Nile: Atbara to Merowe	Main Nile: Dongola to Aswan	Main Nile: Merowe to Dongola	Sudd Swamp	Bahr El Ghazal Swamp	Marchar Marshes
	Modeled as Flow Variable Loss				Modeled as Evaporation				
Jan	15	255	52	54	52	38	2002	1316	301
Feb	11	135	42	62	60	44	1897	1083	273
Mar	9	113	38	78	64	47	1869	973	247
Apr	8	94	41	88	88	65	1689	737	224
May	8	192	39	87	99	72	1687	573	203
Jun	9	365	51	93	102	74	1461	450	191
Jul	96	495	117	81	92	67	1387	468	203
Aug	6	633	288	73	94	68	1500	633	251
Sep	142	700	255	72	94	68	1588	921	324
Oct	411	597	157	68	87	64	1774	1292	373
Nov	48	510	86	59	66	48	1903	1487	367
Dec	24	424	63	51	53	39	1943	1500	335
Annual	787	4513	1228	866	950	695	20700	11433	3291

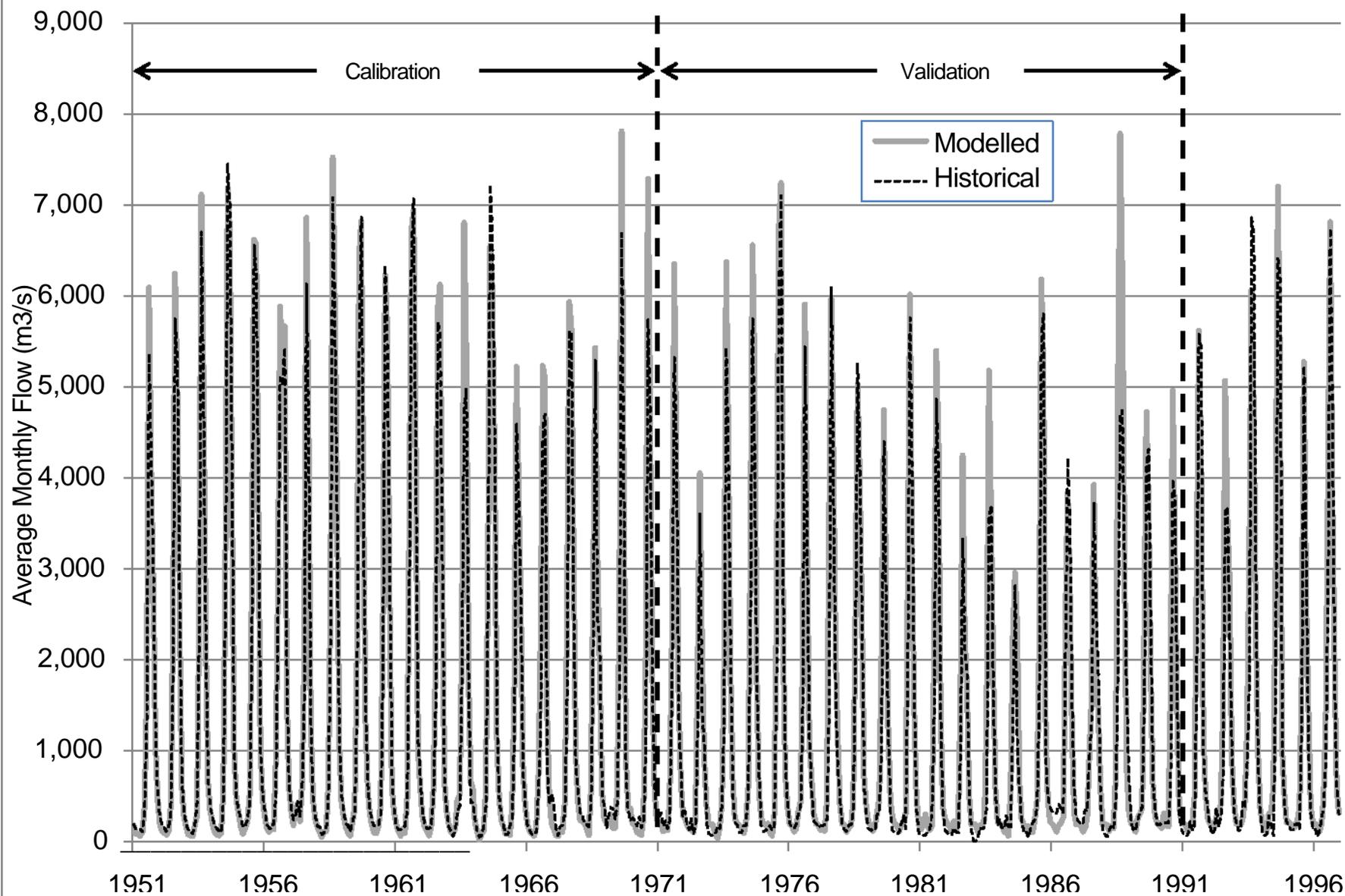
