Delft University of Technology

The practice and opportunities in re-operating dams for the environment

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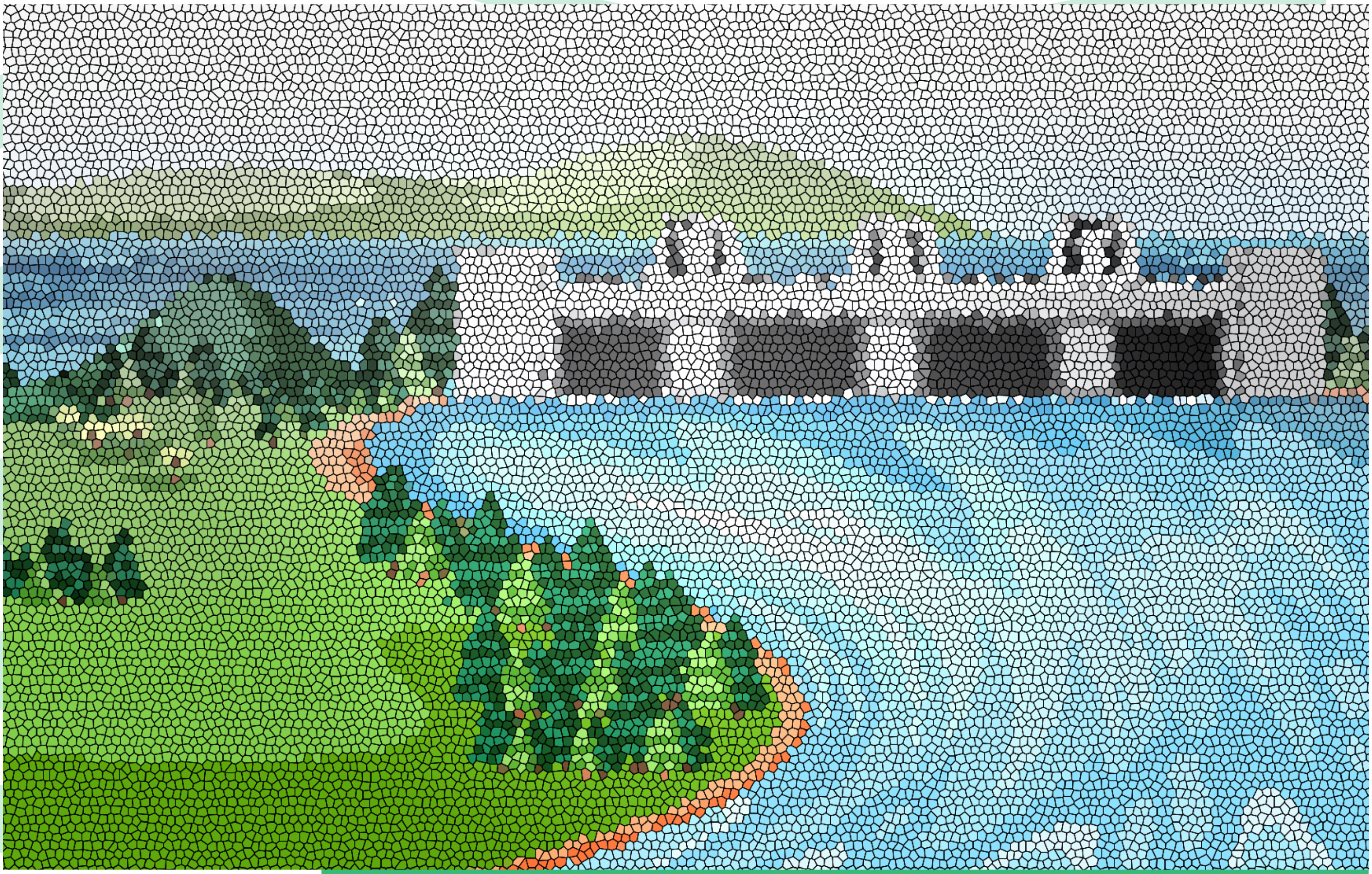
DOI
10.4233/uuid:35343fa4-0dd3-4039-ac58-b2999a9aa2d0

Publication date
2022

Document Version
Final published version

Citation (APA)
Owusu, A. G. (2022). *The practice and opportunities in re-operating dams for the environment*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:35343fa4-0dd3-4039-ac58-b2999a9aa2d0



The Practice and Opportunities in Re-operating Dams for the Environment

Afua G. Owusu

THE PRACTICE AND OPPORTUNITIES IN RE-OPERATING DAMS FOR THE ENVIRONMENT

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DISSERTATION

Submitted in fulfilment of the requirements of
the Board for Doctorates of Delft University of Technology
and
of the Academic Board of the IHE Delft
Institute for Water Education
for
the Degree of DOCTOR
to be defended in public on
Wednesday, 30th November 2022, at 10:00 hours
in Delft, the Netherlands

by

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This research was conducted under the auspices of the TU Delft Graduate School and the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

Published by IHE Delft Institute for Water Education
www.un-ihe.org

ISBN 978-90-73445-45-1

Cover art: BrushPic

To my parents, Kwaku and Levina

ACKNOWLEDGEMENTS

This PhD journey has been a challenging but rewarding experience and I have a lot of people to thank for helping me and cheering me on along the way.

To my family, thank you for your confidence in me. I am fortunate to have the *most* - and I use that qualitatively and quantitatively - supportive and loving parents, sister, cousins, aunts and uncles, nieces and nephews, in-laws and grandparents.

To Kwadwo, thank you for being kind, calm and understanding. You are the only other person who experienced the daily grind of this research and as usual, you were wonderful! To my son Yaw, thank you for your company. People often asked how I could do a PhD with a toddler but my answer to that now is: “How could I have done my PhD without you?”. You made me keep sensible hours and take a complete - and enjoyable - break from my work at the end of each day.

To my supervisors, I enjoyed working with you and have learned so much from you. Marloes, soon after we met in Accra I told you that I was going to be you in 10 years and I can only hope that I am close to achieving that goal seven years later. You continue to inspire me with the breadth and depth of your knowledge. You are also kind and always helpful. Jill, I enjoyed our one-on-one meetings so much. You were full of practical advice and funny anecdotes on living in the Netherlands, raising Yaw and getting my research deliverables through. Pieter, thank you for demanding only the best, for your humour and the witty article titles. With you on my supervisory team, I knew I had a strong advocate at the highest levels in IHE.

From our early days in Trento, hiking, eating, kayaking and learning about e-flows, working together with my fellow ESRs and the rest of the EuroFLOW team was always a fun affair. I am grateful to the project lead, Lee, Megan and Pazit, at the University of Leeds; the organisers of workshops and activities; and my secondment supervisors, Martin and Michael at UFZ, and Francois at CEH. I look forward to future collaborations.

I am grateful to all the experts, particularly from the Water Research Institute in Ghana who readily spared some time to answer questions and share their knowledge on the Lower Volta River Basin. Also, a special thanks to the team from the Department of Fisheries and Watershed Management at KNUST, especially, Prof. Adjei-Boateng, who answered an email from a stranger, and Dr. Obirikorang who put up with constant requests from me after our fieldwork at Sogakope.

To my fellow PhD colleagues at IHE and TPM, Akosua, Shanoor, Irene, Jonatan, Natalia, Adele, Meseret, Tesfaye, David, Abby, Hammond, Floortje, Sharlene, Mannat, Andrike, Kees, Vladimir and Jie, thank you for your friendship. Akosua, you were a great help especially at the start of my PhD. Thank you also to Michael, Angeles, Anne, Rebecca, Leon, Jazmin, Benjamin, Wendy and my colleagues at IHE, TPM and other institutions.

Nicole, Evelyn and Frank, thank you very much for taking care of Yaw and me. To the rest of my Ghanaian family in Delft, Linda and Abaka, Bro. Salifu, Afua Ampomah, Afi, Sammy, Kukuaa, Edmond, Fred, Shadrak, Godwin, Sabinah, Orstin, Eddy, Boabeng, Richard, Afua, and Bernice, thank you for your companionship, for taking care of Yaw and for the good food and music. I am also grateful to my friends from home; you are too numerous to name but I appreciate the phone calls when I was in Delft, and the time together whenever I returned home.

I am grateful to the leaders and members of the churches I fellowshipped with in the Netherlands; RCCG Mount Zion Church in Delft, Presbyterian Church of Ghana in Den Haag and the IHE Delft Christian Fellowship. To the pastors, Hyacinth, Helena and Taco; and the elders, thank you for your prayers and warmth.

The length of this Acknowledgement shows that indeed it takes an army to produce this little book. All praise and thanks to God Almighty for blessing me with my army of family, friends and colleagues and for His guidance and protection over the years. *Me kra, hyira Awurade*!

SUMMARY

For most of the 20th century, the design and operation of dams prioritized traditional economic considerations such as hydropower generation, flood risk reduction and provision of water for irrigation and domestic use. This resulted in altered river flow regimes, degraded riverine ecosystems and ecosystem services, and biodiversity loss. Implementation of environmental flows (e-flows), freshwater flows for the environment, is a means to restore some of the benefits of naturally flowing rivers and halt the rapid deterioration of freshwater and estuarine habitats, flora and fauna. Since its early days in the 1940s, e-flows science has grown and there now exists a wide array of methodologies for establishing flow-ecology relationships. The concept of e-flows also has a firm place in many national water laws and policies across the world. Despite this progress, actual implementation of e-flows has not followed suit and remains limited.

This research was aimed at generating insights into how e-flows evolve from recommendation into practice and the trade-offs that are identified between conventional water uses and e-flows during conception or implementation. The study focused in particular on e-flows implementation through the re-operation of existing dams. This study addressed two major shortcomings in e-flows science, specifically, the lack of a global record of e-flows implementation and the lack of insight into why certain e-flow recommendations have been implemented while others have not.

The research followed an exploratory, sequential, mixed methods approach beginning with a systematic literature review and a global survey of practical cases of dam re-operation for e-flows. A logic model of the process was used to develop a conceptual framework of how e-flows are implemented in practice. While the systematic literature review identified the inputs, activities and outputs of dam re-operation in successful cases, the global survey of stakeholders with first-hand experience in dam re-operation attempts revealed how stalled attempts at dam re-operation significantly differed from successful attempts through a comparison of the survey responses for the two groups using statistical methods.

This extensive research phase looking at cases of dam re-operation across the globe formed the first part of this research and was then followed by a case study to investigate the synergies and trade-offs between water users when dam operations are changed to implement e-flows. The Akosombo and Kpong dams in the Lower Volta River, Ghana, were chosen as the case study. The choice of case study was partly informed by the findings from the systematic literature review and survey. Attempts at dam re-operation in this location have stalled despite it possessing some of the key characteristics of successful cases. It thus presented an interesting case for further investigation. While past studies had already developed e-flows for the Lower Volta, these were based on the natural flow paradigm: an e-flows design approach based on the natural, pre-dam flow

regime of a river. An additional e-flow was designed based on the designer e-flows paradigm whereby components of a river's hydrograph are compiled to meet a desired ecological outcome. Owing to the data scarce situation in the case study, a Bayesian Belief Network (BBN) was used to link river flows to the state of the Volta clam fishery, an important artisanal industry in the basin. Finally, a simulation-optimisation technique, Evolutionary Multi-Objective Direct Policy Search (EMODPS), was applied to the case study to determine the trade-offs and synergies between the environment and key water users in the Lower Volta Basin. The new e-flow recommendation developed for the Lower Volta River, together with the past recommendations based on the natural flow of the river, served as inputs to this trade-off analysis.

This research reveals that e-flow recommendations are usually implemented through a collaborative analytical process which makes use of existing supporting frameworks such as legislation, but also takes advantage of opportunities that may arise to advance the process of dam re-operation for e-flows such as flow experiments. The process is usually non-linear and it is important to emphasize the local context which makes each process of dam re-operation unique. A global database of successful e-flow implementations through dam re-operation has also been created. This records the inputs, activities, and outputs as well as the stakeholders involved and the e-flows implementation approaches in successful cases.

Moreover, in regard to stalled re-operation attempts, four hypotheses were derived for further study on why some attempts at dam re-operation are at an impasse, namely:

1. In undertaking scientific studies for determination of e-flows, first a consensus on the priorities, knowledge gap, and solutions must be reached together with local stakeholders.
2. Genuine, carefully designed consultations and negotiations between stakeholders can overcome hurdles encountered in the process
3. Local-level legislation and policy on e-flows provide the enabling environment for dam reoperation for e-flows.
4. Scientists are important stakeholders in the process of dam re- operation, but should play a supportive role rather than drive the process.

Through the in-depth context-dependent examination of a unique stalled case, the Lower Volta, this research demonstrated that a parsimonious ecologically grounded, designer e-flows assessment method using a BBN can be applied successfully in data scarce areas. This resulted in an alternative designer e-flow recommendation for the Lower Volta River for low flow releases during the Volta clam veliger larva and recruitment life stages from November to March. Two other complementary management strategies were also recommended for the Lower Volta: annual full breaching of the sandbar which regularly builds up at the Volta Estuary and prohibition of sand winning from the river bed.

The multi-objective trade-off analysis of water users in the Lower Volta highlighted the dominance of hydropower in the river basin and quantified the amount by which firm hydropower demand from the Akosombo and Kpong dams would have to decrease for the implementation of e-flows under current and future climate scenarios. Notably, and curiously, both an increase and a decrease in annual inflows to the Akosombo Dam reduce the trade-off and create synergies between e-flows and hydropower generation. This is because climate change leading to increased annual inflows to the Akosombo Dam results in increased water availability for both hydropower and e-flows while climate change resulting in lower inflows provides the opportunity to strategically deliver dry season e-flows, that is, reduce flows sufficiently to meet low flow requirements for key ecosystem services such as the clam fishery.

This research has generated knowledge on the process of dam re-operation for e-flows implementation; the enabling factors for successful dam re-operation; the hurdles typically encountered and how they have been overcome in successful cases; as well as inter-sectoral trade-offs that must be made between e-flows and conventional water uses in delivering e-flows in a unique case study. These insights inform attempts to scale up efforts in e-flows implementation through the sustainable and equitable operation of dams for people and the environment.

SAMENVATTING

In de 20ste eeuw lag de prioriteit in het ontwerp en beheer van dammen bij traditionele economische overwegingen, zoals waterkrachtopwekking, vermindering van overstromingsrisico's en de watervoorziening voor irrigatie en huishoudelijk gebruik. Dit resulteerde in veranderde rivierafvoerregimes, aangetaste rivierecosystemen en een verlies aan ecosysteemdiensten en biodiversiteit. De implementatie van milieudebieten (e-flows), zoetwater afvoeren voor het milieu, is een middel om enkele van de voordelen van natuurlijk stromende rivieren te herstellen en de snelle achteruitgang van zoetwater en estuariene habitats, flora en fauna een halt toe te roepen. Sinds 1940 is de wetenschap van e-flows gegroeid en bestaat er nu een breed scala aan methodologieën voor het vaststellen van de relatie tussen debiet en ecologie. Het concept van e-flows heeft ook een vaste plaats in veel nationale waterwetten en -beleidslijnen over de hele wereld. Ondanks deze vooruitgang is de daadwerkelijke implementatie van e-flows niet evenredig toegenomen en blijft deze beperkt.

Dit onderzoek was gericht op het verkrijgen van inzicht in hoe e-flows van aanbeveling naar de praktijk worden gebracht en in de afwegingen die worden geïdentificeerd tussen conventioneel watergebruik en e-flows tijdens de conceptualisering of implementatie. De studie richtte zich met name op de implementatie van e-flows door een aangepast beheer van bestaande dammen. Daarbij licht de focus op twee belangrijke tekortkomingen in de wetenschap van e-flows, namelijk het ontbreken van een globaal overzicht van de implementatie van e-flows en het gebrek aan inzicht in waarom bepaalde e-flow-aanbevelingen zijn geïmplementeerd terwijl andere in het proces zijn vastgelopen.

Het onderzoek volgde een verkennende, sequentiële benadering met gemengde methoden, te beginnen met een systematisch literatuuronderzoek en een globale enquête van praktische gevallen van aangepast beheer van dammen voor e-flows. Een logisch model van het proces van het veranderd beheer van dammen voor e-flows werd gebruikt om een conceptueel raamwerk te ontwikkelen van hoe e-flows in de praktijk worden geïmplementeerd. Terwijl het systematische literatuuronderzoek de input, activiteiten en output van het aangepast beheer van dammen in succesvolle gevallen identificeerde, onthulde de globale enquête onder belanghebbenden hoe vastgelopen pogingen tot het veranderen van het beheer van dammen significant verschilden van succesvolle pogingen door een vergelijking van de antwoorden op de enquête voor twee groepen met behulp van statistische methoden.

Deze uitgebreide onderzoeksfase naar gevallen van aangepast beheer van dammen over de hele wereld werd gevolgd door een gevalstudie om de synergieën en wisselwerkingen tussen watergebruikers te onderzoeken wanneer het beheer van dammen wordt gewijzigd om e-flows te implementeren. De Akosombo en Kpong dammen in de Beneden-Volta rivier, Ghana, werden gekozen als casus. De keuze voor de casus is mede ingegeven door

de bevindingen uit de systematische literatuurstudie en de globale enquête. Pogingen tot het veranderen van het beheer van de dammen op deze locatie zijn tot stilstand gekomen ondanks het feit dat het enkele van de belangrijkste kenmerken van succesvolle gevallen bezit. Het bood dus een interessante casus voor verder onderzoek. Terwijl eerdere studies al e-flows voor de Beneden-Volta hadden ontwikkeld, waren deze gebaseerd op het natuurlijke stromingsparadigma: een benadering van e-flows gebaseerd op het natuurlijke, pre-dam, afvoerregime van een rivier. Een extra e-flow is ontworpen op basis van het ontwerp e-flows-paradigma waarbij componenten van het afvoerregime van een rivier worden samengesteld om een gewenst ecologisch resultaat te bereiken. Vanwege de schaarste aan gegevens in deze casus, werd bij het ontwerpen van de e-flows een Bayesian Belief Network (BBN) gebruikt om rivierafvoeren te koppelen aan de toestand van de zaagjesvisserij in de Volta rivier, een belangrijke ambachtelijke industrie in het stroomgebied. Ten slotte werd een geavanceerde simulatie-optimalisatietechniek, Evolutionary Multi-Objective Direct Policy Search (EMODPS), toegepast op de casus om de wisselwerking en synergieën tussen het milieu en de belangrijkste watergebruikers in het Beneden-Volta stroomgebied te bepalen. De nieuwe e-flow-aanbeveling die is ontwikkeld voor de Beneden-Volta-rivier, samen met de eerdere aanbevelingen op basis van het natuurlijke afvoerregime van de rivier, dienden als input voor deze afwegingsanalyse.

Dit onderzoek toont aan dat e-flow-aanbevelingen meestal worden geïmplementeerd via een gezamenlijk analytisch proces dat niet alleen gebruik maakt van bestaande ondersteunende kaders zoals wetgeving, maar ook van kansen die zich voordoen om in het proces van aangepast beheer van dammen voor e-flows te experimenteren, bijvoorbeeld door middel van afvoerexperimenten. Het proces is meestal niet-lineair en het is belangrijk om de lokale context te benadrukken die elk proces om het beheer van dammen te veranderen uniek maakt. Deze studie heeft ook een database gecreëerd van de succesvolle implementatie van e-flows door aangepast beheer van dammen. Dit registreert de inputs, activiteiten en resultaten, evenals de betrokken belanghebbenden en de implementatiebenaderingen van e-flows in succesvolle gevallen.

In het bijzonder, over de reden waarom sommige pogingen om de dam opnieuw in te richten tot stilstand zijn gekomen, werden vier hypothesen afgeleid voor verder onderzoek over dit onderwerp:

1. Bij het uitvoeren van wetenschappelijke studies voor het bepalen van e-flows moet eerst samen met lokale belanghebbenden overeenstemming worden bereikt over de prioriteiten, kennislacunes en oplossingen.
2. Oprecht, zorgvuldig opgezet overleg en onderhandelingen tussen belanghebbenden kunnen hindernissen die tijdens het proces ontstaan overwinnen
3. Wetgeving en beleid op lokaal niveau met betrekking tot e-flows bieden de gunstige omgeving om het beheer van dammen voor e-flows aan te passen.

4. Wetenschappers zijn belangrijke belanghebbenden in het proces van het veranderen van het beheer van dammen, maar zouden een ondersteunende rol moeten spelen in plaats van het proces te sturen.

Door het diepgaande contextafhankelijke onderzoek van een uniek vastgelopen casus, de Beneden-Volta, toonde dit onderzoek aan dat een spaarzame, ecologisch gefundeerde, ontwerp e-flows methode met behulp van een BBN met succes kan worden toegepast in gebieden met weinig gegevens. Dit resulteerde in een alternatieve ontwerp e-flow-aanbeveling voor de Beneden-Volta rivier voor lage afvoeren tijdens de veliger larve en rekruterings levensfasen van de tweekleppige Volta zaagjes gedurende de periode van november tot maart. Twee andere complementaire beheerstrategieën werden ook aanbevolen voor de Beneden-Volta: de jaarlijkse volledige doorbraak van de zandbank die zich regelmatig opbouwt in het Volta-estuarium en een verbod op zandwinning van de rivierbedding.

De multi-objectieve afwegingsanalyse van watergebruikers in de Beneden-Volta benadrukte de dominantie van waterkracht in het stroomgebied en kwantificeerde de hoeveelheid waarmee de basisvraag naar waterkracht van de Akosombo- en Kpong-dammen zou moeten verminderen om de implementatie van een van de drie eerder vastgestelde e-flows in het stroomgebied mogelijk te maken onder huidige en toekomstige klimaatscenario's. Zowel een toename als een afname van de jaarlijkse waterinstroom naar de Akosombo-dam vermindert de wisselwerking en creëert synergieën tussen e-flows en waterkrachtopwekking. De resultaten toonden ook aan dat de afweging tussen de ontwerp e-flow en het belangrijkste beperkende waterverbruik in het stroomgebied, waterkracht, lager is dan die tussen waterkracht en de e-flows bepaald voor het stroomgebied op basis van het natuurlijke afvoerregime.

Dit onderzoek heeft kennis opgeleverd over het proces van het aangepast beheer van dammen voor de implementatie van e-flows; de voorwaarden voor een succesvol aangepast dambeheer; de hindernissen die men doorgaans tegenkomt en hoe deze in succesvolle gevallen zijn overwonnen; evenals de intersectorale afwegingen die gemaakt moeten worden tussen e-flows en conventioneel watergebruik bij het implementeren van e-flows in een unieke casus. Deze inzichten vormen de basis voor pogingen om de inspanningen voor de implementatie van e-flows op te schalen door dammen op een duurzame en rechtvaardige manier te beheren voor mens en milieu.

CONTENTS

1

INTRODUCTION

1.1 BACKGROUND

1.1.1 Dams and development

Rivers lie at the heart of many civilisations (Evenden and Castonguay, 2012; Anderson *et al.*, 2019; Macklin and Lewin, 2020). In the past, they were crucial for agriculture, transportation and trade and therefore naturally, people living on the banks of a river progressively engineered that river to enhance these benefits while protecting themselves from droughts and floods (Price, 1994; Konishi, 2000; Macklin and Lewin, 2020). With time, simple modifications to rivers such as short diversions, small weirs, locks and dams gave way to more sophisticated modifications including water transfers between basins, channelization of long river stretches, and construction of large dams. Large dams, in particular, were seen as the epitome of development worldwide (Sneddon, 2015) and were hailed variously as "temples of modern India", “treasure troves of wealth”, "one of the world’s wonders", and "the white gold of Switzerland". Overall, dams were seen as a way to transform an unpredictable and thus inefficient natural system into one that could be reliably controlled and harnessed for tangible economic benefits (Rice, 2013). Dams also delivered political benefits, serving as instruments by which landscapes could be reordered and water and land rights centralized to advance particular ideologies and their powerful elites (Ahlers *et al.*, 2014; Sneddon, 2015; Swyngedouw, 2015; Beattie and Morgan, 2017; Ahlers, 2020). The tangible economic benefits and the indirect political benefits led to a peak in dam development in the 1970s. In this period, on average, two large dams with a height of at least 15 m were built each day for various purposes such as irrigation, hydropower, flood protection, navigation or a combination of these (World Commission on Dams (WCD), 2000; Postel and Richter, 2003). By the turn of the century, there were over 45,000 large dams in 140 countries (WCD, 2000). In time, however, a greater awareness developed of the full cost of dams, encompassing social costs such as involuntary resettlement of people and the submersion of religious and historical sites, as well as direct and indirect environmental costs (WCD, 2000; Bosshard, 2010; Khagram, 2018; Slinger and Vreugdenhil, 2020). The direct environmental costs include the alteration of flow (Andrews and Pizzi, 2000; Poff *et al.*, 2007; Wang *et al.*, 2016), sediment (Schmidt *et al.*, 2001; Appeaning Addo *et al.*, 2020) and temperature (Olden and Naiman, 2010) regimes of rivers as well as changes in aquatic and riparian biodiversity (Power *et al.*, 1996; Dudgeon *et al.*, 2006). The indirect costs include river fragmentation and the loss of ecosystem-related activities such as flood recession agriculture, and reduced ecosystem services such as wood or fish harvesting for downstream riparian communities (Ayivor and Ofori, 2017; Nukpezah *et al.*, 2017). A landmark report in 2000 by the World Commission on Dams (WCD) was pivotal in highlighting the societal and environmental costs of dams (WCD, 2000; Bosshard, 2010). In particular, the WCD report noted that the contribution of dams to human development was often achieved through “an unacceptable and often unnecessary” cost to taxpayers, downstream communities, and the natural environment (WCD, 2000). The report and the growing public debate on dams led to a temporary slowdown in the commissioning of dams, dam re-operation initiatives and even the decommissioning and removal of some dams (Doyle *et al.*, 2003; Fitzhugh and Richter, 2004; Olden *et al.*, 2014). These initiatives were complemented by ecological and flow restoration programs (Gleick, 2003; Bernhardt *et al.*, 2005; Kubly, 2009).

1.1.2 Environmental flows

What are environmental flows?

The science of environmental flows (e-flows), which are water flows to sustain or restore freshwater and riparian ecosystems, has both developed alongside and helped to spur the change in attitudes towards dams (Tennant, 1976; Poff *et al.*, 1997; Bunn and Arthington, 2002; Arthington, 2012; Acreman, Overton *et al.*, 2014; Poff *et al.*, 2017; Taljaard et al., 2017; van Niekerk *et al.,* 2019). It established the key role played by a river's natural flow regime in shaping habitats, supporting the life cycles of aquatic species, controlling invasion by exotic species, as well as supporting ecosystem services that are of benefit to humans (Poff *et al.*, 1997; Bunn and Arthington, 2002; Richter *et al.*, 2006). The provision of e-flows represents a shift in water management from a purely human-centred endeavour to one that recognises that a certain "quantity, timing, and quality of freshwater flows and levels [is] required to sustain aquatic ecosystems which in turn support human cultures, economies, sustainable livelihoods, and well-being" (The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018), cited in Arthington *et al.* (2018)).

There are two main paradigms shaping e-flows science. Behind the first, the natural flow paradigm, is the view that it is only a river's natural flow regime that encompasses all that is required for a healthy, native ecosystem to flourish and as such, the goal of e-flows should be to restore rivers to natural or near natural conditions (Poff *et al.,* 1997). In contrast, the designer flow paradigm (Acreman *et al.,* 2014) recognizes that in heavily regulated river systems and under a changed climate, a return to natural flows are not pragmatic and as such the goal of e-flows in such rivers should be to define and quantify flow components to support desired ecosystem services. From these e-flow paradigms, a host of methods for assessing e-flows have developed and now number in the hundreds (Tharme, 2003; Poff *et al.*, 2017; Williams *et al.*, 2019). Initially, e-flows were determined simply as a minimum flow requirement, a water 'reserve' for the environment, based on hydrological statistics (Acreman and Dunbar, 2004; Acreman *et al.*, 2014). Subsequently desktop methods which take into account hydraulic, geomorphological and/or biological criteria in addition to the hydrology of a catchment were applied (Estes, 1996; Hughes *et al.*, 2014). More complex data intensive approaches, such as the Building Blocks Methodology or DRIFT (Downstream Response to Imposed

Flow Transformations), are now available to link a dynamic flow regime to aquatic ecosystems and human livelihoods (Arthington *et al.*, 2003; King, 2016; Niayifar and Perona, 2017; van Niekerk *et al.,* 2019). Accordingly, similar to the ebbs and flows characteristic of rivers under natural free flowing conditions, the implementation of e-flows is not only the release of flows such as minimum flows or flood releases, but also encompasses the curbing of flow to meet dry season low flow requirements. These dry season flows are especially important in intermittent rivers, which naturally dry out for certain periods in the year, as well as rivers with highly seasonal flow (Costigan *et al.,* 2017; Acuña *et al.,* 2020; Papadaki *et al.,* 2020; Sharma and Dutta, 2020).

The importance of environmental flows

E-flows are primarily about restoring or supporting the hydrology of rivers, lakes and estuaries. The hydrology of these waterbodies controls their physical habitats, temperature, sediment, turbidity and salinity fluctuations and therefore in turn impacts their physio-chemical quality and biology (Parasiewicz *et al.*, 1998; Hancock and Boulton, 2005; Sengo *et al.*, 2005; Muehlbauer *et al.*, 2009; Robinson, 2012; Taljaard *et al.*, 2017). Providing e-flows is essential because aquatic ecosystems in the world are at a critical point, with one of the highest rates of decline in biodiversity as compared to other habitats (Postel and Richter, 2003; Dudgeon *et al.*, 2006; Strayer and Dudgeon, 2010; Olden *et al.*, 2014; Castello and Macedo, 2016; Danijela *et al.*, 2017; He *et al.*, 2017; Barlow *et al.*, 2018). While valuation of ecosystem services is controversial (Bingham *et al.*, 1995; Sengo *et al.*, 2005; Baveye *et al.*, 2013), there is no dispute that freshwater ecosystems such as rivers have an intrinsic value and provide essential benefits to humans like water and fish, as well as non-extractive benefits such as habitats for birds and wildlife, flood control, pollution dilution, soil fertilization and recreation opportunities. Furthermore, locations near rivers and coasts are favoured areas for urban development thereby providing a cultural service (Small and Nicholls, 2003). The pressure on freshwater systems is therefore expected to increase as the demand for water, water related services, and land near water grows with the increase in global population, particularly the urban population (Postel and Richter, 2003; Fitzhugh and Richter, 2004; Mahe *et al.*, 2013). Increasing global average temperatures and the associated effects on river systems mean that climate change is expected to exacerbate the pressure on rivers, lakes and estuaries (Arnell, 1999; Nijssen *et al.*, 2001; Mahe *et al.*, 2013).

The existence of e-flows legislation in some countries and regions reflects the growing recognition of the importance of e-flows. For example, in South Africa, the 1998 National Water Act recognizes the river itself as a legitimate water user, on a par with water for basic human needs (King and Brown, 2006). Similarly, under the Australian Water Resources Act 2007, e-flows are recognized with other consumptive water entitlements, and authorities are directed to “consider principally the ecological needs of aquatic ecosystems” in preparing e-flow guidelines (Australian Capital Territory, 2007). In

Europe, the flagship water legislation which came into force in 2000, the European Union Water Framework Directive (WFD) (European Commission, 2000), does not mention e-flows directly, but the framework requires a "hydrological regime consistent with the achievement of the environmental objectives of the WFD". The framework is ecologically based with the goal that water bodies achieve 'Good Ecological Status' whereby there is little deviation from their biology and water quality under natural conditions (European Commission, 2000). For heavily modified water bodies, a modified goal of 'Good Ecological Potential' which takes into consideration their importance for navigation or other critical uses, is prescribed (European Commission, 2000). Accordingly, the European Commission has issued Guidance Document No. 31 which specifically deals with the assessment and implementation of environmental flows in line with the WFD (European Commission, 2015).

1.1.3 Environmental flows and dams

Despite being considered as one of the main culprits in degrading riverine ecosystems, dams can also provide the means of implementing e-flows through dam re-operation (Opperman *et al.*, 2019). Re-operation of existing dams is all the more important because, following a lull in the commissioning of dams in the early 2000s, there is now renewed interest in building new dams particularly in developing countries (Yankson *et al.*, 2018; Ahlers, 2020). Here, they are seen as a means to spur on development particularly through the provision of energy and water for irrigation (Ahlers *et al.*, 2014). Furthermore, the rate of dam removal is outpaced by the commissioning of new dams and is mainly reserved for relatively small, aging dams which have become financial liabilities due to high costs of operation and maintenance (WCD, 2000; Doyle *et al.*, 2003). While integrating e-flows in the design and construction of new dams is relatively easily achieved, re-operation of existing dams is key to restoring ecosystems and ecosystem services that have already been impacted by the construction and traditional operation of dams (Richter and Thomas, 2007; Robinson, 2012).

In a study by Warner et al. (2014), three approaches to implementing e-flows through dam re-operation were identified based on how learning and the opportunity to provide e-flows was structurally incorporated into dam operations. In the Adaptive Management approach, learning is central and therefore flow releases are tested, monitored and continuously modified to meet desired ecological goals. Alternatively, in Blanket Operation, sweeping long-term changes are made to dam operations based on existing knowledge. Finally, with Episodic Implementation, e-flows are not structurally incorporated into dam operations but instead, they are provided when hydrological 'opportunities' such as floods or droughts which require or allow for changes in dam operations occur.

A major critique faced by advocates of dam re-operation for e-flows is that the link between prescribed e-flows and the expected ecological outcomes is uncertain (Olden *et* *al.*, 2014; Growns, 2016; Horne, Webb *et al.*, 2017; Thompson *et al.*, 2018). Defining e-flow targets, despite the development of numerous methodologies, remains challenging as the response of aquatic ecosystems and ecosystem services to changes in flow regime are complex, with natural lags, and also are location specific (Efstratiadis *et al.*, 2014; Thompson *et al.*, 2018). The absence of clear flow-ecological responses may also be ascribed to the difficulty of carrying out large-scale, long-term biological sampling as well as to poor experimental design and monitoring of e-flow studies (Konrad *et al.*, 2011; Olden *et al.*, 2014; Thompson *et al.*, 2018). Since dam re-operation usually impacts directly on tangible economic benefits, such as the maximum potential power generation or the yield from irrigated agriculture (Olden *et al.*, 2014; Thompson *et al.*, 2018), it is important that the need for e-flows, their potential benefits, and uncertainties in the outcome of dam re-operation on ecosystems and societies are systematically explored and that stakeholders are informed.

This links directly to another major obstacle to re-operation: the multiple competing demands and by extension, the multiple stakeholders in river basins, who may be opposed to changes in the current operation practices as they may lose out (Hurford and Harou, 2014; Fanaian *et al.*, 2015; Hurford *et al.*, 2020). Dam re-operation to allocate water to the environment therefore depends on the trade-offs stakeholders and societies are willing to make. These trade-offs are encompassed in economic, social and institutional arrangements which pertain to and support the existing operations of a given dam (Kashaigili *et al.*, 2005; Reilly and Adamowski, 2014; Jorda-Capdevila and Rodríguez-Labajos, 2015; Arthington *et al.*, 2018).

Translating the ecological goals of e-flows into practice demands that the uncertainties, owing to constraints on knowledge and the multi-actor complexity, are overcome. These uncertainties unfortunately often serve as excuses for inaction and maintaining the status quo by dam operators and other stakeholders (Hirji and Panella, 2003; Poff and Zimmerman, 2010; Arheimer *et al.*, 2018). There is therefore a strong need to generate and disseminate the lessons learned from dam re-operation, whether this was successful or not, and whether the lessons were anticipated or unexpected (Poff and Zimmerman, 2010; Konrad *et al.*, 2011; Olden *et al.*, 2014). In line with the Global Action Agenda for e-flows outlined in Arthington *et al.* (2018) and the e-flows research priorities identified by Horne *et al.*, (2017), it is anticipated that identifying the instances of dam re-operation and drawing upon the wide pool of attempts at dam re-operation will lead to advances in the science of e-flows and may enhance e-flows implementation. Collating and analysing these experiences is viewed as an important step in developing a consistent framework for dam re-operation, so that lessons can be drawn regarding dam re-operation and e-flow implementation across many more river basins (Arthington *et al.*, 2018).

1.1.4 The knowledge gaps

In recent decades, the concept of e-flows has gained a lot of traction as the effects of dams and other anthropogenic pressures on rivers have become more evident. Unfortunately, actual dam re-operation to implement e-flows has lagged behind advances in e-flows theory and assessment (Olden 2014; Horne, Webb *et al.*, 2017; Arthington *et al.*, 2018). In this respect, there are questions yet to be addressed on: 1) how e-flows are integrated into dam operation policy and practice; 2) why some efforts at e-flow implementation have failed; and 3) what role trade-offs play in dam re-operation for e-flows implementation (Reilly and Adamowski, 2014; Horne, Webb *et al.*, 2017; Arthington *et al.*, 2018). Figure 1.1 illustrates these knowledge gaps regarding e-flows implementation.

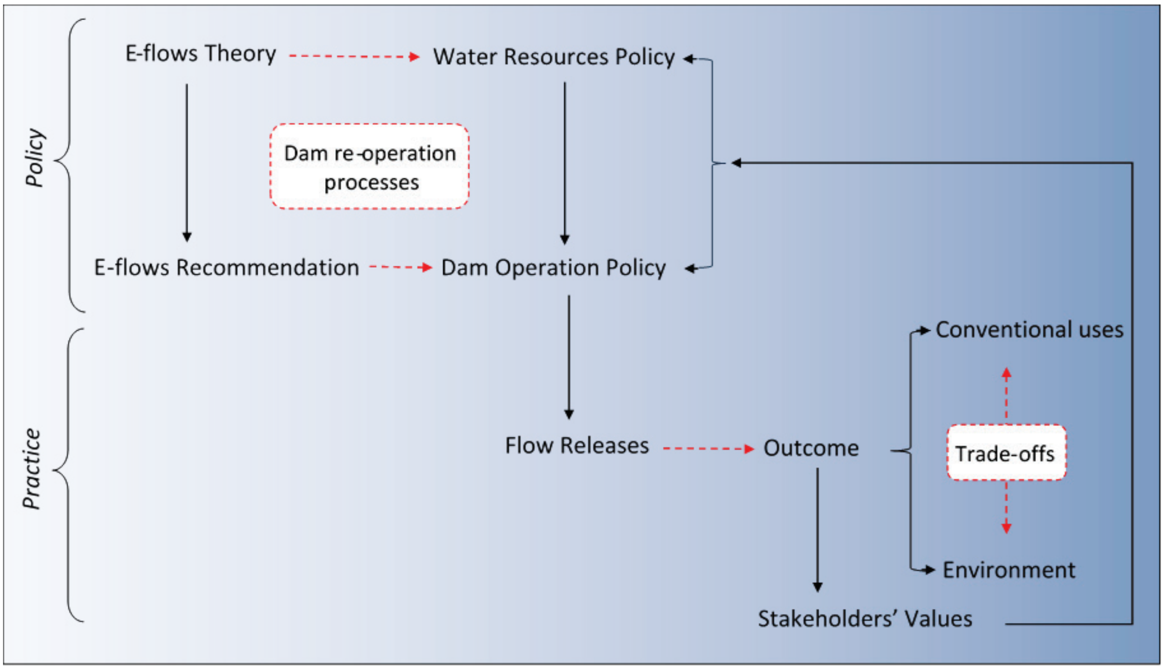


Figure 1.1. Problem framework for dam re-operation for e-flow implementation (red components indicate the research gaps i.e.: how dam re-operation process leads to e-flows implementation, uncertainties associated with establishing flow-ecology relationships and the synergies and trade-offs that are made between conventional water uses and e-flows)

Dam operation policy as used here refers to the guidelines and overall purposes for operating a particular dam. Thus, an example with regard to e-flows implementation would be the stipulation that a dam releases a certain high flow pulse and a certain minimum flow in a hydrological year. The focus of this study is on existing dams which were originally designed and/or operated primarily for conventional purposes such as hydropower generation, flood protection and irrigation. Dam re-operation is therefore defined as a change in dam operation policy to accommodate downstream aquatic ecosystem needs. Accordingly, the study excludes dams where e-flows were planned and released since operations began. It however includes dams for which e-flows were part of the design, but were not included in the operation, as these cases offer insights into obstacles to the incorporation of e-flows in dam operation.

1.2 RESEARCH OBJECTIVES AND QUESTIONS

This research aims to deepen understanding of dam re-operation processes to accommodate e-flows, focussing on existing dams, and further seeks to investigate the synergies and trade-offs that exist between e-flows and conventional water uses. While the process of re-operating dams for e-flows can be studied at a local, national and even global scale (Robinson and Uehlinger, 2003; Richter *et al.*, 2006; Opperman *et al.*, 2019), the synergies and trade-offs between e-flows and conventional uses depend on the complex, location specific response of a freshwater ecosystem and its ecosystem services to changes in flow regime (Efstratiadis *et al.*, 2014; Thompson *et al.*, 2018). This implies that the second objective will require a site-specific research focus. A focus on one specific site was chosen. The two research objectives were addressed by answering four research questions in total.

Objective 1: Deepen understanding of dam re-operation processes to accommodate e-flows

RQ 1.1 How are e-flows recommendations developed into actual dam re-operation?

RQ 1.2 What factors explain why some attempts to re-operate dams for the environment stall?

Objective 2: Investigate the synergies and trade-offs between e-flows and conventional water uses, taking the site-specific nature of e-flows into account

RQ 2.1 What are the e-flow requirements of the study site?

RQ 2.2 What are the synergies and trade-offs between e-flows and conventional water uses and how do they affect the potential for dam re-operation in the study site?

1.3 RESEARCH APPROACH AND DESIGN

The approach adopted in this research (Figure 1.2) is shaped by a pragmatic worldview which seeks to understand the *what* and *how* of issues and recognizes that research takes place in socio-cultural and political contexts (Feilzer, 2010; Creswell and Creswell, 2018). As such, this study bears the following hallmarks of pragmatism as identified by Creswell and Creswell (2018): it is problem-centred, adopts a pluralistic methodology, and is oriented towards real-world practice. The approach is problem-centred in that it addresses a relevant societal problem and will focus on the actors at the forefront of dam re-operation, i.e. dam operators, scientists and other relevant stakeholders, to trace their actions, assessments and opinions regarding dam re-operation (Witzel and Reiter, 2014). The pluralistic nature of the study stems from the mixed method design which will draw from both quantitative and qualitative procedures and techniques for data collection and analyses (Feilzer, 2010). Moreover, it has a real-world practice orientation in that the goal is to learn how dam re-operation works in practice with the ambition that the lessons learnt will ultimately contribute to the design and implementation of future dam re-operation projects.

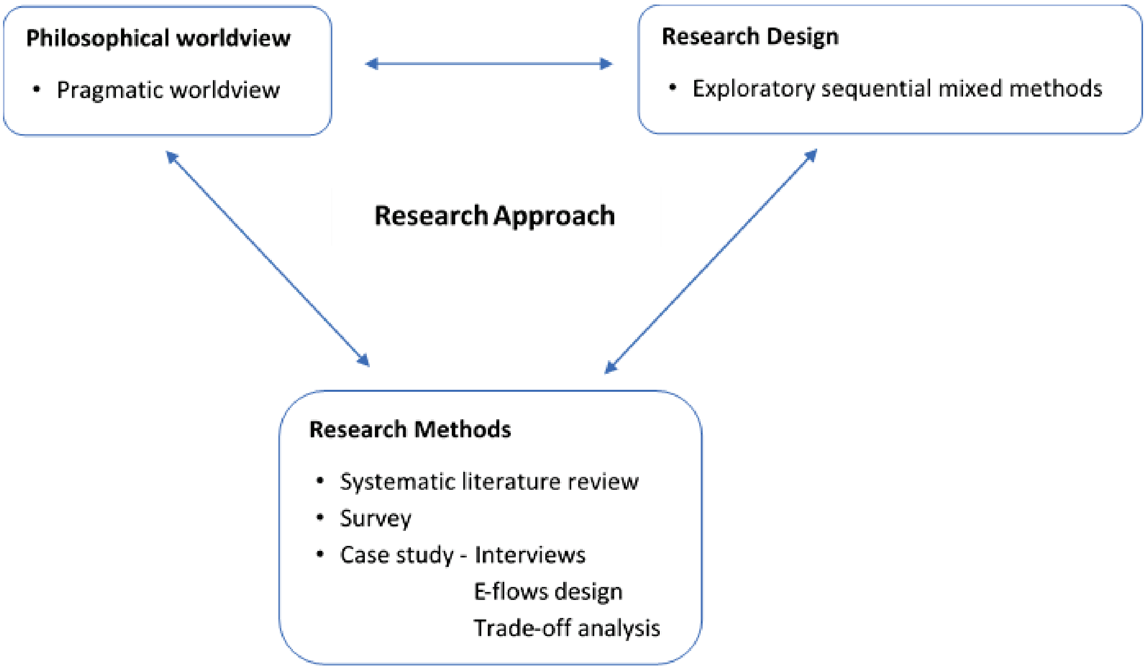


Figure 1.2 Research approach (adapted from Creswell and Creswell, 2018)

The core research design (Table 1.1) was exploratory, sequential and used mixed methods whereby a primarily quantitative research phase preceded a qualitative phase. The study began with a systematic literature review of dam re-operation. From this review, a database of successful dam re-operation projects was generated and a conceptual framework of how dam re-operation to implement e-flows occurs was developed. It was found, however, that there was a dearth of information in the scientific literature on stalled attempts at dam re-operation. This led to the next research activity, a global survey of researchers and practitioners involved in actual implementation of e-flows through dam re-operation, to capture these stalled dam re-operation attempts. The responses from the survey were analysed using statistical methods to determine how successful attempts at dam re-operation differed from the stalled attempts. The survey was conducted following approval of the data management and survey protocol by the Human Research Ethics Committee (HREC) of the Delft University of Technology, Netherlands (Delft University of Technology 2009) (Appendix C). These two activities, the systematic literature review and survey addressed the first research objective of deepening the understanding of the dam re-operation process for e-flows.