Kessie Gage



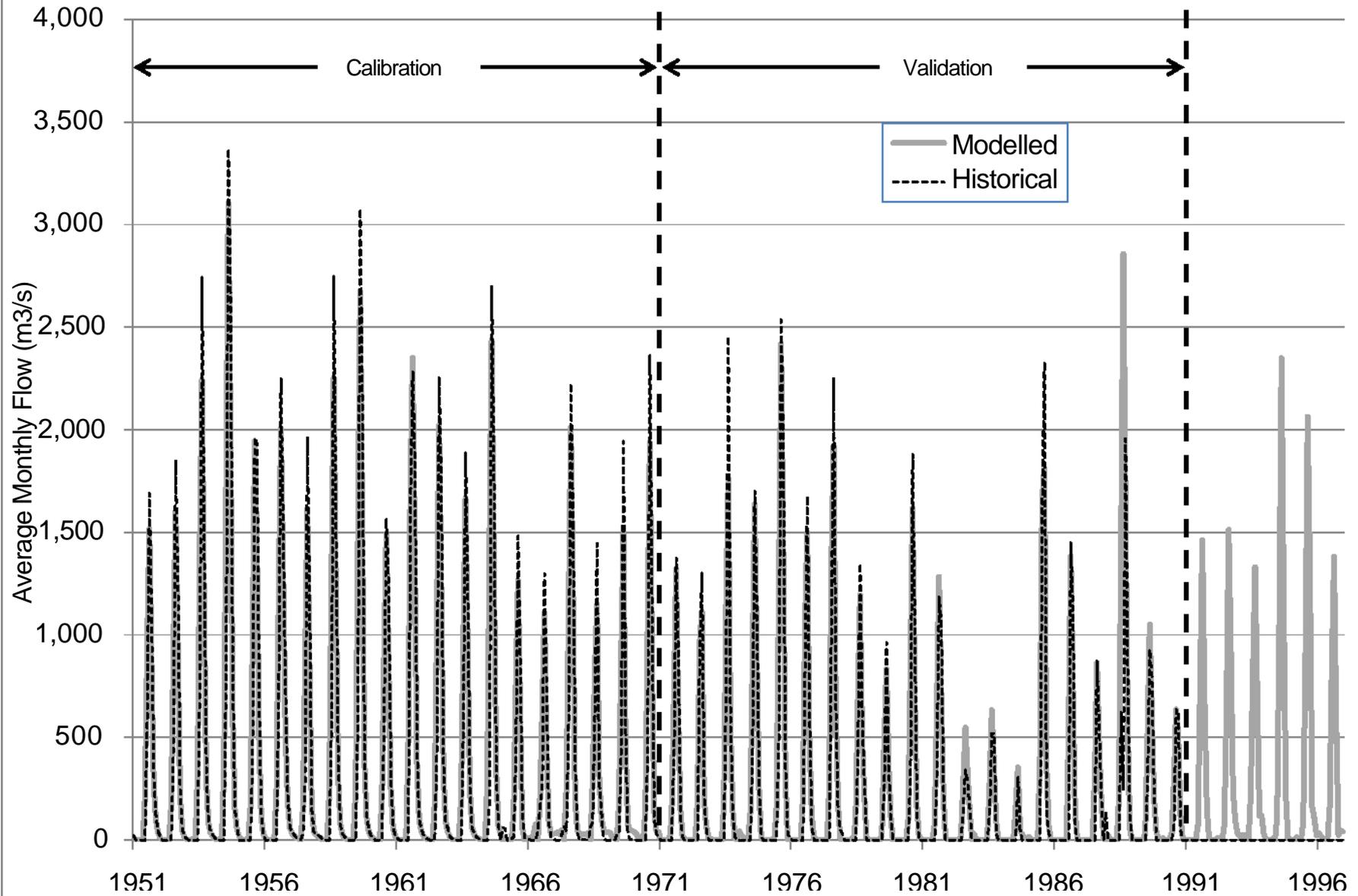
El Diem Gage



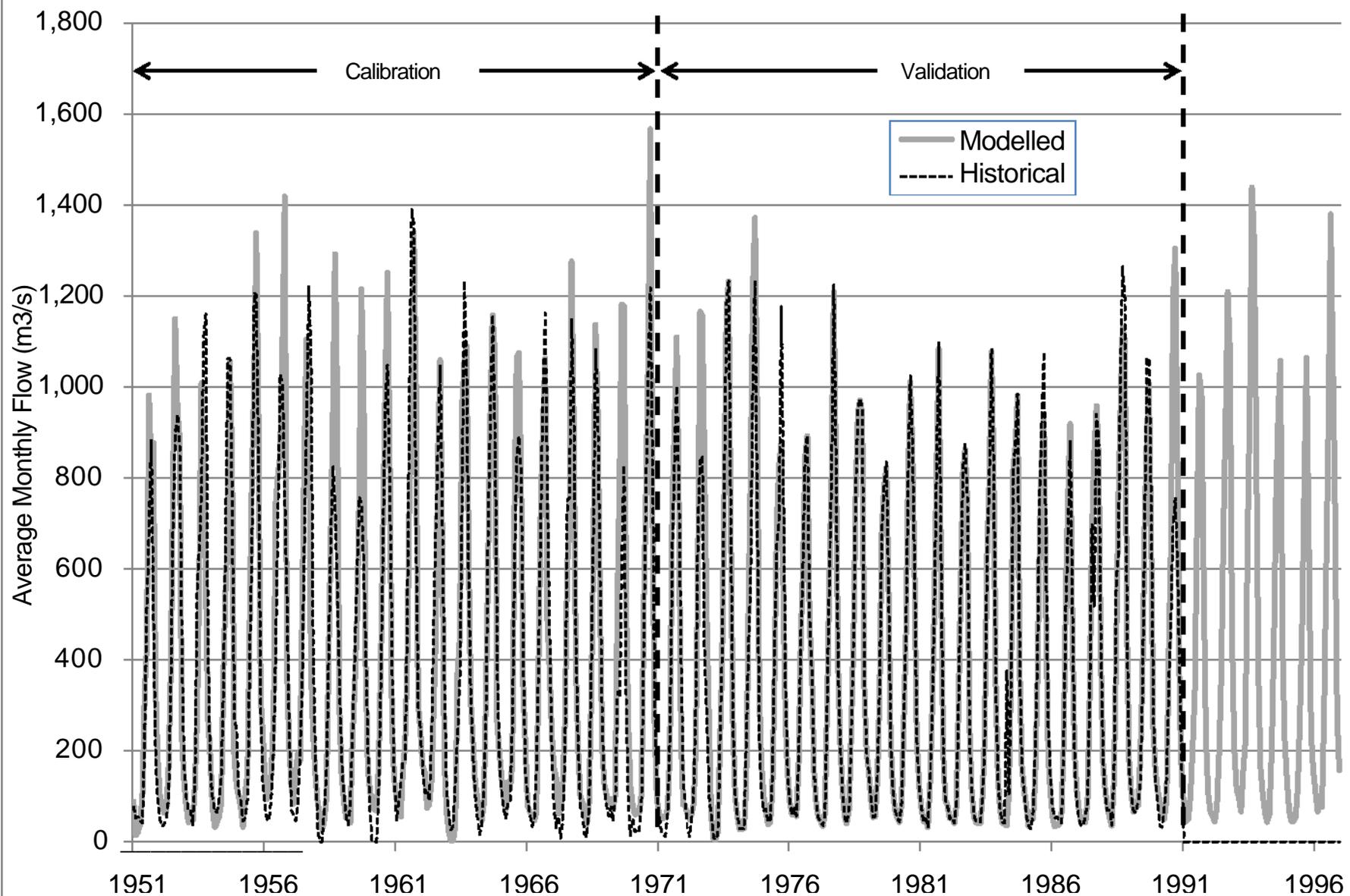
Khartoum at Soba Gage



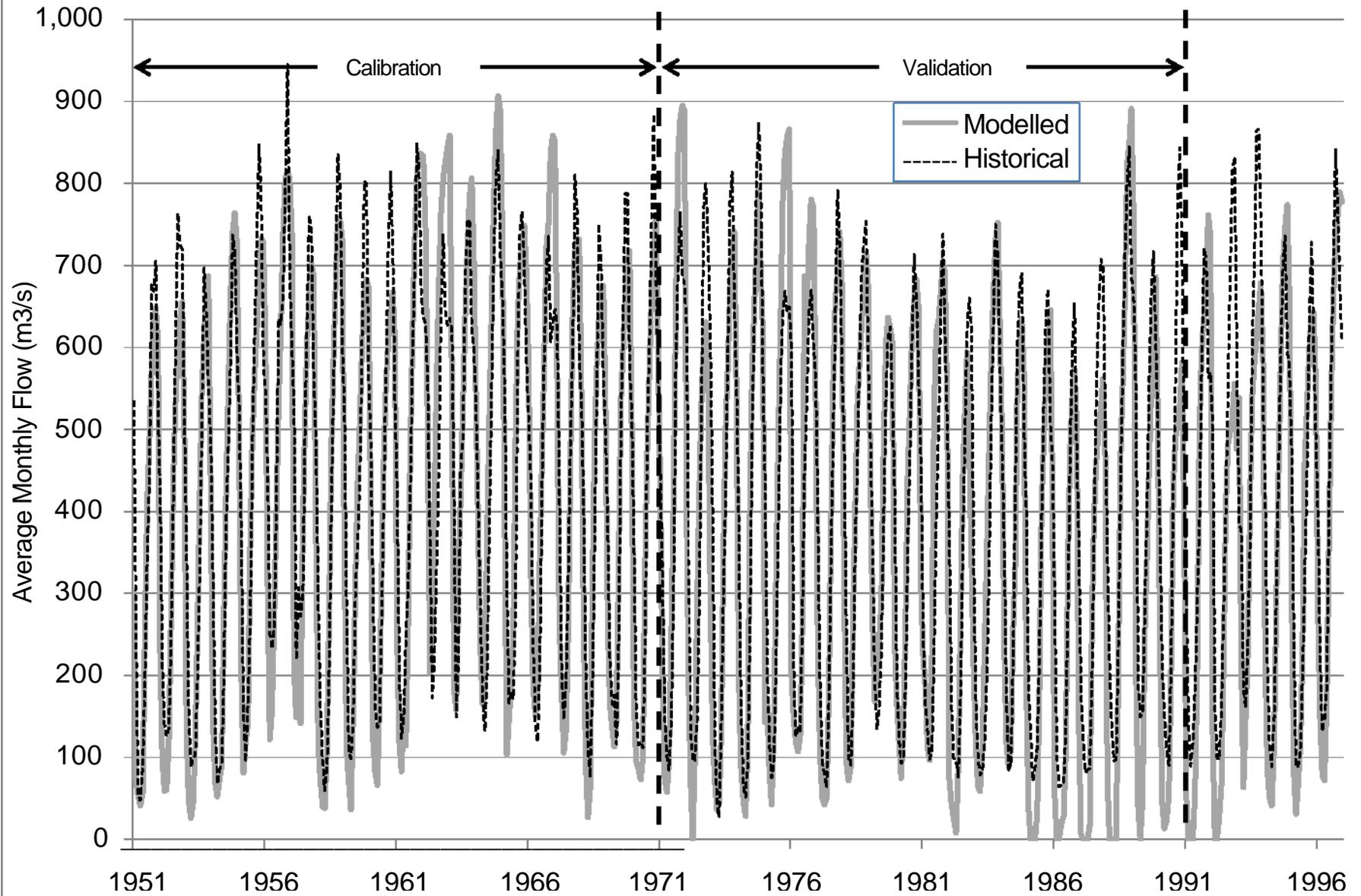
Atbara at Kilo 3 Gage



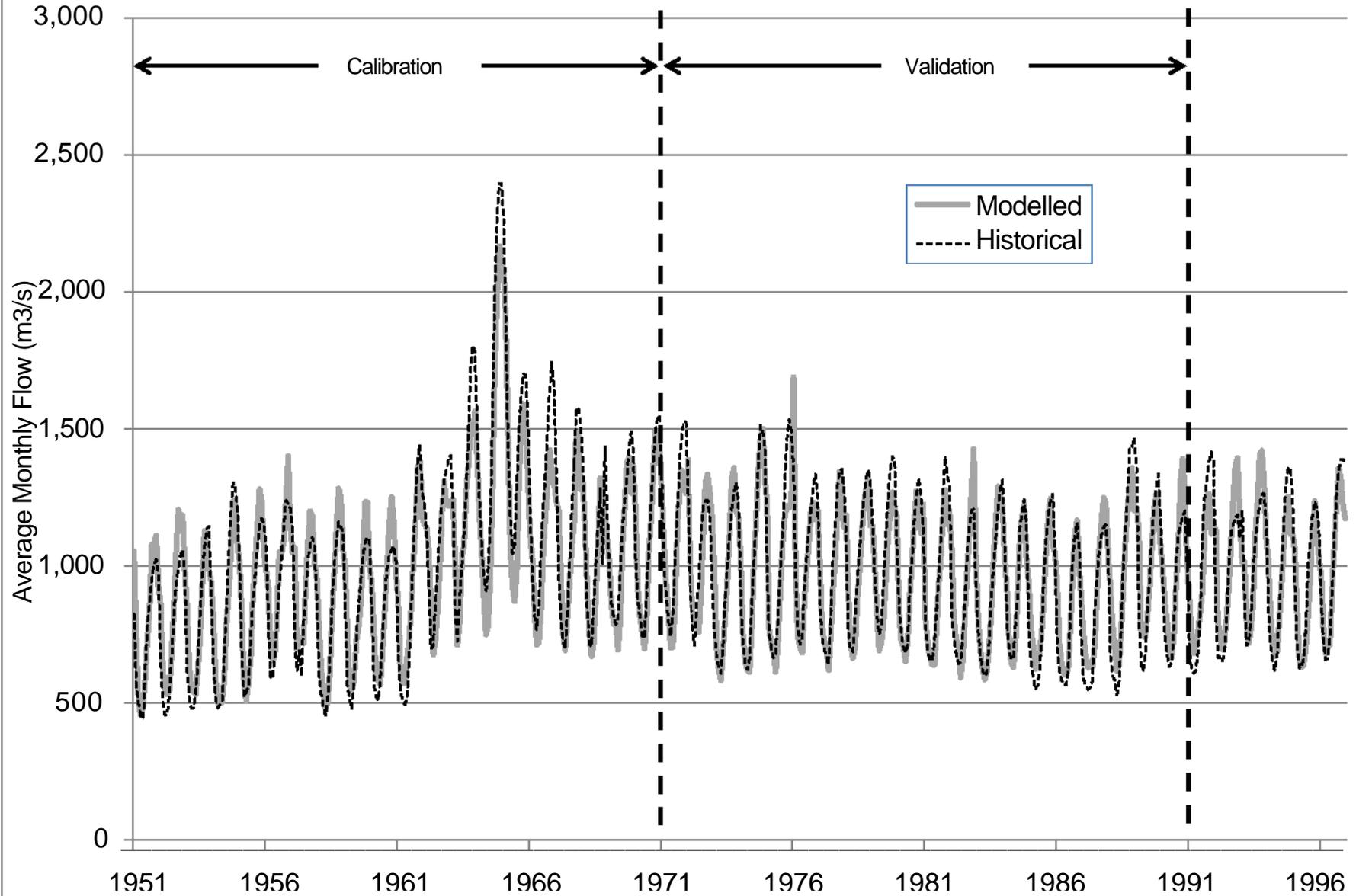
Baro at Gambella Gage



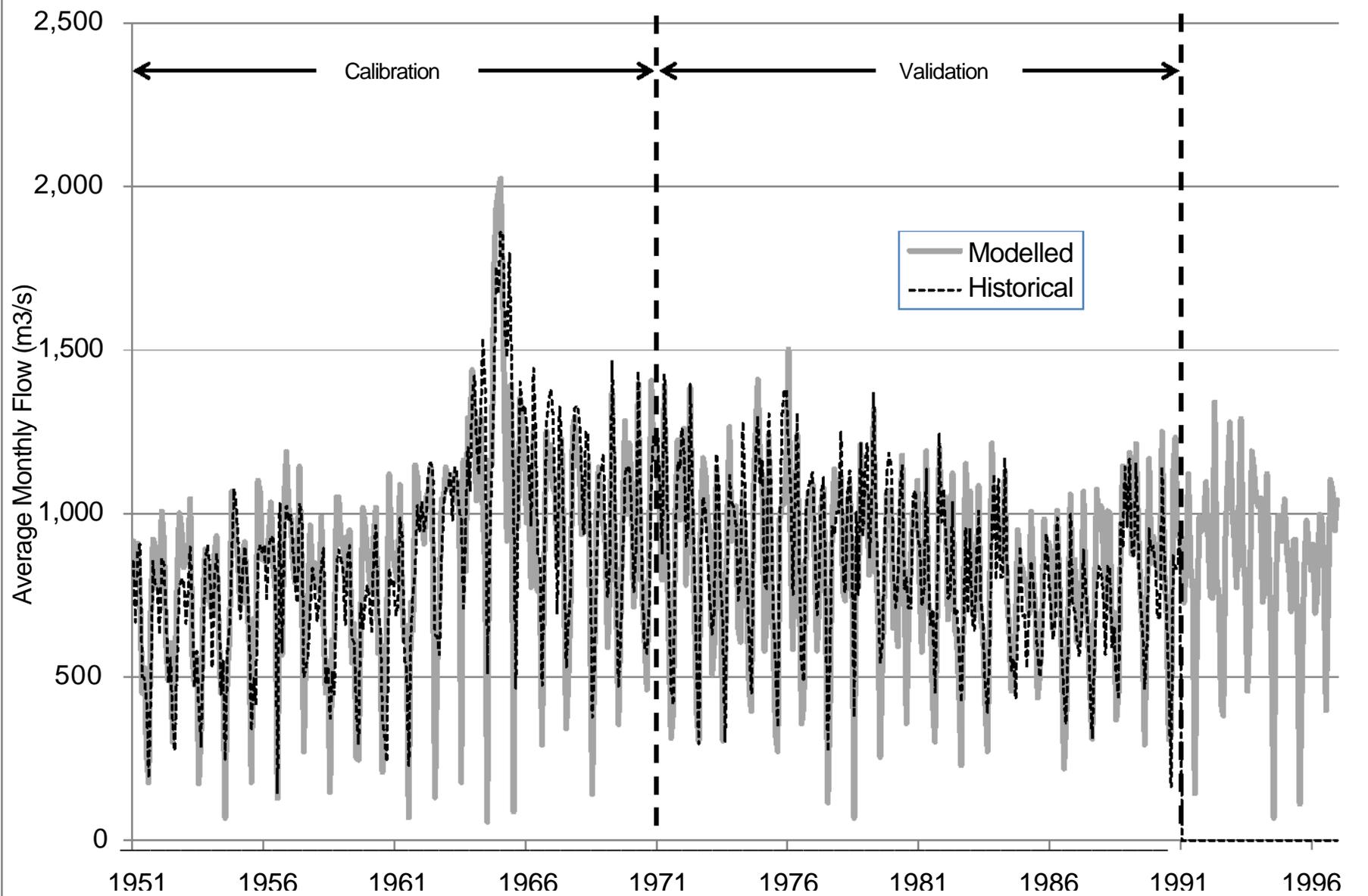
Sobat at Hillel Doleib Gage