In addressing the second objective of investigating the synergies and trade-offs between e-flows and conventional water uses, a case study approach was taken. This is because ecosystem responses to flow changes differ per location and therefore, so do the trade-offs that exist in dam re-operation as these depend on the different stakeholders involved, and their interests and power in relation to the dam in question (Ackermann and Eden, 2011). The advantage of the case study approach is that it allows for detailed examination of phenomena in their real-life context (Yin, 2009). This approach lends itself well to answering questions on '*what', 'how' and 'why'* and thus can be used to explore and explain phenomena within the contexts in which they appear (Yin, 2009; Crowe *et al.*, 2011). The disadvantage, however, is that the findings in case studies may not be easily generalized to other cases so that it may have a low external validity (Druckman *et al.*, 2011). As acknowledged by Olden *et al.* (2014) in a review of the results of e-flow implementation and then by Horne *et al.* (2017) in identifying research priorities with respect to e-flows, published work on e-flows is heavily biased towards Europe, North America and Australia, thus this research sought to extend the knowledge base beyond these areas. The case study therefore chosen in this research was the Akosombo and Kpong dams in the Lower Volta River, Ghana. Other criteria considered in the selection of the Lower Volta are given in Table 1.2. These criteria include the potential trade-offs that exist between e-flows and traditional water users, namely, hydropower, irrigation and flood control, in the case. Additional features that make it an interesting case study are the high residence time of the Akosombo reservoir (approximately 4 years) and its age (57 years) since higher residence times are associated with higher disruption to the natural flow regime while the older a dam, the less likely that e-flows were considered in its design as is the case for the Akosombo Dam. The uniqueness of the case with respect to cases from the systematic literature review and survey, as well as practical considerations about access to the case study, data availabilty and the potential to address key gaps within the scope of a four-year PhD study completed the criteria for selection of the case study.

The case study phase began with a literature review on the Lower Volta River system; the different water users in the basin, the pre- and post-dam state of ecosystem services in the basin and the stalled attempt at dam re-operation. Interviews were also held with thirteen experts to gain additional insight regarding the pre- and post-dam state of ecosystem services in the basin. As part of the stalled attempt at dam re-operation, e-flows based on the natural, pre-dam flow regime have been determined for the Lower Volta. However, guided by the pragmatic worldview taken in this research, an additional designer e-flow was determined using a Bayesian Belief Network (BBN) to link flows to the state of one of the ecosystem services, the Volta clam fishery, an important livelihood supporting activity. The BBN made it possible to accommodate the data-poor situation in the Lower Volta in developing the flow-ecology relationship. As such, it was the preferred approach as compared to the alternative method considered, the Service Provision Index (SPI) method which creates a response function of ecosystem services to flows using service suitability (SS) curves (Fanaian *et al.*, 2015; Korsgaard *et al.*, 2008).

To investigate the trade-offs and synergies between water users in the Lower Volta, a range of methods including simulation-only modelling techniques using WEAP (Water Evaluation And Planning System) (Annor *et al.* 2017), as well as simulation-optimization techniques including the IRAS-2010 (Interactive River-Aquifer Simulation-2010) model coupled with ε-NSGAII (epsilon dominance non- dominated sorting genetic algorithm-II) used by Hurford and Harou (2014), and the linked STREAM (Spatial Tools for River basins and Environment and Analysis of Management options) model and GAMS (General Algebraic Modelling Systems) optimisation model used by Kiptala *et al.* (2018) were considered. The simulation-optimization modelling was preferred over simulation-only techniques as with this method, dam releases are not fixed *a priori* and can be optimised to meet a range of benefits. The final choice of an Evolutionary Multi-Objective Direct Policy Search (EMODPS) framework (Giuliani *et al.,* 2016) was dictated by the access of the researcher to expertise and training on the EMODPS framework. This simulation-optimization technique was applied to assess the synergies and trade-offs in the Lower Volta, thereby indicating whether and how re-operation could be possible in a stalled case, under current and future climate change scenarios.

Full details of the methods adopted in this research are given in following chapters and accompanying appendices. The research approach was consecutive in nature and in all stages emergent ideas from the previous stages were incorporated. Finally, in this thesis the research questions were answered by reflecting on the findings of each of the four components of the research – captured in chapters 2 to 5 – and synthesising conclusions on the research as a whole.

Table 1.1: Research design in this dissertation: an exploratory, sequential, mixed method research design shaped by a pragmatic worldview

Research objectives	Research questions	Activities	Outputs	Parts	Paper (Chapter)
1: Deepen understanding of dam re-operation processes to accommodate e-flows	1.1 How do e-flows recommendations develop into actual dam operation?	Systematic literature review of dam re-operation	Dam re-operation database Conceptual framework of dam re-operation process	Part I	Re-operating dams for environmental flows: From recommendation to practice (Chapter 2)
	1.2 What factors account for why some attempts to re-operate dams for the environment stall?	Global survey of stakeholders involved in real world cases of dam re-operation	Hypothesis on factors that increase the odds of successful dam re-operation Identification of common barriers to implementation		May the Odds Be in Your Favour: Why Many Attempts to Re-operate Dams for the Environment Stall (Chapter 3)
2: Investigate synergies and trade-offs between e-flows and conventional water uses	2.1 What are the e-flow requirements of the case study?	Case study: interviews; e-flows design using a Bayesian Belief Network	Development of benefit functions linking e-flows to ecosystem services	Part II	The clam and the dam: A Bayesian Belief Network approach to environmental flow assessment in a data scarce region (Chapter 4)
	2.1 What are the synergies and trade-offs between e-flows and conventional water uses and how do they affect the potential for dam re-operation in the study site?	Case study: trade-off analysis through simulation and optimization of dam releases	Analysis and visualisation of re-operation trade-offs with different basin policies		Quantifying the trade-offs in re-operating dams for the environment in the Lower Volta River (Chapter 5)

Table 1.2. Criteria for selecting the case study: the Akosombo Dam in the Lower Volta River Basin, Ghana

Parameter	Criteria	Reason
Trade-offs	Clear conflict between provision of e-flows and conventional uses	Representative of the complexity of implementing e-flows due to multiple interests. In the case study, multiple water users including hydropower, irrigation and flood control exist and thus need to be considered in the implementation of e-flows.
Characteristics of dam	Residence time > 1 year Age – from the era of peak dam building in the mid 20th century	Significant disruption of the natural flow regime due to dam. The lake formed by the Akosombo Dam is the largest by surface area globally and hence has had a major impact on ecosystem services. It was designed in the 60's with no provision for e-flows and hence is a suitable case for studying the opportunity for dam re-operation in a highly modified system.
Similarity and differences	Similarity and/or differences with dam dataset from literature review/survey	The chosen case is a stalled dam re-operation case with some key characteristics of successful cases. Therefore intriguing as study case.
E-flows studies	Established e-flow studies and gaps	Information on synergies between eflows and other conventional uses is required. There has been an attempt at providing e-flows in the case study. It is therefore possible to address any key gaps within the scope of this thesis.
Data availability	Access to historical hydrological data, ecosystem service production functions	Inputs for modelling and trade-off analyses While data limitations can be expected in the Lower Volta, from the previous attempt at dam re-operation, data sources as well as experts and local stakeholders can be identified.
Other practical reasons	Ease of access by the researcher; language	To meet academic time constraints and ensure quality of qualitative data The researcher is Ghanaian and is fluent in English and Twi which are widely spoken in the Lower Volta.

1.4 RESEARCH SIGNIFICANCE

This research helps to address two major shortcomings in e-flow science, specifically, (a) the lack of a global record on e-flows implementation and (b), a lack of insight into why certain e-flow recommendations have been implemented while others have failed (Arthington *et al.*, 2018). It also examines how the trade-offs with traditional water uses affect e-flows implementation. This research therefore contributes to the 2018 Global Action Agenda on e-flows, specifically regarding two of the Brisbane Declaration and Global Action Agenda on Environmental Flows (2018) statements:

- "Environmental flows have been compromised and today many aquatic systems around the world are at risk"
- "Implementation of environmental flows requires a complementary suite of policy, legislative, regulatory, financial, scientific, and cultural measures to ensure effective delivery and beneficial outcomes".

The agenda calls for a set of actions on three fronts: research; leadership and governance; and management (Arthington *et al.*, 2018). This study contributes to the research action points for the two declaration statements above, namely, the identification of the barriers to e-flows implementation across the world, and research into new and existing mechanisms for e-flows implementation within water resource management systems (Arthington *et al.*, 2018).

1.5 EUROFLOW - EUROPEAN TRAINING AND RESEARCH NETWORK FOR ENVIRONMENTAL FLOW MANAGEMENT IN RIVER BASINS

This research was undertaken as part of a larger project on e-flows, EuroFlow (EUROpean training and research network for environmental FLOW management in river basins), funded by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant Agreement (MSCA) No 765553 (University of Leeds, 2022). Under this project, there were four scientific work packages (WP) addressing the abiotic environment, aquatic biodiversity, functional processes associated with river modification, and ecosystem services in relation to e-flows. This thesis fell under the work package on ecosystem services which aimed to identify the socio-economic costs and benefits of e-flows and also contribute to the deliverable on the formulation of best practice guidelines (Owusu *et al.*, 2020a) to assist river basin authorities to deliver improved reservoir operation.

1.6 READING GUIDE

The introductory chapter of this thesis establishes the need for the research, the research objectives, questions and methods applied, as well as the significance of the research. The thesis is structured into two parts, with the next two chapters forming Part I which covers global dam re-operation efforts, in line with the first research objective. Part II is the case study research and is comprised of chapters 4 and 5 which are focused on the second research objective. This second part begins with a short introduction to the case study.

Part I- Global dam re-operation efforts

Chapter 2: Re-operating dams for environmental flows: From recommendation to practice (adapted from Owusu *et al.,* 2021*)*

This following chapter addresses Research Question 1.1 through a systematic literature review on practical cases of dam re-operation for the implementation of e-flows. A logic model is used to develop a conceptual understanding of how recommendations for e-flows are implemented in practice. The results indicate that e-flows legislation, environmental impact studies on the effect of dams as well as flow experiments are important features of successful dam re-operation for e-flows implementation.

Chapter 3: May the Odds Be in Your Favour: Why Many Attempts to Re-operate Dams for the Environment Stall (*adapted from* Owusu, Mul, van der Zaag *et al.*, 2022)

This chapter reports on a survey of researchers and practitioners involved in dam re-operation attempts. It builds on the findings of the systematic literature review in Chapter 2 by exploring the impasse narrative on dam re-operation through a comparison of the processes, hurdles and attempts at overcoming hurdles in both successful and stalled attempts at dam re-operation. Four hypotheses on why the process of dam re-operation stalls in some cases are presented. This chapter primarily addresses Research Question 1.2 but also contributes to answering Research Question 1.1.

Part II- The case study

Part II begins with a brief introduction to the case study through a description of the preliminary research undertaken on the Lower Volta and the interviews that were carried out with experts on the basin ecosystem services.

Chapter 4: The clam and the dam: A Bayesian Belief Network approach to environmental flow assessment in a data scarce region (*adapted from* Owusu, Mul, Strauch *et al.*, 2022)

In this chapter, there is the shift to case study research. The choice of case study, the Lower Volta River Basin in Ghana, was partly informed by the findings of the systematic literature study (Chapter 2) and the survey (Chapter 3). Attempts at dam re-operation in this location have stalled despite it possessing some of the key characteristics of successful cases. It thus presents an interesting case for further investigation. First, Research Question 2.1 had to be answered for this case study for which the flow regime has been significantly modified since 1965. While past studies had already developed e-flows for the Lower Volta, these were based on the natural flow paradigm: an e-flows design approach based on the natural, pre-dam flow regime of a river. This chapter presents an ecologically grounded, parsimonious approach for developing e-flows for the Lower Volta, based on the designer e-flows paradigm. Under this paradigm, components of a river's hydrograph are compiled to meet a desired ecological outcome. In heavily modified basins such as the Lower Volta, designer e-flows have a higher likelihood of implementation compared to the restoration of natural or near-natural flows.

Chapter 5: Quantifying the trade-offs in re-operating dams for the environment in the Lower Volta River

This chapter addresses Research Question 2.2. An advanced simulation optimisation technique is applied to the case study to determine the trade-offs and synergies between the environment and key water users in the Lower Volta Basin. The new e-flow recommendation developed in Chapter 4, together with the past recommendations based on the natural flow of the Lower Volta serve as inputs to trade-off analyses in this chapter. The results highlight the dominance of hydropower in the basin and quantify the extent to which this hydropower requirement has to be reduced for each of the three e-flow configurations to become possible under current and predicted climate futures in the Lower Volta.

Chapter 6: Conclusion

This final chapter returns to the research questions to provide answers based on the aggregate findings of Chapters 2 to 5. The contributions and limitations of this research are also reflected upon and suggestions for future research on dams and environmental flows are made.

Chapters 2, 3, and 4 have been published in peer reviewed journals while Chapter 5 is under review at the time of writing of this dissertation. While this introductory chapter of the dissertation summarises the overall research approach, each subsequent chapter presents the detailed methods applied and thus a separate section on methodology is not included here.

PART I: GLOBAL DAM RE-OPERATION EFFORTS

There is a recognition that actual e-flows implementation is lagging far behind developments in e-flows theory and methodology. In Part I of this thesis, global dam re-operation attempts are reviewed through a systematic review of cases found in literature and a survey of researchers and practitioners who have first-hand experience in dam re-operation attempts. The steps constituting the process in each case are identified to create a conceptual model of the process of dam re-operation in both successful cases and stalled cases. Through this, general patterns across these two groups of dam re-operation attempts are identified. The findings from this first part of the thesis inform future efforts to incorporate e-flows into the operation of existing dams

2

RE-OPERATING DAMS FOR ENVIRONMENTAL FLOWS: FROM RECOMMENDATION TO PRACTICE

The content of this chapter was adapted from: Owusu, A. G., Mul, M., Zaag, P. van der, and Slinger, J.: Re-operating dams for environmental flows: From recommendation to practice. River Research and Applications, 37(2), 176–186. https://doi.org/10.1002/rra.3624, 2021.

The data that support the findings of this chapter are available in the 4TU.Centre for Research Data repository at https://doi.org/10.4121/uuid:5824e7a3-4ca1-469c-b014-595a19f0ff6d. Supplementary material to this chapter is available in Appendix A.

Image: Downstream view of the Akosombo Dam, Lower Volta, Ghana

Abstract

Dam construction and operation are known to alter the hydrology of rivers and degrade riverine ecosystems. In recent decades, the call to reverse these negative impacts by re-operating dams has become stronger. Dams can support riverine ecosystems by releasing environmental flows (e-flows). Unfortunately, despite the development of numerous methodologies to determine e-flows and optimise dam releases, actual implementation has not followed suit. Integrating e-flow requirements in the design of new dams is relatively easier than changing operations of existing dams; however, re-operating existing dams is essential to restore ecosystems and ecosystem services that have already been affected by the construction and operation of dams. This study provides insights into how e-flows evolve from recommendation to practice through a systematic literature review on practical experiences to integrate e-flows in dam operations. Sixty-nine cases of successful dam re-operation have been identified, ranging from the well-documented case of the Glen Canyon Dam in the United States to less known cases such as the Katse Dam in Lesotho. We find that the most important factors that facilitate the successful implementation of e-flows are the existence of e-flows legislation or policy, the development of a research base in the form of an environmental impact study, and then flow experimentation. Illustrations of the important role of collaboration between various stakeholders and set timelines for implementation of recommendations are also given. These insights will inform how existing dams can be re-operated and governed more equitably and sustainably for both humans and the environment.

2.1 BACKGROUND

The origins of many ancient societies and modern-day cities can be traced to rivers and other freshwater bodies. These water bodies not only provided water for drinking and agriculture but served as vital transportation, trade and communication links (Konishi, 2000). River regulation, in the form of dams, locks and weirs supported many of these uses, becoming more and more sophisticated over the years as demand for water increased. Modification to natural river systems, however, comes with some unintended consequences (Poff *et al.*, 1997; WCD, 2000; Petts, 2006). In particular, large dams are now recognised as one of the major stressors on freshwater ecosystems because they create large stagnant water bodies and disrupt the natural dynamic flow regime of rivers (Poff *et al.*, 1997). This natural flow regime plays a key role in shaping riverine habitats and biotic communities, triggering life-history strategies of aquatic species, maintaining lateral and longitudinal connectivity, and controlling exotic species invasion in rivers (Bunn and Arthington, 2002).

The provision of flows for the environment, e-flows, is a means to mitigate the negative impacts of river regulation and protect or restore the benefits of naturally flowing rivers. The increasing importance of providing e-flows is reflected in the fact that in some countries and states, e-flows are enshrined in law. For instance, the 1998 Water Act of South Africa recognises aquatic ecosystems as having a right to water, and in Colorado in the United States, Senate Bill 73-97 instituted the ‘In-stream Flow and Natural Lake Level’ water rights in 1973 (Shupe, 1988; King and Brown, 2006). Despite adopting e-flows in their laws, implementing environmental flow releases in accordance with the law is challenging (King and Brown, 2006; Smith *et al.*, 2011; Bischoff-Mattson and Lynch, 2016).

Integrating e-flow requirements into the design of new dams is relatively easier than changing operations of existing dams; however re-operating existing dams is essential to restore ecosystems and ecosystem services that have already been affected by the construction and operation of dams (Richter and Thomas, 2007; Mul, Ofosu *et al.*, 2017). Unfortunately, while the theories and concepts for e-flows estimation abound, actual implementation is minimal (Tharme, 2003; Warner *et al.*, 2014; Horne *et al.*, 2016; Arthington *et al.*, 2018). In this respect, there are questions yet to be addressed on how e-flows are integrated into dam operation policy and practice; and on why some efforts at e-flow implementation have failed. The physical and institutional setting of each river basin and dam is unique; however, in cases where there have been re-operation or at least an attempt at re-operation, there are common themes that can be identified as keys to success or barriers to implementation (Patten *et al.*, 2001; Richter *et al.,* 2006; Warner *et al.*, 2014). This study provides insights into how e-flows evolve from recommendation to practice through a systematic literature review on practical experiences to integrate e-flows into dam operations.

2.2 LITERATURE REVIEW

This review analyzes the process of how e-flows are incorporated in reservoir operations. Thus, the focus is on the inputs, activities, drivers and barriers to operational changes for the release of e-flows from dams (Thissen and Twaalfhoven, 2001). The study does not look at the impacts of dam releases on downstream ecology as this has been the focus of several papers already (see Olden *et al.*, 2014; Gillespie, *et al.*, 2015; Thompson *et al.*, 2018).

2.2.1 Systematic journal database search

The methodology for the systematic literature review is adapted from the guidelines by the Centre for Evidence-Based Conservation (Collaboration for Environmental Evidence, 2013). The search string was made up of three parts: the target population: dams; the intervention type: re-operation; and then the topic: environmental flows. Variants of each were also included (see Table A1, Appendix A). The term river restoration was not included as it is too broad and encompasses physical and geomorphological interventions in rivers that do not necessarily involve e-flow releases from dams.

The publication databases used were selected based on accessibility and the relevance of the journals curated to the subject matter of this review. The databases selected are Scopus, ISI Web of Science, Google Scholar, JSTOR, Worldcat.org and SciELO.

2.2.2 Article selection and exclusion criteria

Studies were initially selected based on the presence of one term in all three categories of the search terms in the title or abstract. The selected papers were then retained if they included at least a case study or documentation of (a) A process of change or continuous modification in the operation of a dam to implement e-flows; (b) A process of development or modification of dam operation rules and/or policies to implement e-flows.

Exclusion criteria included studies which only test or model dam re-operation outcomes without actual implementation. The selected papers included cases documented before November 2018 when the database search was completed.

2.2.3 Data synthesis and framework of analysis

To develop an understanding of the process of dam re-operation, a logic model of the process was developed from the data gathered from the cases identified in the literature (Figure 2.1). The basic form of a logic model captures the inputs, activities, outputs, outcomes and impacts of a project. This study focused on the first three components where the last of these, 'output' is defined for successful re-operation projects as a modification to the flow releases from the dam to meet e-flow requirements (Figure 2.1). Borrowing from the classification by Thissen and Twaalfhoven (2001), 'inputs' refer to the products informing recommendations for e-flows while 'activities' relate to the process and organisation of dam re-operation to fulfil the recommendations.

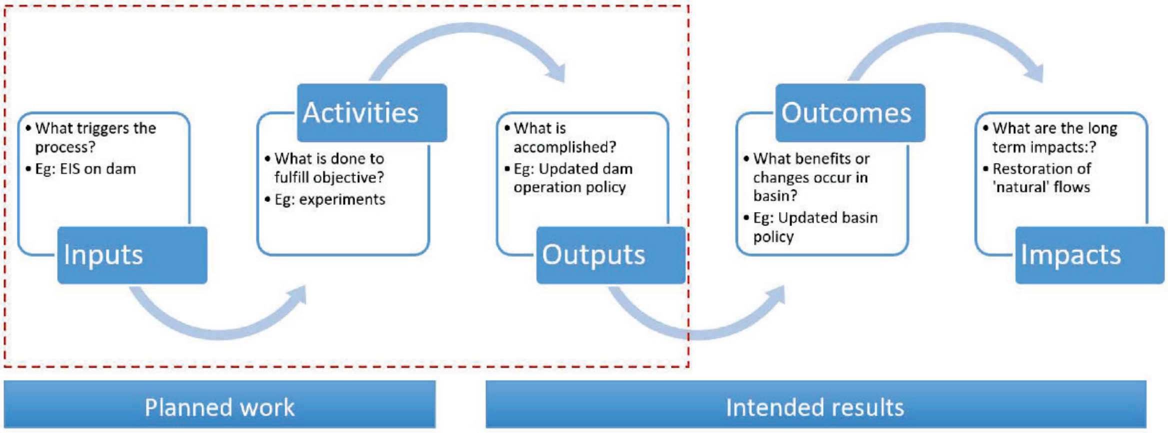


Figure 2.1. Framework of analysis for developing logic model of dam re-operation with examples of events at each stage. The red box outlines the focus in this study

It is acknowledged that reviewing the outcomes and impacts of dam re-operation are important for understanding the entire life cycle of dam re-operation; however, the research objective of this study was to generate insights on how dam re-operation occurs, that is, the steps resulting in dam re-operation and not the results of dam re-operation.

Article organisation

The selected papers were stored and tagged in the Mendeley reference-managing software (v. 1.19.3) and then classified according to the logic model in Figure 2.1 (Owusu *et al.*, 2019). The final sets of parameters and tags, which can be found in Table 2.1, were informed by the descriptions used in the studies. Frequency statistics of the tags associated with the parameters were calculated to determine the characteristics of documented cases of dam re-operation.

Table 2.1 Parameters and textural tags for systematic classification of literature under review. The first category of parameters, system attributes, is useful to generate a description of the dam and its location. The categories that follow describe the studies and policies preceding dam re-operation which serve as inputs to the process; the activities undertaken to re-operate the dam; and the output of the process which is the dam operation policy.

	Category	Parameter	Tags
	System attributes	System name	-
		System type	Delta; Estuary; Floodplain; Lake; River
		Facility name	-
		Location (state/ province; country; coordinates)	-
		Purpose	Hydropower; Water supply; Flood control; Irrigation; Navigation
		Dam height	In metres
		Maximum storage volume	In cubic kilometres
		Mean unregulated streamflow	In cubic metres per second
		Residence time	In weeks
Input	Research base	Motivation for e-flow implementation	Commercial resource; Endangered species; Recreation, Scientific knowledge; Habitat protection/restoration; Other
		Type of study	Environmental impact assessment, E-flow study
		E-flow method	Hydrological; Hydraulic; Holistic, Habitat modelling, Expert opinion
		Stakeholders involved	Citizens; Dam operators; Local government; National Agencies; NGOs; Scientists; Other
		Year of study	year
	Legislation/Policy	Legislation/Policy name	-
		Policy Level	Basin, National, International, Local

	Category	Parameter	Tags
		Year of implementation	year
	Requests/Complaints	Type	Lawsuit, Request
		By whom	-
	Natural event	Event	Flood, drought, Other
		Year	year
	Other input	Other input	year
Activities	Workshops	Stakeholders involved	Citizens; Dam operators; Local government; National Agencies; NGOs; Scientists; Other
		Number of workshops	-
		Purpose of workshops	Orientation; Flow recommendations dev't.; Monitoring plan dev't.
	Flow experiments	Flow manipulation, if re-operated	Minimum flow; Experimental flood; High flow pulse; Entire flow regime; Other
		Number of experiments	Single event; Multiple; Continuous
		Year of experiments	year
		Features of experiment	-
	Physical modification	Modification	Outlet level; Outlet size-; Outlet number; Other
		Features of modification	-
		Year completed	year
	Modelling	Type of modelling	Simulation; Optimisation; Both
		Features of model	-
	Other activity	Other activity	-
Output	Re-operation policy	Feature of re-operation	-
		Re-operation approach	Adaptive management/Scientific validation; Blanket operation; episodic implementation
		Year of implementation	year
		Pathway to re-operation	Inputs-> Activities-> Re-operation approach
		Enabling factors	Eg: Collaboration, Clear timeline, Simple e-flow recommendation, Trigger event, Opportune timing, Iconic target species

Kappa assessment of classification

Cross-checking of the systematic classification was carried out for consistency using Kappa analysis, which compares the amount of agreement with what would be expected by chance alone (Collaboration for Environmental Evidence, 2013; Smeeton, 1985). In this method, 20% of the selected papers are reclassified by an external reviewer and a minimum agreement level of 50% must be achieved (Collaboration for Environmental Evidence, 2013) while an agreement level of 80% and above shows that the review results can be replicated independently (Filoso *et al.*,2017). An agreement of 61% was achieved in this study.

2.3 RESULTS

After the keyword search in the six databases, a total of 121 papers were retained for data extraction (Figure 2.2). These revealed 50 river systems with 69 dams, which have been re-operated for e-flows implementation (see Figure 2.3a for the location of these dams). Re-operation of the Glen Canyon Dam on the Colorado River was the most documented program with 54 papers reporting on the adaptive management program for this dam.

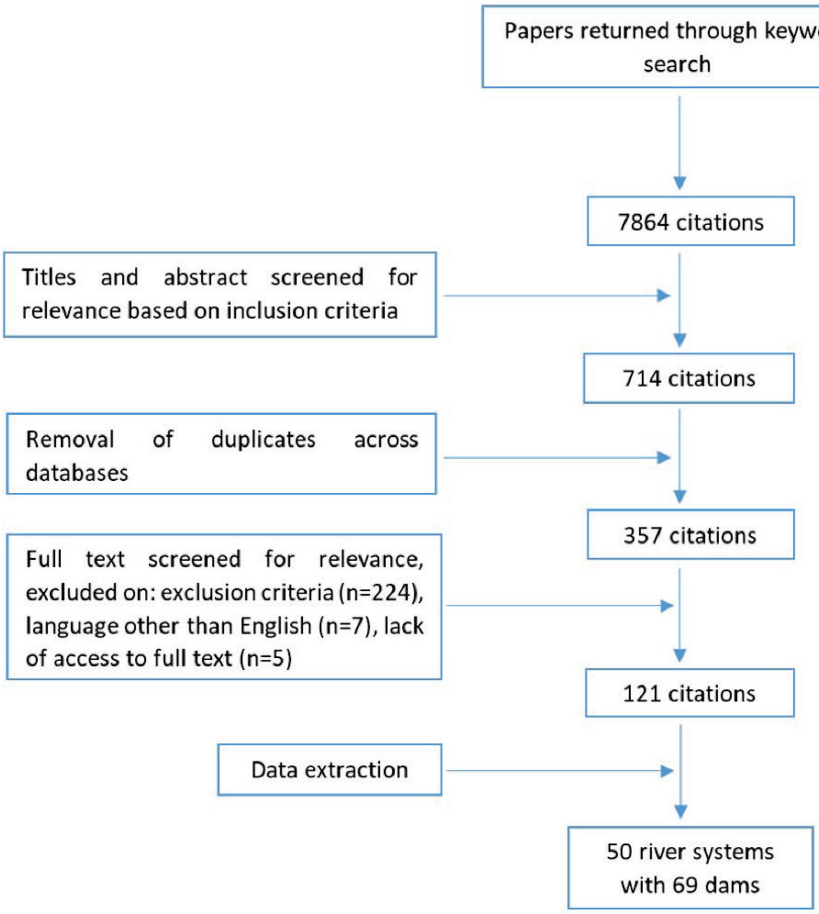


Figure 2.2. Results of database search on dams re-operated for e-flows implementation

2.3.1 Location of re-operated dams

The locations where dams have been re-operated generally correspond to the locations where large-scale flow experiments have occurred, as found by Olden *et al.* (2014) (Figure 2.3a). The documented cases of dam re-operation begin in 1983 with the Derby and Stampede dams on the Truckee River in the United States (Rood *et al.*, 2003; Figure 2.3b). The most recent documented cases of dam re-operation occurred in 2014 with the Espinasses, La Saulce, Escale and the Cadarache dams on the Durance River in France as well as the Morelos dam upstream of the Colorado Delta in United States (Bêche *et al.*, 2015; Kendy *et al.*, 2017; Pitt and Kendy, 2017; Ramírez-Hernández *et al.*, 2017; Shafroth *et al.*, 2017; Loire *et al.*, 2018).

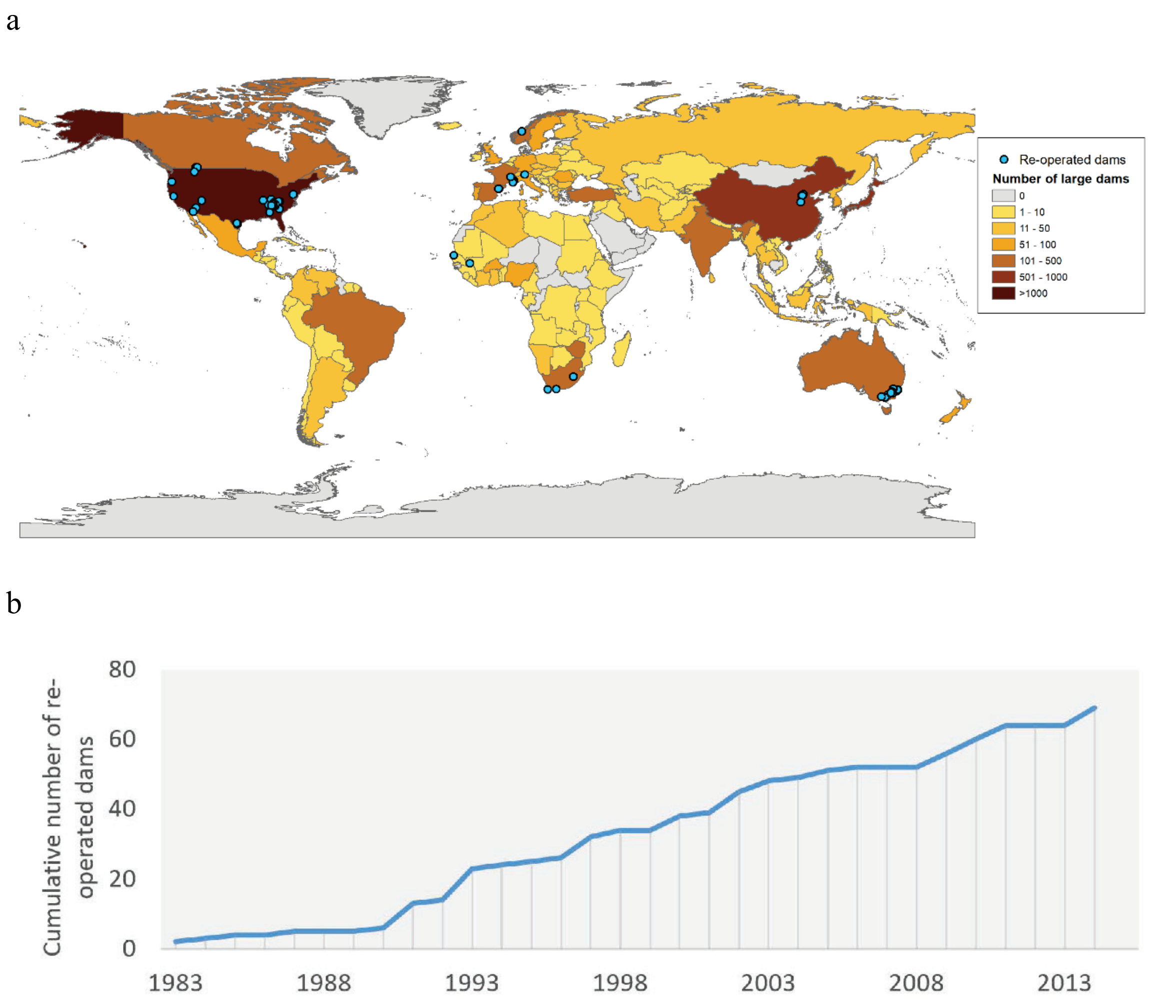


Figure 2.3. (a) Locations of re-operated dams mentioned in the papers (n = 69). Shading at the country level represents the number of large dams (≥0.1 km^3*), as found in the Global Reservoir and Dam Database (GRanD, n = 6,862; Lehner et al., 2011). (b) Cumulative number of re- operated dams over time*

2.3.2 What are the inputs in dam re-operation?

Legislation is found to be the main trigger (input) in dam re-operation, followed by environmental impact studies (EIS) or e-flow studies (Figure 2.4). Legislation can have different forms; Figure 2.5 shows the breakdown of the type of legislation that triggered dam re-operation. The majority of implemented cases have local or basin level legislation for e-flows objectives in place. It is hypothesized that this is because such policies for water management and dam operation are framed with local interests in mind and thus more easily implemented. In contrast, it is more difficult to reconcile large-scale decisions and directives, as found in international legislation such as the Water Framework Directive of Europe with local interests in dam operation (Acreman and Ferguson, 2010). The one case where a change in dam level operation policy led to actual dam re-operation was at Seli'š Ksanka Qlispe' Dam (formerly Kerr Dam) on the Flathead River in the United States. Here, the Federal Energy Regulatory Commission (FERC) changed the status of the dam from a load-following and power-peaking status to a baseload status, thus creating room for the provision of eflows (Barfoot *et al.*,2018). It is worth noting that for many cases, there may have been overlapping international, national and local level policies that have fed into each other and led to dam re-operation. It was, however, not possible to identify these overlaps completely and consistently with certainty based on the papers in this study.

For 36 dams, either an EIS of the dam on downstream ecology or an e-flow study to determine e-flow requirements was carried out. The New South Wales (NSW) local government in Australia, for instance, conducted studies on the water needs for Sydney as well as requirements for irrigation and e-flows, leading to re-operation of eight dams (Growns and Reinfelds, 2014; Growns, 2016).

The growing number of requests for a review of the operations of dams in the Tennessee Valley was an input to the provision of e-flows at 16 dams (Schulte and Harshbarger, 1997; Higgins and Brock, 1999; Bednarek and Hart, 2005). For other locations, a more contentious route was taken with lawsuits regarding the operations of four dams being filed. This included two dams on the Neuces River in Texas, USA. Although there was a law in place for this river system when the Wesley Seal and Choke Canyon dams were built, the requirement to supply water to the estuary was not fulfilled until shellfish declined and a shrimper organisation filed a complaint with the Texas Water Commission in 1989 (Montagna *et al.*, 2009; Smith *et al.*, 2011). Again, for the Putah Diversion Dam in California, USA, a drought which caused a river stretch of 32 km downstream of the dam to completely dry up resulted in a lawsuit being filed and won by the local area council against the irrigation and water supply agencies (Kiernan *et al.*, 2012).

Observations in the aftermath of natural hydrological events such as the ‘Millennium Drought’ from 2000 to 2010 in the Murray-Darling Basin and a two-year drought in the Ebro basin in Spain also initiated a collaboration to determine e-flows by water managers (Banks and Docker, 2014; Gómez *et al.*, 2015). Likewise, natural floods in the Grand Canyon in 1983 led to an emergency release which showcased how much the Glen Canyon Dam had altered the downstream ecology as in the aftermath, backwater reaches critical for native fish had been restored, eroded areas had been replenished with sand, and non-native vegetation had declined (Collier *et al.*, 1997). Much in the same manner, planned upgrades or maintenance also provided the opportunity for experimentation as in the case of the River Spöl in Switzerland, or the review of existing dam operations at the Glen Canyon and the Seli'š Ksanka Qlispe' dams in the United States (Patten *et al.*, 2001; Scheurer and Molinari, 2003; Barfoot *et al.*, 2018).

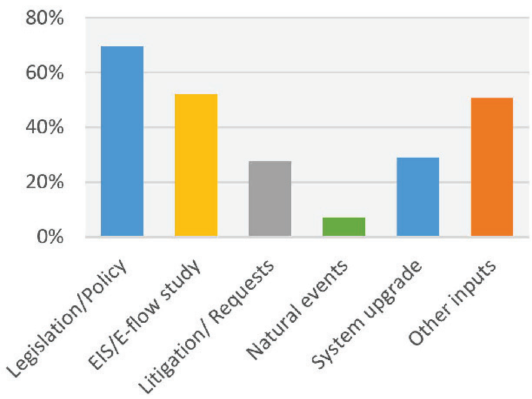


Figure 2.4. Frequency distribution of inputs to dam re-operation across documented cases (n = 69)

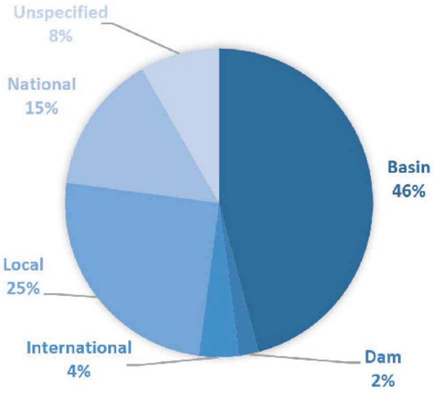


Figure 2.5. Legislation/policy level in cases where legislation was an input in dam re-operation (n = 48)

2.3.3 What activities are carried out to re-operate dams?

The majority of the activities undertaken in dam re-operation are flow experiments (Figure 2.6), with the most frequent of these being the release of experimental floods and high flow pulses (Figure 2.7). This corresponds with the findings of Olden *et al.* (2014), who found that these were the most frequent flow experiments. Note that in this current study, these flow categories, namely, experimental floods and high flow pulses, were kept separate and categorized according to the descriptions of the authors reporting on the flow experiments since these flow categories have different ecosystem influences as described by Mathews and Richter (2007). The median number of flow experiments of this subset of re-operated dams was four, and the median number of years between the first and most recent experiments as of November 2018 was 3 years.

Physical modifications to dams occurred at seven dams, including four dams: Avon, Cataract, Cordeaux and Nepean Dams in NSW, Australia, for which new release outlets were added in 2008 (Growns and Reinfelds, 2014; Growns, 2016). On the other hand, for some cases such as the Katse Dam in Lesotho and the Glen Canyon Dam in the United States, the recommended e-flows, particularly for larger floods, were rather reduced to fit the existing physical infrastructure (Brown and King, 2012; Rice, 2013).

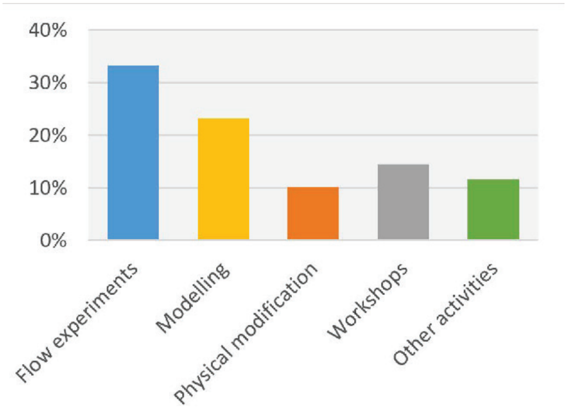


Figure 2.6. Activities in dam re-operation (n = 69)

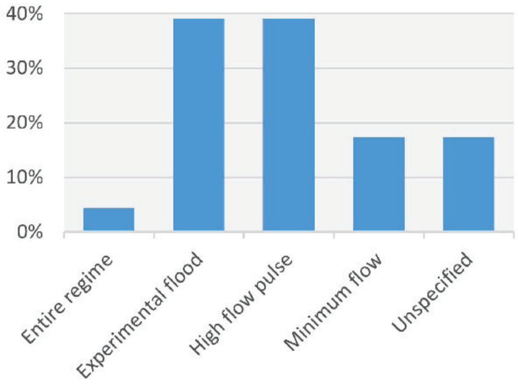


Figure 2.7. Manipulation in flow experiments (n = 23)

2.3.4 What are the outputs of dam re-operation?

Thirty-two dams were re-operated to provide minimum flows (Figure 2.8). In contrast to the activities stage (Figure 2.7), high flow pulses and flood releases were less frequently implemented. Flow changes or outputs falling into the 'Other' category included bulk water allocations for e-flows or the establishment of transparency and translucency rules for dams such that low flows are allowed to pass through completely based on a transparency threshold while a percentage of flows above this threshold, translucency flows, are allowed to pass through to maintain flow regime dynamics (Growns and Reinfelds, 2014).

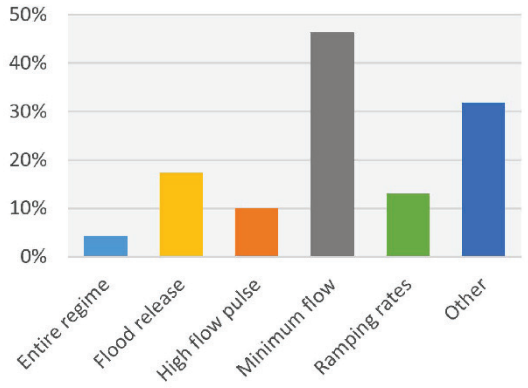


Figure 2.8. Implemented flow change (output) in dam re-operation (n = 69)

2.3.5 Which approach is taken in re-operating dams to implement e-flows?

The approaches to dam re-operation were categorised into three based on Warner *et al.* (2014). One approach is Adaptive Management, where prescribed dam releases for e-flows, are essentially treated as flow experiments for scientific validation of hypothesis regarding flow components. These releases are thus monitored and continuously refined. An example of this is the case of the Glen Canyon Dam on the Colorado River in the United States (Rice, 2013). The second approach is Blanket Operation, where broad changes in dam operations are made based on available management and ecological information. The large-scale implementation of minimum flow and increase in floods from the Katse Dam on the Malibamat'so River in Lesotho is an example of this (Arthington *et al.*, 2003; Hirji and Panella, 2003; Brown and King, 2012). The third approach, Episodic Implementation, is an opportunistic approach to dam re-operation driven by prevailing hydrological conditions that allow for modifications to dam operations. The ad hoc releases to the Baiyandian Lake from Angezhuang Reservoir and three other dams in China since 1997 fall into this category (Yang and Yang, 2014).

Blanket operational changes to dam operations to provide e-flows were made at 44 dams (64%), while 12 dams were adaptively managed. For 13 dams, episodic implementation was practiced.

2.3.6 Enabling factors in dam re-operation for e-flows

In the documented cases of dam re-operation, certain factors stand out as important to successful and timely implementation. These factors include: minimal impact on existing water uses, the importance of setting implementation timelines and collaboration. These will be illustrated with examples in this section.

The common misunderstanding that implementing e-flows will certainly conflict with existing dam operation objectives is refuted in at least six cases. For instance, for the Green River Dam in Kentucky, USA, traditional objectives of flood protection were maintained, and in addition, water quality, recreation and storage for water supply were enhanced with the implementation of e-flows (Warner *et al.*, 2014). In the case of the River Spöl in Switzerland, the water required for test releases was available, and overall, there was no loss in power generation or revenue for the dam operator (Robinson *et al.*, 2004; Scheurer, 2014). Again, in implementing Minute 319 that governed the Colorado Delta pulse flow, a policy of ‘no harm to existing water users’ was the overarching constraint, and this was met (Pitt and Kendy, 2017). Furthermore, at Diama Dam in the Senegal River Basin, artificial floods for inundating the Diawling Park required only 1% of flows routinely released in average years, and new dry season floods used only 10% of dry season releases from the dam (Duvail and Hamerlynck, 2003). Another example of how dam re-operation impacted minimally on existing water uses is found in the case of the Glen Canyon Dam in the United States, where the cost of the 1996 flood was estimated at $3.8 million in lost power generation and other additional costs. This is against the $80 million annual value of rafting and associated tourism, which depends on the presence of sand bars, which were meant to be replenished by the floods (Andrews and Pizzi, 2000). Finally, flushing flows on the Ebro since 2003 were seen to effectively remove macrophytes while yielding positive results for the hydropower company by preventing clogging of water intakes (Gómez *et al.*, 2015). The average cost of two flushing flows was pegged at €76,000 in autumn and € 33,000 in spring- only 0.16% of the mean annual revenue of the hydropower company (Gómez *et al.*, 2015).

The benefit of having clear timelines or implementation plans for flow experiments is also clear. For example, in the Sustainable Rivers Project, out of thirty-six dams selected as demonstration sites for e-flow studies, there was a lack of momentum to transition from flow experiments to actual change in dam operations after twelve years at all but one: the Green River Dam, Kentucky where 3 years for flow tests was set (Warner *et al.*, 2014). For the River Spöl as well, where artificial floods have been incorporated into the operations of the Ova Spin Dam, an initial 3-year period was set for flow experiments (Scheurer and Molinari, 2003; Robinson *et al.*, 2004). Again, in the case of the pulse flow to the Colorado Delta, scientists and dam operators had approximately two years to submit a delivery design for the pulse flow for approval by a joint Mexican and American water commission, after which the pulse hydrograph could not be changed (Pitt and Kendy, 2017).

In many of the cases where the operations of dams have been successfully changed to allow for e-flows, collaboration between dam operators, governing institutions, scientists and other stakeholders was a key factor in successful dam re-operation (Duvail and Hamerlynck, 2003; Scheurer and Molinari, 2003; Richter *et al.*, 2006; Warner *et al.*, 2014; Pitt and Kendy, 2017). The numbers involved in some cases were huge, as in the case of the Blue Ridge Dam and 16 other dams in the Tennessee Valley in the United States, where almost 1,200 people attended the meetings to review the EIS on the dams and provided 627 written and 196 verbal responses (Higgins and Brock, 1999). Marzolf *et al.*, (1999) also stress how collaboration between the agencies in charge of various aspects of the Colorado River and Glen Canyon dam led to the 1996 controlled flood. In the case of the Sustainable Rivers Project in the United States, Richter *et al.* (2006) point out that the involvement of stakeholder agencies in the e-flow recommendation process makes them supportive of its implementation.

2.4 DISCUSSION

Irrespective of the dam database used, the documented cases of dam re-operation identified in this study make up a small fraction of existing dams - compared to the GRanD database, they make up approximately 1%. Furthermore, in line with recommendations by Olden *et al.* (2014) in the case of flow experiments, there is the need to expand and document cases of dam re-operation in countries beyond the United States, Australia and Western Europe. It is encouraging nonetheless that the countries where methodologies for determining e-flows were pioneered in the 1970s and 1980s are now at the forefront in their implementation, thus becoming examples for other countries to follow (Tharme, 2003).

This review confirms that there is no single combination of inputs and activities that will guarantee actual dam re-operation for e-flows. Two alternative models have been suggested in the literature: the analytical or traditional science model and the opportunistic or political model. On the one hand, the analytical approach to problems seeks to use research and analysis to solve problems (Mayer *et al.*, 2013). In this approach, there is intelligence, design, choice and implementation over a series of iterations (Simon, 1977). The re-operation of the Ova Spin and Punt dal Gall dams on the River Spöl follows this model, starting with the identification of the problem of deteriorating downstream conditions. This led to an EIS of the dams in the 1990s followed by experimentation from 2000 to 2001 and then adaptive management of the dams. On the other hand, there are political models for decision making such as the Garbage Can Model (Cohen *et al.*, 1972) or Kingdon's Streams model where opportunism is the underlying paradigm (Cohen *et al.*, 1972; Enserink *et al.*, 2010; Vreugdenhil *et al.*, 2010). The case of the Mequinenza and Ribarroja dams on the Ebro basin fall within this category since it was a drought and macrophyte bloom which triggered dam re-operation (Banks and Docker, 2014; Gómez *et al.*, 2015). In some cases, dam re-operation does not fall neatly into either category and has elements of both models. For instance, for the Blue Ridge Dam on the Taccoa River in the United States, over twenty years of studies, pilot projects and tests had been undertaken when growing public requests for a review of dam operations triggered another round of intelligence, design, choice and implementation finally culminating in blanket re-operation (Higgins and Brock, 1999; Schulte and Harshbarger, 1997; Bednarek and Hart, 2005).

As the most common input to e-flow implementation, legislation provides the legal backing for dam operations to be changed. Even in cases where these laws are mostly overlooked, they provide the basis for challenges to be made against those in charge of the operation of dams. This was the case in dam re-operation in two cases in the United States following drought events. Thus drafting these laws causes changes to be made, however reluctantly, by those in charge of dam operations. Existing legislation may also explain why blanket re-operation was most prevalent in the documented cases of re-operation since dam operators and other stakeholders are mandated by law to provide e-flows and thus go ahead in following the letter of the law. The downside to this approach is that it provides no established avenue for monitoring and further improvements on dam operations for the environment.

Experimentation, which was the most frequent activity in dam re-operation, along with the adaptive management approach and even the episodic implementation approach to dam re-operation, provides the opportunity to test out proposed solutions. This is because it is usually unclear which dam releases will provide the desired results. As observed by Richter *et al.* (2006), stakeholders were reluctant to provide quantitative flow targets for the Thurmond Dam on the Savannah River until they were reminded of how these proposed flows would be considered approximations to be refined through adaptive management. Rice (2013) proposes that this hesitancy is in line with a re-enchantment with nature, which has come about due to the realization of the uncertainty, complexity and vibrancy of ecological processes. Therefore, now it is acknowledged that an action at a dam cannot be predicted with certainty to have a specific result downstream. In a number of cases, timelines for re-operating dams have served to overcome the hesitancy in e-flow implementation. Timelines force a decision to be made between business-as-usual, which is leading to deteriorating habitats in many cases, and implementation of some changes to dam operations based on best available data on river ecosystems. In contrast to this hesitancy in dam re-operation, the era of dam building in the mid-20th century was characterised by an attitude of confidence in man's mastery over and disenchantment with nature (Rice, 2013).

2.5 CONCLUSION

Re-operation of dams may be considered a ‘wicked’ (Rittel and Webber, 1973), ‘messy’ (Ackoff, 1974) or ‘unstructured’ problem due to the multiple stakeholders involved as well as the numerous problem definitions, solutions and conflicts (Weber and Khademian, 2008; Enserink *et al.*, 2010). The documented cases of dam re-operation thus shed light on how this problem has been successfully tackled. These documented cases of dam re-operation show that there is no one sure way to dam re-operation and that analytical, political as well as mixed approaches have been equally successful. This review, however, highlighted that the inputs and activities most commonly found in cases of successful re-operation are legislation and flow experiments, respectively. The establishment of minimum flows downstream of dams remains the most commonly implemented flow change. The review also revealed that e-flows are not always in conflict with traditional water uses for which dams have been built. This study adopted a systematic literature review and logic model framework approach to identify and analyse cases where the operations of dams had been changed to implement e-flows. This provides a comprehensive overview of dam re-operation worldwide, however, the cases identified are limited to those found in the scientific and grey literature that are curated in English in the six scientific databases selected. As such, it is acknowledged that there will certainly be more cases of dam re-operation to be found in government documents and in other languages across different countries. It is also acknowledged that in less extensively documented dam re-operation cases, there is some ambiguity in deducing the timeline of events to determine if a specific event was an input or activity in the process of dam re-operation. It is therefore recommended that detailed studies of these cases be undertaken to record the process of re-operation for these dams accurately.

Finally, it may be the case that for some dams, the process of re-operation to implement e-flows has stalled despite some of the same inputs, activities and even opportunities being present. It remains unclear why this is the case. Some of the documented cases of successful dam re-operation touch on hurdles that were overcome in the process, and the activities carried out hint at an effort to overcome certain limitations; for instance, physical modifications to the dam are carried out to allow for larger flow discharges to be released. It is recommended that future research look at cases that have stalled as these will highlight the obstacles encountered in re-operating of dams, thereby balancing out the narrative and better informing stakeholders on the process of dam re-operation.

3

MAY THE ODDS BE IN YOUR FAVOUR: WHY MANY ATTEMPTS TO RE-OPERATE DAMS FOR THE ENVIRONMENT STALL

The content of this chapter is adapted from:: Owusu, A., Mul, M., van der Zaag, P., and Slinger, J.: May the Odds Be in Your Favor: Why Many Attempts to Reoperate Dams for the Environment Stall. *Journal of Water Resources Planning and Management*, 148(5). https://doi.org/10.1061/(asce)wr.1943-5452.0001521, 2022.

The data that support the findings of this chapter are available in the 4TU.Centre for Research Data repository at https://doi .org/10.4121/uuid:0007a286-56d8-4f37-bf47-338738200c69

Supplementary material to this chapter is available in Appendix B and C.

Image: The Lower Volta River with the Adomi Bridge in the background, Ghana

Abstract

The provision of flows for the environment, e-flows, is a means to restore the benefits of naturally flowing rivers. Despite the development of numerous methodologies to determine e-flows and optimize dam releases, actual implementation is relatively limited. Examples of successful e-flows implementation through dam re-operation exist in scientific literature; however, there is a missing narrative on cases where dam re-operation has been attempted but not successfully implemented. This study explores this impasse narrative and presents four hypotheses for further research on this subject: (1) Scientists are important stakeholders in the process of dam re-operation, but should play a supportive role rather than drive the process; (2) In undertaking scientific studies for determination of e-flows, a consensus on the priorities, knowledge gap, and solutions must be reached together with local stakeholders; (3) Local-level legislation and policy on e-flows provide the enabling environment for dam re-operation for e-flows; and (4) Genuine, carefully designed consultations of, and negotiations between, stakeholders can overcome hurdles encountered in the process of dam re-operation for e-flows implementation.

3.1 BACKGROUND

Environmental flows (e-flows) are flows to sustain or restore freshwater and riparian ecosystems (Poff *et al.*, 1997; Bunn and Arthington, 2002; Tharme, 2003). Providing e-flows represents a shift in water management from a purely human-centred endeavour to one that recognizes that a certain "quantity, timing, and quality of freshwater flows and levels [is] required to sustain aquatic ecosystems which in turn support human cultures, economies, sustainable livelihoods, and well-being" (Brisbane Declaration, 2007). The concept of e-flows has gained traction in recent years. This is evidenced in the numerous methodologies that have been developed to determine e-flows for rivers and also to optimize dam releases (Tharme, 2003; Pitta *et al.*, 2010; Yin *et al.*, 2011; Olivares *et al.*, 2015; Mao *et al.*, 2016; Slinger *et al.*, 2017; Horne *et al.*, 2018; Stamou *et al.*, 2018; Owusu *et al.*, 2021, Owusu *et al.*, 2022).

Although dams are considered one of the main causes of degrading riverine ecosystems through alteration of river flow regimes, they can also provide the means of implementing e-flows through dam re-operation. Dam re-operation, the change in flow release practices to accommodate downstream aquatic ecosystem needs, thus represents an important approach to maintaining or restoring some of the benefits that free-flowing rivers provide. Notably, although theories and concepts for e-flows abound, actual implementation has remained minimal to date (Tharme, 2003; Warner *et al.*, 2014; Horne *et al.*, 2016; Arthington *et al.*, 2018; Brown *et al.*, 2020; Owusu *et al.*, 2021). For instance, a systematic literature review of dam re-operation for e-flows revealed only 69 documented cases spanning the period 1983 to 2014 (Owusu *et al.*, 2021). These successful cases served to identify important factors in facilitating the implementation of e-flows, namely, the existence of e-flows legislation or policy, the development of a research base in the form of an environmental impact study, and flow experimentation (Owusu *et al.*, 2021).

The documented cases of successful dam re-operation tell one side of the story because the literature review did not reveal cases where dam re-operation was attempted or recommended but not actually implemented. Information on such stalled processes is crucial to deepen understanding of how dam re-operation processes can be facilitated to increase the likelihood of success. However, stalled cases have not yet been reported in the scientific literature. The aim of this study was to fill this gap and identify where the differences lie between successful and stalled dam re-operation attempts by investigating the variables identified through the systematic literature review of Owusu *et al.*, (2021) on how dams are re-operated. These variables were categorized based on a logic model of the process as the inputs to dam re-operation, the activities undertaken during the process, and the output of the process (Owusu *et al.*, 2021).

Furthermore, in this study, we also compared who was involved in the process (stakeholders), what dams they worked on (location and original purpose), and why the release of e-flows was desired in the first place (motivation). For instance, does the difference in success lie in the inputs to the process of dam re-operation such that some inputs (e.g., a scientific research base or supporting legislation) lay a better foundation for dam re-operation to occur? Or does the distinction lie in the original purpose for which the dam was operated such that certain water uses (e.g., hydropower, irrigation, or recreation) are more easily aligned with the release of e-flows? This study endeavoured to answer these questions. Additionally, the main hurdles encountered in the process of dam re-operation and how these were successfully overcome on the one hand, or how these stalled the process on the other, were investigated.

To this end, a survey of dam operators, water managers, and other stakeholders with wide-ranging experience in dam re-operation for the release of e-flows was conducted. The survey method formed the favoured approach for this study because it facilitates access to both published and nonpublished data on individual cases of dam re-operation from those with first-hand knowledge of the process. The significance of this study is that it complements and deepens the understanding of dam re-operation for e-flows obtained from the systematic literature review of Owusu *et al.*, (2021). It also provides information to water resource planners and allocation optimizers on hurdles to dam re-operation. Furthermore, this study is also of relevance to people studying the concept of impasse, deadlock, or “stuckness,” which refers to the gap between what we know to be desirable and achieving this desired outcome in practice (Bolten 2009; Shomura 2016). In environmental management, this concept extends beyond the field of e-flows, and indeed water resources management, to environmental conservation and management (Bryant, 1997; Biggs *et al.*, 2017), post-conflict reconstruction (Kreimer *et al.*, 1998; Bolten, 2009), and policy transfer (Minkman *et al.*, 2019). As such, this study adds insights on the conditions that contribute to hindering the desired management practice outcome of dam re-operation for e-flows and vice versa.

Following a more detailed explanation of the methods adopted (Methods section), the results of the survey are presented (Results section). The findings are then discussed with a particular focus on the hurdles to successful implementation in the Discussion section before the Conclusion section.

3.2 METHODS

3.2.1 Selection of variables for investigation

How Dam Re-operation Occurs: Logic Model

This study adopted a logic model framework to understand the process of dam re-operation for e-flows (see Figure 2.1, Chapter 2). For clarity, dam re-operation in this study refers to the change in the operation of a dam that hitherto was operated solely for conventional purposes such as hydropower generation, irrigation, flood control, or others, to now release flows for the environment as part of its operation. As such, the focus was on dams where there has been a modification, or an attempted modification, of operations to improve downstream riverine environments.

Logic models are flow diagrams that show the inputs, activities, outputs, outcomes, and impacts of a project (Yin, 2009; Kneale *et al.*, 2015). With respect to dam re-operation, the (desired) output is a change in flow release practices to release e-flows for downstream ecosystem needs. Inputs represent the drivers, actions and conditions that lead to a recommendation or decision to re-operate dams, and activities are the practices adopted to implement the decision to re-operate the dam (Thissen and Twaalfhoven, 2001). The relatively long-term effects of dam re-operation, the outcomes and impacts, were not covered in this study because the focus is on understanding how dam re-operation for e-flows occurs and not on the aftereffects of dam re-operation. These outcomes of dam releases on downstream ecology have been the focus of several papers already (e.g., Olden *et al.*, 2014; Gillespie *et al.*, 2015; Thompson *et al.*, 2018).

The Who, What, and Why of Dam Re-operation for E-Flows

In addition to using the logic model framework to understand how dams are re-operated, the stakeholders involved in the process (who), the motivation for e-flows release (why), and the original purpose of the dams (what) were investigated. The elements compared under each of these variables were informed by literature on dam re-operation and e-flows. For instance, for the stakeholders involved, the elements compared comprised stakeholder groups typically mentioned as forming part of e-flows studies and assessments in the literature. These include national, regional, and local government agencies, dam operators, and non-governmental organizations (NGOs), among others. The option of indicating additional elements, such as new stakeholder groups not identified by the authors, was covered by providing survey respondents with the option to select “Other” in answer to the relevant survey question and then fill in a bespoke answer.

Hurdles to Dam Re-operation

The hurdles to the process of dam re-operation were identified through open-ended questions on what main hurdles were encountered in the process, when these hurdles were encountered, and what was done in an effort to overcome these hurdles. The open-ended question type was used here to elicit maximum information so that nuances that could be lost in closed-ended questions could be captured for analysis.

3.2.2 Data Collection: Survey

Survey Setup and Administration

The target participants in the survey were dam operators, water managers, researchers, and other resource persons who have been involved first-hand in e-flows implementation through dam re-operation across the world. The initial list of potential survey respondents was derived from three sources, namely

- authors of scientific papers on e-flows identified through the systematic literature review of Owusu *et al.*, (2021),
- the existing network of the authors of the present study, and
- the European training and research network for environmental flow management in river basins (EuroFLOW) project network, of which this study forms part.

From the initial list, recommendations as well as introductions to other potential survey respondents who have been involved first-hand in dam re-operation projects were also sought. Additionally, as part of the survey itself, respondents were asked if they could identify people in their network who were familiar with dam re-operation and these people were then included as potential respondents. In total, the survey was sent to 109 experts and remained active for a period of six weeks beginning November 12, 2019. The non-random convenience sampling approach taken in this study was necessitated by the criteria that survey respondents must have first-hand experience in dam re-operation for e-flows and also to expedite data collection. The disadvantage of this is the reduction in the power of statistical analysis and introduction of bias due to the overrepresentation of one or more subgroups (Smith, 1983).

The self-administered structured internet survey (a copy is given in Appendix B) was developed using qualtrics.XM software (Qualtrics, 2019b). An important consideration in designing the survey was to keep the time required for completion to a minimum, ideally under 15 min, to limit participant fatigue (Creswell and Creswell, 2018). A mix of closed-ended and open-ended questions was adopted, the former to ensure that a minimum input was received from each respondent because the closed-ended questions are easiest to answer, and the latter to draw out additional insights that are unique to the specific cases. Respondents were also given the option of repeating the survey for a second case of dam re-operation if they had been involved in more than one case. The survey was pre-tested by two resource persons to evaluate the length of time required for completion and also to improve on the structure, instructions, and content of the survey. This led to minor modifications and improvement of the instructions to respondents.

A three-phase process over a period of four weeks was followed in administering the survey (Salant and Dillman, 1994). An advance notice of the survey was sent out a week before the actual survey to the respondents identified through the researchers' network. For those in the EuroFLOW network, an advance notice was placed in the monthly newsletter. The second email contained the actual survey sent via qualtrics.XM. This was followed 1 week later by a short reminder to non-respondents.

Ethical Considerations

The choice of qualtrics.XM as the survey tool was informed by the fact that it is General Data Protection Regulation (GDPR) [Regulation (EU) 2016/679–General Data Protection Regulation] compliant and allows for anonymization such that responses are not associated with any personal data, location, or IP address (Qualtrics, 2019a). Furthermore, data collected using qualtrics.XM are completely owned and controlled by the creator of the survey (Qualtrics, 2019a). These attributes of qualtrics.XM fit within the data management plan created by the researchers to protect the privacy of respondents. The data management plan and the overall survey protocol was approved by the Human Research Ethics Committee (HREC) of the Delft University of Technology in the Netherlands (Delft University of Technology, 2009) (Appendix C).

Data Cleaning

In line with the survey protocol adopted, referrals and any information that gave away identities or were deemed sensitive, particularly in response to open questions, were anonymized. The coordinates for the dams were identified, and background research was carried out on each dam to validate their classification as either successful or stalled. In the cases where one dam was reported on multiple times, these were consolidated and inconsistencies corrected based on available literature.

3.2.3 Data Analysis

Tests of Independence

The survey results were organized into two groups: successful cases of dam re-operation and stalled cases of re-operation. To detect any distinguishing characteristic between the two groups of cases, a statistical test of independence was carried out on the inputs, activities, and output of dam re-operation, as well as the original purpose of dam, motivation for e-flows, and the stakeholders involved in the process of dam re-operation. The comparison between the two groups of cases was undertaken using Fisher's Exact Test (Fisher, 1925) and then validated using Barnard's Exact Test (Barnard, 1945). Both tests are nonparametric tests of independence for two nominal variables with small sample sizes. Fisher's Exact Test, the more popular test, assumes that the row and column totals are conditioned, thus making it conservative when either one is unconditioned, as is the case in this study (Mehta and Hilton, 1993). However, the improvement in power is small using other alternative tests, such as Barnard's Exact Test (McDonald, 2014). The debate on which exact test is most appropriate persists. In this study, the equality of the probabilities of successful and stalled dam re-operation are calculated and presented for both tests (Table 3.1), but the primary interpretation is undertaken using Fisher's test because it is the more conservative test with results that are more intuitively understood.

The null hypothesis for Fisher's and Barnard's test, (H_0), is that there is no difference between the relative proportions of two variables. This will be rejected in favour of the alternative hypothesis (H_1) that the probability of successful or stalled dam re-operation differs significantly depending on the approach taken to dam re-operation, if a two-tailed *p-value* ≥ 0.05 is returned by both tests with a 95% confidence interval that excludes the null value of 1 for odds ratios. The two-sided p-value is used since the direction in which a given approach impacts the outcome of dam re-operation is unknown (McDonald, 2014).

In this study, the Bonferroni correction (Bonferroni, 1936) was applied as a correction for the multiple comparisons undertaken. The goal of such corrections is to reduce the number of false positives (i.e., the rejection of the null hypothesis when it is in fact true) when a large number of statistical tests are carried out, but on the other hand these correction factors have the disadvantage of increasing the number of false negatives (Rothman, 1990; Perneger, 1998; Nakagawa, 2004; McDonald, 2014). As such, any statistically significant variables found before application of the multiple comparisons correction factor in this study are also highlighted for discussion.

Qualitative Analysis

To analyse the hurdles encountered, the time they occurred, and the approaches taken in overcoming them, a content analysis was carried out on the responses received to the open-ended questions by a single coder. First, a broad categorization of the responses received to each question was carried out. This was an inductive, response-level categorization carried out manually to identify the major themes in each response. This was followed by a comparison of the categories in the successful and stalled re-operation cases.

3.3 RESULTS

The findings from the survey are presented in this section, beginning with a profile of the respondents and the dams elaborated on. This is followed by results of the statistical tests of independence and then by the qualitative analysis of the hurdles encountered in the groups of cases of successful and stalled dam re-operation.

3.3.1 Profile of the Respondents

A total of 25 completed surveys, covering 25 unique cases, were returned at the close of the survey period, representing a relatively high (23%) survey return rate (Owusu *et al.*, 2020b). Although two of the respondents reported on the same case, another respondent reported on two unique cases. The majority of the respondents were scientists, but two respondents were civil society advocates and one was a dam operator. An overview of the expertise of the survey respondents, specifically, their years of experience in water resources management, cases of dam re-operation they have worked on, and the number of unique river systems that these cases consider is shown in Figure 3.1.

An analysis of the survey respondents by their experience shows that over 60% have more than 10 years of practical experience in the field of water management. Their wide-ranging experience is also borne out in the map of the cases considered, with at least one case each of successful and stalled dam re-operation in all six continents with dams (Figure 3.2).

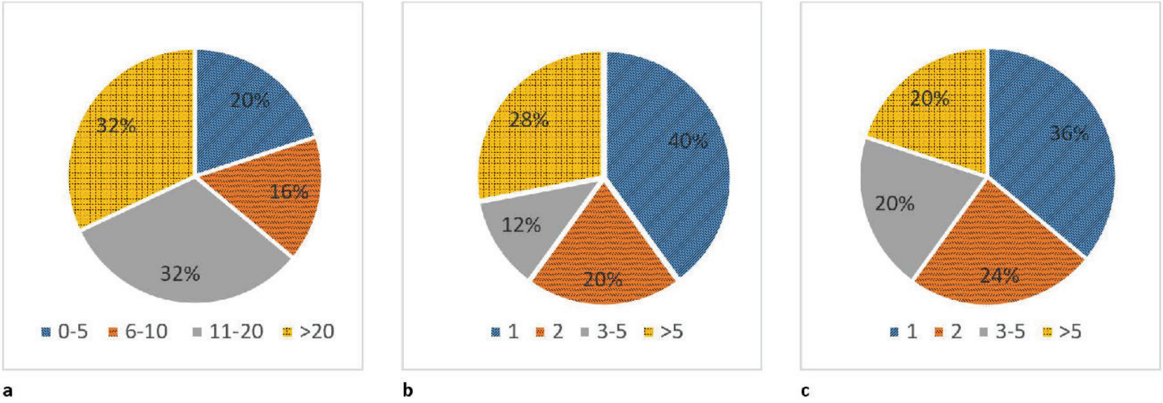


Figure 3.1. Overview of respondents' expertise: (a) years of experience in water management of survey respondents; (b) cases of dam re-operation respondents have worked on; and (c) different river systems covered in the cases of dam re-operation.

3.3.2 Dam Re-operation Cases

Figure 3.2 shows the location and names of dams elaborated on by the respondents. These dams included 13 successful cases and 12 stalled cases of dam re-operation. In previous literature reviews, primarily cases from Europe, southern Africa, and Australia were reported (Olden *et al.*, 2014; Owusu *et al.*, 2021). This survey managed to obtain information on cases on all continents, notably in South America as well, which may have been underrepresented in previous studies due to language differences.

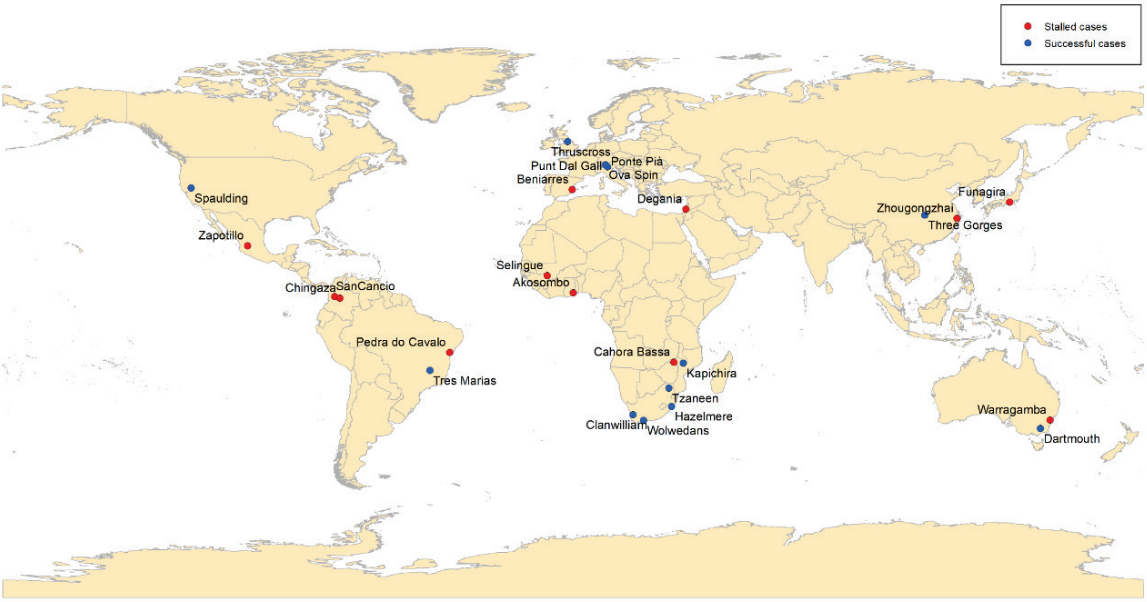


Figure 3.2. Names and locations of the dams reported on in the cases of successful and stalled dam re-operation identified and elaborated by survey respondents

3.3.3 Comparison of Approaches to Successful and Stalled Dam Re-operation

Test of Independence

The results of the tests of independence using Fisher's and Barnard's exact tests are presented in Table 3.1. With 41 comparisons, applying the Bonferroni correction results in a p-value of 0.0012. The significant difference between stalled and successful dam re-operation attempts lies in the involvement of scientists. Before correction for multiple comparisons however, the results also point to a difference between successful and stalled cases of dam re-operation when it comes to having legislation and a scientific research base as Inputs to the process; undertaking flow experiments as an Activity; and the inclusion the general public as stakeholders in the process. These are therefore areas that should be further investigated. It's worth noting that the results of Barnard's exact test are consistent with those of Fisher's except on whether flow experiments are undertaken as an activity in dam re-operation.

Using the significant test result for *Scientists* under *Stakeholders* as an illustration, the Fisher Exact Test result is interpreted as follows: the success rate of dam re-operation is statistically significantly related to having scientists as stakeholders in the process, with the odds of scientists as stakeholders being 2.6 to 1,700 times higher for successful cases than stalled cases. For the sample of dams identified in this survey, the probability of scientists as stakeholders in the process of re-operation is over 29 times higher for the successfully re-operated dams than for stalled cases of re-operation identified by respondents. For odds ratios less than 1, it is more easily understood using the multiplicative inverse of the odds ratio, which is then interpreted as the odds of stalled re-operation to successful dam re-operation.

Table 3.1 Results of Fisher's and Barnard's Exact Tests (2 significant figures) (n = 25). Significant variables before multiple comparisons correction in bold text; significant variable after multiple comparisons corrections in bold italic text.

Category	Variables	Elements	Fisher's Exact Test				Barnard's Test		
			p-value	95% confidence interval		Odds ratio	Statistic	p-value	Nuisance parameter
How	Inputs	**Legislation**	**0.015**	**1.2**	**130**	**9.8**	**-2.6**	**0.011**	**0.44**
		Scientific studies	**0.015**	**0.0074**	**0.80**	**0.10**	**2.6**	**0.011**	**0.44**
		Natural trigger	1.0	0.023	∞	∞	-0.98	0.064	0.53
		Requests							
		Man-made trigger	0.48	0.18	∞	∞	-1.4	0.21	0.11
		Planned upgrade							
		Other	0.073	0.0023	1.5	0.13	2.0	0.053	0.25
	Activities	Legislation	0.48	0.18	∞	∞	-1.4	0.21	0.11
		Flow experiments	**0.0017**	**2.6**	∞	∞	**-3.3**	**0.00099**	**0.50**
		Workshops	0.38	0.29	36	2.6	-1.1	0.35	0.91
		Scientific studies	0.645	0.17	26	1.8	-0.60	0.61	0.90
		Physical modification	0.22	0.40	∞	∞	-1.8	0.11	0.50
		Modelling	1.0	0.19	7.7	1.2	-0.23	0.83	0.35
		Other	0.48	0	36	0	1.06	0.35	0.084
	Flow Target (Output)	Minimum flow	1.0	0.18	8.9	1.2	-0.27	0.81	0.27
		High flow	0.38	0.36	39	3.0	-1.2	0.24	0.30
		Flood releases	0.59	0.21	190	3.2	-1.0	0.40	0.14
		Entire flow regime	0.70	0.10	4.0	0.64	0.58	0.65	0.50

Category	Variables	Elements	Fisher's Exact Test				Barnard's Test		
			p-value	95% confidence interval		Odds ratio	Statistic	p-value	Nuisance parameter
		Ramping rates	0.48	0.18	∞	∞	-1.4	0.21	0.11
		Other	1.0	0.011	78	0.92	0.059	1.0	0.50
What	Original Purpose	Flood control	1.0	0.14	21	1.5	-0.40	0.76	0.17
		Hydropower	0.41	0.33	20	2.3	-1.0	0.40	0.85
		Irrigation	1.0	0.18	8.9	1.2	-0.27	0.81	0.27
		Navigation	0.48	0.18	∞	∞	-1.4	0.21	0.11
		Recreation	1.0	0.011	78	0.92	0.059	1.0	0.50
		Water supply	1.0	0.13	5.3	0.84	0.23	0.83	0.68
		Other	1.0	0.024	∞	∞	-0.98	0.53	0.064
Why	Motivation	Habitat protection	1.0	0.067	18	1.1	-0.09	0.10	0.50
		Commercial resource	1.0	0.089	130	2.0	-0.54	0.71	0.13
		Endangered species	1.0	0.024	∞	∞	-0.98	0.53	0.06
		Scientific knowledge	0.38	0.028	3.4	0.38	1.1	0.35	0.089
		Other	0.073	0.79	470	8.6	-2.1	0.044	0.47
Who	Stakeholders	National agencies	0.38	0.29	36	2.6	-1.1	0.35	0.91
		Regional agencies	0.11	0.64	39	4.4	-1.8	0.088	0.40
		Local gov't agencies	1.0	0.13	5.3	0.84	0.23	0.83	0.68
		Dam operator	0.030	0.98	590	11	-2.4	0.021	0.71
		NGO	1.0	0.14	5.4	0.86	0.19	0.91	0.50
		Civil society groups	0.67	0.25	16	1.83	-0.72	0.28	0.064
		General public	**0.030**	**0.0016**	**0.93**	**0.087**	**2.4**	**0.016**	**0.50**
		Scientists	***0.00098***	***2.6***	***1700***	***29***	***-3.4***	***0.00060***	***0.50***
		Other	0.67	0.25	16	1.8	-0.72	0.53	0.064

Hurdles to Dam Re-operation

The types of hurdles encountered in the process of re-operation are shown in Figure 3.3. The main hurdles were placed into four groups after content analysis of the responses to open questions on hurdles faced during dam re-operation: technical or science-related hurdles, hurdles to do with the stakeholder network involved in the process of dam re-operation, policy-related hurdles, and finally, hurdles arising from physical constraints in available water or infrastructure resulting in a high economic trade-off between e-flows and traditional water uses. Examples of the hurdles that fall into the four categories are given in Table 3.2.

Table 3.2: Examples of the hurdles encountered for each of the four main categories of hurdles to dam re-operation for e-flows implementation

Categories of hurdles identified	Example of hurdles in each category
Technical/ Science	Lack of data; challenges in translating e-flow requirements into practical dam releases
Social/ Stakeholder	Extended discussions or negotiations; pushback from key stakeholders; lack of interest of some stakeholders; change in personnel
Policy/ Legislation	Lack of supporting legislation; no political will; externally funded or backed project with little local support
Physical/Economic	Not enough water; reduced revenue; interactions with other dams; possible damage to dam

In the case of successful re-operation, the approaches taken to overcome the main hurdles are shown in Figure 3.4, and the attempted solutions in the case of stalled re-operation are presented in Figure 3.5. Once again, the categories of approaches for both successful and stalled re-operation were created based on the responses to an open-ended question. It can be seen that cases of successful and stalled dam re-operation have two approaches to overcome hurdles in common. These are (1) consultations or negotiations between stakeholders, and (2) scientific studies. While consultations were the most common approach in overcoming the main hurdles in successfully re-operated dams, in 7 out of 13 stalled cases of dam re-operation, nothing was even attempted to overcome the main hurdle, and the process came to a halt.

Regarding when the main hurdle to dam re-operation was en-countered once the process began, in all but 1 of the 13 cases of successful re-operation, the responses were “immediately”, “at the start” or “from the beginning” implying that there was an awareness of the challenges to be overcome right from the beginning of the process. As such, all activities could be tailored to overcoming that hurdle at the outset, thereby increasing the likelihood of a successful outcome. In contrast, in half of the stalled cases, a period of 1 year to a maximum of 4 years went by before the main hurdle to dam re-operation was encountered.

Figure 3.3. Types of hurdles encountered in successful and stalled cases of dam re-operation. In some stalled cases, two main hurdles were reported

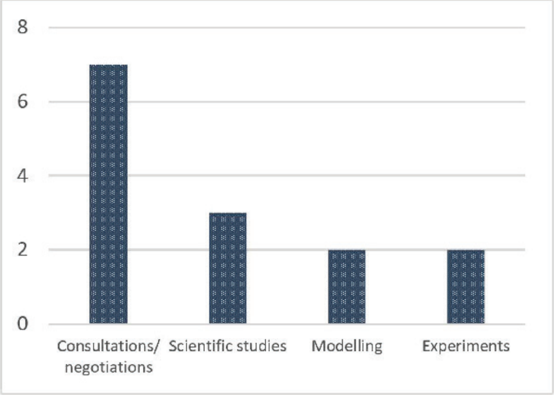


Figure 3.4. How the main hurdles were overcome in cases of successful re-operation. In some cases, more than one approach was adopted to overcome the main hurdle

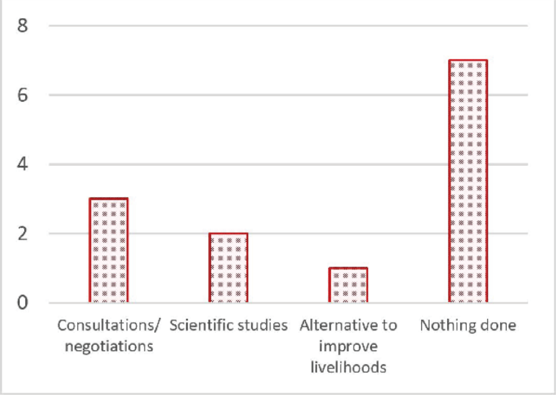


Figure 3.5. Attempts made to overcome hurdles in stalled dam re-operation cases. In some cases, more than one approach was adopted to overcome the main hurdle

3.4 DISCUSSION

Each case of dam re-operation for the release of e-flows occurs in a unique social and environmental context. Even so, by comparing cases of successfully re-operated dams with stalled attempts of dam re-operation from different geographic locations with varying biophysical as well as socioeconomic conditions, it is possible to identify characteristics that transcend the local context of each case to identify what distinguishes the two groups from one another (Baskerville and Lee, 1999). Considering the small number of survey responses, however, the observed trends are not interpreted rigidly but can be considered as hypotheses for further study. These are discussed in this section using evidence from literature.

It is found that the original purpose for which a dam was built, the motivation for implementing e-flows, and the target of flow manipulation in providing e-flows are similar for both groups and have no significant bearing on the outcome of dam re-operation. The key difference lies in the stakeholders involved, especially the involvement of scientists, who increase the odds of successful dam re-operation. Other differences worth highlighting for future investigation lie in the drivers (i.e., Inputs) and the Activities in the process of dam re-operation. The odds of a successful outcome are potentially higher when legislation is an input to the process, but the odds of the process stalling appear higher when scientific studies are an Input.

At first glance, the fact that having scientific studies as an Input has the potential to reduce the odds of dam re-operation may seem peculiar - more so because it seems to contradict the fact that scientists are important stakeholders whose involvement significantly improve the odds of success. However, there is a subtle interpretation. It is not science itself but its positioning in the process of dam re-operation that makes it an enabling or hindering factor, i.e., whether science engages in a dogmatic manner to promote and push e-flows or adopts a more egalitarian manner and facilitating role to support the re-operation process.

In research on pilot projects in water management, Vreugdenhil *et al.*, (2010) referred to the positioning of science as the "knowledge orientation" and identified two models: the communicative model and the expert-driven model. In the communicative model, local stakeholder knowledge is central, with expert knowledge forming a complement (Vreugdenhil *et al.*, 2010). In contrast, there is the expert-driven model, where priorities, knowledge, and solutions are defined and prepared by "experts" with a focus on technical and biophysical impacts (Dosi, 1988; Vreugdenhil *et al.*, 2010). This orientation is perfectly captured in a comment by one respondent regarding a stalled case: "Too much [of] an outside approach by environmental NGOs trying to provide evidence for the justification of an e-flow approach using studies." Indeed, Richter *et al.*, (2006), in their work on the Sustainable Rivers Project, promoted the ideal of the communicative model because this fosters ownership of the process and a commitment to see e-flows implemented. Based on over 25 years of experience in the e-flows field, O'Keeffe (2018) also identified the need for "local champions" as essential for successful training and implementation of e-flows.

In line with the positioning of science argument, where the general public is involved in the dam re-operation process, the tests for independence suggest a reduced chance of success. Possible explanations of this phenomenon relate to the phase at which the general public became involved. As argued in the preceding paragraphs, in situations where experts, officials, or scientists have preconceived ideas and solutions and the general public are involved at a late stage, much resistance to the "solutions" can be encountered (Arnstein, 1969; Cuppen, 2012). Alternatively, a perfunctory or an unstructured stakeholder engagement process in which the general public is involved can lead to delays, confusion, and frustration (Tritter and McCallum 2006; Cuppen, 2010). Fruitful stakeholder engagement requires careful design (D'Hont, 2020).

The possible increase in the odds of success when legislation is an Input can be explained using the findings of Cosens and Chaffin (2016), who examined the role of law in the assertion of water rights by indigenous peoples in Australia. They found that although internal innovation and self-organization may exist with respect to water rights, legislation serves as a catalyst for the establishment of supporting institutions, and even more importantly, legitimizes the activities and results of these institutions. In this light, legislation requiring or supporting e-flows enhances the chances of success of dam re-operation. It is also unsurprising that in half of the stalled cases, the major hurdle encountered was the absence of supporting legislation, manifesting as the absence of political will or local support.

The lack of legitimacy of groups attempting to implement e-flows is recognized as a stumbling block in some of the stalled cases. For example, with regard to the Selingue Dam in Mali, a respondent stated in response to a question on the efforts to overcome hurdles: "We are trying to establish an e-flow committee that has sufficient stakeholders and is politically embedded and is given the mandate to now run a full-fledged e-flow process." E-flows legislation may come at different levels, as found by Owusu *et al.*, (2021); however, in the majority of successful cases where legislation was an input to the process, local- or basin-level legislation, which is more in tune with local needs, existed. This should, however, not discount the fact that regional-level legislation like the Water Framework Directive in the European Union is also helping to push the e-flows agenda to the fore in member countries (Acreman *et al.*, 2009; Acreman and Ferguson, 2010).

Finally, in considering how the Inputs to dam re-operation influence the outcome, one might interpret the potential of legislation as an Input to increase the odds of success as proof that the top-down approach works in the process of dam re-operation. On the other hand, the fact that scientific studies as an Input appears to decrease the odds of success may be interpreted as showing the opposite; that bottom-up approaches are needed for successful dam re-operation. It can be argued that a combination of the two approaches is needed, so that there is a response from the bottom to top-down approaches and vice versa (Keare, 2001). As such, e-flows legislation and policy may serve to provide an enabling environment for e-flows implementation, and scientific studies developed and carried out with local stakeholder participation provide the bottom-up information and commitment necessary to success (Bryant, 1997; Keare, 2001; Vreugdenhil *et al.*, 2010; Tevapitak and Helmsing, 2019).

This bottom-up - top-down interaction could apply to water allocation optimization where preferably, end-users are involved in the development of models as opposed to just being the recipients of finished products (Horne *et al.*, 2016). The importance of this interaction also extends to other fields and is cited as one of three interrelated reasons for deadlock in the transfer of the Dutch Delta Approach to other countries (Minkman *et al.*, 2019). Bolten's (2009) analysis of postwar efforts at rebuilding the agricultural sector in Sierra Leonne also addressed this disconnect between the government and international non-governmental organizations (INGO) on the one hand and local people on the other as a reason for the standstill in postwar development.