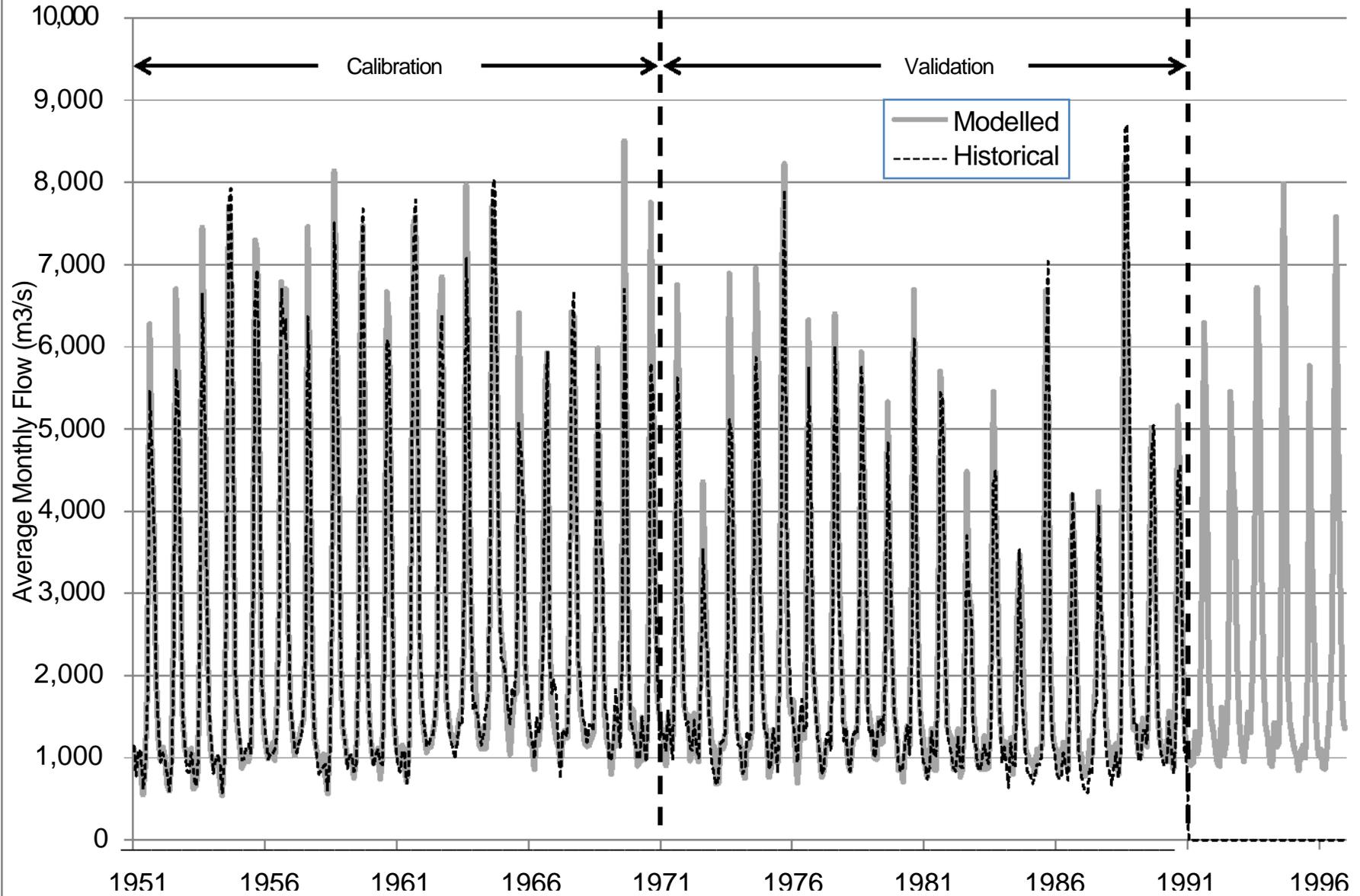
Malakal Gage



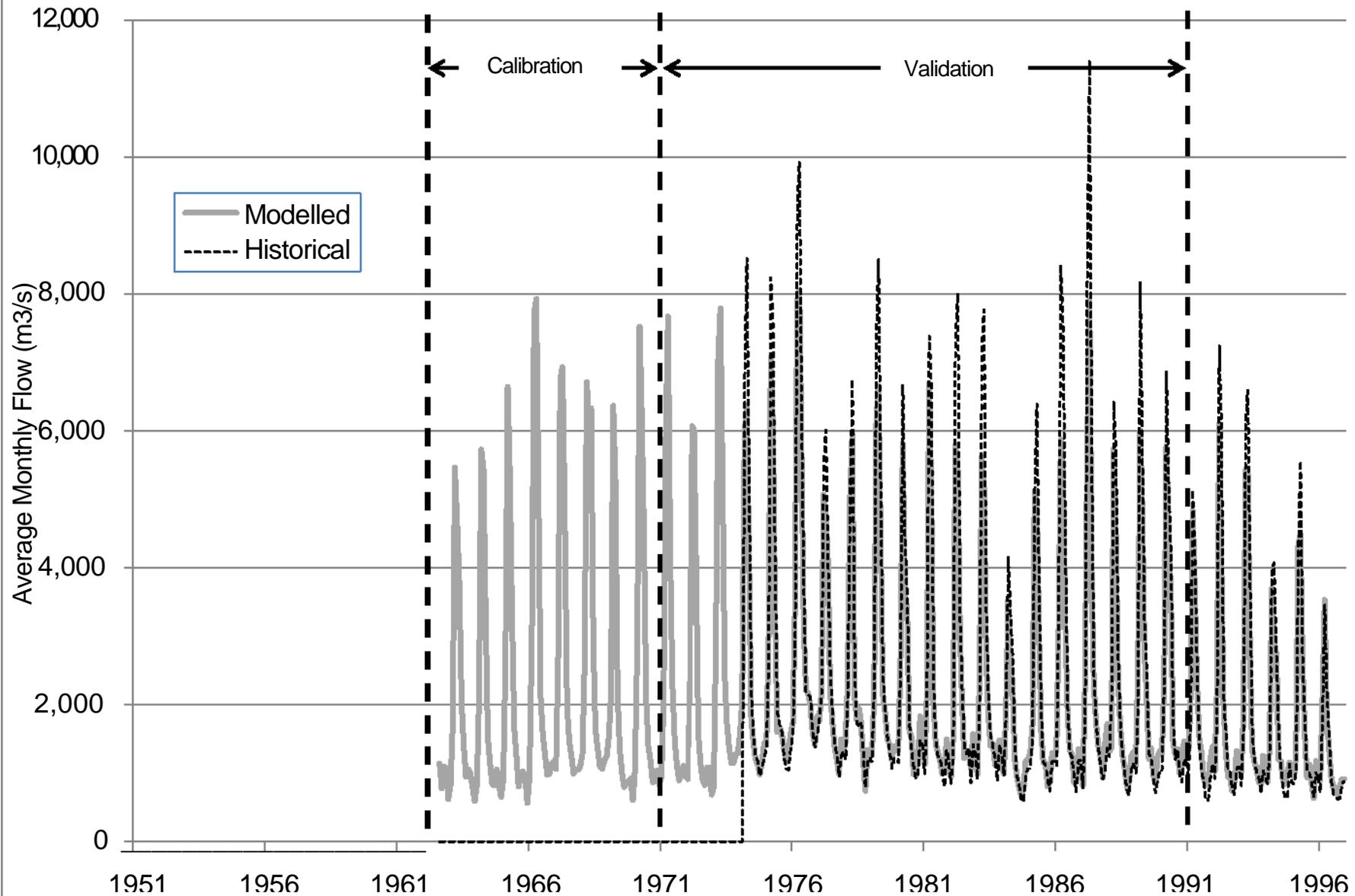
Mogren Gage



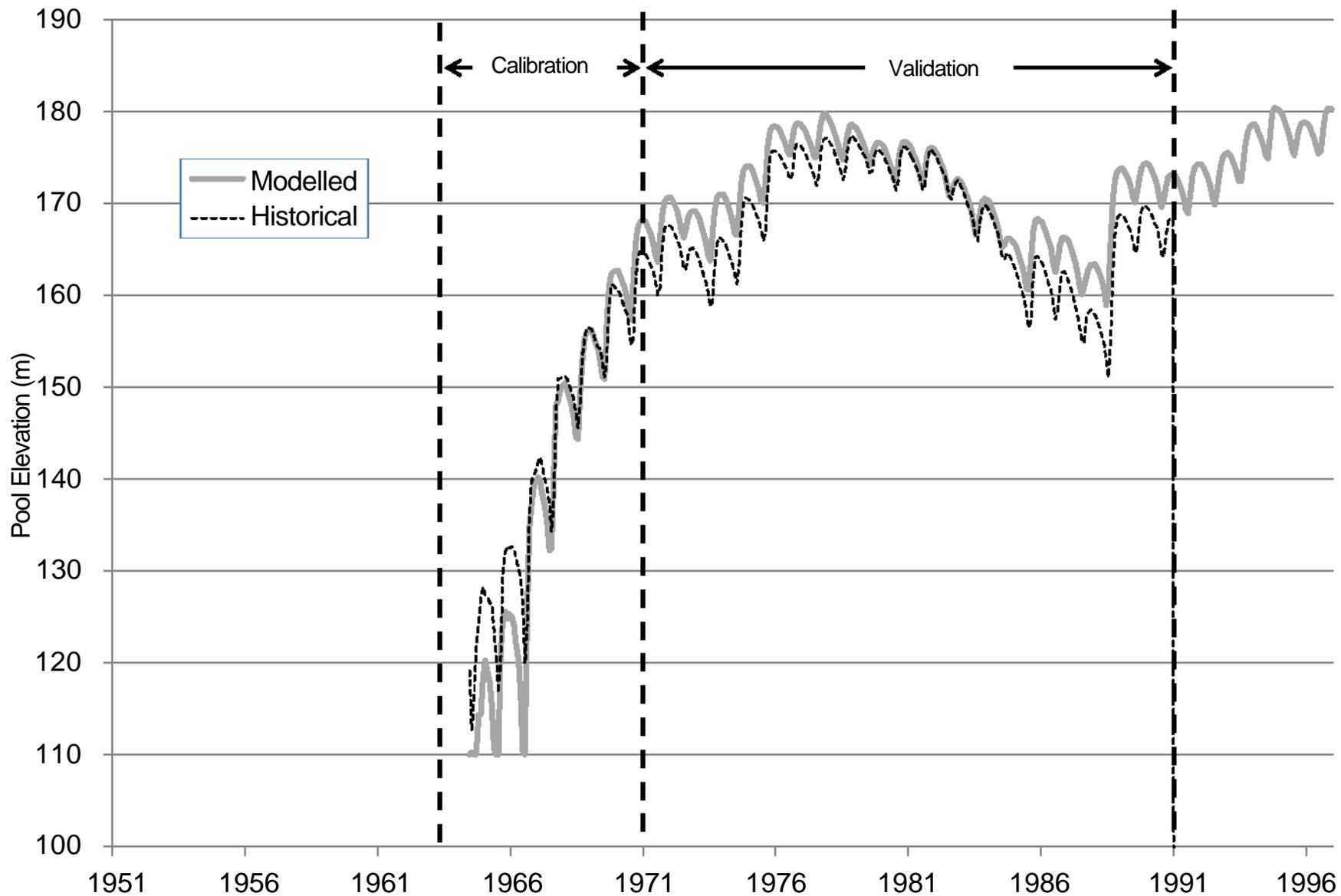
Tamaniat Gage