The activities carried out by both successful and stalled cases of dam re-operation are very similar. The exception seems to be flow experiments: in the sample of dams in this study, none of the cases of stalled re-operation had implemented flow experiments compared with 8 out of 13 successfully re-operated cases. It is hypothesized that this stems from the fact that flow experiments require a high level of collaboration and consensus to set up and also require the buy-in of institutions with the power to change, albeit temporarily, the operation policy of the dam in question (Robinson and Uehlinger, 2003; Kubly, 2009; Warner *et al.*, 2014).

An examination of the major hurdles that eventually caused the process of dam re-operation to halt in the stalled cases reveals that the political will and/or the stakeholder consensus required was absent in nine different stalled cases (Figure 3.3 and Table 3.2). This is in line with the experience of O'Keeffe (2018), who identified challenges associated with entrenched positions of stakeholders as the most frequent and intractable cause of the suspension of e-flow initiatives. The absence of stakeholder consensus and commitment may also account for the fact that hurdles were identified relatively late in the process of dam re-operation in stalled cases compared with successful cases, and also why in more than half of stalled cases, nothing was done when the major hurdle to dam re-operation was encountered. These would suggest that in the stalled cases, the three dynamics necessary for collaborative governance as framed by Emerson and Nabatchi (2015), namely principled engagement, shared motivation, and the capacity for joint action, were absent so that stakeholders could not reach consensus on dam re-operation.

In contrast, the most frequent hurdles in successful dam reop-eration had to do with physical constraints to releasing environmental flows given the design of the dam itself and the surrounding infrastructure, or with inadequate water to satisfy e-flow requirements and other users. Faced with these hurdles, negotiations and consultations between stakeholders were the go-to strategy, despite the fact that hurdles specifically related to stakeholders occurred only in three successful cases. This is in line with findings from Beierle (2002) on stakeholder-based decisions, where joint fact finding was noted as important to conflict resolution. It is acknowledged that although consensus is a worthy pursuit, it should not come at the expense of the strategic interest of stakeholders, particularly disadvantaged groups (Manzungu, 2002). However, collaborative governance does improve ecological outcomes (Scott, 2015; Ulibarri, 2015) and a consensus on water allocation must be reached for dam re-operation to occur. As set forth by Richter *et al.*, (2006, p. 301), a key point of emphasis among stakeholders to encourage consensus should be "by keeping the whole system healthy, each part of the system should benefit."

Ultimately, the reality of reaching a consensus to release e-flows in the long term may be that in extremely dry years other water users take precedence. In the words of one of the respondents in a successful case, “Every time we have a drought we do not have e-flows.”

It is important to note that the findings of this study are based on a sample size of 25 dams following a nonrandom convenience sampling. This relatively small sample size implies that small or even moderate effects are hard to detect, and the sampling approach also resulted in the overrepresentation of scientists (Little, 1989; McDonald, 2014; Morgan, 2017). As such, it is recommended that further studies featuring larger databases of dams or perhaps more detailed case studies are important to fully investigate the impasse narrative in dam re-operation to accommodate e-flows.

3.5 CONCLUSION

Using a self-administered structured internet survey, this study draws on first-hand practical experience of experts who have taken part in dam re-operation projects for e-flows implementation to identify the variables affecting its success. Differences related to who was involved in the process, what the original operation of the dam was, and why e-flows were desired were investigated in a number of cases of successful and stalled attempts to re-operate dams. On the question of how dam re-operation occurs, a logic model approach was used to distinguish between the drivers to the process, the activities undertaken to reach the goal of changing dam operations, and the output or flow change targeted. In addition, the hurdles encountered and the attempts made to overcome these hurdles were investigated. This study therefore fills an important knowledge gap because stalled cases of dam re-operation for the environment have not yet been reported in the scientific literature.

The results indicate that the difference between success and stalling lies mainly in the who of dam re-operation and to a lesser extent, the how. With respect to the stakeholders involved in the process, scientists increase the odds of success, whereas participation of the general public potentially decreases the odds of success. With respect to Inputs or drivers to the process, the odds of a successful dam re-operation appear higher when legislation is in place, but in contrast the odds are lowered when scientific studies drive the process. Furthermore, flow experiments are found to be the activity most associated with successful dam re-operation. Finally, the analysis of the hurdles encountered and how they were overcome reveals that a strong stakeholder network is important in achieving a successful outcome.

Based on these results, it is possible to propose a number of facilitating factors in re-operating dams for further investigation as follows:

- Scientists are important stakeholders in the process of dam re-operation, but should play a supportive role rather than drive the process.

- In undertaking scientific studies for determination of e-flows, a consensus on the priorities, knowledge gap, and solutions must be reached together with local stakeholders.
- Local-level legislation and policy on e-flows provide the enabling environment for dam re-operation for e-flows.
- Genuine, carefully designed consultations and negotiations between stakeholders can overcome hurdles encountered in the process of dam re-operation for e-flows implementation.

Finally, there is a dearth of information on individual cases of dam re-operation that have stalled and remain at an impasse. Future in-depth studies on these cases are needed to draw out the unique social and environmental contexts in which they occurred and how these contextual factors influenced the outcome. Such knowledge will serve as an additional resource for water managers and other stakeholders in future attempts to re-operate dams in diverse contexts.

PART II: THE CASE STUDY

Flow-ecology relationships are location specific and so are trade-offs that are associated with dam re-operations for e-flows. Hence a case study research method was chosen to investigate the synergies and trade-offs associated with dam re-operation for e-flows (Table 1.2). The Lower Volta River in Ghana was selected as a case study. A short background on the stalled attempt at dam re-operation in this location, the reason for the choice of this particular case study and the preliminary work done on this case study are presented here, in the introduction to Part II of this thesis before addressing the research questions (2.1 and 2.2) in Chapters 4 and 5.

PREVIOUS ATTEMPTS TO RE-OPERATE AKOSOMBO AND KPONG DAMS

In the Lower Volta River Basin in Ghana, years of research following the construction of the Akosombo and Kpong dams recorded the changes in downstream ecosystems and associated services (Biswas, 1966; People and Rogoyska, 1969; Lawson, 1972; Gyau-Boakye, 2001; Tsikata, 2008; Obirikorang *et al.*, 2013) (Sections 4.1 and 5.2). While arrangements were made to compensate and relocate the upstream communities flooded by the filling of the Akosombo Dam in 1965, no such consideration was made for the people living downstream. Incidentally, many of the relocated upstream people had been placed in these downstream communities. Decades later, in a bid to address the challenges faced by downstream communities as a result of the operation of the dams, the Water Resources Commission (WRC), the government institution charged with managing the country's water resources, and the Natural Heritage Institute (NHI), a non-governmental organisation, embarked on a two-year period of consultation with the dam operator (Volta River Authority (VRA)), downstream communities and other government agencies in 2005 (Ntiamoa-Baidu *et al.*, 2017). This initial consultation resulted in the formation of a project development team made up of representatives of relevant government agencies including the Ministry of Energy, universities, governmental and non-governmental research organisations, the VRA and traditional leaders of downstream communities. The project development team drew up the objectives, outputs and projected impacts of a dam re-operation project for the Lower Volta in May 2007. The main objective of the project was "to contribute to economic growth and poverty reduction through improvement of downstream ecosystem functions and livelihoods by re-operating and re-optimizing the Akosombo and Kpong dams" (Ntiamoa-Baidu *et al.*, 2017, page 6). From August 2012 to June 2016 the Re-operation and Re-optimisation of the Akosombo and Kpong Dams Project (RRAKDP), funded by the African Water Facility (AWF) of the African Development Bank (ADB) was carried out with extensive local stakeholder involvement (Ntiamoa-Baidu *et al.*, 2017). In the case of the Lower Volta, even by the mid-term review, it was clear that "due to the energy situation in Ghana and the forecasted energy challenges in the near future, the re-operation experimentation was not feasible" (Ntiamoa-Baidu *et al.*, 2017, page 10). The dire energy situation in Ghana at the time of this project involved power rationing across the country. At its worst by early 2016, households in major cities enjoyed only 12 hours of power for every 24 hours without power. The project thus shifted to exploring alternative measures that could be put in place to address the challenges faced by downstream communities as a result of the operation of the dams.

Though a stalled case, the Lower Volta River has a number of characteristics of the majority of successfully re-operated dams studied in the systematic literature review (Chapter 2) and the survey (Chapter 3):

- E-flows are recognised in water legislation. In Legislative Instrument (L.I.) 1692 Water Use Regulations, Ghana, 2001, environmental water use is the "release or maintenance of a certain flow of water for the purpose of maintaining specific environmental and recreational purposes" and is one of the water uses which is regulated by the WRC. It is worth noting that e-flows, like all the other water uses in the L.I., is neither a requirement nor a priority; but it is one of eleven legitimate water uses permitted and managed by the WRC.
- Extensive local stakeholder input and involvement characterised the attempted dam re-operation project in the Lower Volta. Stakeholders included traditional leaders and citizens of downstream communities, the dam operator (VRA), government agencies, governmental and non-governmental organisations, universities and research institutions. The main objective of the project, namely, economic development and poverty reduction, reflected the priorities and interests of these stakeholders.
- The main hurdle in the Lower Volta dam re-operation attempt falls into the same category as that of the majority of successful cases of dam re-operation from the survey (Chapter 3); the 'Physical/Economic hurdles' category. At the time of the RRAKDP, it was concluded that there was insufficient water to meet both energy (hydropower) and the e-flows demand due to the high dependence of Ghana on the energy generation of Akosombo at that time. The energy context currently in Ghana has however changed and now "this crisis of shortage [has] quickly [been] replaced with one of overabundance" (Dye, 2020, Page 4)

Considering these points of divergence from the general findings of the systematic literature review and survey results, the changed energy context of Ghana and the reasons listed in the Introduction (Table 1.2), the Lower Volta River presents an interesting case study for addressing RQ 2.1 and 2.2.

PRELIMINARY INTERVIEWS ON WATER USERS AND ECOSYSTEM SERVICES IN THE LOWER VOLTA

A literature review on the Lower Volta River system was carried out on its history, the different water users in the basin, the pre- and post-dam state of ecosystem and ecosystem services in the basin, and the stalled attempt at dam re-operation (RRAKDP). Additionally, following approval of the data management and interview protocol by the Human Research Ethics Committee (HREC) of the Delft University of Technology, Netherlands (Delft University of Technology, 2009) (Appendix C), interviews were conducted with experts on the Lower Volta River Basin. The interview data are located on the 4TU Research Data repository, with doi: 10.4121/20425629. They are published with restrictive license as specified in the Ethics Approval Application (Delft University of Technology, 2009) (Appendix C) with the informed consent of the interviewees.

It must be noted that in addition to gaining a better understanding of the RRAKDP, ecosystem services and livelihoods in the Lower Volta, the initial intention behind these interviews was to develop service suitability (SS) curves for key ecosystem services (Fanaian *et al*., 2015; Korsgaard *et al*., 2008). The Service Provision Index (SPI) approach using SS curves to link flows to a key ecosystem service was ultimately abandoned for an alternative approach using a BBN as the latter is better suited to the data-scarce situation in the Lower Volta. Nonetheless, the interviews provided important background information for understanding the case study, choosing the indicator species for designing e-flows (Chapter 4) and also informed the set-up of the trade-off problem (Chapter 5).

Twelve experts on the river basin who were part of the RRAKDP were interviewed (Table i). These interviews were held in person in early 2020. Later, in October 2020, an expert who was not a part of the RRAKDP was interviewed on the clam fishery, an important industry in the Lower Volta. Each interview lasted approximately 40 minutes and was semi-structured with a set of pre-determined questions (Appendix C) but also room for following up on other points of interest. The experts were selected via a snowball approach initially starting with contact with the lead researchers in the RRAKDP who then recommended for interview other experts on specific ecosystem services in the Lower Volta. Subsequent to the interviews, additional literature review served as validation for the interviews.

Table i: List of experts interviewed on the Lower Volta.

Affiliation of expert	Date	Ecosystem service/Topics
Private researcher (consultant on RRAKDP)	17/Feb/2020	Aquaculture
Volta Basin Authority (VBA)	24/Feb/2020	VBA, Flooding, socio-economic impact of dams on downstream communities
Water Research Institute, Ghana	26/Feb/2020	Flood recession agriculture

Affiliation of expert	Date	Ecosystem service/Topics
Water Research Institute, Ghana	26/Feb/2020	Fisheries
University of Energy and Natural Resources	04/Mar/2020	Aquatic weeds, RRAKDP
Water Research Institute, Ghana	04/Mar/2020	Macrophytes/ aquatic weeds
Water Research Institute, Ghana	10/Mar/2020	Sediment, coastal erosion
Water Research Institute, Ghana	10/Mar/2020	Phytoplankton
Water Research Institute, Ghana	10/Mar/2020	Aquatic weeds and diseases
Fisheries Commission	12/Mar/2020	Aquaculture and fisheries
Institute for Environment and Sanitation Studies	16/Mar/2020	Background on RRAKDP
Water Resources Commission	20/Mar/2020	Flood recession agriculture, hydropower, RRAKDP
Department of Fisheries and Aquaculture, KNUST	30/Oct/2020 (online)	Volta clam fishery

4

THE CLAM AND THE DAM: A BAYESIAN BELIEF NETWORK APPROACH TO ENVIRONMENTAL FLOW ASSESSMENT IN A DATA SCARCE REGION

The content of this chapter is adapted from: Owusu, A., Mul, M., Strauch, M., van der Zaag, P., Volk, M., and Slinger, J. (2022). The clam and the dam: A Bayesian Belief Network approach to environmental flow assessment in a data scarce region. Science of The Total Environment, 810, 151315. https://doi.org/10.1016/J.SCITOTENV.2021.151315

Supplementary material to this chapter is available in Appendix D.

Image: Freshly picked Volta clams in a canoe, Lower Volta, Ghana

Abstract

The Volta clam, *Galatea paradoxa,* is a freshwater macrobenthic bivalve which is endemic to the Lower Volta River in Ghana. The range of occurrence of the clam has been influenced by the flow regime in the Lower Volta which is in turn controlled by operation of two dams located upstream. Previous research has documented the changes to the Lower Volta due to the dams and attempts have been made to design environmental flows (e-flows), freshwater flows to sustain ecosystems, to inform the re-operation of the dams. The past attempts were based on the pre-dam, natural flow regime of the Lower Volta. In this study, a designer e-flow approach is explored using the Volta clam as an indicator species. Using knowledge garnered from various sources on the lifecycle, habitat and the local conditions corresponding to historical and current states of the Volta clams, the factors influencing its extent are visualized and quantified in a Bayesian Belief Network (BBN). Based on this BBN, an e-flow recommendation for the Lower Volta is for low flows, between 50 m^3/s and 330 m^3/s, for four months during the Volta clam veliger larva and recruitment life stages which occur in November to March. In addition, it is recommended that full breaching of the sandbar which regularly builds up at the Volta Estuary is done annually and that sand winning on the river bed is prohibited. These e-flow and management recommendations will have consequences for other water users and these have to be investigated, for instance by flow experiments and trade-off analysis. The results show that a BBN is potentially suitable for modelling the linkages between flows, management practices and the status of ecological indicators for the development of e-flows for highly modified rivers in data scarce regions.

4.1 BACKGROUND

The Volta clam, *Galatea paradoxa*, is a freshwater macrobenthic bivalve which was previously abundant in West African rivers such as the Lower Volta River in Ghana, Sanaga River in Cameroon and the Nun and Cross Rivers in Nigeria (Etim and Brey, 1994; Obirikorang *et al.*, 2013). In Ghana, it is an important source of protein and supports an artisanal fishing industry near the estuary (Obirikorang *et al.*, 2009; Adjei-Boateng *et al.*, 2012). Before construction of two dams in the Lower Volta, the Akosombo Dam in 1965 and the run-of-the river Kpong Dam in 1982, natural *G. paradoxa* beds covered a river length of approximately 80 km, stretching from Akuse to Sogakope (Lawson, 1972; Tsikata, 2008) (Figure 4.1). Due to the flow alteration associated with the operation of the dams over the decades, this range has shifted downstream and narrowed to a fraction of the pre-dam state, now stretching approximately 10 km from Agave-Afedume to Big Ada (Figure 4.1)(Adjei-Boateng *et al.*, 2012).

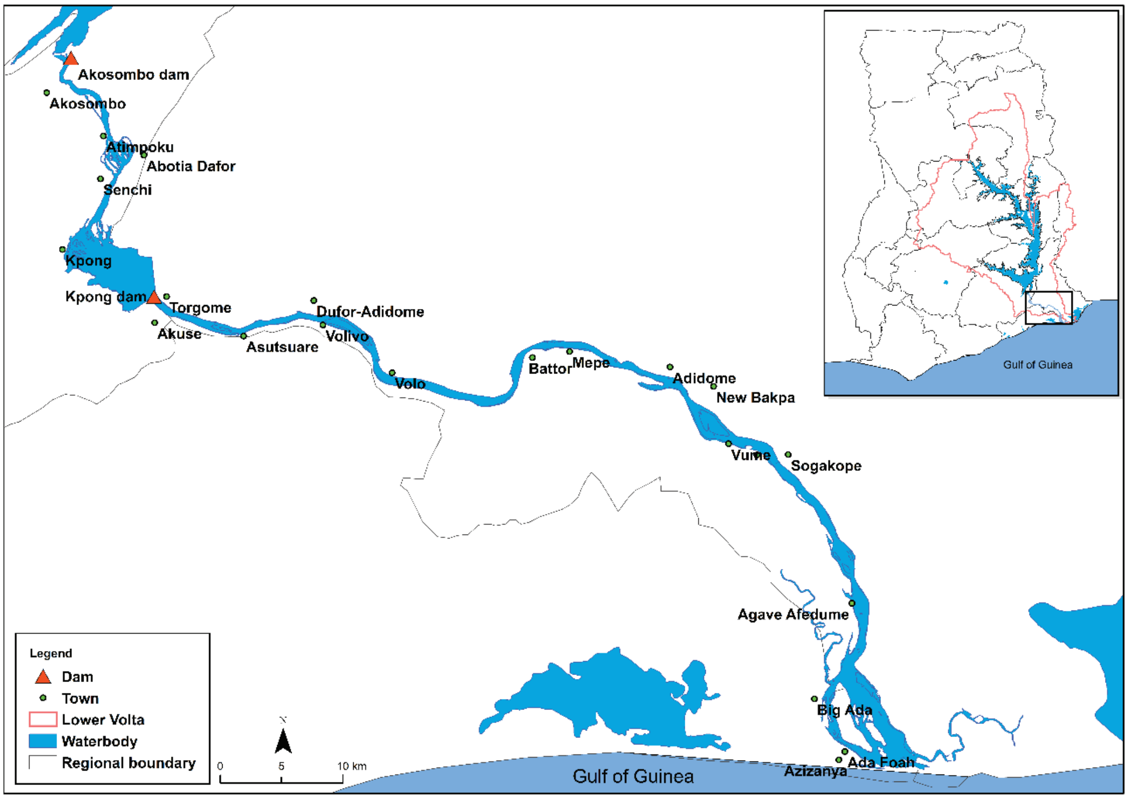


Figure 4.1. Lower Volta basin. Under pre-dam flow conditions, the natural clam bed stretched from Akuse to Sogakope while at present, the active natural clam bed is found between Agave Afedume and Big Ada.

Under natural flow conditions in the Lower Volta, clam gathering, which was done by hand, began in the low flow season in December until July when water levels began to rise (Lawson, 1972). Up to 8000 tons of clams were caught annually by this method by about 2000 to 3000 full time divers (Lawson, 1972; Tsikata, 2008). The clam fishery was one of the most lucrative activities in the Lower Volta, particularly for women (Moxon, 1969; Lawson, 1972; Tsikata, 2008). For instance, in a survey in 1954 at Battor, one of the riparian communities in the Lower Volta, about half of the women in the community were engaged in clam picking while for two-thirds of these women, clam picking was their main source of livelihood (Tsikata, 2008).

Rural life and nutrition, especially in developing countries like Ghana, are based on natural resources and as such, livelihood trajectories are directly shaped by environmental factors. In the Lower Volta, livelihoods were changed drastically once construction of the Akosombo Dam (with a residence time of approximately 3.9 years) begun in 1961. During the dam construction, there were no large floods and income from the clam beds increased three-fold (Lawson, 1972). After this short period of plenty, the clam industry collapsed spectacularly along with creek fishing and floodplain agriculture (Moxon, 1969; People and Rogoyska, 1969; De-Graft Johnson, 1999; Tsikata, 2008). Under operation of the Akosombo Dam, the variable flow regime of the Lower Volta has changed into a steady flow regime with an average monthly flow rate of approximately 1000 m^3/s perennially, suitable for hydropower production, formal irrigation farming and flood control. By 2000, the clam fishery had an annual yield of 1700 tons/year (Adjei-Boateng *et al.*, 2012a) and by 2012, *G. paradoxa* was at risk of commercial extinction due to the reduction in size of its natural habitat, limited saltwater intrusion due to the formation of a sandbar at the mouth of the Volta Estuary, as well as overfishing due to the use of more sophisticated equipment in clam picking (Tsikata, 2008; Adjei-Boateng, Agbo *et al.*, 2012). The industry has been salvaged somewhat by the practice of harvesting young clams from the natural clam beds and seeding them onto farmed upstream plots (Adjei-Boateng, Agbo *et al.*, 2012). The once female-dominated industry, however, is now mainly the purview of men who pick clams using diving equipment and air compressors (Adjei-Boateng, Agbo *et al.*, 2012).

The changes in the riverine ecosystem brought on by the construction and operation of dams is hardly unique to the Lower Volta. Indeed, the science of environmental flows (e-flows), freshwater flows to sustain or restore freshwater, riparian and estuarine ecosystems, has developed in response to the effects of the alteration of river flows due to dams and water diversions (Poff *et al.*, 1997; Bunn and Arthington, 2002; Tharme, 2003; Robinson and Uehlinger, 2008; Richter *et al.*, 2010; Melis *et al.*, 2010; Adams, 2014; Fanaian *et al.*, 2015; Slinger *et al.*, 2017; Taljaard *et al.*, 2017; Van Niekerk *et al.*, 2019). Reviews by Adams (2014) and Owusu *et al.* (2021) have also highlighted the importance of supporting legislation and stakeholder collaboration to e-flows implementation. In Ghana however, e-flows legislation does exist (L.I. 1692 Water Use Regulations, Ghana, 2001) and e-flows is a legitimate water use defined as the "release or maintenance of a certain flow of water for the purpose of maintaining specific environmental and recreational purposes". Furthermore, in the case of the Lower Volta, a number of studies have documented the ecological, social and economic changes due to the dams and even attempted, with stakeholder collaboration, to develop alternative flow release regimes to mitigate these changes (Lawson, 1972; Moxon, 1969; De-Graft Johnson, 1999; Tsikata, 2008; Mul, Balana *et al.*, 2017; Mul, Ofosu *et al.*, 2017; Ntiamoa-Baidu *et al.*, 2017; Darko and Tsikata, 2019). However, e-flows implementation has stalled in the Lower Volta. This is because the past efforts at e-flows assessment for the Lower Volta basin and re-operating the Akosombo and Kpong dams have taken as their basis the natural flow regime of the Lower Volta, mainly because there is little data on the riverine ecosystem functioning (Poff *et al.*, 1997; Mul, Balana *et al.*, 2017; Ntiamoa-Baidu *et al.*, 2017). The drawback of this approach is that a return to a near natural flow regime is highly unlikely as the Akosombo Dam has played and continues to play a central role in Ghana's energy production. In this study, a different approach to developing e-flows for the Lower Volta basin, grounded in the e-flows designer flow paradigm

(Acreman, Arthington *et al.*, 2014) is explored. This paradigm recognises that not all rivers can be restored to a near natural state and aims to define and assemble components of a river's flow hydrograph to meet certain ecological and social outcomes (Acreman, Arthington *et al.*, 2014; Horne, Kaur *et al.*, 2017). For instance, Horne, Webb *et al.* (2017), used optimization to design e-flows for the Yarra River, Australia while Papadaki *et al.* (2020) used the Suitable Range of Discharges approach for the Acheloos River, Greece. We use a Bayesian Belief Network (BBN) built for the indicator species *G. paradoxa* in designing e-flows. A BBN represents the joint probability distribution of a set of random variables and their conditional dependencies (Pearl, 1986; Neapolitan, 2003; Stewart-Koster *et al.*, 2010; Aguilera *et al.*, 2011; Frank *et al.*, 2014). BBNs have been applied widely in environmental science and water resource management as reviewed by Landuyt *et al.* (2013) and Phan *et al.* (2016) respectively. In this application, the set of random variables are the riverine ecosystem conditions required for the survival of *G. paradoxa* while the conditional dependencies are the drivers of these ecosystem conditions.

The use of a BBN is an attempt to overcome the ubiquitous problem of uncertainty or fragmentary data in the determination of e-flows, especially in developing countries where relatively few data are available on rivers and riverine ecosystems. In the case of the Lower Volta River and Estuary, there is no continuous monitoring of water levels, water quality, hydromorphology, ecological or biological indicators, and data collection is done in an *ad hoc* manner for projects (Rodgers *et al.*, 2007; Ntiamoa-Baidu *et al.*, 2017). The methods for designing e-flows under such data scarcity use simple hydrological or hydraulic metrics (Tharme, 2003; Efstratiadis *et al.*, 2014) or require a considerable investment of time and resources to collect the data required for the application of sophisticated ecohydrology tools (Tharme and King, 1998; Theodoropoulos *et al.*, 2018). By using a BBN in this study, the linkages between the river flow regime in the Lower Volta downstream of the Kpong Dam and habitat conditions for *G. paradoxa* and its survival, can be explored using existing knowledge with room left for updating as new knowledge becomes available. Apart from its nutritional and socio-economic value in the Lower Volta, *G. paradoxa* is selected as an indicator species because it is a stenotopic, macrobenthic organism whose abundance and biomass are good indicators of ecological integrity (Purchon, 1963). Furthermore, it is unique as it is one of only two freshwater genera in the order Tellinacea, the rest being marine (Purchon, 1963).

The aim of this study is to demonstrate an ecologically grounded, parsimonious method for designing e-flows in a data scarce region. Generally, in data scarce regions, the number and length of data and field observations required by existing e-flow assessment frameworks has been a restricting factor in e-flow determination and implementation.

Accordingly, the assumptions underlying the approach and the additional research required to explore its applicability further will be clarified.

4.2 METHODS

The method followed in designing e-flows for the Lower Volta using a BBN is summarized in Figure 4.2.

BBNs consist of two main parts: a directed acyclic graph (DAG) and conditional probability tables (CPT) (Pearl, 1986; Cowell *et al.*, 1999; Neapolitan, 2003). The DAG is a unidirectional, causal diagram made up of 'nodes' representing random variables.

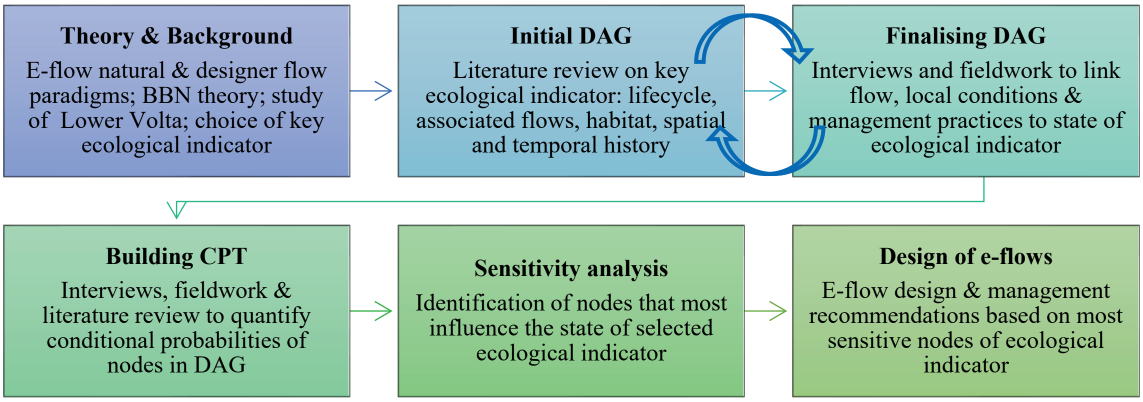


Figure 4.2. Steps followed in designing e-flows for the Lower Volta (BBN - Bayesian Belief Network; DAG - directed acyclic graph; CPT - conditional probability tables). Iteration between steps is indicated by the curved arrows.

Where there exists a causal relationship between any two variables, the two nodes are connected by an arrow or 'directed edge' from the 'parent node' to the 'child node'. The conditional probability distributions for the various states that each node can take given its parent node make up the CPT. As such, when a parent node takes a particular state, the probabilities of child nodes can be estimated using Bayes theorem (Pearl, 1986; Cowell *et al.*, 1999; Neapolitan, 2003) from the relation:

$$P(x|y) = \frac{P(y|x)P(x)}{P(y)} \qquad (4.1)$$

where $P(x)$ and $P(y)$ are the probabilities of observing x and y; $P(x|y)$ is the conditional probability of x,given y ; $P(y|x)$ is the conditional probability of y, given x.

For random variables X, Y and Z in a BBN, such that x is the parent node of y and y is the parent node of z, *i.e.:* $x \rightarrow y \rightarrow z$, the conditional probability distribution of subsequent states of the process depends solely on the current state, not on the sequence of events that preceded it, i.e.: the Markov condition is satisfied, so that:

$$P(x,y,z) = P(x)P(y|x)P(z|y) \tag{4.2}$$

where $P(x,y,z)$ is the joint probability of x,y and z; $P(x)$ is the probability of observing x; $P(y|x)$ is the conditional probability of y, given x; and $P(z|y)$ is the conditional probability of z, given y.

The following assumptions underlie the application of BBN to this study (see Neapolitan, 2003):

i. A manipulation of a parent variable, x, changes the probability distribution of a child node, y, and there is no subset of variables in the set of observed variables for which a manipulation of that subset leads to x no longer changing the probability distribution of y.

ii. The set of variables in the network is causally sufficient meaning that there is no hidden variable outside the set of observed variables with a causal path to two or more variables in the network.

iii. There are no causal feedback loops in the network.

iv. There is no selection bias meaning that all causal relationships are identified for the set of observed variables.

The last three assumptions form the Causal Markov Assumption and once they hold, a DAG, together with estimates of conditional probability distributions, forms a Bayesian network which is representative of our beliefs about a given system (Neapolitan, 2003). The software package, Netica (Norsys Software Corporation, 1998) was used in developing the BBN for the Lower Volta clam.

4.2.1 Building the directed acyclic graph (DAG)

Beginning with a literature review, a picture of the life cycle and habitat preferences of *G. paradoxa* as well as changes in the Lower Volta flow regime and riverine ecosystem was developed. This served as a conceptual model and formed the initial basis for the directed acyclic graph (DAG). This initial DAG was then modified during a field visit to the Lower Volta from 23rd to 29th March 2021. The state of the clam fishery was elicited through interviews with two experts, each with over 12 years' experience studying the Volta clam. In addition, an elder clam fisherman and leader in the clam fishery was interviewed and facilitated informal interviews with clam fishermen actively plying their trade on the river (see Appendix D for table of interviews (Appendix D, Table D1)).

Three additional activities were carried out during the field visit:

1. Mapping of the location of natural and seeded clam beds by logging coordinates of their boundaries as confirmed by the elder clam fisherman and the clam fishermen in the field.
2. Measurement of water depth and the following basic water quality parameters:
    - dissolved oxygen (DO)
    - salinity
    - pH
    - chlorophyll-a
    - nitrate
    - phosphate
    - total dissolved solids (TDS)
    - temperature
3. Determination of the location of the salt-freshwater interface through measurement of the salt water profile during spring tide on March 28th 2021.

The goal of these measurements was to assess and identify whether there are significant differences between conditions within the natural clam beds, the seeded clam beds and other areas and thereby modify the DAG, if necessary. As the current year-round steady flow releases from the Akosombo Dam occasion little variation in the Lower Volta, only one field trip was undertaken near the equinoxal spring when the influence of the sea is likely to be greater. The findings from the field trip are therefore regarded as indicative and serve to complement longer term historical observations of the clam and the physicochemical properties in the Lower Volta (Adjei-Boateng, Agbo *et al.*, 2012; Adjei-Boateng, Essel *et al.*, 2012; Adjei-Boateng and Wilson, 2013a,b; Obirikorang *et al.*, 2013; Nyekodzi *et al.*, 2018).

Sampling locations and procedure

The Lower Volta Bridge, also known as Sogakope Bridge, was chosen as the reference point for sampling downstream/southwards towards the Volta Estuary and upstream/northwards towards the Kpong Dam. The sampling locations were given unique waypoint identities (Appendix D, Figure D1 and D2). Due to the spatial heterogeneity of the southern section, as evidenced by the different fishing and non-fishing activities within the section, the initial 3 km sampling interval was adjusted to 2 km. The northern section was relatively more homogenous and sampling stations were established at 5 km intervals. At each sampling station, coordinates, water depth and physicochemical water quality were recorded in-situ over the water column using a HQ40D Portable Multi meter. Samples were also collected in 500 ml plastic bottles for laboratory analysis of nutrient and chlorophyll-a concentrations with a DR3900 Laboratory VIS Spectrometer. Details on the methods used to determine nutrient and chlorophyll-a are available in the Supplementary material (Appendix D).

At 5.8 km from the mouth of the Volta Estuary (approximately 22 km from the Sogakope Bridge), a Pro Plus Multiparameter probe was set up at 30 cm above the river bed to log salinity, DO, TDS, temperature and pH at 5-minute intervals over a 24-hour period during the spring tide. This was complemented by further in-situ measurements with the HQ40D Portable Multi meter to track movement of the salt- freshwater interface at the peak of the spring tide. The location for this fixed probe was selected because of convenience as there is a 24-hour manned, permanent aquaculture structure situated there.

4.2.2 Building conditional probability tables (CPTs)

Once the DAG was affirmed, the prior probabilities for the various states of nodes in the network were determined using data available in literature complemented by the field measurements and expert input. Where available, empirical data was used to define quantitative prior probabilities, otherwise qualitative values were derived from literature or defined by experts. For such qualitative nodes, the experts were asked to assign probabilities to the node being in a given state for each combination of states of the parent nodes using a seven-point scale (see Appendix D, Tables D2 and D3 for the scale and illustration of the process for assigning probabilities respectively). A simple mathematical aggregation was undertaken whereby the average prior probability value based on the two probability descriptions given by the experts was then assigned to the node for that combination of parent node states (Clemen and Winkler, 1999). For the final node on the Natural_clam_extent which had three states, a behavioural aggregation approach where the experts came to an agreement on the probability of each state given the states of the parent nodes was used (Clemen and Winkler, 1999).

By compiling the network in Netica, the posterior probabilities for all the nodes were calculated using Bayes theorem (Eq. (1)). The validity of a BBN model can be checked by observing the effect of altering the states of nodes on their child nodes and verifying if the effects are logical (Cain, 2001; Van Dam *et al.*, 2013). The network was thus validated by entering the pre-dam and current states of the ‘origin’ nodes i.e.: nodes without any parent nodes (i.e.: Flow (April–June), Flow (July–October), Flow (November–March), Sand winning and Sandbar) and checking the effect on their immediate child nodes and the ‘objective’ node i.e.: the ultimate child node in the network (Natura_ clam_extent). The resulting posterior probabilities were noted as logical.

4.2.3 Designing environmental flows (e-flows) for the Lower Volta clam

The approach to designing e-flows for the Lower Volta clam using the BBN was first to determine which origin nodes, and particularly, which flow origin nodes significantly alter the extent of the clam bed. By performing a sensitivity analysis on the objective node, Natural_clam_extent, the origin nodes in the network which significantly influence its posterior probability were identified. In Netica, sensitivity is calculated as the reduction in uncertainty or entropy of a node given a finding at another node. The current 10 km clam bed from Agave-Afedume to Big Ada was taken as the baseline with the ideal designer flow being one that leads to a high probability that the clam bed extent will increase.

With knowledge of the most significant nodes, e-flows for the Lower Volta were designed by targeting the origin nodes which reduce the entropy of the Natural_clam_extent by more than a percentage when known (i.e.: significant origin nodes). This was done while keeping in mind that a minimum disruption to the current flow regime would be preferable to dam operators as this would help maintain hydropower and other current economic benefits of the upstream dams as much as possible. Since a decrease in the extent of the clam bed is undesirable, the probability of this state occurring was set to null in all scenarios considered. On the other hand, the desirable scenarios were those where there is a 50% or higher probability of the clam bed extent increasing. By setting the insignificant origin nodes to current conditions (to maintain current benefits as much as possible), the changes in the probabilities of the different states of the significant origin nodes were noted for the desired scenarios of the clam bed extent. These changes in probabilities of the states of the significant origin nodes reveal the flow and management strategies which will most likely increase the extent of the natural clam bed in the Lower Volta.

4.3 RESULTS

4.3.1 Directed acyclic graph

Life cycle of the Volta clam and associated flow conditions

The specific life cycle for *G. paradoxa* is yet to be fully determined empirically, although literature on the general life cycle of clams (Abraham and Dillon, 1986; da Costa, 2012) together with empirical knowledge on the gametogenic cycle of *G. paradoxa* in the Lower Volta River and Cross River in Nigeria (Kwei, 1965; Etim and Taege, 1993; Etim, 1996; Adjei-Boateng and Wilson, 2013b, 2016) and interviews with local clam fishers provide a good indication of its key life stages, the timing of these stages and its habitat preferences. Spawning occurs annually from July to October, peaking in September when up to 90% of individuals are spawning (Adjei-Boateng and Wilson, 2013b, 2016). Ripe *G. paradoxa* adults release gametes into water where fertilization occurs (Adjei- Boateng and Wilson, 2013b, 2016). After fertilization, larvae swim through the water, feeding on phytoplankton (Etim, 1996). According to Beadle (1974), while adult clams are freshwater species, the veliger larvae of the Volta clam require salinity of 1 (practical salinity units which is a dimensionless quantity (Lewis and Fofonoff, 1979)) to maintain their water balance. The larvae eventually swim upstream and go through metamorphosis whereby they change from a motile, planktonic phase to a sedentary, benthic existence by establishing clam beds on sandy substrata (da Costa, 2012). Recruitment is continuous with a major pulse in October to March with the smallest clams being observed from November to March (Adjei-Boateng and Wilson, 2012). In the Lower Volta, adult clams can live for up to eight years, feeding primarily on phytoplankton and growing in shell length from an average of 19.4 mm to 73.1 mm (Amoah and Ofori-Danson, 2012; Adjei-Boateng and Wilson, 2013a).

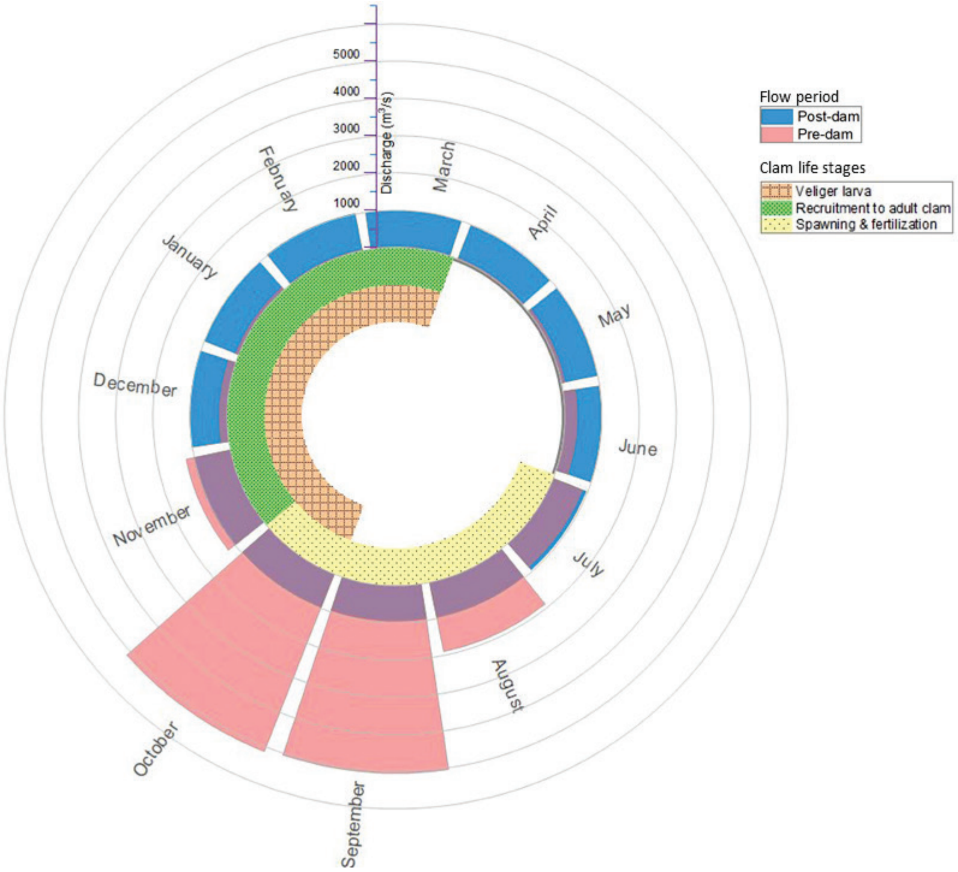


Figure 4.3. Flow magnitudes under pre-dam and post dam conditions and the associated life stages of the Volta clam (using monthly average flow data from Volta River Authority,

Ghana). The purple colour indicates the overlap of post-dam (blue) and pre-dam (red) average monthly flow magnitudes.

By aligning the above knowledge with the flow regime and clam fishery in the Lower Volta, it can be seen that spawning of the Volta clam coincides with the natural period of high flow so ensuring maximum dispersal of gametes for fertilization (Adjei-Boateng and Wilson, 2013b). Furthermore, with regards to the brackish water salinity requirement of 1 for the veliger larva, this salinity value occurs near the saltwater-freshwater interface which forms the downstream boundary of the natural clam bed. Keeping in mind that, in general, the length of time from spawning to recruitment in clams is approximately three weeks (Abraham and Dillon, 1986; da Costa, 2012) and the smallest clams are observed starting from November (Adjei-Boateng and Wilson, 2012), the key life stages up to adult stage for *G. paradoxa* in relation to the flow regime in the Lower Volta are summarized in Figure 4.3.

Habitat of the Volta clam

At present, the natural clam bed is located south of the Sogakope Bridge on the Lower Volta River (Figure 4.4). The entire natural clam bed covers a river stretch of approximately 22 km, but the first 12 km of this 22 km stretch has such a sparse population of clams that fishermen do not dive for clams there. The active natural clam bed, where there is a high abundance of clams and where fishing occurs, is found in the next 10 km stretch of river. As found in literature (Lawson, 1972; Amoah and Ofori-Danson, 2012), the southern (most downstream) boundary of the clam bed roughly corresponds to the fresh-saltwater boundary. From information provided by fishermen it was found that pre-dam, sea water would intrude as far up as Asutuare, approximately 105 km inland. Currently, when fishermen harvest any clams under 5 mm in length from the active natural clam bed, they seed them to marked plots upstream for harvesting during the closed season in December to March. The seeded clam beds extend from the northern limit of the active fishing zone up to about 40 km north of the Lower Volta Bridge, spanning a total distance of 55 km. According to the fishermen, the upstream extent of their seeded clam zone is limited by the costs of transporting harvested clams upstream from the active natural bed. However, they consider that seeding clams along the entire length of the river downstream of the dams is theoretically possible. Furthermore, local fishermen also assert that the clams grow larger in the upstream seeded clam beds than in the area where the natural clam bed now occurs. However, no recruitment takes place at the seeded clam beds. No newly recruited clams have ever been found there since the practice of seeding began nine years ago.

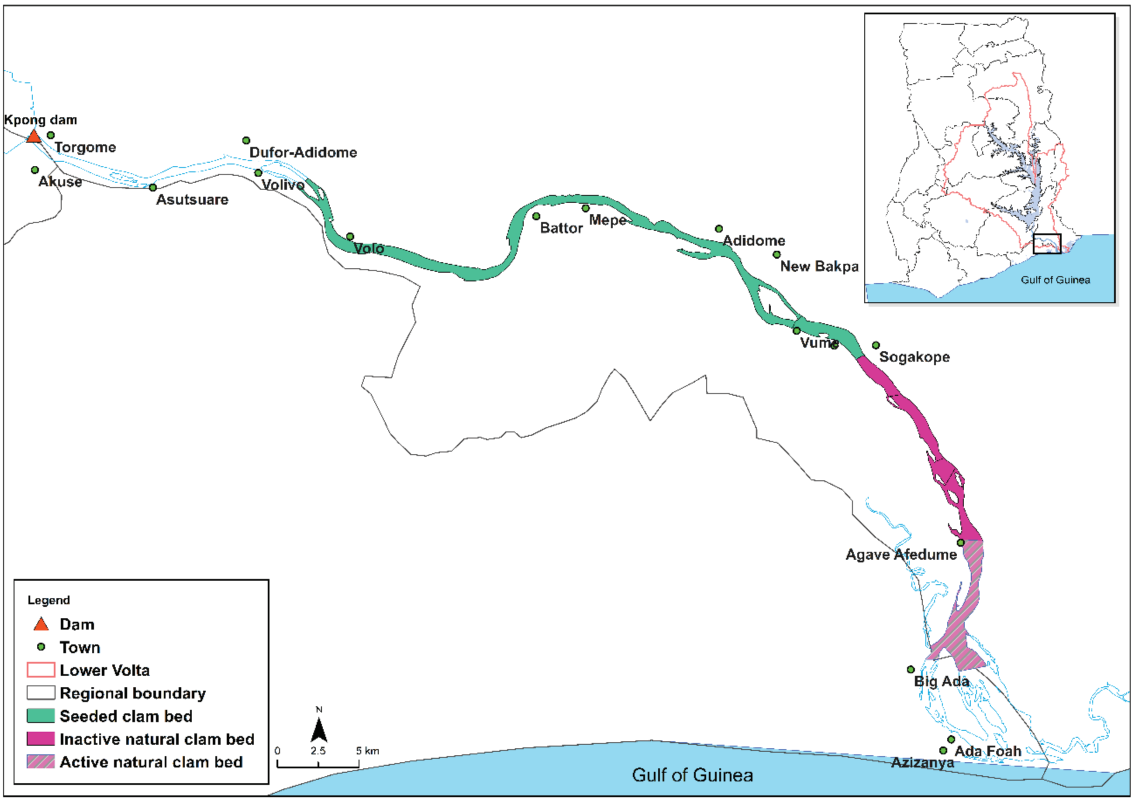


Figure 4.4 The Lower Volta River showing the current extent of natural and seeded clam beds.

Over the decades, sandbars have formed within the Volta Estuary due to changes in river flow and coastal dynamics. Under the natural, pre-dam flow conditions, sediment was scoured from the sandbars in the estuary during the high flow season and no sandbar could persist near the mouth for long periods (Elliott and McLusky, 2002; Potter *et al.*, 2010). Consequently, pre-dam, the width of the river at the estuary was approximately 1.2 km. However, under current dam operation, the flow dynamics lead to a build-up of coastal sediments, constricting the inlet and current flood releases are not high enough to cause full scouring of the mouth. For instance, in 2010 when high inflows to the dam necessitated emergency flood releases, the sandbar that had built up since the last mechanical breaching in 2009 remained intact. At the same time, there was significant flooding in downstream riparian communities, limiting the maximum flood release from the dams. It appears that only mechanical breaching, as carried out by the Volta River Authority (VRA) on four occasions since 1990, is capable of fully breaching the sandbar under the present conditions of dam operation, that is, with year-round steady flow releases and limitations on flood releases. Between 2012 and 2016, groynes were built along the seashore on the eastern side of the Volta Estuary at Ada Foah and since completion, some erosion of the western side of the Volta Estuary has been observed

(Bollen *et al.*, 2011; Roest, 2018) implying that sediment dynamics in the estuary is changing. In summary, the Volta Delta remains a freshwater dominated coastal system, but is exhibiting both coastal erosion and the accumulation of sediment in sandbars within the inlet which serves to limit the upstream extent of seawater influence. This is remedied by mechanical breaching.

While it was initially deduced from literature that a water depth of 2 m to 4 m is an important factor for clam survival, from observations and interviews in the field it was found that the Volta clam can survive and grow in water depths ranging from 2.4 m to 7.4 m. Water depth is also known to influence the upstream extent of salt intrusion, although the constriction of the mouth by sandbars can counteract this influence (Slinger, 2017). By distinguishing three flow states together with dredging of the sandbar in the BBN model, the influence of depth on salt intrusion could be accounted for in the case of the Lower Volta. Accordingly, water depth was not considered in the final DAG. Furthermore, the field visit revealed a new practice of unregulated sand winning from the riverbed in the seeded clam zone. The trajectory and full impact of this industry in the Lower Volta is uncertain. However, it is a further sediment sink on the coastal system (Roest, 2018) and according to the experts and local clam fishermen, it destroys habitat and affects the water quality negatively, thus posing a threat to the restoration of the clam fishery upstream if it persists. A node representing sand winning was therefore included in the BBN.

Water quality in the Lower Volta

Figure 4.5 shows that chlorophyll-a, an indicator of the amount of food available to the clams, decreases slightly from upstream to downstream (left to right in Figure 4.5), while nitrate and phosphate show an overall increasing trend.

While nitrate and phosphate levels are significantly lower from 10 km upstream of Sogakope Bridge, there is no significant difference in nutrient levels between the natural clam beds and the seeded beds from downstream of this point. Therefore, water depth and quality were not included in the BBN.

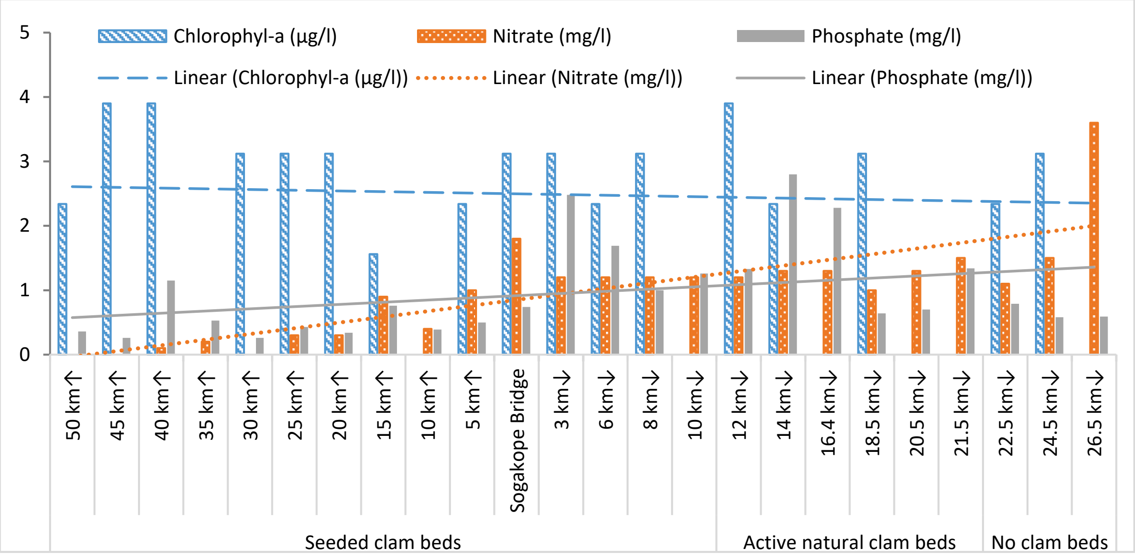


Figure 4.5 Nutrient and chlorophyll-a values in Lower Volta (NB: Sogakope Bridge/Lower Volta Bridge= reference point; ↑ – upstream/northwards from Sogakope Bridge; ↓ – downstream/ southwards from Sogakope Bridge towards the estuary)

Spatial and temporal trends in salinity during spring tide

Up to 7.5 km from the Volta Estuary, where natural clam beds exist, salinities exceeded 8 at depth during the spring tide (Figure 4.6). However, from 8 km to 10 km, the effects of the saltwater intrusion were marginal at depth, while further upstream the salinity was 0.03 throughout the water column (Figure 4.6). This confirms the assertion by Kondakov *et al.* (2020) that the Volta clam, though a freshwater bivalve, has some tolerance to the salinities associated with brackish conditions over short periods (< 4 hours) as observed within the active natural clam bed during the spring tide.

There were significant elevations in salinity during the spring tide when salt water intrusion into the river is at its peak (Appendix D, Figure D3). Two salinity peaks associated with the diurnal tide were recorded by the fixed probe during the 24-hour monitoring period. The saltwater intrusion significantly affected other water quality parameters such as TDS, pH and DO (Appendix D, Table D4). Water temperature near the river bed during the spring tide ranged from 29.3 °C to 30 °C.

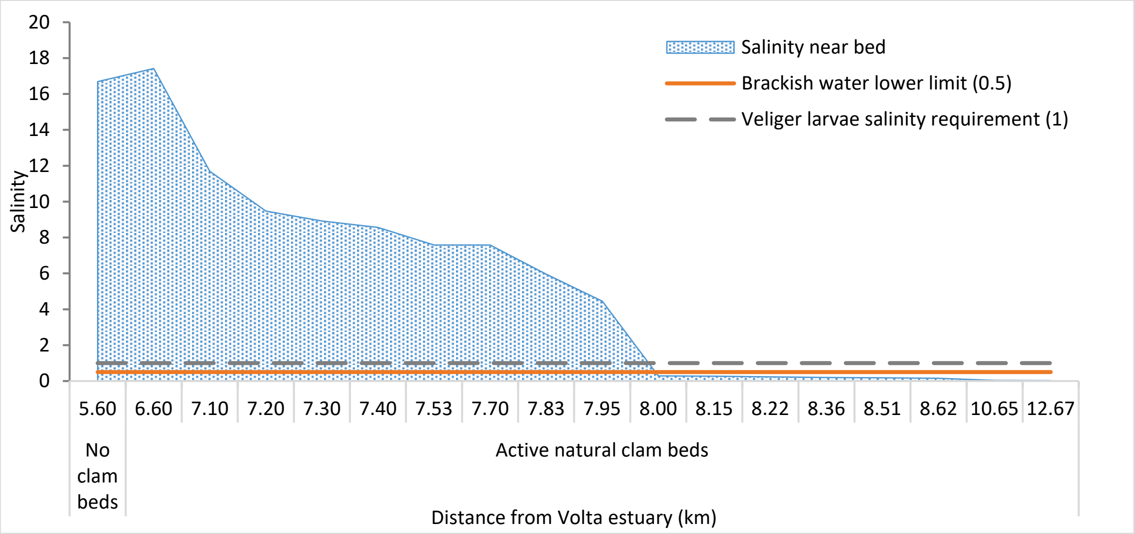
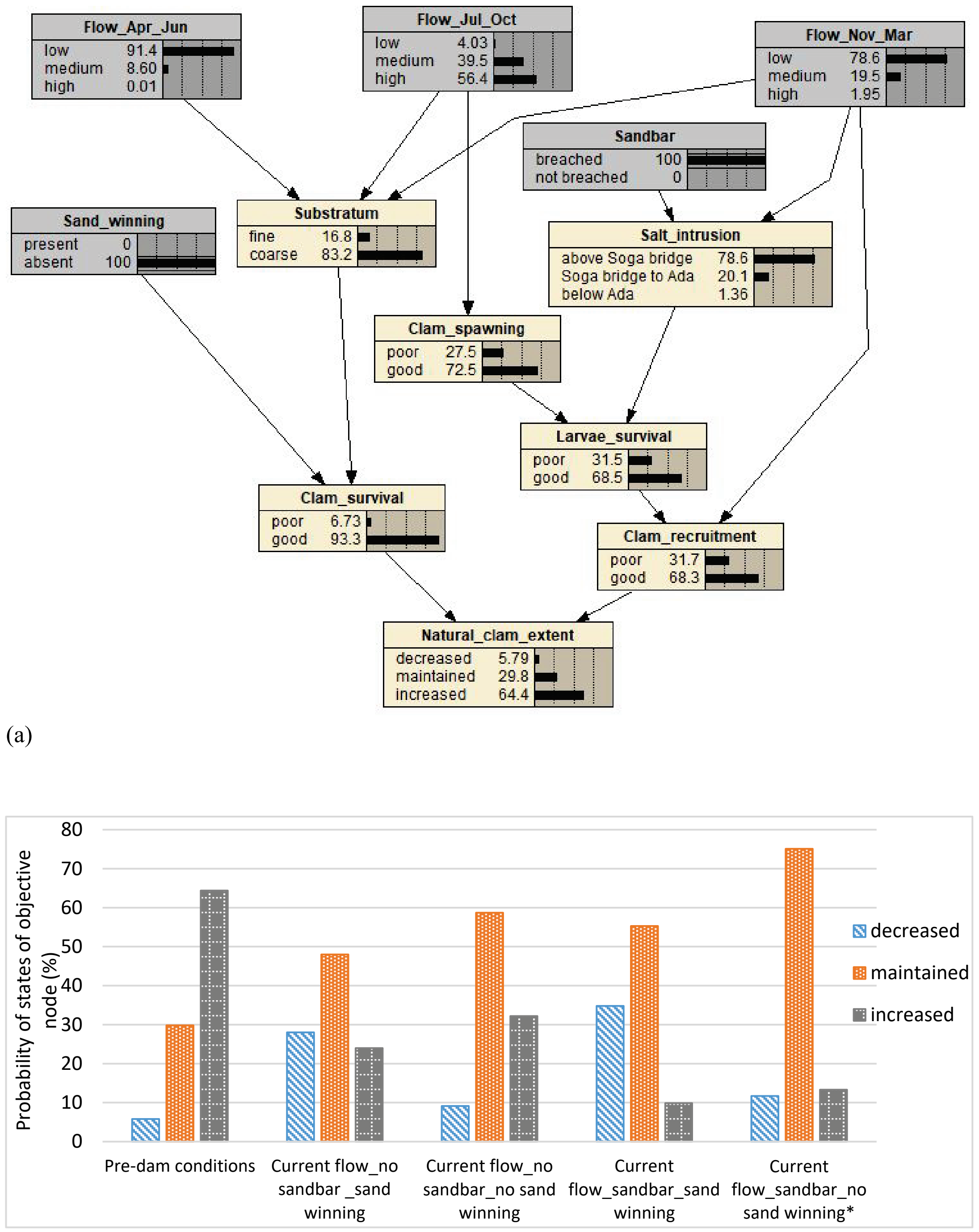


Figure 4.6 Salt intrusion measured near the bed during the spring tide with the salinity values for the lower limit for brackish water and the Volta clam veliger larval stage indicated

4.3.2 Bayesian Belief Network for the Volta clam

Figure 4.7(a) shows the BBN for the Volta clam with the origin nodes set to pre-dam conditions. Details on the nodes, states and their descriptions are included in the Appendix D, Table D5. The final BBN for the Lower Volta clam consists of 12 nodes and 15 directed edges. The year-round flow was separated into three distinct periods based on the life-cycle of the Volta clam up to the adult stage: July to October when spawning occurs; November to March when the clams are in their veliger larva stage and recruitment to adult clams occurs; and then April to June. The probabilities that the clam bed extent is 'decreased', 'maintained', or 'increased' relative to the current 10 km extent given various states of the origin nodes are shown in Figure 4.7(b). It can be seen that, as expected, pre-dam conditions lead to a relatively higher probability (64.4%) of the natural clam bed increasing. Alternatively, current conditions where flows predominantly fall in the medium range all year round, the sandbar is not fully breached and there is no sand winning in the active natural clam bed leads to a 75.1% probability of the active natural clam bed extent staying as it is. Figure 4.7(b) also shows that it is important that sand winning activities are curtailed as these activities lead to relatively higher probabilities of the natural clam bed extent decreasing under current flow conditions with (28% vs 9.1%) or without (34.8% vs 11.7%) the full breaching of the sandbar at the estuary.



(a)

(b)

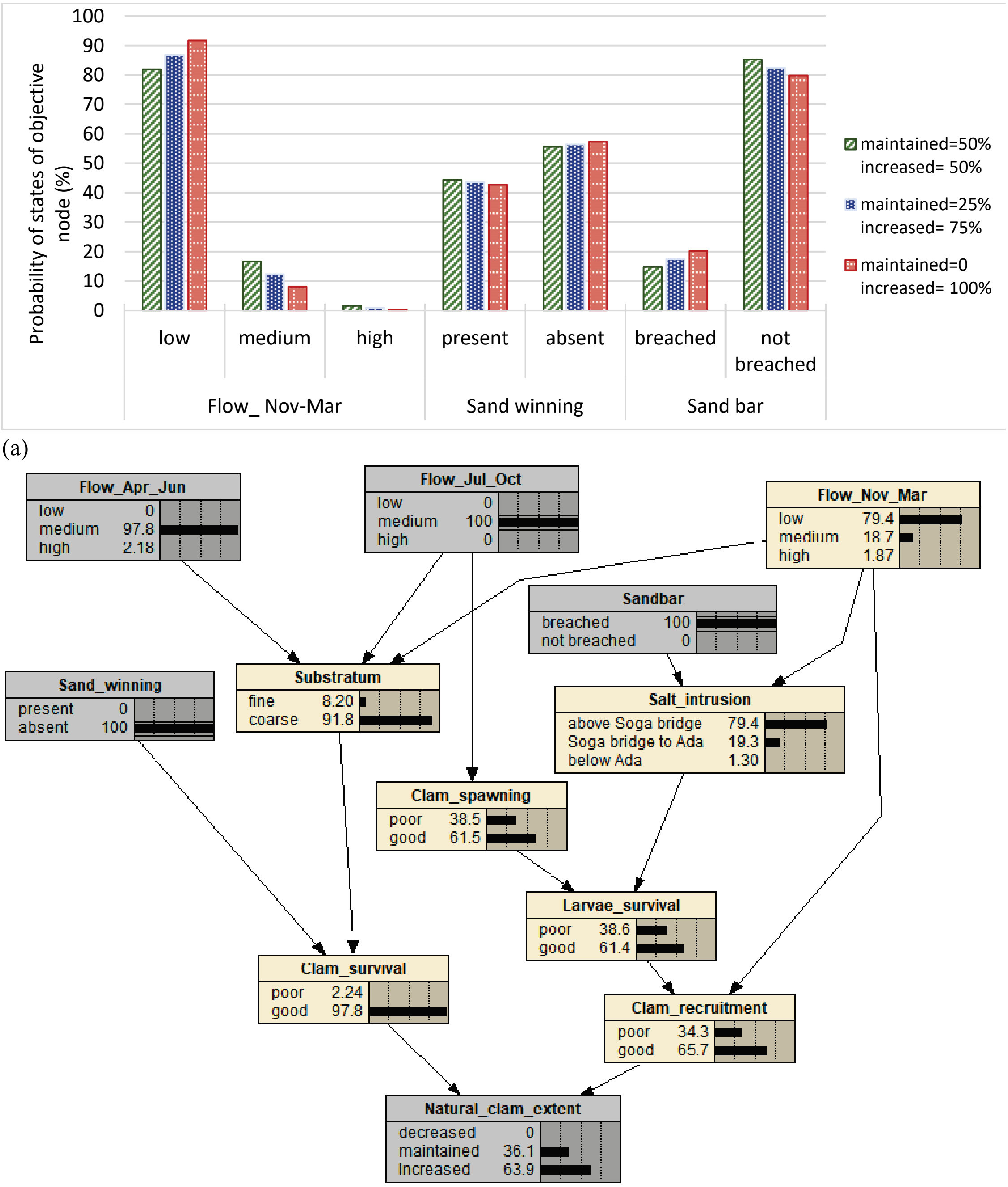
*Figure 4.7 (a) Bayesian Belief Network (BBN) for Lower Volta clam under pre-dam conditions. The dark grey nodes are the origin nodes for which the probabilities of their states have been set (in this case to pre-dam conditions). (b) Probability distribution of the objective node, natural clam bed extent, under different scenarios of the origin nodes: flow, sandbar, sand winning. *Present conditions in the natural clam bed in Lower Volta.*

4.3.3 Environmental flows for the Lower Volta

The result of sensitivity analysis on the Natural_clam_extent node is included in the Supplementary material (Figure D4). In general, nodes closer in proximity to the objective node can be expected to have a stronger effect on it. Therefore, by comparing nodes at similar levels in the network, those nodes with the highest influence on the objective can be identified. For instance, a comparison of clam survival and recruitment shows that the latter has a higher influence on the extent of the clam bed. Of the origin nodes, the flow regime from November to March has the highest influence on the clam bed. Moreover, the results show that managing the sandbar and sand winning activities have bigger impacts on the clam bed extent compared to managing flow releases from April–June and July–October, which reduce uncertainty in the objective node by less than 1%.

The probability distribution of origin nodes which lead to the highest entropy reduction in the objective node under different scenarios are shown in Figure 4.8(a). Because of data uncertainty, the interpretation of the probabilities is not rigid but improves our understanding of what moves the clam bed extent in the right direction. For higher probabilities of the desired objective (i.e. increased active natural clam bed extent), longer periods of low flows are required in November to March, sand winning should be absent, and the sandbar should be fully breached. Figure 4.8(b) shows the BBN for the ideal scenario where the sandbar is fully breached annually and sand winning is absent while the other origin nodes are set to current flow conditions. In all of these scenarios, it can be seen that flow in November to March should be low for about 80% of the time for a high probability of the active natural clam bed extent increasing.

This can be translated as a designer e-flow requirement for flows of between 50 m^3/s to 330 m^3/s for an average of four months starting in November or December, thus satisfying the requirement for low flows 80% of the time over the 5-month period from November to March. In addition, prohibiting sand winning within the natural and seeded clam beds, as well as annual dredging of the sandbar, enhance the habitat of the Volta clam and form recommendations complementary to the designed e-flow.



(a)

(b)

Figure 4.8 (a) Probability distribution of origin nodes which lead to highest entropy reduction in the objective node under different scenarios of the objective node with other origin nodes set to current conditions. For higher probabilities of the desired objective (i.e. increased clambed extent), longer periods of low flows are required in November to March, sand winning should be absent, and the sandbar should be fully breached. (b) Probability distribution of Flow_Nov_Mar node under ideal conditions where sand winning is absent, sandbar is fully breached annually and the other origin *nodes are set to current flow conditions. The dark grey nodes are the origin nodes for which the probabilities of their states have been set (in this case, Flow_Apr_Jun and Flow_Jul_Oct have been set to current flow conditions; Sand_winning, Sandbar and Natural_clam_extent have been set to ideal conditions, i.e.: respectively: 'absent', 'breached' and no probability of the clam bed decreasing).*

4.4 DISCUSSION

4.4.1 Designer environmental flows using Bayesian Belief Networks

Free flowing rivers, by virtue of their dynamic character, not only define but also support healthy riverine environments (Hart and Finelli, 1999; Bunn and Arthington, 2002). Therefore, any modification to the flow regime of a river may lead to a modification of its physical environment and diminish its ability to support the flows, features, and habitats required for native species to thrive (Poff and Zimmerman, 2010; Castello and Macedo, 2016). It is on this basis that the natural flow regime of a river is the ideal e-flow as it encompasses the full spectrum of flow requirements and cues for native species as well as traditional rural livelihoods (Poff *et al.*, 1997). The designer flow is however a more realistic and achievable approach in river basins where there is intense pressure on water resources such that a return to pre-altered state is all but impossible (Bunn and Arthington, 2002; Chen and Olden, 2017). This is the case in the Lower Volta River where electricity generation from the two dams, Akosombo and Kpong, trades-off sharply against the natural flow regime (Annor *et al.*, 2017; Balana *et al.*, 2017). Yet in the case of the Lower Volta, whereas the natural, pre-dam flow regime is known and easily prescribed, a designer flow presents a different challenge. This is because in order to define and quantify flow components that make up the designed e-flow, an understanding of the complex processes, interactions and interconnectivities underpinning species or ecosystems is necessary (Rubin *et al.*, 2002; Melis, 2011). Long-term, consistent and continuous monitoring of water levels, water quality and various species is usually the basis of this understanding. This is seldom available especially in data-poor regions like the Lower Volta basin (Van de Giesen *et al.*, 2001). In such regions, parsimonious e-flow assessment methods using hydrological and/or hydraulic data are the straightforward and thus, the preferred approach to designing e-flows (Efstratiadis *et al.*, 2014; Tegos *et al.*, 2018; Sharma and Dutta, 2020). However, these approaches are not ecologically grounded. In this regard, BBNs provide a useful tool by virtue of the fact that knowledge in various forms, including that of local communities can be used directly to link flow-related changes, ecological factors and ecosystem services (Petts and Brooks, 2006; Van Dam *et al.*, 2013). In the case of the Lower Volta, the factors that influence the lifecycle and habitat of the Volta clam were visualized, linked and quantified despite the fact that no continuous measured data exists for either the Volta clam, water levels or water quality. This BBN model was developed by piecing together information from *ad hoc* data collected during past projects, contemporary field data, official historical records, information on the clam species worldwide, and then local and expert knowledge of the historical range and abundance of the Volta clam, the flow regime and other management practices in the Lower Volta. Considering that there have been relatively few BBN studies in tropical regions or developing countries (Phan *et al.*, 2016), its application to the Lower Volta adds to the body of knowledge in these regions where landcover/land use change, climate change and population growth are of major concern (Lambin *et al.*, 2003; Rathburn *et al.*, 2009; Ouedraogo *et al.*, 2010). The drawback with the BBN approach for designing e-flows is the requirement that feedback loops between nodes are absent (Neapolitan, 2003; Landuyt *et al.*, 2013). In the case of the Volta clam, while spawning and recruitment is an annual occurrence (Adjei-Boateng and Wilson, 2013b, 2016), newly recruited adult clams do not reach sexual maturity for two to three years (da Costa, 2012) therefore any extension in the natural clam bed resulting from e-flows implementation should be observable before the new clams add to the clam numbers. Within this time period the required assumptions of BBNs are valid. However, this drawback of BBNs along with the loss of information due to discretization of variables, makes it unsuitable for modelling more complex systems where multiple ecological indicators are modelled (Landuyt *et al.*, 2013; Niazi *et al.*, 2021) or where there are strong feedbacks between critical variables such as salinity and mouth state in wave dominated estuaries, for instance (Van Niekerk *et al.*, 2019; Slinger, 2017).

4.4.2 Lower Volta environmental flow recommendation

The e-flow recommendation for the Lower Volta is for low flows to support the veliger larva and recruitment stages of the Volta clam. These life stages were found to be the critical stages which give the clam its stenotopic characteristic, and thus where changes to flow and other management practices will have relatively high impact on the extent of the natural active clam bed. By designing the e-flows for the time when these life stages occur, changes to the current flow regime are minimised thereby safeguarding electricity production which is the overriding constraint to e-flows implementation in the Lower Volta (Annor *et al.*, 2017; Balana *et al.*, 2017; Mul, Ofosu *et al.*, 2017). Low flows during these life stages serve two purposes: They enable the freshwater-saltwater interface, where the veliger larva salinity requirement of 1 occurs, to migrate deeper inland, over a longer reach and also results in relatively calmer water which aids the motility of the veliger larvae upstream (Beadle, 1974; Amedzro, 2015). These conditions will allow the veliger larvae to settle over a larger area during recruitment to adult clams thereby colonising a larger area. This low flow e-flow recommendation is not a minimum flow recommendation: the latter is a minimum threshold of flow that has to be released while the former is an upper threshold of flow that should not be exceeded. This seasonal low flow e-flow recommendation is to some extent unusual as historically, the overriding task for e-flow proponents has been to reserve or recover some water as minimum flows, flushing flows or artificial floods (Schmidt *et al.*, 2001; Gippel *et al.*, 2002; Slinger *et al.*, 2005; Robinson and Uehlinger, 2008; Mueller *et al.*, 2017; Shafroth *et al.*, 2017). But due to upstream flow regulation, the annual flow hydrograph for the Lower Volta was flattened and the flow has since been maintained at an all year-round medium flow rate so that both the annual floods and the seasonal low flow have disappeared (Lawson, 1972; Tsikata, 2008; Ntiamoa-Baidu *et al.*, 2017). The 'unusual' e-flow recommendation may prove implementable even in drought years, which are usually a challenge in the cases where high flows are recommended (Owusu, Mul, van der Zaag *et al.*, 2022). The water saved as the result of implementing low flows for part of the year may then be used to supplement flows during the natural high flow period in September to October. This could contribute to flushing flows or artificial floods possibly required for enhanced ecosystem health in the Lower Volta, but which lie outside the scope of this study with its focus on the low flow requirements of a single indicator species.

As evidenced by the BBN analysis for the Volta clam in this study, the low flows - like the annual floods - play a part in defining and supporting unique habitats and lifecycles of native species. This is especially pertinent for many Mediterranean and tropical rivers which typically experience significant variation in flow per year, sometimes flowing intermittently. For such rivers, previous research has highlighted the shortcomings of existing e-flow assessment methods, particularly those that prescribe a minimum flow throughout the year (Costigan *et al.*, 2017; Acuña *et al.*, 2020; Papadaki *et al.*, 2020; Sharma and Dutta, 2020). Consequently, there have been studies specifically focussed on intermittent streams (Theodoropoulos *et al.*, 2018) or the low flow periods in perennial Mediterranean rivers (Papadaki *et al.*, 2020). The BBN approach adopted in this study is potentially applicable to such rivers with highly variable flows as the ranges of flows for different periods can be considered based on the requirements of the indicator species.

4.4.3 Environmental flow trade-offs

The choice of a single ecological indicator in this study is in line with recent trends (Siddig *et al.*, 2016), however, it is acknowledged that no single organism can fully reflect ecosystem complexities. Furthermore, a change in flow in the Lower Volta has implications on other water uses. As such, a full trade-off analysis is required to investigate the impact of low flows from November to March on other biota and water users (Hurford *et al.*, 2014; Annor *et al.*, 2017). This is especially important given data uncertainty and the fact that only one indicator was used to design the e-flows in this study. From previous research and interviews, it is possible to anticipate some impacts of the designed e-flows and already recommend further examination. In addition to the anticipated increase in the extent of the natural active clam bed, it is expected that the recommended e-flows will be beneficial in controlling aquatic weeds as well as water borne and water related diseases like river blindness, bilharzia and malaria (Akpabey *et al.*, 2017; Nyekodzi *et al.*, 2018). It is also expected that aquatic biodiversity of phytoplankton, macroinvertebrates and fish will increase (Akpabey *et al.*, 2017; Mul, Ofosu *et al.*, 2017) and that the shift from a mix of salt and freshwater species to predominantly freshwater species that followed construction of the dams (Akpabey *et al.*, 2017; Mul, Ofosu *et al.*, 2017) may be reversed in some reaches. Considering that formal water supply and irrigation supplies are tapped from Kpong Dam, the recommended e-flows will have minimal impact on these, however adjacent communities withdraw water directly from the river and a higher salt content during the low flow period will impact informal domestic and irrigation water supplies. The main foreseen impact will be a shortfall in national electricity generation in the four months concerned as well as reduced capacity to store flood water at the start of the rainy season (Annor *et al.*, 2017; Balana *et al.*, 2017). While lake fishing is now an important industry, it is anticipated that the recommended e-flows will have a minimal impact on this industry. It is possible that under duress, the recommendation for four months of low flow may be reduced to a minimum of one month, November (Xu *et al.*, 2017). This is because while the window for the veliger larva and recruitment stages occurs from November to March, for an individual clam this period is approximately three weeks long (Abraham and Dillon, 1986; da Costa, 2012). As such, assuming that the peak period for the veliger larva and recruitment stages follows the peak of spawning and fertilization in September to October, this one-month period in November is the time when the clams will derive the most benefit from low flows. Flow experiments investigating the 'real-world' impact of recommended e-flows as well as different durations and timing of low flows on the extent of the Volta clam bed and the trade-off with other water users would favour the successful implementation of e-flows in the Lower Volta (Owusu *et al.*, 2021). Flow experiments would also help to assess the institutional capacity of governing agencies, including traditional governance structures, and the perceptions of the downstream communities regarding the recommended e-flows. This is important because although perceptions of the current flow regime are unfavourable, there are competing interests even within communities (Baah-Boateng *et al.*, 2017).

4.5 CONCLUSION

The provision of environmental flows (e-flows) is essentially the management of water resources to sustain riverine ecosystems which not only have an intrinsic value but also support livelihoods. Using a Bayesian Belief Network (BBN), an e-flow recommendation for the Lower Volta is for low flows (50-330 m^3/s) for four months during the Volta clam veliger larva and recruitment life stages which occur in November to March. In addition, it is recommended that the sandbar which regularly builds up within the Volta estuary is fully breached annually and sand winning from the river bed is prohibited. These e-flow and management recommendations will have consequences for other water users. Therefore, flow experiments and a full trade-off analysis which considers future scenarios including climate change are recommended to assess the implications of implementing the recommended e-flows on the Volta clam and other water users in the Lower Volta River basin.

5

QUANTIFYING THE TRADE-OFFS IN RE-OPERATING DAMS FOR THE ENVIRONMENT IN THE LOWER VOLTA RIVER

The content of this chapter is adapted from: Owusu, A., Mul, M., van der Zaag, P., and Slinger, J.: Quantifying the trade-offs in re-operating dams for the environment in the Lower Volta River. Manuscript submitted for publication, https://doi.org/10.5194/hess-2022-270, 2022.

Supplementary material to this chapter is available in Appendix E

Image: Power lines leading from the Akosombo Dam, Lower Volta, Ghana

Abstract

The construction of the Akosombo and Kpong dams in the Lower Volta River Basin in Ghana changed the downstream riverine ecosystem and affected the lives of downstream communities, particularly those who lost their traditional livelihoods. In contrast to the costs borne by those in the vicinity of the river, Ghana as a whole, has enjoyed vast economic benefits from the affordable hydropower, irrigation schemes and lake tourism that developed after construction of the dams. Herein lies the challenge; there exists a trade-off between water for river ecosystems and related services on the one hand, and anthropogenic water demands such as hydropower or irrigation on the other. In this study, an Evolutionary Multi-Objective Direct Policy Search (EMODPS) is used to explore the multi-sectoral trade-offs that exist in the Lower Volta River Basin. Three environmental flows, previously determined for the Lower Volta are incorporated separately as environmental objectives. The results highlight the dominance of hydropower production in the Lower Volta but show that there is room for providing environmental flows under current climatic and water use conditions if firm energy requirement from Akosombo Dam reduces by 12% to 38% depending on the environmental flow regime that is implemented. There is uncertainty in climate change effects on runoff in this region, however multiple scenarios are investigated. It is found that climate change leading to increased annual inflows to the Akosombo Dam reduces the trade-off between hydropower and the environment while climate change resulting in lower inflows provides the opportunity to strategically provide dry season environmental flows, that is, reduce flows sufficiently to meet low flow requirements for key ecosystem services such as the clam fishery. This study not only highlights the challenges in balancing anthropogenic water demands and environmental considerations in managing existing dams, but also identifies opportunities for compromise in the Lower Volta River.

5.1 BACKGROUND

Freshwater resources are under increasing pressure worldwide (WWF, 2018; He *et al.*, 2019). As global population and standards of living have gone up, the capacity of many river basins to meet social, economic and environmental water demands has declined (Postel and Richter, 2003; Fitzhugh and Richter, 2004; Best, 2019). In the mid-20th century, many dams were built with ambitious goals for hydropower generation, flood control and irrigation among others and dam construction is seeing a resurgence in recent years (Grill *et al.*, 2015; Best, 2019). This phenomenon is occurring, despite the fact that even the economic justification for many existing dams is being called into question (Ansar *et al.*, 2014; Flyvbjerg and Bester, 2021), the life cycle emissions of some dams is above the median emissions for fossil fuel plants (Schlömer et al., 2014; Almeida *et al.* 2019), and the negative social and environmental impacts of dams on riparian ecosystems and communities have been established for some time (WCD, 2000; Duflo and Pande, 2007; Richter *et al.*, 2010; Stone, 2011). Proponents of dam construction argue that in developing regions, particularly in Africa, the large energy deficit (Hafner *et al.*, 2018) coupled with high inter-annual rainfall variability and the fact that 75% of the population live in semi-arid or arid regions (Smith, 2004; Vörösmarty *et al.*, 2005), makes multipurpose dams important infrastructures for energy and food security. Evidently, tools are required for investigating operation policies for managing and maximising the benefits of dams and the water resources they control.

Multi-objective evolutionary algorithms (MOEAs) are one such tool for assessing the trade-offs between water users in a river basin. MOEAs use stochastic search tools to simultaneously find the Pareto approximate set across multiple objectives (Reed et al., 2013; Matrosov et al., 2015; Hurford et al., 2020; Zatarain Salazar et al., 2016; Kiptala et al., 2018). The Pareto approximate or non-dominated set of solutions are the suite of solutions for which increasing the water allocation to one user leads to a reduction in the benefit to others. The advantage of MOEAs is that they do not require pre-specifying preferences across objectives, thereby supporting unbiased a posteriori decision making (Reed et al., 2013; Hurford et al., 2014). Furthermore, MOEAs allow for heterogeneous and non-linear problem formulations with incommensurable objectives and different risk attitudes across objectives. Accordingly, non-market objectives can be evaluated alongside conventional economic objectives. This is particularly useful for including environmental flows (e-flows) and ecosystem services for which monetary valuation is often difficult and contested (Bingham et al., 1995; Costanza et al., 1997, 2014; Luisetti et al., 2011). The capability of MOEAs to find Pareto approximate strategies for a suite of water systems applications has been thoroughly assessed by Reed et al. (2013), and for multi-purpose reservoir operations by Zatarain Salazar et al. (2016). In this paper, an Evolutionary Multi-Objective Direct Policy Search (EMODPS) framework is applied to map the states of a system, in this case, reservoir levels and time of the year, to actions, the release of water for different water uses (Giuliani et al., 2016; Zatarain Salazar et al., 2017). This approach has been applied to find Pareto approximate operating policies for multi-objective, multi-reservoir systems (Quinn et al., 2017; Wild et al., 2019). The motivation to use EMODPS was informed by the fact that for the selected case study, multi-objective reservoir operating policies had to be found under uncertainty. Traditional approaches for optimal control, such as stochastic dynamic programming, do not permit finding the Pareto approximate policies across multiple objectives in a single run, requiring instead that the Pareto front is constructed by testing different weights for each of the system's objectives. Such a method increases the computational burden and yields a sparse Pareto front thereby potentially missing regions of suitable policies. The use of EMODPS overcomes this challenge by generating the trade-offs across all the system's objectives simultaneously in a single algorithmic run, creating a diverse and more accurate Pareto front (Giuliani et al, 2016). This motivates the use of direct policy search, in which radial basis functions are used to find a flexible shape to map storage levels and time to release decisions for multiple objectives.

In many of the studies where MOEAs have been applied, the e-flow objective in the simulation component of the model either meets a minimum flow release (Zatarain Salazar *et al.*, 2017; Kiptala *et al.*, 2018; Hurford *et al.*, 2020; Gonzalez *et al.*, 2021) or minimizes the deviation of flow from the natural, unregulated flow regime (Hurford and Harou, 2014). The former objective, minimum flow releases, fails to thoroughly capture the essence of e-flows which are the "quantity, timing, and quality of freshwater flows and levels required to sustain aquatic ecosystems" (Brisbane Declaration, 2018). The latter, the objective of returning fully to the natural flow regime, is an unlikely objective in many highly modified and utilized river basins (Acreman, Arthington *et al.*, 2014; Horne, Webb *et al.*, 2017). In this study, a multi-objective analysis of the trade-offs between key water users and the environment in the heavily modified Lower Volta River Basin in Ghana is carried out. The environmental objectives are e-flows, including designer e-flows (Acreman, Arthington *et al.*, 2014) developed for different ecosystem services in the basin. In contrast to the aim of restoring a river to a near natural state, designer e-flows define and construct parts of the flow hydrograph of a river to meet certain desired ecological and social outcomes (Acreman *et al.*, 2014; Horne, Webb *et al.*, 2017). Three e-flows, defined for the Lower Volta River in previous studies, are investigated and compared: one to support the Volta clam (Galatea paradoxa) (Owusu, Mul, Strauch *et al.*, 2022) and the other two to support multiple ecosystem services including fisheries, aquatic weed control, flood recession agriculture and sediment transport (Mul, Ofosu *et al.*, 2017). In addition, future climatic scenarios are investigated. This study highlights the challenges faced by dam operators in balancing environmental and anthropogenic water demands for existing dams in heavily modified and utilized river basins, and simultaneously investigates the room for compromise in the case of the Lower Volta River under uncertainty. The main contribution of the paper is twofold: First, it explores the room for compromise in the Lower Volta by the quantifying the Pareto approximate trade-offs when e-flows previously prescribed for the basin are implemented. Secondly this paper is a new application of the EMODPS under high uncertainty where only the system goals and direction of preference are specified in the multi-objective decision problem.

In the following section, a description of the Lower Volta River Basin is given, followed by the methods section in which (i) the simulation model for the lower Volta is described, (ii) the multi-objective evolutionary optimization set up is explained, (iii) the objective functions are formulated, and (iv) relevant climate-induced effects on discharge are specified. Next is the results section where we present the trade-off analysis between e-flows and other water uses in the Lower Volta for the current baseline scenario and possible future scenarios. We conclude with a discussion on the implications of implementing e-flows in the Lower Volta and draw lessons for the application of EMODPS in other heavily modified basins under uncertain future conditions.

5.2 LOWER VOLTA RIVER BASIN

The Lower Volta River, located in Ghana is one of four sub-basins in the Volta River Basin in West Africa (Figure 5.1). It is located furthest downstream, flowing into the Gulf of Guinea and covering an area of 66,700 km^2, approximately 16% of the Volta Basin. The most important hydraulic infrastructure in the Lower Volta is the Akosombo Dam, which was built in 1965 for hydropower production with an installed capacity of 1,038 MW (VRA, 2021). In 1981, a smaller 160 MW run-of-the-river dam, the Kpong Dam, also began operation downstream. The lake created by the Akosombo Dam is the largest man-made lake in the world by surface area at about 8,500 km^2. It has an average depth of 18.8 m and holds approximately 148 km^3 of water at maximum capacity (VRA, 2021).

Construction of the Akosombo Dam led to the resettlement of over 80,000 people (Alhassan, 2009; Darko and Tsikata, 2019) and also changed the dynamic flow regime of the river from one with average low and high flows of approximately 36 m^3/s in March and 5,100 m^3/s in September-October respectively, to a steady flow of about 1,000 m^3/s all year round with no account taken of seasonality (Ntiamoa-Baidu *et al.*, 2017). Consequently, the riverine ecosystem changed and so did the lives of downstream communities. Creek fishing, floodplain agriculture and the clam fishing industries, which together made up three-quarters of total real income of the Lower Volta riparian population in 1954, collapsed (Moxon, 1969; Lawson, 1972; De-Graft Johnson, 1999; Tsikata, 2008). In addition, invasive aquatic weeds proliferated, providing habitat for disease vectors including mosquitoes and snails and thereby increasing the prevalence of waterborne and water related diseases such as malaria and schistosomiasis (Gyau-Boakye, 2001; Akpabey *et al.*, 2017). Other environmental costs include changes to the sediment load leading to erosion along the coastline of Ghana, Togo and Benin (Bollen *et al.*, 2011; Roest, 2018; Appeaning Addo *et al.*, 2020), as well as a reduction in salt water intrusion (People and Rogoyska, 1969; Beadle, 1974; Nyekodzi *et al.*, 2018). Among the population in the Lower Volta, perceptions of the Akosombo and Kpong dams downstream, are still overwhelmingly negative: in a survey of over 400 citizens older than 50 years in 2016, approximately 92% considered their socio-economic conditions to be better under pre-dam natural flows (Baah-Boateng *et al.*, 2017).

Figure 5.1. The Akosombo and Kpong dams located in the Lower Volta River Basin, which discharges into the Gulf of Guinea

The costs borne by the river ecosystem and the communities in the vicinity of the dams in the Lower Volta is in strong contrast to the vast economic benefits that Ghana as a whole has enjoyed from the relatively affordable hydropower, irrigation schemes and tourism that developed after construction of the dams (Alhassan, 2009; Eshun and Amoako-Tuffour, 2016). After construction, the Akosombo Dam provided over 70% of Ghana's electricity and is credited with powering Ghana's industrialization and making it one of the most developed countries in West Africa (Alhassan, 2009). The dam currently makes up about 20% of the installed electricity generating capacity in Ghana (Dye, 2020) and is operated by the Volta River Authority (VRA).