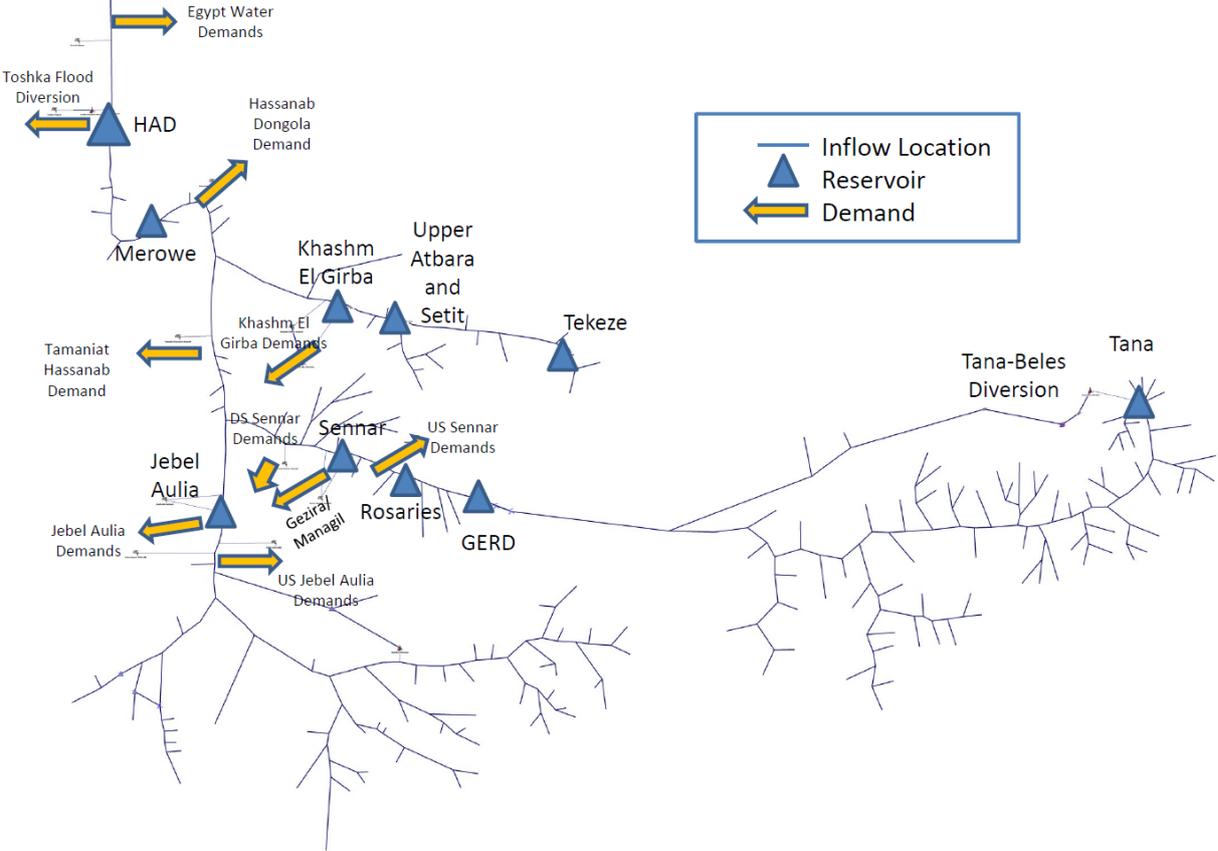
Dongola Gage



High Aswan Dam Pool Elevation



Eastern Nile RiverWare Model Schematic



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