The local-national mismatch in benefits deriving from the operation of the Akosombo dam has been investigated in previous studies, notably in 2016 by Ntiamoa-Baidu *et al.* (2017). The 2016 study adopted a simulation based approach using the Water Evaluation and Planning (WEAP) tool to compare the current flow regime with the natural flow regime and two other scenarios for re-operating the Akosombo dam (Annor *et al.*, 2017; Mul, Balana *et al.*, 2017). The alternative dam operation scenarios were found to reduce power generation by 45% to 74%, which were both deemed undesirable (Annor *et al.*, 2017). This was at a time when Akosombo and Kpong dams made up about 40% of installed capacity and Ghana was experiencing power rationing due to low water levels in the Volta River and a shortfall in gas supply to other power plants (Dye, 2020). The present energy context of Ghana is very different and is characterized by an "overabundance" of electricity generation potential - almost twice the peak load demand and therefore the potential for a reduced dependence on power generation at Akosombo and Kpong dams. (Kumi, 2017; Dye, 2020). While installed capacity does not directly translate into power delivery, it is worth re-examining the trade-offs between water users in the Lower Volta under this changed situation given that it is as a result of 'take-or-pay' power purchase agreements with private power companies whereby 90% of the power made available by these companies has to be paid for irrespective of whether it is used or not (Dye, 2020). In 2018, the cost of this extra capacity was approximately 5% of the country's gross domestic product (GDP) (The World Bank, 2018; Dye, 2020)

5.3 METHODS

The simulation model for this study was developed using the mass balance of inflows, net evaporation rates and releases from the Akosombo Dam from 1981 to 2012. In addition to net evaporation and inflows, additional input data to the model consisted of downstream water levels and physical characteristics of the dam such as the storage-area-level relationships. The model was initially set up using the current baseline dam operation policy for hydropower, flood control and irrigation over a wet (2010), dry (2006) and normal (1985) year. The choice to calibrate for years with specific conditions as against the full historical timeseries was a practical one to expedite the calibration phase of the study. The Nash-Sutcliffe model efficiencies of 0.89, 0,91 and 0.90 were obtained when the modelled and observed reservoir volumes were compared for each of the wet, dry and normal years respectively, thus indicating a good model fit (Figure E1-E3, Appendix E).

Radial Basis Functions (RBF) were used to parameterize the control policies for mapping reservoir levels and the time into daily release decisions (Zatarain Salazar *et al.*, 2016, 2017). RBFs are non-linear approximating networks that allow time dependent operating decisions to depend on more than a single variable. Most importantly, RBFs can accommodate multiple objectives simultaneously (e.g., hydropower, irrigation, flood prevention, and e-flows). By providing alternative Pareto approximate solutions, it is possible to visualise trade-off between the objectives and thereby inform policy decisions. In a comparative analysis, Giuliani *et al.* (2016) found that RBF solutions performed better in terms of convergence, consistency and diversity of solutions as compared to another widely used universal approximator, Artificial Neural Networks (ANN). Indeed, using such a non-linear approximating network avoids "restricting the search for the optimal policy to a subspace of the decision space that does not include the optimal solution" (Giuliani *et al.* 2018).

5.3.1 Multi-objective problem formulation for the Lower Volta system

When the storage volume in the reservoir is known at time t, and the decision time step is set to 1, the downstream releases can be determined for the time interval $[\mathrm{t}, \mathrm{t}+1]$. The release from Akosombo Dam (r_{t+1}^{Ak}) is determined by the irrigation, hydropower, environmental and flood control demands (r_{t+1}^{IHEF}) (Eq. (5.1)) (Figure 5.2). Kpong Dam is operated as a run-of-the-river hydropower system by VRA after water is diverted for irrigation (Eq. (5.2)).

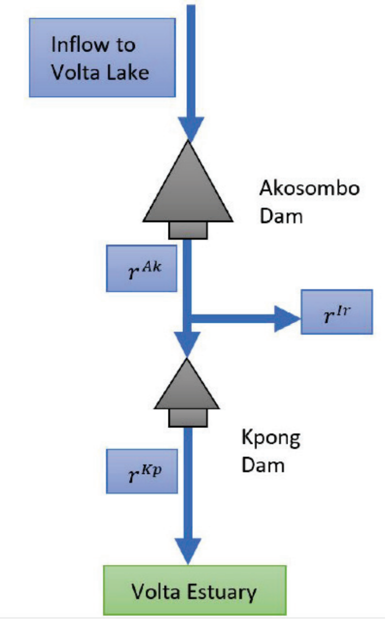


Figure 5.2 Topology of reservoir system in the Lower Volta. r^{Ak}, r^{Kp} *and* r^{Ir} *are the flow releases from Akosombo, Kpong and for irrigation respectively.*

The release from Kpong Dam (r_{t+1}^{Kp}) is therefore calculated as the difference between the release from Akosombo Dam and irrigation (r_{t+1}^{Ir}), and represents the downstream releases for hydropower, e-flows and floods (r_{t+1}^{HEF}).

$$r_{i+1}^{Ak} = r_{i+1}^{IHEF} \tag{5.1}$$

$$r_{i+1}^{Kp} = r_{i+1}^{Ak} - r_{i+1}^{Ir} = (r_{i+1}^{HEF}) \tag{5.2}$$

The operating policy is commonly parametrised as a function of the reservoir storage volume at a particular time. The parameterized operating policy f is then defined as a mapping between the decisions $\boldsymbol{u}_t$ and the policy inputs z_t comprising the time t and system state, or storage volume, x_t, Eq. (5.3) , namely:

$$\boldsymbol{u}_t = f(z_t) \tag{5.3}$$

The kth decision variable in the vector $\boldsymbol{u}_t$ (with $k = 1, \dots, n$) is therefore defined as a weighted sum of radial basis functions, as specified in Eq.(5.4):

$$u_t^k = \sum_{i=1}^{N} w_{i,k} \varphi_i\,(z_t) \tag{5.4}$$

where N is the number of radial basis functions $\varphi_i(\cdot)$, and $w_{i,k}$ is the non-negative weight of the ith radial basis function, and the N weights sum to unity. The ith Gaussian radial basis function is then given by Eq. (5.5):

$$\varphi_i(z_t) = exp\left[-\sum_{j=1}^{M}\left(\frac{\left(z_t - c_{j,i}\right)^2}{b_{j,i}^2}\right)\right] \tag{5.5}$$

Where $j = 1, .., M$ is the number of input variables, z_t is the policy input (e.g. time t, reservoir level x_t) and $c_{j,i}$ and $b_{j,i}$ are the centres and radii respectively of the ith Gaussian radial basis function for the jth input variable. The parameter vector θ is defined as $\theta = (c_{i,j}, b_{i,j}, w_{i,k})$ with $i = 1, .., N$; $j = 1, .., M$; $k = 1, .., n$, where the centre and radius are normalized with $c_{i,j} \in [-1,1]$ and $b_{i,j} \in (0,1]$. The policy parameters θ are determined by simulating the system over the time horizon H under the policy $f = \{f(t, x_t, \theta) \colon t = 0, \dots, H-1\}$. In this way the inputs to the RBF policy (time index and reservoir storage volume) are mapped to the outputs (release decisions). The policy parameters are evaluated by solving the multi-objective problem function, *f,* specified in Eq.(5.6) in the objective space using an informed search algorithm θ^*. The objective functions J are the operating objectives of the reservoir as defined in Eq.s (5.7) to (5.12) with any maximization objectives multiplied by -1 to reformulate all the objectives as minimizations.

$$f\theta^* = \arg\min_{\theta} J(\theta) \tag{5.6}$$

The number of RBFs used in this study was four (i.e. $n = 4$). Thus, the total number of parameters (θ) for the control policy in this study is 24. A daily decision timestep, representative of "real operations" of the two dams by VRA was used (Annor *et al.*, 2017). The simulation time horizon, *H*, of 29 years using historical data starting from January 1984, was constrained by the availability of data. This period however encompasses key dry and wet periods. In 1997-2000 and 2006-2007, there was power rationing in Ghana as water levels in the Akosombo reservoir fell to 73.01 m (July 1999) and 72.16 m (August 2006) respectively; both lower than the minimum operating level of 73.15 m (VRA, 2021). On the other hand, in 1991 and 2010, extremely high inflows caused the reservoir water level to rise to 83.90 m and 84.42 m, respectively, close to the maximum operating level of 84.73 m, and necessitated the opening of the spillways. The 2010 reservoir level remains the highest point ever recorded at Akosombo. The four objectives considered in this study are described in more detail below:

1. Annual hydropower: Maximization of the annual hydropower generated at Akosombo and Kpong dams as defined in Eq. (5.7). While the annual firm power requirement from Akosombo Dam is 4,415 GWh/year, the amount of electricity generated has typically exceeded this target in the past due to high national dependence on power generation from this dam. As such, operations at Akosombo has generally been to maximise power considering the reservoir volume and inflows to the dam (Annor *et al.*, 2017). There is no firm power target at Kpong which is a run-of the river dam and generates power with releases from Akosombo after the diversion for irrigation.

$$J_H = \sum_{t=1}^{I} HP_t \qquad (5.7)$$

where energy production (HP_t) in GW is given by Eq. (5.8):

$$HP_t = \eta g \rho_w h_t \, q_t^{turb} \, .10^{-9} \qquad (5.8)$$

where $t \in I$ are the days in a year, η is the turbine efficiency (dimensionless), g is acceleration due to gravity (9.81 m/s ^{2}), ρ_w is water density (1000 kg/m^3), h_t is net hydraulic head (m) and q_t^{turb} is flow through the turbines (m^3/s). The hydropower objective at Akosombo is subject to constraints on the minimum daily firm power requirement of 6 GWh/day for system stability and the maximum possible power production due to turbine capacity (1,603 m^3/s) at the maximum safe operating level of 84.73 m.

2. Irrigation: Maximization of the volumetric reliability of water supply to meet irrigation demand as described in Eq.(5.9).

$$J_I = \frac{1}{H} \sum_{t=1}^{H} \frac{q_t}{V_t} \qquad (5.9)$$

subject to the constraint in Eq. (5.10):

$$0 \le q_t \le Q_t \qquad (5.10)$$

where V_t, q_t and Q_t are the irrigation demand, the diverted water and the flow at diversion point at time t, a day within the simulation horizon H. The current irrigation demand is 10 m^3/s but there have been plans since 2009 for this to be increased to 38 m^3/s for the Accra Plain Irrigation Project and the expansion of the Kpong left bank irrigation project (GIDA, 2009). These projects are yet to be fully realized however, and in this study the anticipated irrigation demand of 38 m^3/s is used as the baseline value.

3. Flood control: Minimization of flood occurrences defined by the average number of days where downstream flow releases from Kpong, r_{t+1}^{Kp}, exceed 2300 m^3/s, the bank full capacity of the river (Q_F) (Eq.(5.11)). Opening of the spillways of the Akosombo and Kpong dams is quite rare and has occurred only twice, in 1991 and 2010. Consequently the riparian communities are ill-prepared for flood releases and incur high losses whenever floods are released (Ayivor and Ofori, 2017).

$$J_F = \frac{1}{H}\sum_{i}^{H}\left(\frac{\max\left(r_{i+1}^{Kp} - Q_F,\ 0\right)}{Q_F}\right) \tag{5.11}$$

4. E-flows: The trade-off between the three objectives defined above and three different e-flows (Figure 5.3) are investigated in separate runs in this study. As such, three different configurations of the trade-off problem are investigated.
    a. Clam e-flows (Figure 5.3a): This e-flow was designed for the Lower Volta River using the Volta clam, a stenotopic, freshwater bivalve, as an indicator species (Owusu, Mul, Strauch *et al.*, 2022). The recommended flow is a low flow range of 50 - 330 m^3/s from November to March to support the clam's veliger larvae stage, a key life stage in its lifecycle. An 80% reliability of this flow occurring in the stipulated months is an acceptable compromise for the survival of the clam veliger larvae (Owusu, Mul, Strauch *et al.*, 2022). While only a low flow is prescribed for five months in this e-flow recommendation, this necessarily implies that flow releases at other times of the year will be higher, although the magnitude, duration and timing of this such flow is not defined and thus does not form a constraint for clam e-flows. The historical minimum for high flows in September and October under pre-dam flows was 1052 m^3/s.
    b. Natural flow dynamics considering bank full flows (e-flows 2) (Figure 5.3b): This e-flow reinstates natural flow dynamics in the Lower Volta to support multiple ecosystem services including fisheries, aquatic weed control and sediment transport (Mul, Ofosu *et al.*, 2017). The minimum discharge for the high flow period in September to October is 2,300 m^3/s, (which is the bank full flow rate) to ensure that river overtopping and thus some minimum flooding of pre-dam

floodplains occurs. The maximum dry season discharge for the rest of the year is 700 m^3/s.

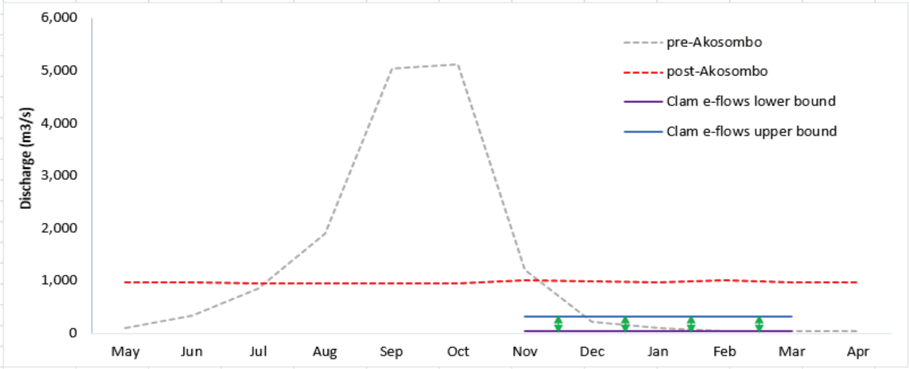
c. Natural flow dynamics considering future dry season irrigation (e-flow 3) (Figure 5.3c): This e-flow also re-instates natural flow dynamics of the Lower Volta while providing water for future dry season irrigation demands (Mul, Ofosu *et al.*, 2017). The minimum high flow in September and October is 3000 m^3/s, which inundates an area of approximately 156 km^2, to support creek fishing and flood recession agriculture. The maximum dry season flow rate is 500 m^3/s, representinga further reduction in dry season flow closer to the natural situation.

The three alternative e-flow objectives (clam e-flows, e-flows 2 and e-flows 3) were modelled as a maximization of the reliability of the recommended flow rates occurring (Eq. (5.12)):

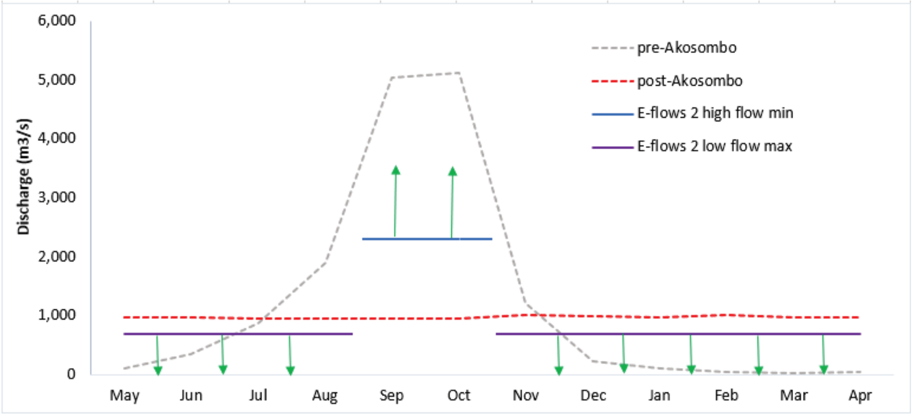
$$J_E = 1 - \frac{\mathrm{n}_E}{n_T} \tag{5.12}$$

where n_E is number of days when downstream flow falls outside the e-flow range and n_T is the total number of days when the recommended e-flows are required.

a. Clam e-flows



b. E-flows 2



c. E-flows 3

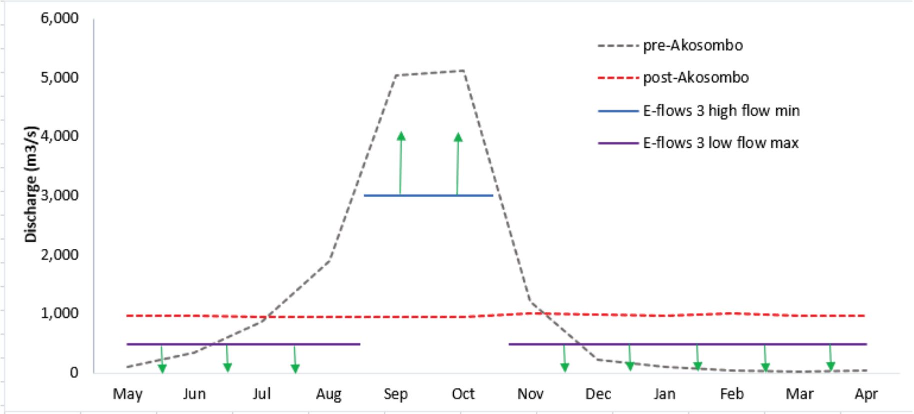


Figure 5.3 E-flow configurations considered in this study with pre-dam (natural) and current post dam flow regime in the Lower Volta provided for comparison (using monthly average flow data from Volta River Authority, Ghana) for a hydrological year which starts in May in the Lower Volta. For clam e-flows the green arrows show the range of low flows recommended from November to March. For e-flows 2 and 3, the prescribed flow for September and October are a minimum threshold while for the other ten months, this flow is a maximum threshold. The green arrows begin at these thresholds and point in the direction of where the flows should be per the e-flow recommendation.

5.3.2 Future climate scenarios

In addition to a baseline scenario optimizing the trade-offs between hydropower, irrigation, flooding and e-flows under the present climate, future scenarios representing different climate futures were analysed. The recent Sixth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC) projects that mean temperature in West Africa will increase 1.5 °C by 2040 and projects with high confidence that monsoon rainfall over West Africa will increase in the mid (2041-2060) to long term (2081-2100) but have a delayed start (IPCC, 2021). Future projections made with medium confidence relate to the delayed retreat of the monsoon rains and an increase in the frequency and duration of droughts in the latter part of the 21st century (IPCC, 2021).

These latest climate projections draw a mixed picture of future climate in the West African sub-region. A further review of the anticipated impacts of climate change specifically on runoff in the Lower Volta was carried out with the goal of identifying studies that focussed on the entire Volta basin, either as a whole or all sub-basins. A search was conducted in Scopus using the search string: TITLE-ABS-KEY (Volta AND climate AND (change OR impact), AND (flow OR discharge OR water) AND (availability OR resources)). From the 60 papers returned, a review by Roudier *et al.* (2014) on climate change impacts on runoff in West African Rivers provided the first point of reference. From this review by Roudier *et al.* (2014), four studies meeting the search criteria were identified. An additional four papers from the Scopus search results, not reviewed by Roudier *et al.* (2014), were also retained for analysis.

Four papers (Kunstmann and Jung, 2005; Aerts *et al.*, 2006; Jung *et al.*, 2012; Abubakari, 2021) found that annual runoff in the Volta will increase (by 4% to 65%), and of these papers, three (with the exclusion of Aerts *et al.* (2006)) also presented monthly trends which generally showed an increase in wet season flow from June to October and a decrease in dry season flow. The findings on only monthly trends of Jin *et al.* (2018) are also in line with these predictions. McCartney *et al.* (2012) and Sood *et al.* (2013), in contrast, find that there will be a decrease in annual runoff (ranging from -13% to -45%) while Amisigo *et al.* (2015) find that the results across the various scenarios are inconsistent. Table E1 in Appendix E provides further details on the papers, the climate change scenarios considered and the models used. It is important to note that using a combination of models, i.e.: global and regional climatic models and then hydrological models, introduces uncertainty in the findings of climate projections for runoff (McCartney *et al.*, 2012) and the wide-ranging results from the reviewed papers show that particularly in the case of the Volta the direction of change in runoff is still unclear.

The climate-runoff studies, just as the latest IPCC report, present a mixed picture for the Lower Volta. Therefore, bearing the high level of uncertainty in mind, five scenarios indicative of the range of climate-induced changes predicted for the Volta discharge for the mid to long term are investigated (Table 5.1). These include both increases and decreases in annual runoff as well as seasonal variations in runoff into the Lake Volta.

Table 5.1. Design of future scenarios encompassing climate-induced changes in the Lower Volta discharge

Scenario	**Annual decrease**	**Annual increase**		**Seasonality**		
	Decrease -45%	**Increase +12%**	**Increase +65%**	**Dry season decrease (Nov to May) -10%**	**Wet season increase (Jun to Oct) +10%**	**Wet season increase (Jun to Oct) +55%**
1	x	-	-	-	-	-
2	-	x	-	-	-	-
3	-	-	x	-	-	-
4	-	-	-	x	x	-
5	-	-	-	x	-	x

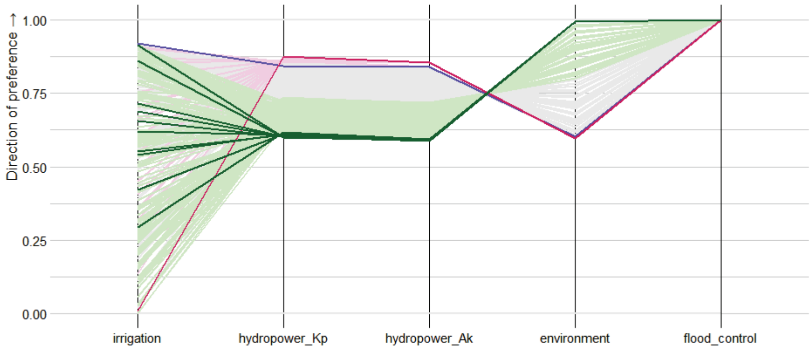
5.4 RESULTS

The relationship between different water users in the Lower Volta is presented using parallel axis plots (Figure 5.4 and Figure 5.5). Every line crossing the axes is a Pareto approximate (non-dominated) solution and shows the performance of each water user under an alternative dam operation policy for the Lower Volta system. The range of values for each water user has been normalized using its maximum and minimum values with the best performance featuring at the top of each axis. For irrigation and the environmental objectives, the highest value is interpreted as a dam operation policy whereby 100% of irrigation demand and e-flows are provided, while for the flood control objective, this is interpreted as there being no downstream flow releases above the flooding flow threshold of 2300 m^3/s over the simulation horizon. For hydropower at Akosombo and Kpong dams, the maximum and minimum values used in the normalization encompass the maximum and minimum annual hydropower generated across all the scenarios considered: at Akosombo Dam these are 5,100 and 845 GWh/year respectively and at Kpong Dam, 1,000 and 130 GWh/year respectively. The trade-offs between the three e-flow objectives and other water users are shown with the 'best' or highest performing operation policy for each objective in that scenario highlighted. Additionally, room for compromise, characterised in this study as operation policies meeting the firm hydropower demand of 4,415 GWh/year for Akosombo Dam ("fair hydropower") and e-flow demands at least 80% of the time ('fair environment'), have also been highlighted. It is important to note that, the terms 'best' and 'fair' as used here, are not qualifying adjectives but solution descriptors in the Pareto approximate space with the latter used to denote ‘reasonable’ or ‘satisfactory’ rather than ‘equitable’ solutions. Cumulative distribution graphs showing the function values for the baseline and future scenarios are presented in Figure E2 in the supplementary materials.

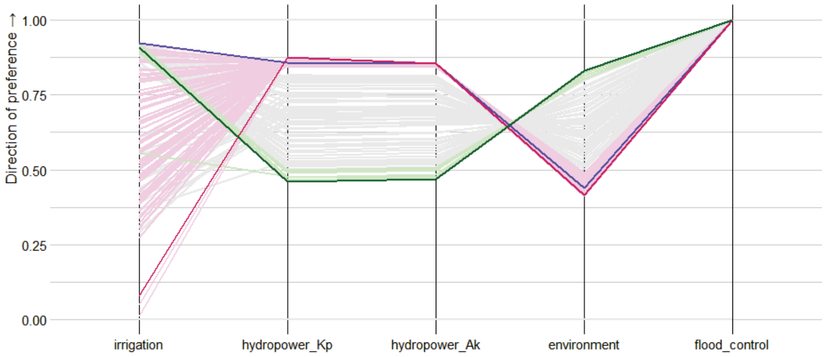
5.4.1 Baseline scenario

For the baseline scenario (Figure 5.4), the highest performing dam operation policies for hydropower trade-off sharply with the provision of e-flows (all configurations) in the Lower Volta such that there is no overlap even among ‘fair’ solutions for either objective for all e-flow configurations considered in this study. To meet the current firm energy requirement of 4,415 GWh/year at Akosombo, e-flows can only be released about 60%, 49% and 47% of the required time for the clam e-flows, e-flows 2 and e-flows 3, respectively. From the environmental perspective, the results show that hydropower demand from Akosombo and Kpong have to fall to approximately 3,903 GWh/year and 760 GWh/year respectively for the release of clam e-flows; or approximately 3,000 GWh/year and 563 GWh/year for the release of e-flows 2; or alternatively approximately 2,711 GWh/year and 508 GWh/year for the release of e-flows 3 to become possible 80% of the recommended time under current climatic conditions. The solutions for clam e-flows generally lead to higher hydropower generation compared to the other e-flows because for seven months of the year there is no constraint on water releases in the Lower Volta for the environment, hence hydropower generation can be maximised in these months. Comparing the dynamic e-flow configurations, e-flows 2 yields higher hydropower generation because its dry season flow recommendation is higher at 700 m^3/s as compared to that of e-flow 3 which is 500 m^3/s thus allowing for higher power generation in the dry season.

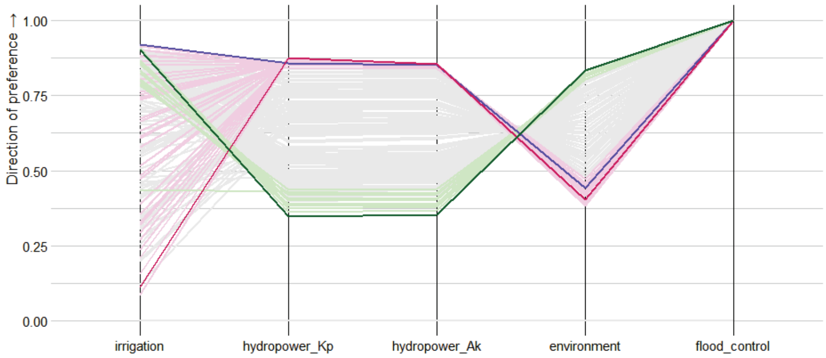
Considering the relatively low water demand for irrigation as compared to hydropower, marginal increases in hydropower generation at Kpong lead to significant reduction in the amount of irrigation demand that is met in the baseline scenario. The solutions for all e-flow configurations perform well for the flood control objective even though e-flow 2 and 3 prescribe flood releases for two months of the year. As such, comparing clam e-flows to e-flows 2 and 3, there is a reduction (0.99 for clam e-flows vs. 0.83 for e-flows 2 and 3) in the performance of the ‘best environment’ solution for the latter two, as expected, showing that the requirement for floods for two months in a year in those e-flow configurations are not being met.



a: Clam e-flows



b: E-flows 2



c: E-flows 3

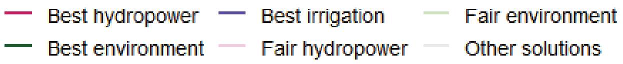


Figure 5.4: Full set of non-dominated solutions in the baseline scenario with the 'best' solution for each water user and 'fair' solutions for hydropower and environment highlighted. The objective values for each water user have been normalised using the minimum and maximum values over all simulations with the highest performance for each objective placed at the top of the axes. The order in which water users are presented has been chosen to highlight trade-offs between them.

5.4.2 Future scenarios

The effects of different climate futures on the Pareto approximate solutions for the Volta basin are presented in Figure 5.5. Scenario 1, where there is 45% decrease in annual inflows to Akosombo dam stands out as the system becomes water stressed so that the best performing operation policies even for hydropower lead to only about 2,776 GWh and 550 GWh annual power generation at Akosombo and Kpong respectively for all e-flow configurations. The best operating policies for the environment however improve slightly from 0.99 to 1 for clam e-flows and remain unchanged at 0.83 for e-flows 2 and 3 relative to the baseline. This is because these solutions, even in the baseline scenario are those for which only dry season low flows are released. In contrast to Scenario 1, under Scenario 3 and to a lesser extent Scenario 2, where annual flows to the Akosombo Dam increase by 65% and 12% respectively, the solutions move up on the two hydropower axes and some fair solutions for the environment lead to higher annual hydropower production of up to 4,242, 3,392 and 2,926 GWh/year for clam e-flows, e-flows 2 and e-flows 3 respectively at Akosombo.

Seasonal climate change effects on the Lower Volta system under scenarios 4 and 5 are comparable to annual climate change effects. As a result, the solutions for Scenario 4 are similar to Scenario 2 while those for Scenario 5 are similar to Scenario 3 save for the slightly lower hydropower generation values for Scenario 5 and hence fewer 'fair hydropower' solutions in line with its relatively lower inflows (+65% annual inflows for Scenario 3 vs 55% wet season inflows for Scenario 5). This is due to the high residence time of water in the Lake Volta (3.9 years) and the fact that the Lower Volta has highly seasonal inflows naturally so that an annual inflow increase applied to inflows across the year, as applied in Scenario 2 and 3, results in a minimal increase in the absolute values of inflows to the dam in the dry season but a relatively significant increase in the absolute values of wet season inflows, thus amplifying seasonality.

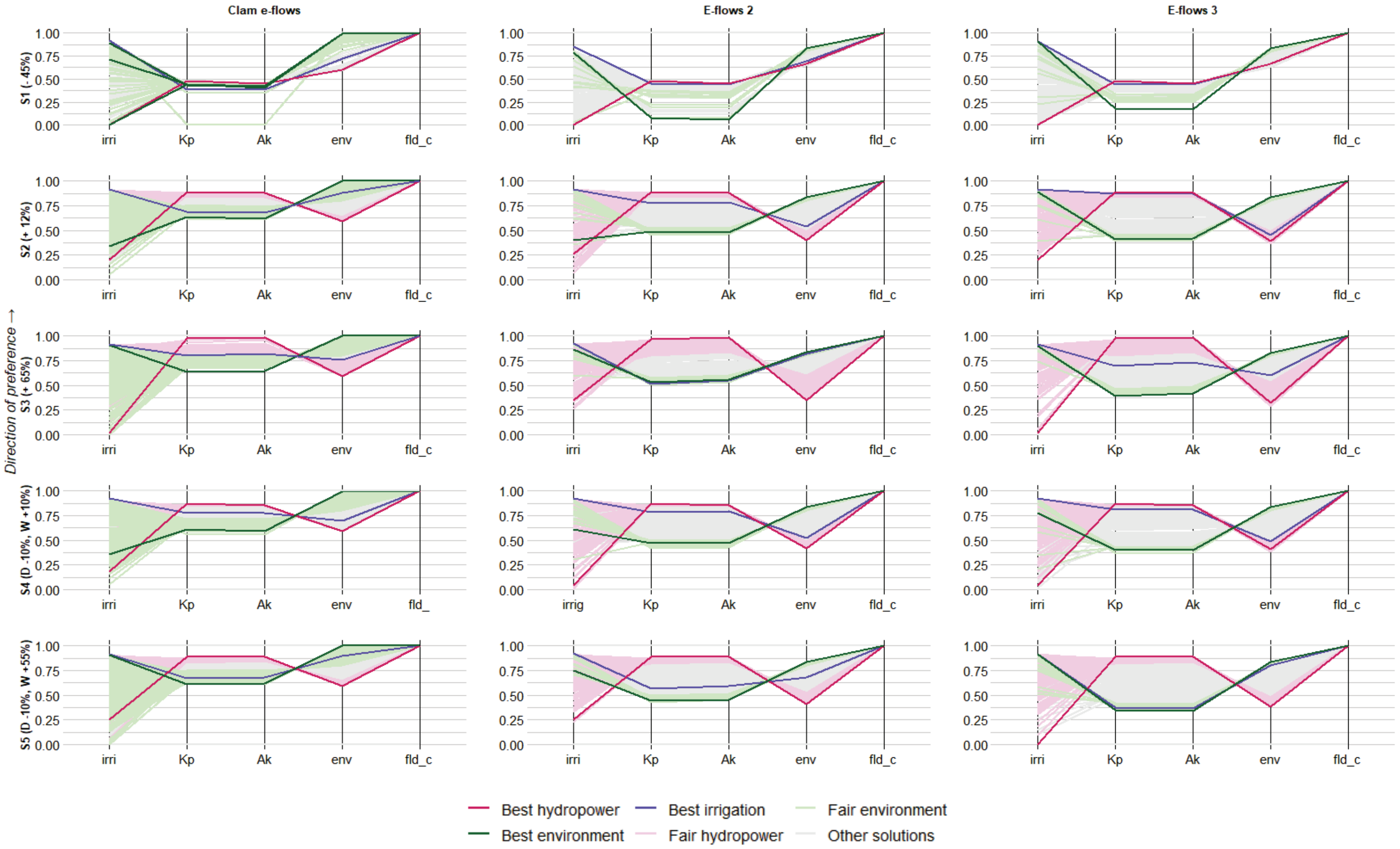


Figure 5.5: Full set of non-dominated solutions in the future scenarios with the 'best' solution for each water user and 'fair' solutions for hydropower and environment highlighted. The objective values for each water user have been normalised using the minimum and maximum values over all simulations with the highest performance for each objective placed at the top of the axes. The order in which water users are presented has been chosen to accentuate the trade-offs. Notation- water users: Irri- irrigation, Kp- hydropower from Kpong Dam, Ak- hydropower from Akosombo Dam, env- environment (clam e-flows, e-flows 2 or e-flows 3), fld_c- flood control. Notation- scenarios: S1 to S5- Scenario 1 to 5, D- dry season flow, W-wet season flow.

5.5 DISCUSSION

The Lower Volta River System is characterized by the dominance of hydropower generation for Ghana and its neighbouring countries. This has come at a high cost to downstream ecosystem services and communities (Lawson, 1972; Tsikata, 2008; Ntiamoa-Baidu *et al.*, 2017). The results from this study show that likewise, some cost to hydropower production would have to be borne for e-flows implementation and the restoration of some of these ecosystem services under current climatic conditions. To elaborate, for the implementation of clam e-flows 80% of the time, i.e. a fair environmental solution, the country would forfeit at least 11.6% of the firm annual power demand from Akosombo Dam. For the implementation of only the dry season flow recommendations of e-flows 2 and 3, about 32% and 38% respectively of current firm energy requirement would have to be supplemented with power generation from other sources. The release of floods as recommended in the dynamic e-flow configurations (e-flows 2 and 3) is not a *Pareto-optimal* operation policy within the current operating constraints of the Akosombo Dam because in addition to flooding pre-dam floodplains which are now permanently inhabited (Ayivor and Ofori, 2017), releasing flows above the maximum turbine capacity of 1,603 m^3/s at Akosombo means that these water volumes are lost to power generation. Flood releases also far exceed irrigation water demands.

While the majority of climate predictions for the Volta River generally point to an increase in annual water availability (Kunstmann and Jung, 2005; Aerts *et al.*, 2006; Jung *et al.*, 2012; Jin *et al.*, 2018; Sylla *et al.*, 2018; Abubakari, 2021), based on this study, an argument can be made that both an increase or a decrease in inflows to the Lower Volta enhance the potential for e-flows implementation compared to the current baseline. On the one hand, an increase in inflows to the Akosombo dam as applied in scenario 3, reduces the amount of the firm energy requirement that would have to be supplemented by other sources for the implementation of ‘fair environmental solutions’ to about 3.9% (vs. 11.6%) for clam e-flows, and then 23.2% (vs. 32%) for e-flows 2 and 33.7% (vs. 38%) for e-flows 3. On the other hand, a decrease in inflows to the Akosombo Dam as in scenario 1, whereby at best only 2,774 GWh/year of hydropower can be generated, provides opportunity to strategically release recommended dry season e-flows (i.e. the release of less water than usual post-dam) to reap some environmental benefits out of a ‘bad’ situation where annual flow releases from the dam will be low anyway. This operation policy under dry climate scenarios could also be adopted in dry years, in essence adopting the Episodic E-flows Implementation approach, which is an opportunistic approach to dam re-operation that takes advantage of prevailing hydrological conditions (Warner *et al.*, 2014; Yang and Yang, 2014; Owusu *et al.*, 2021). This contrasts with the alternative approaches, Adaptive Management and Blanket Operation which represent more structural inclusion of e-flows in the dam operation policy.

Only future climate scenarios were modelled in this study. However, inferences can also be made on the effect of simple energy and water demand futures on the Lower Volta system. For instance, an increase in irrigation demand will trade-off against hydropower production at Kpong Dam and an increase in the firm energy requirement or the continuation of the *de facto* policy of hydropower maximisation at Akosombo Dam, despite the availability of alternative installed power generation capacity (Kumi, 2017; Dye, 2020), will weaken the potential for re-operation of the dam for the riverine environment. Changes in upstream water consumption as well as the construction of new dams such as the Pwalugu Dam in northern Ghana will also affect inflows to the Akosombo Dam (Rademaker, 2022; Buskop, 2022). Gonzalez *et al.* (2021), however, show that practical coordination of the operation of major infrastructure in the Volta Basin, as compared to the current approach whereby dam operators fail to consider downstream built infrastructure, reduces the impact on inflows to the Akosombo Dam in particular, and also maximises basin-wide benefits. Undoubtedly this coordination should extend beyond the Volta Basin to include the entire electricity generation portfolio of Ghana to further reduce the impact of e-flows implementation in the Lower Volta on power provision in the country. The explicit consideration of these aspects; the impact of dam re-operation on electricity prices and carbon emissions is however beyond the scope of this paper.

In the potential re-operation of the Akosombo and Kpong dams, one has to consider that the majority of the alternative sources of power in Ghana use carbon fuels (Dye, 2020) and thus most likely contribute more to climate change compared to power generation from these two existing dams (dos Santos et al., 2006; Barros et al., 2011). It is therefore recommended that future studies encompass an overview of the energy landscape of Ghana and investigate carbon emissions, as well as examining energy price and economic implications. By exploring the room for compromise in the Lower Volta with respect to e-flows implementation this research has taken a first step towards a comprehensive assessment of the trade-offs involved at a national and local level. The potential for re-operation of the Akosombo and Kpong dams can benefit from (i) the groundwork laid by research on the pre- and post-dam river system (Lawson, 1972; De-Graft Johnson, 1999; Tsikata, 2008; Adjei-Boateng *et al.*, 2012; Obirikorang *et al.*, 2013; Nyekodzi *et al.*, 2018; Owusu, Mul, Strauch *et al.*, 2022), (ii) insights deriving from interviews and extensive stakeholder engagement (Ayivor and Ofori, 2017; Nukpezah *et al.*, 2017; Ohemeng *et al.*, 2017), and (iii) existing supporting legislation for e-flows implementation (L.I. 1692 Water Use Regulations, Ghana, 2001). Indeed, research on successful and stalled cases of dam re-operation indicates that stakeholder engagement and supporting legislation enhance the chances of successful e-flows implementation (Owusu *et al.*, 2021; Owusu, Mul, van der Zaag *et al.*, 2022).

Finally, the successful application of the EMODPS framework in exploring trade-offs inherent to e-flows implementation in a heavily modified river under uncertainty holds promise for similar applications elsewhere. In order to find a policy for multiple objectives in such cases, a flexible structure to map states to actions is needed. With traditional control optimization techniques, the uncertainties need to be modelled explicitly, which creates a high computational burden and limits the ability to evaluate a large set of uncertainties (Giuliani et al, 2016). EMODPS overcomes this challenge by directly conditioning the decisions to exogenous information without requiring an explicit probabilistic model. With EMODPS, only the goals and direction of preference are required in setting up the multi-objective decision problem, making the use of this method feasible even in data scarce conditions. This study therefore concurs with Herman et al. (2020) who argue that direct policy search methods are a promising technique to enable adaptivity in water resources assessment by allowing the flexible integration of new information about the system into management decision making.

5.6 CONCLUSION

A dam is designed with future uses in mind - this provides the justification for its construction. The future, however, can turn out differently from that envisaged in the dam design. Therefore, re-operation of the dam to meet changing demands is a likely necessity. This study investigates current and future trade-offs between water users in the Lower Volta River Basin and specifically explores the potential to deliver environmental flows to support various ecosystem services that have been negatively impacted by the current operation of the Akosombo and Kpong dams. The results highlight the dominance of hydropower production in the Lower Volta; if this relaxes there is more room for restoration of the riverine environment under current climate and water use conditions and even more so under future scenarios where inflows to the Lake Volta potentially increase. In future scenarios whereby inflows to the Lake Volta potentially decrease, it is still possible to strategically manage and time water releases to provide dry season low flows which will support the clam fishery and help control aquatic weeds and some water borne diseases in the Lower Volta. This study applied advanced optimisation techniques to identify and analyse dam operation policies for e-flows under discreet climatic scenarios. Future studies should focus on the robustness and limits of these policies under multitudinous future climatic and water use scenarios. Such robustness studies, together with flow experimentation, will reveal dam operation policies that may be adopted with some confidence presently. It will also build on groundwork already laid, through e-flows legislation and extensive collaborative scientific studies, for the successful re-operation of the Akosombo and Kpong dams for the environment and other water users.

6

CONCLUSION

The preceding chapters in this thesis have separately addressed four research questions to meet the research objectives of creating a deeper understanding of the dam re-operation process to accommodate e-flows and investigating the synergies and trade-offs between e-flows and conventional water uses, taking their site-specific nature into account. In the final chapter, the research objectives and questions are revisited and addressed by drawing on the aggregate findings of the preceding chapters. The thesis concludes with the contributions of this research, reflections on the research methods and limitations, and finally recommendations for future research.

Image: Coastal defense walls at the Volta Estuary, Ghana

6.1 GLOBAL DAM RE-OPERATION EFFORTS

Efforts to re-operate dams have previously been documented on a case-by-case basis. In this section, the conclusions drawn from a global review of cases of dam re-operation for e-flows are presented by highlighting the general patterns as well as actions commonly associated with successful and stalled attempts.

6.1.1 Moving from e-flow recommendations to dam re-operation

A systematic review of literature on dam re-operation for the release of environmental flows (Chapter 2) was the main activity carried out to understand global dam re-operation efforts. The survey of stakeholders involved in dam re-operation (Chapter 3) also contributed to meeting this research objective.

Each successful case of dam re-operation can be placed on a scale which has, at one end, cases following the traditional science or analytical model (Simon, 1977; Mayer *et al.*, 2013), and at the other end, the opportunistic or political model (Cohen *et al.*, 1972; Enserink *et al.*, 2010; Vreugdenhil *et al.*, 2010). The traditional science model or analytical approach is characterised by a fairly orderly progress from problem identification to research and then solution. Alternatively, in the opportunistic or political model to dam re-operation, “Problems are often solved, but rarely by the choice to which they were first attached” (Cohen *et al.*, 1972, page 11). This latter model highlights the fact that implementation of e-flows may not be linear, but rather ‘messy’, consisting of parallel processes, multiple iterations and seeming dead ends (Cohen *et al.*, 1972; Rittel and Webber, 1973; Ackoff, 1974; Weber and Khademian, 2008; Enserink *et al.*, 2010; Vreugdenhil *et al.*, 2010). However, these messy processes do not occur in a vacuum, as even in cases following the opportunistic model in dam re-operation some groundwork or general learning had occurred or was being pursued when delays or hurdles were encountered followed later by opportunities to successfully complete the process (Higgins & Brock, 1999; Bednarek & Hart, 2005; Gómez *et al.*, 2015). For proponents of dam re-operation, it is therefore possible to think of successful dam re-operation cases closer to the analytical model end of the scale as those that mostly went according to plan and vice versa. The opportunistic model of how dam re-operation occurs therefore suggests that those stakeholders who embrace the ultimate goal of protecting or restoring ecosystems, must stay the course and be ready to take advantage of opportunities that may arise to make further progress.

For both models of dam re-operation, however, the results of the survey offer some insight on the positioning of science and the role of scientists by showing that local context and needs must be taken into consideration. These encompass the historical, political and socio-economic contexts in which dams were built and are operated. In essence, a compelling scientific argument for e-flows on its own is not enough to carry the process through to implementation. Instead, collaboration between stakeholders, an enabling factor identified in many of the successful dam re-operation cases (Chapter 2), or as framed in Chapter 3, a communicative model in the "orientation of knowledge" in the dam re-operation process, proves key to e-flows recommendations being implemented. As such, e-flows science and expertise must address the priorities and questions that emerge from local stakeholder engagement (Prell *et al.*, 2007). A careful review of cases like the Ova Spin and Punt dal Gall dams on the River Spöl which followed the analytical approach shows that local stakeholders such as the power company operating the dams, the Swiss National Park where the dams are located, and also national, regional and local authorities were all involved (Robinson and Uehlinger, 2008). Similarly, in cases closer to the opportunistic model like the re-operation of the Mequinenza and Ribarroja dams on the Ebro River, Spain, macrophyte blooms catalysed collaboration between the river basin authority, scientists and the dam operator to deliver e-flows (Gómez *et al.*, 2015).

In relation to specific inputs in the process of successful dam re-operation for e-flows implementation, e-flows legislation and environmental impact studies or scientific studies were identified as the most common inputs from the systematic literature review (Chapter 2). The survey results suggest that e-flows legislation may be a missing input to the process in stalled cases. However, this difference was statistically insignificant and may require further study (Chapter 3). Scientific studies are indeed a key input, but the positioning of science and the communication approach used need to be collaborative. Flow experiments were the most common activity leading to successfully re-operated dams and this is due to the fact that they provide a real-world opportunity for validation or modification of recommended e-flows in a partially controlled setting. The fact that minimum flow releases were the most common output of the dam re-operation process and that blanket operation, where broad changes are made to dam operations, was the implementation approach taken in a majority of successful cases also buttress the point that flow-ecology relationships are difficult to establish, resulting in the implementation of 'easy' solutions which may not necessarily be the most effective e-flow provisions. This is because minimum flow releases are typically the bare minimum of water for the environment and eliminate seasonal high and low flows across the year while the blanket operation approach provides little room for further learning and review of e-flows. Finally, it is worth noting that particularly with respect to the inputs to dam re-operation, in more than half of the successful cases in the systematic literature review, there were unique inputs, falling outside the common categories identified showing that there were (additional) individual circumstances which helped to start the process (Chapter 2). In contrast, on the activities carried out to implement e-flows recommendations, there were fewer activities falling outside the common ones categorized, i.e. flow experiments, modelling, physical modifications and workshops. On e-flow outputs, dry season low flows did not feature in the common categories identified in the systematic literature review as they were only provided at one dam, the Kogelberg Dam on the Palmiet River in South Africa, thus showing that there is more emphasis on releasing flows rather than withholding flows in implementing e-flows.

In conclusion, on how e-flows recommendations develop into actual dam operation, this thesis finds that e-flow recommendations are usually implemented through a collaborative analytical process which makes use of existing supporting frameworks such as legislation, but also takes advantage of opportunities that may arise to advance the process of dam re-operation for e-flows such as flow experiments. The process is usually non-linear and it is important to emphasize the local context which makes each process of dam re-operation unique and should therefore inform each dam re-operation attempt.

6.1.2 Factors impeding dam re-operation attempts

The survey of stakeholders with first-hand experience in dam re-operation (Chapter 3) was the main research method applied in understanding the reasons for impasse in many attempts at dam re-operation. The case study also shed light on why an individual case of dam re-operation stalled (Chapter 4).

The systematic literature review revealed what had been done in successful cases, but this begged the question: What has hindered the process in cases where dam re-operation for e-flows has been attempted but has stalled? In addition to investigating how dam re-operation occurs, the survey also investigated who was involved, the motivation for dam re-operation (why), the original purpose of the dam (what) as well as the hurdles encountered in the process. The responses from the survey were grouped into two: successfully re-operated dams and stalled attempts at dam re-operation. A statistical analysis of the two groups was carried out to find out where significant differences between the two groups lay.

Specifically, in answer to questions on hurdles to the process of dam re-operation, two main categories of hurdles were common to stalled cases: hurdles arising from social or stakeholder issues, and hurdles associated with policy or legislation. From these two common hurdle categories and the findings from the statistical analysis of how, what, why and who was involved in dam re-operation attempts, it is found that in contrast to successful cases, the following factors existed in the majority of stalled cases:

- Consensus on e-flows recommendations could not be reached among stakeholders due to the expert-driven approach taken, or
- There was no supporting local level e-flows legislation, or
- Nothing was attempted to address and overcome hurdles that were encountered

It follows then that, in general, dam re-operation advocates should work to create an enabling legal and/or regulatory environment at the local and/or basin level and also carefully design stakeholder engagement to overcome obstacles to implementation. In particular, the role of scientists should be to support the implementation process and not to drive it.

It is important to stress that each dam re-operation attempt is unique, and there are always exceptions to the rule, as in the case of the Lower Volta River Basin, Ghana. There, in addition to existing legislation on e-flows, there was extensive local stakeholder involvement in the design and implementation of a project to re-operate the Akosombo and Kpong dams, yet the dam re-operation attempt has nevertheless stalled. The main hurdle encountered, namely, insufficient water to meet hydropower demands if environmental flows are released, is also one that was common to successful cases from the survey responses. At the time, Akosombo and Kpong dams accounted for approximately half of installed power generation in Ghana. This made the Lower Volta case a particularly intriguing one as it highlights the complexity of dam re-operation and shows that general patterns identified in a number of cases may not apply universally. It also reinforces the importance of the local context in which dam re-operation attempts are made.

6.2 CASE STUDY: AKOSOMBO AND KPONG DAMS IN THE LOWER VOLTA RIVER BASIN

Research question 2.1 and 2.2 were answered through a case study since flow-ecology relationships are specific to river locations. The case study chosen was the Lower Volta River in Ghana which is a stalled case despite having some of the key features of successfully re-operated dams. Before the construction of the Akosombo Dam in 1961 on the Lower Volta River, the monthly average flow rate in the wet season was approximately 140 times the dry season flow rate. With the current operation of the Akosombo Dam and later, the run-of-the-river Kpong Dam, this dynamic annual flow regime has been changed to a steady flow regime, effectively eliminating both the annual floods and the dry season flow. This has led to many changes in the downstream ecosystem and the lives of downstream riparian communities who depend on the river for their livelihoods (Adjei-Boateng *et al.*, 2012; Ayivor and Ofori, 2017; Nukpezah *et al.*, 2017).

A number of studies have investigated the pre- and post-dam conditions in the Lower Volta (Lawson, 1972; Tsikata, 2008; Ntiamoa-Baidu *et al.*, 2017; Nyekodzi *et al.*, 2018). One of these, the RRAKDP, looked at re-operating the dams to release two e-flows determined from assessments of the pre-dam, natural flow regime of the river (Ntiamoa-Baidu *et al.*, 2017). However, in long-term heavily modified rivers like the Lower Volta, a return to natural or near natural flows is challenging. As such, an additional e-flow assessment, applying a method suitable for data poor environments using a BBN, was carried out as part of this research for the Lower Volta River.

The main challenge in past efforts at implementing e-flows in the case study was the overriding high demand for water to generate electricity (Annor *et al.*, 2017; Balana *et al.*, 2017). Considering that the past attempt at re-operating the Akosombo Dam coincided with one of the worst energy crises in Ghana, this trade-off was judged to be too high despite the extensive collaborative analytical process that was undertaken (Ntiamoa-Baidu *et al.*, 2017). The local energy situation in the Ghana has since changed and therefore a trade-off analysis of the main traditional water users and e-flows was carried out.

6.2.1 Establishing e-flow requirements

The new e-flow for the Lower Volta was assessed based on the designer e-flow paradigm which aims to bring together components of a river's flow regime to meet specific ecological goals (Acreman, Arthington *et al.*, 2014). A stenotopic macrobenthic organism, the Volta clam (*Galatea paradoxa*), which supports an important artisanal fishery in the basin and thereby serves a key economic activity, was used as an indicator species to design e-flows using a BBN (Chapter 4). The historical changes in the status of the Volta clam as well as its life cycle in relation to the flow regime of the Lower Volta were determined. It was found that the current flow regime of the Lower Volta limits saline intrusion in the dry season thereby constraining the veliger larval stage of the Volta clam and limiting the range of its habitat (Chapter 4). A reduction of the current flows to low flows during the time from November to March together with other management strategies, specifically dredging of the sandbar that builds up at the Volta Estuary and prohibition of sand winning in the clam bed, were therefore recommended as e-flows (Chapter 4).

Two results were realized in answering this research question, one specific to the Lower Volta and the other more generalizable to other cases. For the Lower Volta, an additional e-flow to the two already prescribed, in this case, a designer e-flow to support the important artisanal Volta clam fishery, was determined. Second, the application of BBNs in an ecologically grounded designer e-flow assessment was demonstrated for possible application to other data-scarce regions. While there are many e-flow assessment methods available (Poff *et al.*, 2017; Tharme, 2003), in reality, the applicability of the majority of these methods is limited in data-scarce regions where long term, continuous monitoring of water levels and quality or biological and ecological indicators are unavailable for e-flows assessment (Tharme, 2003; Van de Giesen *et al.*, 2001). The BBN approach demonstrated in Chapter 4 thus serves as an ecologically grounded, parsimonious alternative to the simple hydrological and hydraulic e-flow assessment approaches typically applied in such regions (Efstratiadis *et al.*, 2014; Sharma and Dutta, 2020; Tegos *et al.*, 2018).

Therefore, in answer to the research question, "What are the e-flow requirements of the study site?", there are three different e-flow configurations assessed for the Lower Volta (Table 1), one of which, clam e-flows, was derived from this present research. The other two, e-flows 2 and e-flows 3 are e-flow recommendations made by Mul, Ofosu et al. (2017) to restore near natural flow conditions. These were derived during the previous attempt to re-operate the Akosombo and Kpong dams, the RRAKDP. The differences between the configurations arise from the different e-flow paradigms informing the assessment methods used as well as differences in their ecological objectives.

Table 6.1. The different e-flow requirements determined for the Lower Volta

E-flow	Dry season flow	Wet season flow	Ecological objectives	E-flows paradigm
Clam e-flows (Chapter 4)	50 – 330 m^3/s (November to March)	- (April to October)	To support the Volta clam fishery	Designer
E-flows 2 (Mul, Ofosu *et al.*, 2017)	≤ 700 m^3/s (November to August)	≥ 2300 m^3/s (September to October)	To support fisheries, aquatic weed control and sediment transport	Natural
E-flows 3 (Mul, Ofosu *et al.*, 2017)	≤ 500 m^3/s (November to August)	≥ 3000 m^3/s (September to October)	To support creek fishing and flood recession agriculture	Natural

6.2.2 Trade-offs between e-flows and conventional water uses and the potential for dam re-operation in the study site

Providing e-flows to support ecosystems usually impacts on other water users who have benefitted from the construction of dams (Fanaian *et al.*, 2015; Hurford *et al.*, 2020; Hurford and Harou, 2014). Considering the changed energy context of Ghana and the assessment of a new designer e-flow (clam e-flows, Table 6.1) for the Lower Volta River, an Evolutionary Multi-Objective Direct Policy Search (EMODPS) framework was used to investigate whether and how dam operation policies for the Akosombo and Kpong dams could support e-flows. In addition to e-flows, objective functions for three other major water users in the Lower Volta, namely, hydropower, irrigation and flood control, were set up. The multi-objective trade-off problem was formulated for current climatic conditions and future climate conditions. Five future climate change scenarios were considered to accommodate the high uncertainty in the direction and magnitude of change in water availability due to climate change in West Africa and the Volta Basin.

The main conclusion of the trade-off analysis is that hydropower generation dominates water use in the Lower Volta currently. However, if this decreases by a minimum of 11.6% there is room for e-flows, specifically dry season e-flows. Furthermore, the trade-off between dry season e-flows and hydropower generation reduces under climate change scenarios irrespective of the direction of change in the volume and timing of inflows to the Akosombo Dam. The detailed results of the trade-off analysis for the Lower Volta are presented in Box 1.

Box 1: Trade-offs and synergies between e-flows and traditional water uses in the Lower Volta River

- The best performing dam operation policies for hydropower and e-flows trade-off sharply against each other; the best hydropower solutions are the worst e-flows solutions and vice versa.
- To produce the firm energy target of 4,415 GWh/year at Akosombo Dam under current climate conditions, clam e-flows can only be released 60% of the recommended time while e-flows 2 and e-flows 3 can be released only 49% and 47% of the recommended time, respectively.
- Alternatively, for the release of e-flows during 80% of the recommended time under current climatic conditions, firm power generation at Akosombo would have to fall by about 11.6%, 32% and 38% for clam e-flows, e-flows 2 and e-flows 3, respectively.
- The e-flows trade-off with energy is less if climate change leads to increased annual inflows. With a 65% increase in inflows, only 3.9%, 23.2% and 33.7% of energy from Akosombo Dam would have to be forfeited for the realization of clam e-flows, e-flows 2 and e-flows 3, respectively.
- Under dryer future conditions (-45%), it is still possible to release dry season (low flows) e-flows since at best only 2,774 GWh/year can be generated at Akosombo showing that some synergy exists between e-flows and the environment in this situation.
- Marginal increases in hydropower generation at Kpong lead to significant reductions in the amount of irrigation demand that is met in current and future climate conditions.
- The designer e-flows, i.e. clam e-flows, has a lower trade-off with hydropower as compared to e-flows 2 and 3 across all scenarios because for seven months there is no constraint on flow releases and these can be managed solely to benefit the other water users

Considering that the Lower Volta case remains a stalled dam re-operation case despite the collaborative analytical process followed since 2005, the cases studied in Chapters 2 and 3 provide some examples of how the impasse may be overcome to move the process of dam re-operation forward. For instance, additional inputs such as an opportunity for observation of the biotic and abiotic response to low flows during naturally dry years may present itself. Observations in the aftermath of the 2010 flood releases revealed that the anticipated reduction in aquatic weeds was short-lived, while damage to property in nearby communities was high. Alternatively, a further change in the energy context of Ghana whereby the other existing sources of energy are tapped as opposed to the current situation whereby Akosombo remains a base energy source, may also provide an opening for e-flows implementation. Other inputs may come in the form of a change in public perception on dams and the environment in Ghana or climate-induced changes to inflows.

As such, from the perspective of those in favour of e-flows, it is possible to consider stalled cases such as the Lower Volta case as temporarily so, with previous work done in the process viewed as initial inputs awaiting further triggers for progress to be made in the process or even for dam re-operation for e-flows to finally occur. To these advocates, considering the multiple iterations and apparent dead ends, the Lower Volta case falls squarely in the category of cases following the opportunistic or political model towards dam re-operation.

6.3 CONTRIBUTIONS OF THIS RESEARCH

It has been 15 years since The Brisbane Declaration (2007) was first drafted to formally define e-flows and set the agenda for e-flows science, policy and practice. Since then, the declaration and agenda have been renewed (Arthington *et al.*, 2018) and in addition, there have been further developments in e-flows assessment methods (Tharme, 2003; Poff *et al.*, 2017; Williams *et al.*, 2019), reviews of the impacts of e-flows on ecosystems (Gillespie *et al.*, 2015; Olden *et al.*, 2014) and a growing number of e-flow implementation programs (Robinson *et al.*, 2018; Warner *et al.*, 2014). On the last point, e-flow implementation, however, progress remains underwhelming (Arthington *et al.*, 2018). To understand why this is so, this thesis addressed the knowledge gap on how e-flows are integrated into dam operation policy and practice, why some efforts at e-flows implementation through dam re-operation have failed and others succeeded, as well as how trade-offs with other water users impact dam re-operation for e-flows implementation. The significance of this research lies in the contribution it makes to the research action points for two Brisbane Declaration statements (Section 1.4). These action points call for the identification of barriers to e-flows implementation and research into new and existing mechanisms for e-flows implementation.

On the first objective of deepening the understanding of the process of dam re-operation, this research has contributed the following:

- A generalization of the process followed in dam re-operation attempts that have been successful. All the successful cases identified in the literature were assessed using a logic model and this provided a structured framework to capture and analyse the process; identifying specific actions taken as well as establishing general underlying models of the process based on the patterns identified in the cases. Elaborating on the specific actions, the most common inputs, activities and outputs of successful dam re-operation attempts are respectively, e-flows legislation and scientific studies; flow experiments; and provision of minimum flows. On the general patterns identified, it is found that successful dam re-operation attempts usually follow a non-linear, collaborative analytical process which makes use of existing supporting frameworks but also takes advantage of opportunities that may arise to advance the process.

- New insights on the importance of a collaborative positioning of science, local level legislation and flow experiments in the process of dam re-operation for the environment. This orientation of knowledge, input and activity, respectively, were key components of successful dam re-operation attempts and largely missing in stalled attempts.
- A global record of successful e-flow implementation through dam re-operation. This database (Owusu *et al.*, 2019) records the inputs, activities, and outputs as well as the stakeholders involved and the e-flows approaches taken in each case.
- Four hypotheses on why some dam re-operation attempts have stalled based on a comparison of the dam re-operation process of stalled attempts and successful attempts. The four hypotheses developed can serve as a starting point for further research on understanding why some attempts at dam re-operation for the environment stall. These are:
    1. In undertaking scientific studies for determination of e-flows, first a consensus on the priorities, knowledge gap, and solutions must be reached together with local stakeholders.
    2. Genuine, carefully designed consultations and negotiations between stakeholders can overcome hurdles encountered in the process.
    3. Local-level legislation and policy on e-flows provide the enabling environment for dam re-operation for e-flows.
    4. Scientists are important stakeholders in the process of dam re- operation, but should play a supportive role rather than drive the process.
- An in-depth context-dependent examination of a unique stalled case of dam re-operation that does not completely fit into the generalized findings on successful dam re-operation and why dam re-operation usually stalls. This case study further highlights the importance of local context in the success of dam re-operation for the environment.

On the second objective of investigating the synergies and trade-offs between e-flows and conventional water uses, this research has contributed the following:

- A parsimonious, ecologically grounded, designer e-flows assessment method using Bayesian Belief Networks (BBN) for application in data scarce areas.

- An alternative designer e-flow for the Lower Volta River. The trade-off between this e-flow and the main water use in the basin, hydropower, is lower than the trade-off between hydropower and the dynamic e-flows previously determined for the basin based on the natural flows.
- An application of the Evolutionary Multi-objective Direct Policy Search (EMODPS) optimization approach to investigate the Pareto approximate solution space in the provision of e-flows in the Lower Volta River
- New insights into the trade-offs between e-flows and hydropower in the Lower Volta River under current and future climate change scenarios. Notably, both an increase and a decrease in annual inflows to the Akosombo Dam reduce the trade-off and create synergies between e-flows and hydropower generation.

6.4 REFLECTIONS ON THE RESEARCH

6.4.1 Research design and philosophical worldview

The research design adopted was exploratory and sequential in addressing the research questions on dam re-operation for the environment. The advantage of this is that the findings and emergent ideas from previous stages of work could be incorporated into subsequent stages. For instance, from the systematic literature review, the logic model framework as well as specific actions common to the dam re-operation process were identified and these were used to frame questions and structure the survey sent out to dam re-operation practitioners. Again, the similarities and differences between the dams analysed in the systematic literature review and survey influenced the choice of the case study. Finally, the e-flow configuration developed in answer to RQ 2.1 was incorporated as one of three e-flows configurations used in investigating the trade-offs and synergies between water users in the Lower Volta. This research method is advocated for future problem-centred studies which are aimed at understanding real world problems and how processes work in practice.

The pragmatic worldview adopted in this study is borne out in the mixed methods research design whereby the systematic literature review and survey generally provided quantitative data on dam re-operation efforts while the case study of the Lower Volta system formed the qualitative part of the research. The designer flow paradigm underpinning the application of BBNs to design e-flows to support the Volta clam fishery is also aligned with this worldview as it is the pragmatic e-flows paradigm which recognizes that not all rivers can be restored to natural or near-natural conditions (Acreman *et al.,* 2014). This pragmatic e-flow paradigm is therefore better suited to heavily regulated river basins with high competing water demands such as the Lower Volta

6.4.2 Extensive vs. intensive research in e-flows science

The results from the systematic literature review and survey are based on real world cases and provide stakeholders with general, context-independent knowledge on the dam re-operation process for e-flows implementation. The results from these research activities therefore serve as an initial reference of *Do's and Don'ts* for the process of dam re-operation. The literature review and survey may be characterised as the extensive research phase of this study whereby general properties and common patterns in a relatively large sample of dams were sought (Sayer, 2010). This general knowledge is valuable as baseline information for stakeholders in dam re-operation. However, the disadvantage is that contexts that are unique to individual cases are not captured. The case study exemplifies this limitation of extensive research, similar to ecological fallacy bias in statistical interpretation whereby aggregate findings for a group do not necessarily apply to individuals (Connolly, 2006; Flyvbjerg, 2001; Jargowsky, 2005; Kramer, 1983). This is because the 'normally' successful factors identified in the group may not lead to success in the specific case studies.

The case study approach taken to address the second research objective on trade-offs in the dam re-operation process was necessitated by the fact that trade-offs between water users are location and context specific. The case chosen is a 'black swan' within the general patterns identified in the extensive research phase (Flyvbjerg, 2006, 2001; Tsang, 2014) and served as the focus of the intensive research phase of this research (Sayer, 2010). It thus provided a detailed narrative on one case - the history, impacts and trade-offs unique to the riverine communities, dam operators and government in that particular case. Such phenomenological details on the reality of dams, the environment and people are diluted in extensive research but are also important to build up knowledge on the dam re-operation process. This intensive research phase may suffer from the main limitation of case study research, i.e. a limited external validity of findings from an individual case (Steinmetz, 2004; Stoecker, 1991). However, it is argued that there is value in focusing on a particular case to inform the people living in that case (Stoecker, 1991). Furthermore, in this research, the context-dependent knowledge of the case study in this research complements the context-independent knowledge of the systematic literature review and survey. It is also worth noting that, while the results of the case study, i.e. the designer e-flows and trade-offs, are specific to the Lower Volta, the method demonstrated in designing e-flows is applicable to other locations. This notwithstanding, a multiple-case study design, including also a 'classic' stalled case, could have further enhanced the understanding of the process of dam re-operation for the environment.

6.4.3 Research limitations

Uncertainty of e-flows recommendation outcomes

Three unique e-flow configurations have been determined for the Lower Volta River and so far, no flow experiments have been conducted to validate these recommended e-flows and their effects on their target ecosystem services or other water users. Furthermore, in this study, the trade-off analysis considered each e-flow recommendation separately and no attempt was made to synergise between the three e-flows. Until flow experiments are carried out or re-operation of the Lower Volta dams occurs using one of these e-flows recommendations, the actual impact of these e-flows remain uncertain. This uncertainty is characteristic of the challenge of e-flows implementation, i.e. the link between prescribed e-flows and ecological outcomes is uncertain (Olden *et al.*, 2014; Growns, 2016; Horne, Webb *et al.*, 2017; Thompson *et al.*, 2018). While governments, conventional water users and even e-flow advocates desire proof of the benefits of e-flows *a priori*, it is impossible to attain this proof with certainty for a given location without flow experimentation or actual implementation. Reviews on the outcomes of successful implementation attempts provide important evidence in support of e-flows in general (Gillespie *et al.*, 2015; Olden *et al.*, 2014). However, the value of local e-flow recommendations can only be judged on the results. In effect, with respect to the local impacts of e-flows, the proof of the pudding is in the eating. This notwithstanding, it is clear that the conventional 20th century approach to dam building and operation has resulted in many negative social and environmental effects worldwide and this status quo must change (Dudgeon *et al.*, 2006; Power *et al.*, 1996; WCD, 2000). E-flows thus remain part of the suite of solutions for restoring and protecting riverine and estuarine ecosystems (Tickner *et al.*, 2020). Still, the associated uncertainty in the outcomes of e-flows must be acknowledged and ideally be incorporated in the implementation process through an adaptive management approach. In this approach, the outcomes of flow releases are continuously monitored and refined (Warner *et al.*, 2014).

Data limitations

Like many studies, this research suffered from data limitations. For example, in the survey, the small number of responses prescribed the statistical methods that could be used and the conclusions that could be drawn from the analysis. The challenge of data availability was a prominent issue in answering RQ2.1 for the selected case study and was therefore directly addressed in the method demonstrated in assessing a new designer e-flow for that location. The data poor situation thus dictated the choice of e-flows assessment method (BBN vs SPI) and constrained the number of indicators species that could be used as linkages resulting from building a BBN using multiple indicators could not be clearly determined. In the trade-off analysis, while the main water uses in the Lower Volta were incorporated, information on other water uses, such as the required water levels for aquaculture or tourism, would have been beneficial, particularly given that low flows are the e-flows which featured in Pareto approximate solutions to the trade-off problem for the case study. Furthermore, in the preliminary stage of the case study, when experts on the case were being interviewed, insights from one of the key stakeholders, namely the dam operator (VRA), were missing as it proved impossible to gain an interview with a representative despite multiple attempts.

6.4.4 EuroFLOW Training Network

The EuroFlow project, which this research was a part of, offered a platform for acquiring the requisite baseline knowledge on e-flows and developing an extensive network in the field of e-flows. Through training workshops and summer schools, an introductory course on e-flows was completed along with lectures on the WFD, invasive species and the ethics of collaborative research, among others. Other activities of the network included data collection during an artificial flood from the Ova Spin Dam on the River Spöl; and field visits to the Swiss National Park, Switzerland and the hydropower regulated Noce River, Italy. Overall, the experience of conducting research as part of this training network was an enjoyable one.

6.5 FUTURE STUDIES

The main motivation behind this thesis was to gain an understanding of how e-flows implementation through dam re-operation occurs and thereby inform future endeavours in this field by contributing practical knowledge on the path that past attempts have taken. To conclude this thesis, five areas for further study on the topic are highlighted:

1. *Completion of the logic model for the successful cases*

The systematic literature review and survey used a logic model to capture the *inputs, activities* and *outputs* of the dam re-operation process. A study of the longer-term *outcomes* and *impacts* of the successfully re-operated cases would complete the picture on the process for these captured cases. This may also reveal possible feedbacks from these post-implementation stages and offer further lessons for the complete dam re-operation process.

2. *Further exploration of impasse of dam re-operation for e-flows*

The small number of cases in the survey limited the analyses that could be carried out to flesh out the impasse of the dam re-operation process. Anecdotal evidence suggests that there are many more attempts at dam re-operation occurring worldwide with records of these only published in grey literature at local or national levels. For this current research there was also the issue of language hindering the capture of cases in non-English speaking countries. It is therefore recommended that future studies look at capturing these ‘hidden’ cases of stalled dam re-operation attempts. The four hypotheses developed in this current research provide a good starting point to investigate why these attempts have stalled.

3. *Case study of 'classic' successful and stalled cases*

Case studies are important to advancing knowledge on the dam re-operation process by complementing the knowledge on the general patterns with narratives of individual cases. Additional in-depth studies of cases which fit the successful and even more importantly, stalled cases will therefore expand the knowledge of the process of dam re-operation and the role of trade-offs in the process. These future case studies could potentially use different methods, such as narrative analysis (see Bontje, 2017 or Bruce *et al.* 2016).

4. *Incorporation of e-flows in new dams*

While this dissertation focussed on re-operation of existing dams to implement e-flows, research is needed on how e-flows are incorporated into the design and operation of new dams. This forms an important complement to this research considering the boom in construction of new dams around the world *(*Zarfl *et al.,* 2015*)* and the threats to freshwater and estuarine ecosystems *(*Tickner *et al.,* 2020*)*.

5. *Uncertainties: trade- offs and e-flow responses*

Additional investigation on the effect of uncertainties concerning climate change and changes in riparian water use in the Lower Volta are needed. Specifically, more insight is needed on the probabilities associated with scenarios as well as the robustness of policies across multiple future scenarios. Future research could also investigate adaptive planning, a systematic approach to balancing short term decision making with long term decision horizons (see Versteeg *et al.,* 2021), as a way of including flow response uncertainties into decision making on e-flows.

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APPENDIX A

Table A1: Variants of search terms making up the search string: target population- dams; intervention type- re-operation; and the topic- environmental flow

Target population	Intervention	Topic	
Barrage	design	artificial flood	flow restoration
Dam	management	artificial low flow	fluctuating flow
Impoundment	modification	controlled flood	high flow experiment
Reservoir	operation	controlled release	high flow pulses
Weir	optimisation	ecological release	instream flow
	policy	ecological reserve	minimum flow
	redesign	ecosystem service	modified flow
	re-design	environmental flow	peaking flow
	reoperation	environmental release	planned flood
	re-operation	environmental reserve	scour flow
	re-optimisation	environmental water	scour release
		experimental low flow	simulated flood
		experimental flow	simulated release
		experimental high flow	spate flood
		experimental flood	spate release
		experimental release	test flood
		flow release	test release

APPENDIX B

Survey flow and questions

Block: 1- Participant expertise (6 Questions)
Standard: 2- To get info on specific case (9 Questions)

Branch: New Branch
If
If What is the status of work on e-flows/river restoration/dam re-operation? On hold/ stalled/ abandoned Is Selected

> **Block: 3- (A- Info on stalled cases) (14 Questions)**
>
> **Branch: New Branch**
> **If**
> **If Have you been involved in another dam re-operation case that you consider formative or significant... Yes Is Selected**
>
> > **Standard: N2- To get info on specific case (2) (9 Questions)**
> >
> > **Branch: New Branch**
> > **If**
> > **If What is the status of work on e-flows/river restoration/dam re-operation? On hold/ stalled/ abandoned Is Selected**
> >
> > > **Block: N3- (A- Info on stalled cases) (2) (13 Questions)**
> >
> > **Branch: New Branch**
> > **If**
> > **If What is the status of work on e-flows/river restoration/dam re-operation? Being implemented Is Selected**
> >
> > > **Standard: N4- (B- Info on successful cases) (2) (4 Questions)**
> > >
> > > **Branch: New Branch**
> > > **If**
> > > **If Were any hurdles encountered? Yes Is Selected**
> > >
> > > > **Block: N 5- (B- Info on hurdles in successful cases) (2) (12 Questions)**

Branch: New Branch

If

If Were any hurdles encountered? No Is Selected

Block: N6- (B- Info on successful cases with no hurdles) (2) (6 Questions)

Branch: New Branch

If

If What is the status of work on e-flows/river restoration/dam re-operation? Being implemented Is Selected

Block: 4- (B- Info on successful cases) (4 Questions)

Branch: New Branch

If

If Were any hurdles encountered? Yes Is Selected

Standard: 5- (B- Info on hurdles in successful cases) (13 Questions)

Branch: New Branch

If

If Have you been involved in another dam re-operation case that you consider formative or significant... Yes Is Selected

Standard: N2- To get info on specific case (2) (9 Questions)

Branch: New Branch

If

If What is the status of work on e-flows/river restoration/dam re-operation? On hold/ stalled/ abandoned Is Selected

Block: N3- (A- Info on stalled cases) (2) (13 Questions)

Branch: New Branch

If

If What is the status of work on e-flows/river restoration/dam re-operation? Being implemented Is Selected

Standard: N4- (B- Info on successful cases) (2) (4 Questions)

Branch: New Branch

If

If Were any hurdles encountered? Yes Is Selected

Block: N 5- (B- Info on hurdles in successful cases) (2) (12 Questions)

Branch: New Branch
If
If Were any hurdles encountered? No Is Selected

Block: N6- (B- Info on successful cases with no hurdles) (2) (6 Questions)

Branch: New Branch
If
If Were any hurdles encountered? No Is Selected

Standard: 6- (B- Info on successful cases with no hurdles) (7 Questions)

Branch: New Branch
If
If Have you been involved in another dam re-operation case that you consider formative or significant... Yes Is Selected

Standard: N2- To get info on specific case (2) (9 Questions)

Branch: New Branch
If
If What is the status of work on e-flows/river restoration/dam re-operation? On hold/ stalled/ abandoned Is Selected

Block: N3- (A- Info on stalled cases) (2) (13 Questions)

Branch: New Branch
If
If What is the status of work on e-flows/river restoration/dam re-operation? Being implemented Is Selected

Standard: N4- (B- Info on successful cases) (2) (4 Questions)

Branch: New Branch
If
If Were any hurdles encountered? Yes Is Selected

Block: N 5- (B- Info on hurdles in successful cases) (2) (12 Questions)

Branch: New Branch
If
If Were any hurdles encountered? No Is Selected

Block: N6- (B- Info on successful cases with no hurdles) (2) (6 Questions)

Participant expertise

You are participating in a research study titled Dam re-operation for implementation of environmental flows. This study is being done by Afua Owusu, Dr. Marloes Mul, Prof. Pieter van der Zaag and Prof. Jill Slinger from IHE Delft Institute for Water Education and TU Delft, Netherlands.

This survey will take you approximately 15 minutes to complete. The data will be used to identify the hurdles encountered in re-operating dams and how these hurdles have stalled the process or how they have been overcome. The results of the survey will be published in an open-access scientific journal.

Your participation in this study is entirely voluntary and you can withdraw at any time. No personal data will be shared and all personal data will be deleted 6 months after the end of the study.

We believe there are no known risks associated with this research study; however, as with any online related activity the risk of a breach is always possible. We will minimize any risks by safeguarding the list of respondents. Furthermore, responses will be anonymized and analysed based on the role of respondents with respect to dam re- operation (E.g.: dam operator, local government agency, and scientist).

Thank you in advance for participating in this survey.

This study is being conducted in line with the Integrity Policy of TU Delft, Netherlands. Kindly contact Afua Owusu at: a.owusu@un-ihe.org if you have any questions.

This research is part of the EuroFLOW project (EUROpean training and research network for environmental FLOW management in river basins) funded by the European Union's Horizon 2020 Research and Innovation Programme under the

Marie Skłodowska-Curie grant Agreement (MSCA) No 765553. More information about EuroFLOW is available here.

Useful to know:

This study concerns existing dams which were originally designed and/or operated primarily for conventional purposes such as hydropower generation, flood protection and irrigation.

Dam re-operation is therefore defined as the change in flow release practices to provide environmental flows (e-flows) for downstream aquatic ecosystem needs.

What is your main role with respect to dam re-operation for environmental flows implementation?

○ Civil society advocate/ environmentalist

○ Dam operator

○ Government agency official

○ Scientist/ Researcher

○ Other, please specify

☐

How many years of experience do you have in this role?

○ 0 - 5 years

○ 6 - 10 years

○ 11 - 20 years

○ >20 years

How many cases of dam re-operation have you been involved in?

○ 1

○ 2

○ 3-5 cases

○ More than 5 cases

How many different river systems do these cases cover?

○ 1

○ 2

○ 3-5 river systems

○ More than 5 river systems

1- To get info on specific case

Of these cases, choose a case that you consider formative or significant and answer the following questions in the survey with respect to this case.

Which dam(s) were part of the study?

In which river system are these dams located?

In which country is/are the dam(s) located?

What was the primary purpose of the dam at construction? (Select all that apply)

☐ Flood control

☐ Hydropower

☐ Irrigation

☐ Navigation

☐ Recreation

☐ Water supply

☐ Other, please specify

In which year did work on e-flows/ river restoration/ dam re- operation begin?

What was the motivation/goal for dam re-operation in this case? (Select all that apply)

☐ Habitat protection/ restoration

☐ To protect a commercial resource

☐ To protect an endangered species

☐ To enhance scientific knowledge

☐ Other, please specify

What were the triggers/ enabling conditions for the work on dam re-operation to begin? (Select all that apply)

☐ Legislation or policy on river/ dam/ environment

☐ Research base (eg: findings from environmental impact assessment on dam, models/ study on e-flow requirements of downstream ecosystems)

☐ Natural trigger event (eg: flood, drought)

☐ Man-made trigger event (eg: change in government, new dam operators)

☐ Planned upgrade or maintenance of dam

☐ Request for dam re-operation (including lawsuits)

☐ Other, please specify

What is the status of work on e-flows/river restoration/dam re- operation?

○ On hold/stalled/abandoned

○ Being implemented

2- **(A- Info on stalled cases)**

What activities were implemented to re-operate the dam(s)? (select all that apply)

☐ Drafting/ updating of legislation or policy Flow experiments

☐ Workshops/ meetings with stakeholders

☐ Scientific studies (e.g.: environmental impact assessment of dam, trade-off studies, e-flow studies)

☐ Physical modification to dam Modelling

☐ Other, please specify

Which flow manipulation was targeted in dam re-operation? (Select all that apply)

☐ Minimum flow

☐ High flow pulse (where water levels remain in the main channel banks)

☐ Flood releases (where water levels over-top the main channel banks)

☐ Entire flow regime

☐ Ramping rates/ hydro-peaking rates

☐ Other, please specify

Who were the stakeholders involved in the case? (Select all that apply)

☐ National agencies

☐ Regional/State agencies

☐ Local government agencies

☐ Dam operator

☐ NGOs

☐ Civil society groups/ environmentalists Citizens/ general public

☐ Scientists

☐ Other, please specify

What was the main hurdle encountered? (i.e.: Why did the process of dam re-operation stall?)

How long after work started was this hurdle encountered?

At which stage in the process of dam re-operation was this main hurdle encountered? / At which stage did the process of dam re-operation stall?

○ In establishing a shared understanding among stakeholders that dam re-operation/ e-flows are needed

○ In determining e-flow requirements of downstream ecosystems

○ In translating the e-flow requirements into specific flow releases from the dam

○ In executing the dam release/flow recommendations (ie: moving from recommendation to actual implementation)

○ Other, please specify

What was done to overcome this major hurdle?

In which year did work on e-flows/river restoration/dam re- operation actively stop?

Were there other hurdles to dam re-operation for e-flows implementation?

○ Yes, please list these other hurdles

○ No

What factors/actions would you say was missing in the effort to overcome the hurdles?

☐ Scientific basis to determine e-flows and downstream effects Supporting legislation or policy

☐ Public interest/engagement Flow experiments

☐ Natural trigger event (eg: flood, drought) Physical modification to dam

☐ Simulation or optimization modeling

☐ Synergy (little of no trade-off) with existing water uses of the dam An agreed/fixed timeline for dam re-operation

☐ Collaboration and commitment among stakeholders

☐ Other, please specify

In your opinion how important would these factors/actions have been to successfully overcoming the hurdles and successful dam re-operation overall?

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not at all important (5)
Scientific basis to determine e-flows and downstream effects (x1)	○	○	○	○	○
Supporting legislation or policy (x2)	○	○	○	○	○
Public interest/engagement (x3)	○	○	○	○	○
Flow experiments (x4)	○	○	○	○	○
Natural trigger event (eg: flood, drought) (x5)	○	○	○	○	○
Physical modification to dam (x6)	○	○	○	○	○
Simulation or optimization modeling (x7)	○	○	○	○	○
Synergy (little of no trade-off) with existing water uses of the dam (x8)	○	○	○	○	○
An agreed/fixed timeline for dam re-operation (x9)	○	○	○	○	○
Collaboration and commitment among stakeholders (x10)	○	○	○	○	○
Other, please specify (x11)	○	○	○	○	○

How would you rate the impact of this case in terms of the following?

- the biophysical world (e.g.: target species, downstream habitats)

- the stakeholder network
- the diffusion of the ideas/lessons and established network to other cases (including work beyond dam re-operation)

	1- no positive impact (1)	2 (2)	3- moderate positive impact (3)	4 (4)	5- high positive impact (5)
Biophysical world (1)	○	○	○	○	○
Stakeholder network (2)	○	○	○	○	○
Diffusion of ideas and established network (3)	○	○	○	○	○

Can you share reports about this case and/or emails of others in your network who have information on this case?

NB: Due to privacy constraints and ethical considerations, your response to this survey has been anonymised, however if you are willing to share reports or emails of other resource persons with respect to this case, kindly share your name and email and you will be contacted by the research team. If not, please click 'Next' to proceed to the next question.

○ Yes

☐

○ No

Have you been involved in another dam re-operation case that you consider formative or significant?

NB: Answering 'yes' to this question routes you to question number 5 of the survey for you to answer questions on this 2nd case. This will roughly double the time to complete the survey. Select 'No' to proceed to the end of this survey.)

4- **(B- Info on successful cases)**

What activities were implemented to re-operate the dam(s) for e-flows? (select all that apply)

☐ Drafting/ updating of legislation or policy Flow experiments

☐ Workshops/ meetings with stakeholders

☐ Scientific studies (e.g.: environmental impact assessment of dam, trade-off studies, e-flow studies)

☐ Physical modification to dam Modelling

☐ Other, please specify

Which flow manipulation was targeted in dam re-operation? (Select all that apply)

☐ Minimum flow

☐ High flow pulse (where water levels remain in the main channel banks) Flood releases (where water levels over-top the main channel banks) Entire flow regime

☐ Ramping rates/ hydro-peaking rates

☐ Other, please specify

Who were the stakeholders involved in the case? (Select all that apply)

☐ National agencies

☐ Regional/State agencies

☐ Local government agencies Dam operator

☐ NGOs

☐ Civil society groups/ environmentalists Citizens/ general public

☐ Scientists

☐ Other, please specify

Were any hurdles encountered?

☐ Yes

☐ No

5- (B- Info on hurdles in successful cases)

What was the main hurdle encountered in the process of dam re-operation?

How long after work started was this hurdle encountered?

At which stage in the process of dam re-operation was this main hurdle encountered?

○ In establishing a shared understanding among stakeholders that dam re-operation/ e-flows are needed

○ In determining e-flow requirements of downstream ecosystems

○ In translating the e-flow requirements into specific flow releases from the dam

○ In executing the dam release/flow recommendations (ie: moving from recommendation to actual implementation)

○ Other, please specify

What was done to overcome this major hurdle?

How long did it take to overcome this major hurdle?

Were there other obstacles to dam re-operation for e-flows implementation?

○ Yes, please list these other hurdles

○ No

What factors/actions would you say was missing in the effort to overcome the hurdles?

- ☐ Scientific basis to determine e-flows and downstream effects Supporting legislation or policy
- ☐ Public interest/engagement Flow experiments
- ☐ Natural trigger event (e.g.: flood, drought) Physical modification to dam
- ☐ Simulation or optimization modelling
- ☐ Synergy (little of no trade-off) with existing water uses of the dam An agreed/fixed timeline for dam re-operation
- ☐ Collaboration and commitment among stakeholders
- ☐ Other, please specify

In your opinion how important would these factors/actions have been to successfully overcoming the hurdles and successful dam re-operation overall?

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not at all important (5)
Scientific basis to determine e-flows and downstream effects (x1)	○	○	○	○	○
Supporting legislation or policy (x2)	○	○	○	○	○
Public interest/engagement (x3)	○	○	○	○	○
Flow experiments (x4)	○	○	○	○	○
Natural trigger event (eg: flood, drought) (x5)	○	○	○	○	○
Physical modification to dam (x6)	○	○	○	○	○
Simulation or optimization modeling (x7)	○	○	○	○	○
Synergy (little of no trade-off) with existing water uses of the dam (x8)	○	○	○	○	○
An agreed/fixed timeline for dam re-operation (x9)	○	○	○	○	○
Collaboration and commitment among stakeholders (x10)	○	○	○	○	○
Other, please specify (x11)	○	○	○	○	○

How would you rate the impact of this case in terms of the following:

– the biophysical world (e.g.: target species, downstream habitats)

– the stakeholder network

– the diffusion of the ideas/lessons and established network to other cases (including work beyond dam re-operation)

	1- no positive impact (1)	2 (2)	3- moderate positive impact (3)	4 (4)	5- high positive impact (5)
Biophysical world (1)	○	○	○	○	○
Stakeholder network (2)	○	○	○	○	○
Diffusion of ideas and established network (3)	○	○	○	○	○

Which of the following best describes the approach taken to dam re-operation in this case:

- **Adaptive management** where prescribed dam releases for e-flows are essentially treated as flow experiments for scientific validation of hypothesis regarding flow components.
- **Blanket operation** where broad changes in dam operations are made based on available management and ecological information.
- **Episodic implementation** which is an opportunistic approach to dam re-operation driven by prevailing hydrological conditions allowing for modifications to dam operations.

○ Adaptive management

○ Blanket operation

○ Episodic implementation

Can you share reports about this case and/or emails of others in your network who have information on this case?

NB: Due to privacy constraints and ethical considerations, your response to this survey has been anonymised, however if you are willing to share reports or emails of other resource persons with respect to this case, kindly share your name and email and you will be contacted by the research team. If not, please click 'Next' to proceed to the next question.

○ Yes

○ No

6- (B- Info on successful cases with no hurdles)

What factors/actions would you say were the keys to successful dam re-operation in this case?

☐ Scientific basis to determine e-flows and downstream effects
☐ Supporting legislation or policy
☐ Public interest/engagement
☐ Flow experiments
☐ Natural trigger event (eg: flood, drought)
☐ Physical modification to dam
☐ Simulation or optimization modelling
☐ Synergy (little of no trade-off) with existing water uses of the dam
☐ An agreed/fixed timeline for dam re-operation
☐ Collaboration and commitment among stakeholders
☐ Other, please specify

In your opinion how important would these factors/actions have been to successfully overcoming the hurdles and successful dam re-operation overall?

	Extremely important (1)	Very important (2)	Moderately important (3)	Slightly important (4)	Not at all important (5)
Scientific basis to determine e-flows and downstream effects (x1)	○	○	○	○	○
Supporting legislation or policy (x2)	○	○	○	○	○
Public interest/engagement (x3)	○	○	○	○	○
Flow experiments (x4)	○	○	○	○	○
Natural trigger event (eg: flood, drought) (x5)	○	○	○	○	○
Physical modification to dam (x6)	○	○	○	○	○
Simulation or optimization modeling (x7)	○	○	○	○	○
Synergy (little of no trade-off) with existing water uses of the dam (x8)	○	○	○	○	○
An agreed/fixed timeline for dam re-operation (x9)	○	○	○	○	○
Collaboration and commitment among stakeholders (x10)	○	○	○	○	○
Other, please specify (x11)	○	○	○	○	○

How would you rate the impact of this case in terms of the following?

- the biophysical world (e.g.: target species, downstream habitats)
- the stakeholder network
- the diffusion of the ideas/lessons and established network to other cases (including work beyond dam re-operation)

	1- no positive impact (1)	2 (2)	3- moderate positive impact (3)	4 (4)	5- high positive impact (5)
Biophysical world (1)	○	○	○	○	○
Stakeholder network (2)	○	○	○	○	○
Diffusion of ideas and established network (3)	○	○	○	○	○

In which year was work on dam re-operation completed?

☐

Which of the following best describes the approach taken to dam re-operation in this case:

- **Adaptive management** where prescribed dam releases for e-flows are essentially treated as flow experiments for scientific validation of hypothesis regarding flow components.
- **Blanket operation** where broad changes in dam operations are made based on available management and ecological information.
- **Episodic implementation** which is an opportunistic approach to dam re-operation driven by prevailinghydrological conditions allowing for modifications to dam operations.

○ Adaptive management

○ Blanket operation

○ Episodic implementation

Can you share reports about this case and/or emails of others in your network who have information on this case?

NB: Due to privacy constraints and ethical considerations, your response to this survey has been anonymised, however if you are willing to share reports or emails of other resource persons with respect to this case, kindly share your name and email and you will be contacted by the research team. If not, please click 'Next' to proceed to the next question.

○ Yes

○ No

APPENDIX C

Delft University of Technology
ETHICS REVIEW CHECKLIST FOR HUMAN RESEARCH
(Version 01.02.2019)

This checklist should be completed for every research study that involves human participants and should be submitted before potential participants are approached to take part in your research study.

In this checklist we will ask for additional information if need be. Please attach this as an Annex to the application.

Please upload the documents (go to this page *for instructions).*
Thank you and please check our website *for guidelines, forms, best practices, meeting dates of the HREC, etc.*

I. Basic Data

Project title:	Dam re-operation for implementing environmental flows
Name(s) of researcher(s):	Afua G. Owusu
Research period (planning)	1-09-2018 to 31-08-2022
E-mail contact person	a.owusu@un-ihe.org
Faculty/Dept.	TPM/ Multi-actor Systems
Position researcher(s):[1]	PhD
Name of supervisor (if applicable):	Prof. Jill Slinger
Role of supervisor (if applicable):	

II. A) Summary Research

(Please very briefly (100-200 words) summarise your research, stating the question for the research, who will participate, the number of participants to be tested and the methods/devices to be used. Please avoid jargon and abbreviations).

---

[1] For example: student, PhD, post-doc

The design and operation of dams were traditionally based on economic considerations such as hydropower generation, flood control and provision of water for irrigation and domestic use. This led to alteration of river flow regimes and degraded riverine ecosystems. Provision of flows for the environment, e-flows, is a means to restore the benefits of naturally flowing rivers.

This research answers the question: ‘What is the process of incorporating e-flow recommendations into dam operations and how are the trade are-offs with traditional dam operation objectives considered?’. It is comprised of three phases: a systematic literature review of successful dam re-operation cases, a survey of stakeholders who have been involved in dam re-operation and then a case study comprised of in-depth stakeholder interviews and hydro-economic analysis.

The target participants of both the survey and interviews are dam operators, water managers, and scientists. In addition, for the interviews in the selected case study, community leaders in towns adjacent the dam will also be included. Relevant data (grey literature, reports, and flow data) on the specific cases will also be collected. A semi-structured interview approach will be adopted.

B) Risk assessment

Please indicate if you expect any potential risks for the participants as a result of your research and, if so, how you will try to minimize these.

Please take into consideration any personal data you may gather and privacy issues.

Risk: Lack of informed consent from participants

Mitigation:

- The purpose and methods of the study will be shared with all participants at the beginning of the survey and interviews. The survey and interviews will only proceed once an informed consent is received from the participant.

Risk: Identification of respondents through contact or professional details

Mitigation:

This study will be collecting information only on dam re-operation projects and not individuals. Personal details which will be collected are participant’s name, email address and professional status. Personal details such as ID numbers, dates of birth or location will NOT be collected. However it is acknowledged that there may be sensitive information related to these projects. Therefore the following steps will be taken to protect the privacy and professional career of participants:

- Respondents will be contacted through their professional emails and telephone numbers. These are publicly available for correspondence on their institutional websites or in scientific publications.

- The names of respondents will be safeguarded physically and electronically from people outside the study. This will be destroyed 6 months after the end of the study.
- For the survey, responses will be de-identified and then categorised and reported on according to the broad professional groups participants fall into with respect to the process of dam re-operation such as ‘dam operator’, ‘local government agency’, ‘NGO’ etc.
- For the interviews, participants will be given the option of having their comments anonymised.
- For the interview, transcripts will be shared with each interviewee for consent before publication.
- Care will be taken in consultation with the participant to minimise any potential harm to their professional career.

Risk: Withdrawal of consent to participate in study
Mitigation:

- At the beginning of interviews, participants will be made aware of the option, procedure and timeline to request anonymization or withdraw (without explanation) from the study before publication.

III. Checklist

Question	Yes	No
1. Does the study involve participants who are particularly vulnerable or unable to give informed consent? (e.g., children, people with learning difficulties, patients, people receiving counselling, people living in care or nursing homes, people recruited through self-help groups).		x
2. Are the participants, outside the context of the research, in a dependent or subordinate position to the investigator (such as own children or own students)?[2]		x
3. Will it be necessary for participants to take part in the study without their knowledge and consent at the time? (e.g., covert observation of people in non-public places).		x
4. Will the study involve actively deceiving the participants? (For example, will participants be deliberately falsely informed, will information be withheld from them or will they be misled in such a way that they are likely to object or show unease when debriefed about the study).		x
5. Personal data - Will the study involve discussion or collection of <u>confidential (sensitive) personal data</u>? (e.g., BSN number, location, sexual activity, drug use, mental health)?	X	
If ‘ yes’: Did the <u>data steward</u> approve your data management plan? Please upload proof.	X	
6. Will drugs, placebos, or other substances (e.g., drinks, foods, food or drink constituents, dietary supplements) be administered to the study participants?		x
7. Will blood or tissue samples be obtained from participants?		x

---

[2] **Important note concerning questions 1 and 2.** Some intended studies involve research subjects who are particularly vulnerable or unable to give informed consent. Research involving participants who are in a dependent or unequal relationship with the researcher or research supervisor (e.g., the researcher’s or research supervisor’s students or staff) may also be regarded as a vulnerable group . If your study involves such participants, it is essential that you safeguard against possible adverse consequences of this situation (e.g., allowing a student’s failure to complete their participation to your satisfaction to affect your evaluation of their coursework). This can be achieved by ensuring that participants remain anonymous to the individuals concerned (e.g., you do not seek names of students taking part in your study). If such safeguards are in place, or the research does not involve other potentially vulnerable groups or individuals unable to give informed consent, it is appropriate to check the NO box for questions 1 and 2. Please describe corresponding safeguards in the summary field.

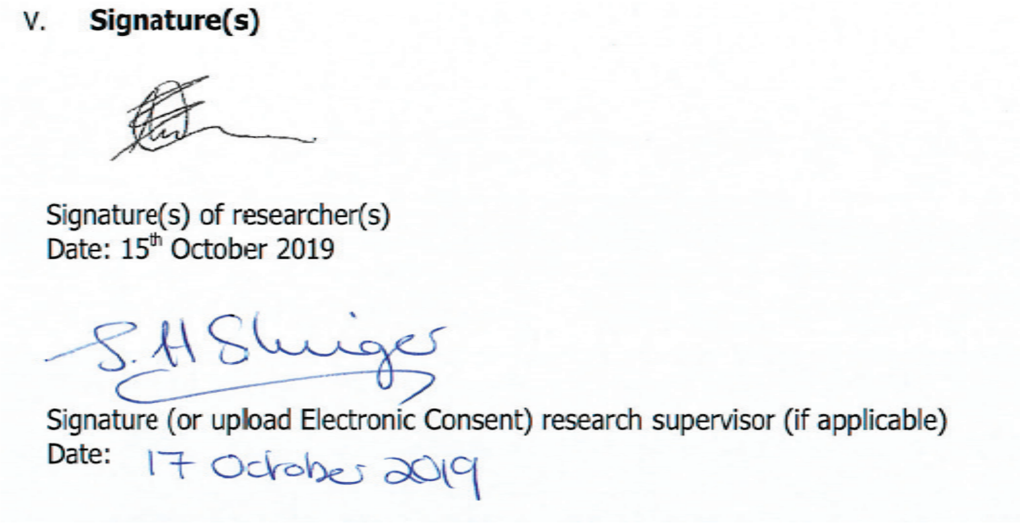
Question	**Yes**	**No**
8. Is pain or more than mild discomfort likely to result from the study?		x
9. Does the study risk causing psychological stress or anxiety or other harm or negative consequences beyond that normally encountered by the participants in their life outside research?		x
10. Will financial inducement (other than reasonable expenses and compensation for time) be offered to participants?		x
Important: **if you answered 'yes' to any of the questions mentioned above, please submit a full application to HREC (see: website for forms or examples).**		
11. Will the experiment collect and store videos, pictures, or other identifiable data of human subjects? [3] If "yes", please fill in Annex 1 and make you sure you follow all requirements of the applicable data protection legislation. In addition, please provide proof by sending us a copy of the informed consent form.	X	
12. Will the experiment involve the use of devices that are not 'CE' certified? *Only, if 'yes': continue with the following questions:*		x
➢ Was the device built in-house?		
➢ Was it inspected by a safety expert at TU Delft? (*Please provide device report, see: HREC website)*		
➢ If it was not built-in house and not CE-certified, was it inspected by some other, qualified authority in safety and approved? *(Please provide records of the inspection).*		
13. Has or will this research be submitted to a research ethics committee other than this one? (*if so, please provide details and a copy of the approval or submission).*		x

---

[3] Note: you have to ensure that collected data is safeguarded physically and will not be accessible to anyone outside the study. Furthermore, the data has to be de-identified if possible and has to be destroyed after a scientifically appropriate period of time. Also ask explicitly for consent if anonymised data will be published as open data.

IV. Enclosures (tick if applicable)

- ☒ Full proposal (if 'yes' to any of the questions 1 until 10)
- ☒ Informed consent form (if 'yes' to question 11)
- ○ Device report (if 'yes' to question 12)
- ○ Approval other HREC-committee (if 'yes' to question 13)
- ○ Any other information which might be relevant for decision making by HREC
- ☒ Data management plan approved by a data steward (if yes to question 5B)



V. **Signature(s)**

Signature(s) of researcher(s)
Date: 15th October 2019

S. H Slinger

Signature (or upload Electronic Consent) research supervisor (if applicable)
Date: 17 October 2019

Appendix1: Privacy and data protection
Please fill this in if you have answered 'yes' to question 11 in the checklist

---

a. *Will the participants have access to their own data? If no, please explain.*

Yes, participants have 2 types of access: access to the transcript (from audio recordings) of their interview within one month of it taking place for review and second, access to the analytical product of the survey and interview as published in journals and the doctoral thesis.

b. *Will covert methods be used? (e.g. participants are filmed without them knowing)*

No, participants will only be recorded (audio) with their consent.

c. *Will any human tissue and/or biological samples be collected? (e.g. urine)*

No, human tissue and/or biological samples will not be collected.

Date 21-10-2019
Contact person Ir. J.B.J. Groot Kormelink, secretary HREC
Telephone +31 152783260
E-mail j.b.j.grootkormelink@tudelft.nl

TU Delft Delft University of Technology

Human Research Ethics Committee
TU Delft
(http://hrec.tudelft.nl/)

Visiting address
Jaffalaan 5 (building 31)
2628 BX Delft

Postal address
P.O. Box 5015 2600 GA Delft
The Netherlands

Ethics Approval Application: Dam re-operation for environmental flows implementation
Applicant: Owusu, Afua

Dear Afua Owusu,

It is a pleasure to inform you that your application mentioned above has been approved.

Good luck with your research!

Sincerely,

Prof. Dr. Sabine Roeser
Chair Human Research Ethics Committee TU Delft

Prof.dr. Sabine Roeser
TU Delft
Head of the Ethics and Philosophy of Technology Section
Department of Values, Technology, and Innovation
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Jaffalaan 5
2628 BX Delft
The Netherlands
+31 (0) 15 2788779
S.Roeser@tudelft.nl
www.tbm.tudelft.nl/sroeser

Informed Consent Form for interviews

Consent form for participation in research on Dam Re-operation for Environmental Flows Implementation

You are being invited to participate in a research study titled **Dam re-operation for implementation of environmental flows**. This study is being done by Afua Owusu, Dr. Marloes Mul, Prof. Pieter van der Zaag and Prof. Jill Slinger from IHE Delft Institute for Water Education and TU Delft in the Netherlands. This research aims to generate insights into how e-flow recommendations evolve from recommendation into practice and the trade-offs that are made between conventional water uses and e-flows during implementation. **This interview** will take approximately **30** minutes and will seek information specifically regarding Akosombo and Kpong dams on the Volta River. Insights from this interview will be published in an open-access scientific journal and a doctoral thesis.

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information on ___ ___ /___ ___ /2020, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
I consent voluntarily to be a participant in this study and understand that I can refuse to answer any questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
I understand that during the meeting, notes will be taken and the conversation will be recorded. I understand that I am allowed to request and be granted access to all information collected during this meeting.	☐	☐
Use of the information in the study		
I understand that information I provide will be used as data input for scientific publication and in the PhD thesis of the interviewer.	☐	☐
I understand that personal information collected about me that can identify me, such as my name or where I work, will be stored securely for the duration of the study until a period of 6 months after the end of the study	☐	☐
I understand that personal information collected about me that can identify me, such as my name or where I work, will not be shared beyond the study team without my written consent.	☐	☐

I agree that information I give can be quoted in research outputs ☐ ☐

I agree that my real name can be used for quotes ☐ ☐

Future use and reuse of the information by others

I give permission for the anonymised output (transcript, service suitability graphs, ideal monthly flow rate graphs, rationale for flow requirements, etc) of the interview that I provide to be archived in ***4TU.ResearchData Repository*** so it can be used for future research and learning. ☐ ☐

Signatures

______________________ ______________________

Name of participant Signature

Date

For participants unable to sign their name, mark the box instead of sign

I have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

___________________________ ________________________

Name of witness Signature

Date

I have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

_________________________ ___________________

Researcher name Signature

Date

Study contact details for further information: Afua Owusu, *+31 684 701 752, +233266702155, a.owusu@un-ihe.org*

This research is part of the EuroFLOW project (EUROpean training and research network for environmental FLOW management in river basins) funded by the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie grant Agreement (MSCA) No 765553.

Semi-structured interview form

______/______/2010

Interviewee: ____

Location: ____

Introduction

- Thanks for sitting down with me for this interview
- Short intro on purpose: to document the flow requirement in terms of SS curves for trade-off analysis. Missing key indicator from past interviews: clams
- Establish expertise: Current role in establishment/ How were you involved with the Akosombo project? What was your specific role?

(Narrow down to the indicator(s) he/she is an expert in)

- Permission to record so I can listen attentively and my hands can be free.
- Agreement on data collected: Send written results/graphs to he/she for confirmation and final permission to use in my research.
- What will happen to the data in the long term:
    - either stored at TPM for 10 years, only accessible to two people - you and me OR
    - openly stored as anonymized data on an international database (4TUdatabase) OR
    - stored with name and all on the database - the database is freely accessible from all over the world

Main questions

- Let's think about an indicator of environmental flow, A OR Which indicator of environmental flow would you like to discuss? (maybe they can give you information on more than one, and you have to repeat this section).
- When you think of the 'ideal' conditions for this indicator, in what terms do you envisage it?
  (E.g.: flow hydrographs, water levels at certain times of the year, flood extent, etc)
- What will this 'ideal' condition yield? (Eg: higher fish catch, reduction in weeds, reliable power)
- When in the past have you had these 'ideal' conditions and resultant yield?
  (In which years relative to when the dam was constructed)
- What conditions does the indicator need for survival/ for it to thrive?

(Translate this contemporaneously into a sketch/ try as much as possible to get quantitative values or descriptions which can be translated into quantitative values through mapping. Fill in the table when listening to recording)

	Question	**Summary of response in words**
How much?	What flows/flood extent/water levels are required? (compare to values already in Akosombo book) What are the upper and lower limits of this?	
When?	Which months are the key periods for the indicator over the year? What happens when there is a month's or more delay? What happens if it comes a month or earlier?	
How long?	How long should the 'ideal' flow rate/water level remain? What are the limits of this duration? (What happens when it's half/twice as long?)	
How often?	How often is this flow rate needed? Annually? Every other year? What interval between 'good' years before the indicator cannot recover? Also, when is it too soon? Say two floods too close to each other, so the system hasn't recovered before the next one comes	

What about concurrent/system effects - say the indicator is a fish, what other things also need to be there for it to thrive, or can have a delayed impact - say its shelter is scoured away then more fish die

Check

- Show the interviewee the sketch/graph developed. Explain by linking the points and lines on the graph to his responses. NB: Separate information given from assumptions I use in extrapolating from those points.
- Discuss gaps. Ok to use pre-dam flow to fill these gaps?
- Where are the nonlinear thresholds?
- What functions can be strengthened now given that it is a different system now?

Final questions and remarks

- Suggestions for other interviewees
- Suggestions for other indicators/things to consider for the research
- Summary of results agreements/timelines for sending any feedback
- Thanks

APPENDIX D

Sampling locations and procedure- Chlorophyll-a and nutrients

Chlorophyll-*a* Determination

Chlorophyll-*a* levels in the collected water samples were determined following methods described by HMSO (1983)[4]. Approximately 100 ml of the sampled water was filtered with a vacuum pump through a Whatman GF/C filter paper to trap the phytoplankton. Following the filtration, the filter paper with the trapped phytoplankton was immersed in 10 ml solution of 98% methanol to extract the chlorophyll. To facilitate chlorophyll extraction, the tubes containing the solvent were loosely capped and immersed into a water bath heated to 70˚C for up to 2 minutes under a fume hood. The tubes were removed from the bath and left to cool in the dark at room temperature after which the filter papers were removed. The tubes containing the extracted chlorophyll were centrifuged for 8 minutes at 3500 rpm to obtain a clear extract for spectrophotometric determination. Absorbances were then measured at wavelengths of 665 and 750 nm before and after acidification with 0.1M HCl.

Chlorophyll-a concentration in the samples were calculated using the equation:

$$Chlorophyll - a\ (\mu g/l) = \frac{13.9(3(Ah - Aj) * V1)}{d * V2}$$

Where; A_h = absorbance at 665 nm, A_j = absorbance at 750 nm, V_1 = initial volume of methanol in mL (usually 10 ml), d = cell length of cuvette in cm (1 cm), V_2 = sample volume in litres (1 L). The absorbance at 750 nm was subtracted from the 665 nm wavelength to give the turbidity-corrected value.

Nutrients determination

Phosphate and nitrate were determined using optical absorbance techniques where specific reagents were added to water samples and the intensity of colour produced measured via the photometric method at different wavelengths (Hach DR3900 spectrophotometer, Hach Lange GmbH, Germany). The Palintest® methods were used to determine nitrate and phosphate following the manufacturer's specifications.

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[4] H.M.S.O. (1983). The Determination of Chlorophyll a in Aquatic Environments, 1980. In Methods for the examination of waters and associated materials. London: Crown.

Building the Directed Acyclic Graph (DAG)

Table D1: Table of interviews with clam fishery experts and local stakeholders

Person interviewed	Dates	Place	Topics covered
Expert 1	30/10/2020	Online interview	The state of clam fishery, clam habitat, lifecycle, pre-dam state, water quality and ecological monitoring
	29/01/2021	Online interview	
	29 /03/2021	Sogakope (In-person)	Modifying initial Directed Acyclic Graph
	31/03/2021	Online interview	Specifying conditional probabilities
Expert 2	29/01/2021	Online interview	The state of clam fishery, clam habitat, lifecycle, pre-dam state, water quality and ecological monitoring
	29 /03/2021	Sogakope (In-person)	Modifying initial Directed Acyclic Graph
	31/03/2021	Online interview	Specifying conditional probabilities
Elder clam fisherman/ community leader	23-29 /03/2021	Lower Volta River (In-person interview before and while in the field)	The state and extent of clam fishery, pre-dam and current state of fishery; salt intrusion, daily catch, how clams are harvested, riverine communities, clam seeding, sand winning activities, other water uses
	1/04/2021	Phone interview	
Clam fishermen	23-29 /03/2021	Lower Volta River (while in the field)	Extent of clam bed, daily catch, current state of clam fishery and salt intrusion, clam seeding, sand winning activities

Sampling locations and procedure

Figure D1: Sampling downstream/southwards toward the Volta Estuary with sampling points identified as GPS waypoints

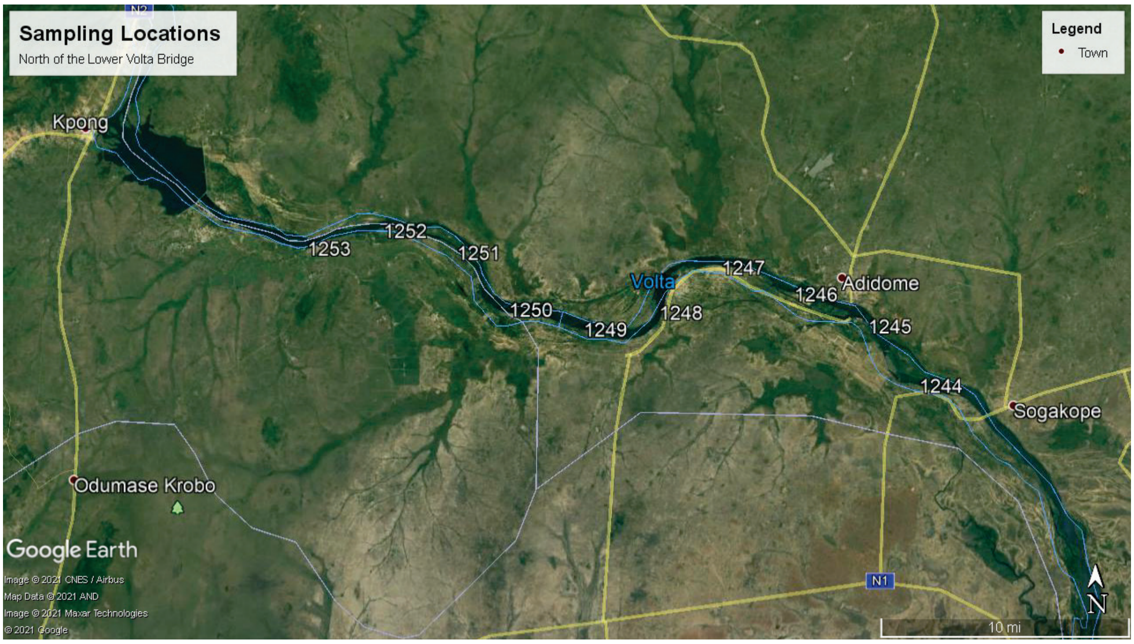

Figure D2: Sampling upstream/northwards toward the Kpong dam with sampling points identified as GPS waypoints

Building Conditional Probability Tables (CPTs)

For qualitative nodes, the experts were asked to assign probabilities to the node being in a given state for each combination of states of the parent nodes using a seven-point scale

(Table D2). To illustrate the process for a child node, Node X with parents Y and Z, using the first row in Table D3 (italic), experts were asked, "What is the probability that *Node X* will be 'poor'/'good' given that *Parent node Y* is present and the *Parent node Z* is poor?"

Table D2: Scale for assigning probabilities to qualitative nodes

Probability description	**Value**
certain	100%
very high	90%
high	70%
fair	50%
low	30%
very low	10%
none	0%

Table D3: Example conditional probability table (CPT) for child node, X, with parent nodes, Y and Z

Node X		**poor**	**good**
Parent node Y	**Parent node Z**		
Present	*Poor*	*high*	*low*
Present	Good	fair	fair
Absent	Poor	low	high
Absent	Good	none	certain

Spatial and temporal trends in salinity during spring tide

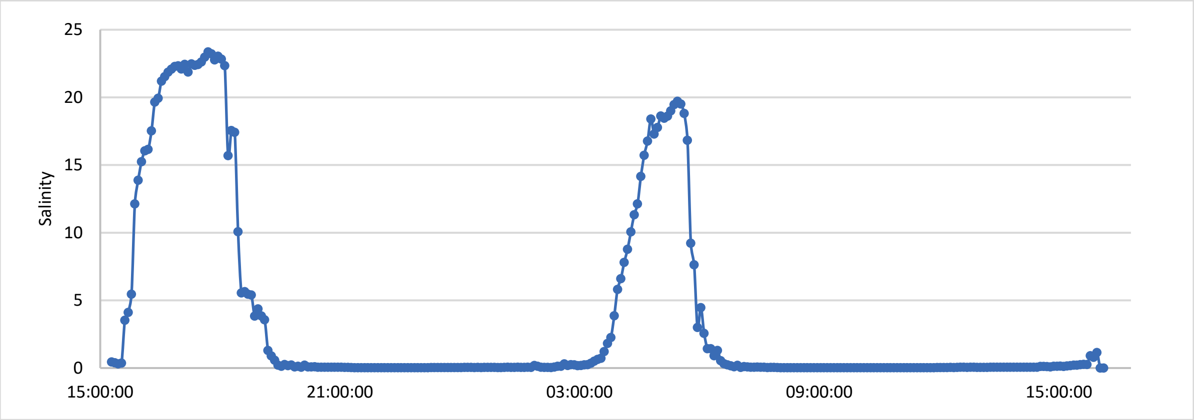

Figure D3: Temporal readings for salinity measured near the river bed at a fixed location 5.8km from the Volta Estuary starting 3pm on 28th March to 3pm on29th March

Table D4: Correlation matrix (correlation coefficients) of the for the assayed water quality data during the spring tide (p-values <0.0001).

	Salinity	**TDS (g/L)**	**DO (mg/L)**	**pH**
Salinity	-	0.99	0.47	0.95
TDS (g/L)	0.99	-	0.48	0.95
DO (mg/L)	0.47	0.48	-	0.43
pH	0.95	0.95	0.43	-

Bayesian Belief Network for the Volta clam

Table D5: Descriptions, units and states of the nodes in the Volta clam Bayesian Belief Network

Node	Description	Unit	States, Prior probabilities	Description of states/Notes	Data source
Flow (Apr-Jun)	Average monthly flow from April to June	m3/s	pre-dam current Low = 91.4% 0 Medium = 8.6% 97.83% High = 0 2.17%	1. High: >2400 m^3/s 2. Medium: between high and low 3. Low: 50 m^3/s – 330 m^3/s	Average monthly flow data from Volta River Authority, Ghana (VRA)
Flow (Jul-Oct)	Average monthly flow from July to October		Low = 4.03% 0 Medium = 39.52% 100% High = 56.45% 0	High flow value -2010 monthly high flow which led to flooding downstream. Low flow – Approximate limits of interquartile range of flow in historical (pre-dam) low flow months from November to July (25%-> 51 m^3/s; 75%-> 327 m^3/s; mean-> 333 m^3/s).	
Flow (Nov to Mar)	Average monthly flow from November to March		Low = 78.57% 0 Medium = 19.48% 97.39% High = 1.95% 2.61%		
Sand winning	Status of sand winning from riverbed	–	Present = 50% Absent = 50%	Sand wining from riverbed for construction. Recent phenomenon (<3 years) outside the natural clam beds but near the banks within the seeded area.	Observation and interviews with experts and locals during field visit.
Sandbar	Status of sandbar at Volta Estuary	–	Breached = 12.9% Not breached = 87.1%	Breached- dredged mechanically in the past year (>1.2 km wide)	Interviews with experts and locals during field visit. Literature (Bollen et al.,

Node	Description	Unit	States, Prior probabilities	Description of states/Notes	Data source
				Not breached- no mechanical dredging in past year /water exchange through narrow opening (<1.2 km wide). The estuary is about 1.2 km wide at the mouth, but owing to the formation of a sand bar, the river enters the sea through a narrow opening. Since 1990, to control aquatic weeds and associated diseases through salt intrusion, the VRA has mechanically dredged 4 times (1990, 1996, 2003 and 2009).	2011; Ntiamoa-Baidu et al., 2017; Nyekodzi et al., 2018; Roest, 2018)
Substratum	Type of substratum	–	fine =1.62% coarse =98.38%	Fine- <0.02 mm Coarse- 0.02-2 mm Adult clams survive better sandy substratum	Literature (Adjei-Boateng et al., 2010, 2012; Obirikorang et al., 2013)
Salt intrusion	Salt intrusion (salinity>1) upstream from Volta Estuary during veliger and recruitment stages	km (from estuary)	Above Sogakope (Soga) bridge Between Sogakope bridge and Ada (waypoint 1261: 5.82950N, 0.638847E)	Salt content above 1 measured during spring tide Above Sogakope bridge -approx. 30 km from estuary (pre-dam situation) Between Sogakope bridge and waypoint 1261 near Big Ada (situation under current flow with sandbar	Field measurements Interviews with experts, locals during field visit. Literature (People & Rogoyska, 1969; Beadle, 1974; Amoah & Ofori-Danson, 2012; Adjei-

Node	Description	Unit	States, Prior probabilities	Description of states/Notes	Data source
			Below Ada (waypoint 1261)	breached) Below waypoint 1261 (current flow regime with no breaching)	Boateng et al., 2012; Obirikorang et al., 2013; Nyekodzi et al., 2018)
Clam spawning	Release of gametes & fertilization	–	poor good	poor- <90% of adult clam spawning good- ≥90% of adult clam spawning	Literature (Kwei, 1965; Etim & Taege, 1993; Etim, 1996; Adjei-Boateng & Wilson, 2013b, 2016)
Larva survival	Survival of veliger larvae which require 0.1% salinity to maintain water balance	–	poor good	In the absence of data on larva survival rates, this a qualitative variable where it is taken that the pre-dam/natural river conditions led to 'good' larva survival and current post dam river conditions leads to a (relatively) 'poor' condition based on literature and interviews.	Interviews with experts, locals during field visit. Literature on the pre and post dam states of the clam fishery (Lawson, 1972; Tsikata, 2008; D. Adjei-Boateng et al., 2012; Ntiamoa-Baidu et al., 2017)

Node	Description	Unit	States, Prior probabilities	Description of states/Notes	Data source
Clam recruitment	Recruitment of adult clams	–	poor good	Occurs November to March when the smallest clams are found. Motile veliger larvae swim upstream from the 0.1% salinity zone to create new clam beds in the freshwater zone. In the absence of data on clam recruitment rates, this a 'qualitative' variable where it is taken that the pre-dam/natural river conditions led to 'good' recruitment and current post dam river conditions leads to a (relatively) 'poor' condition based on literature and interviews.	Interviews with experts, locals during field visit. Literature on pre and post dam states of the clam fishery (Lawson, 1972; Beadle, 1974; Tsikata, 2008; Adjei-Boateng et al., 2012; Ntiamoa-Baidu et al., 2017)
Clam survival	Survival of adult clams		poor good	poor- <75% survival rate good- ≥75% survival rate Adult clams survive better sandy substratum Survival in course substrate = 96.7% Clam survival in fine substrate = 71.4% Based on interviews, it is assumed that the presence of sand winning will hamper clam survival	Interviews with experts, locals during field visit. Literature (Adjei-Boateng et al., 2010, 2012)

Node	Description	Unit	States, Prior probabilities	Description of states/Notes	Data source
Natural clam extent	Extent/length of natural clam bed	–	decreased maintained increased	The length of the active natural clam fishing bed where ‘maintained’ refers to the current active clam fishing zone of approximately 10 km from Agave-Afedume to Big Ada. The states, 'decreased' and 'increased' are both relative to this current extent.	Interviews with experts, locals during field visit.

APPENDIX E

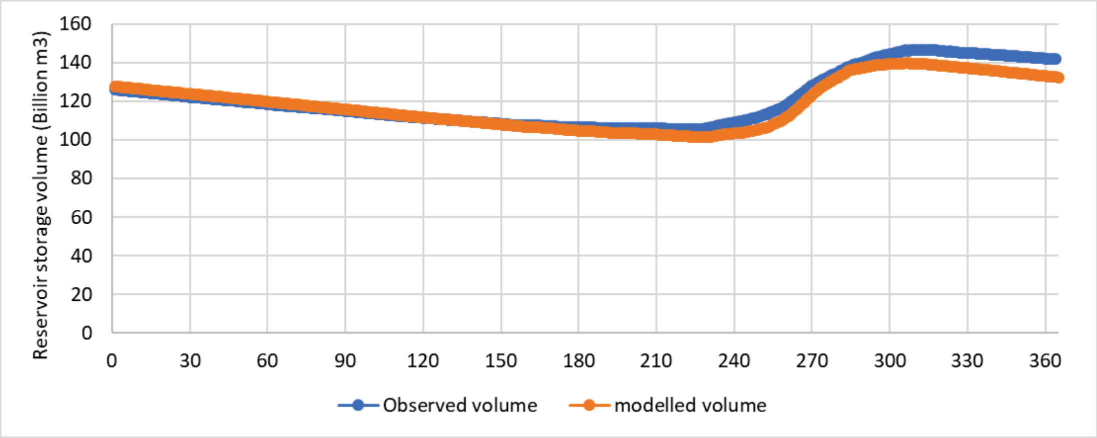

Figure E1: Observed volume as compared with modelled volume (2010, wet year)

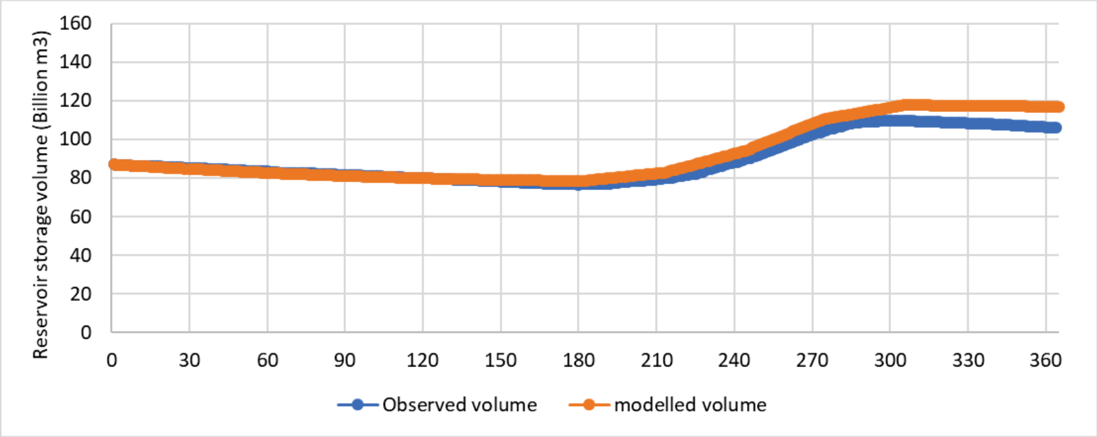

Figure E2: Observed volume as compared with modelled volume (1985, normal year)

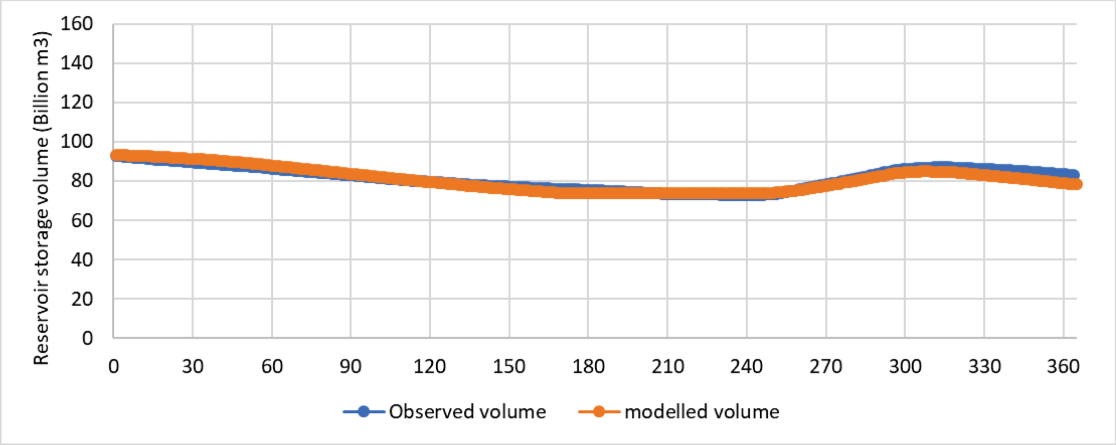

Figure E3: Observed volume as compared with modelled volume (2006, dry year)

Table E1: Papers on climate change effects on runoff in the Volta basin. The first four papers are as reviewed by Roudier et al., 2014 with the exception of the summary of the predictions

Reference	Time period	Climate model	Hydrological model	Scenarios	Predictions
Kunstmann and Jung, 2005	2030-2040	ECHAM4-MM6	OSU-LSM	IS92a	Monthly changes: increase: May-June & Aug-Nov (range 20-55%) decrease: July (10%); Feb-May and Dec (20%-75%) Annual trend: 18% increase in annual runoff
Aerts et al., 2006	2001-2099	ECBilt-CLIO-VECODE	STREAM	A2	Annual trend: 65% increase mean decadal runoff
Jung et al., 2012	2030-2039	ECHAM4-MM5	WaSIM	IS92a	Monthly changes: increase: Jun, Sept & Oct (range 15-30%) decrease: July & Aug (6-8%) Annual trend: 4% increase in annual runoff
McCartney et al., 2012	2071/2100 2021/2050, 1983/2012	ECHAM4-MM5 HadCM3	SWAT and WEAP	A1B	Annual trend: 45% decrease in annual runoff
Sood et al.,2013	2021-2050 2071-2100	ECHAM5	SWAT	A1B	Annual trend: Decrease by 13% in water yield in 2021-

Reference	Time period	Climate model	Hydrological model	Scenarios	Predictions
					2015 Decrease of 40% in 2071-2100
Amisigo et al.,2015	2010-2050	NCAR_CCSM3_0 A2 CSIRO_MK3_0 A2 NCAR_PCM1 A1b IPSL_CM4 B1	WEAP	A2 A1b B1	Inconsistent results across scenarios
Jin et al., 2018	1951-2100	CNRM-CM5 HadGEM2-ES CanESM2	INCA	RCP 8.5	Monthly changes: increase: wet season flow: June to Sept (10-50%) decrease: dry season months
Abubakari, 2021	2011-2040 2041-2070 2071-2100	CFSR	SWAT	A1B	Monthly changes: increase: February to August decrease: September to January Annual trend: 12% increase in annual runoff

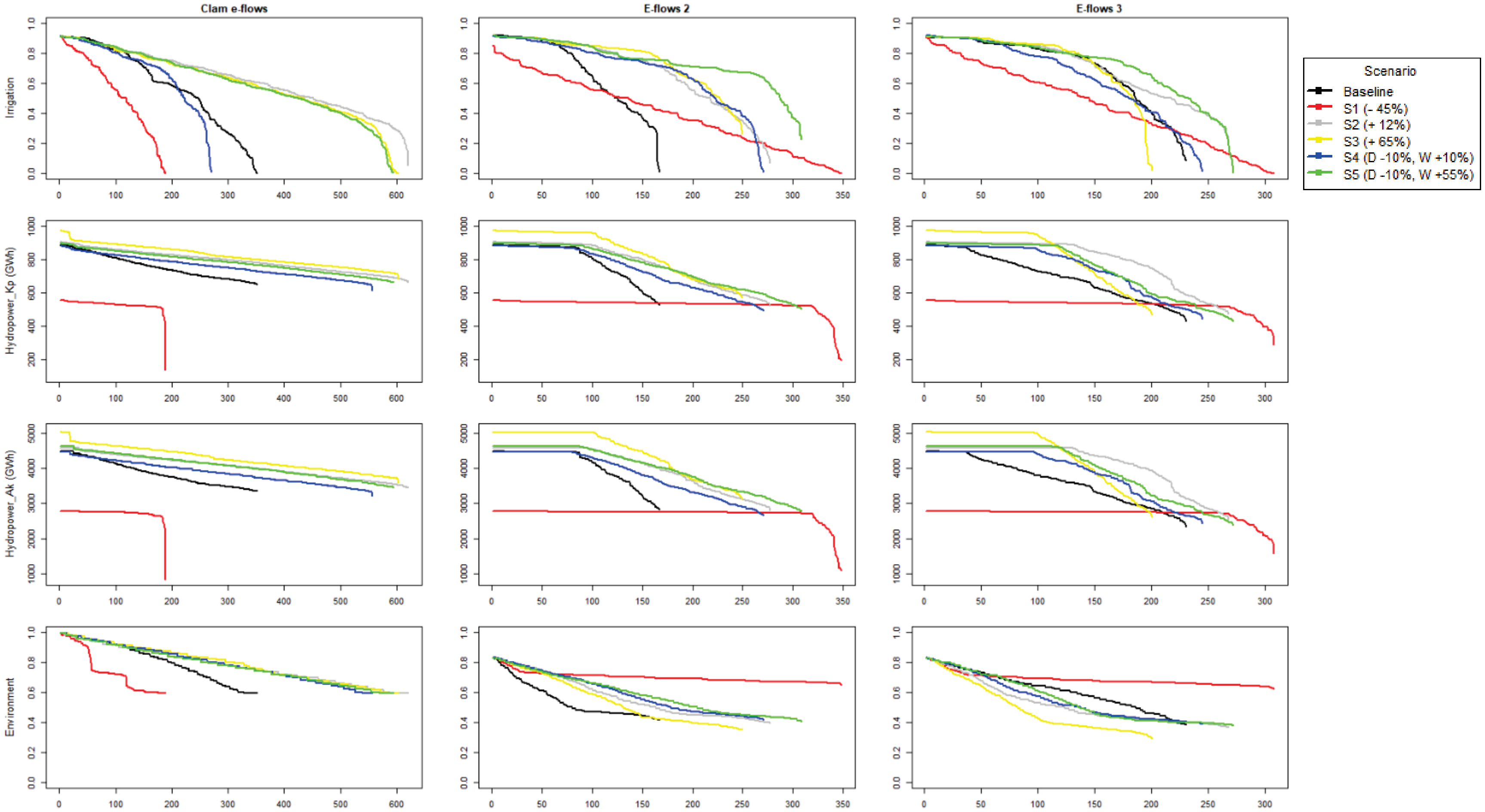

Figure E4: Cumulative distributive graphs showing the function values of all the non-dominated solutions for the baseline and future scenarios. Notation- scenarios: S1 to S5- Scenario 1 to 5, D- dry season flow, W-wet season flow

LIST OF ACRONYMS

ADB	African Development Bank
AWF	African Water Facility
BBN	Bayesian Belief Network
DO	dissolved oxygen
E-flows	environmental flows
EMODPS	Evolutionary Multi-Objective Direct Policy Search
EuroFLOW	EUROpean training and research network for environmental FLOW management in river basins
GIDA	Ghana Irrigation Development Authority
IPCC	Intergovernmental Panel on Climate Change
INGO	International Non-Governmental Organisation
L.I.	legislative instrument
MOEA	Multi-Objective Evolutionary Algorithms
MSCA	Marie Skłodowska-Curie grant Agreement
NGO	Non-Governmental Organisation
NSW	New South Wales
RRAKDP	Re-operation and Re-optimisation of the Akosombo and Kpong Dams Project
SPI	Service Provision index
SS	Service suitability
TDS	Total dissolved solids
VRA	Volta River Authority
WCD	World Commission on Dams
WFD	Water Framework Directive
WP	Work Package

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ABOUT THE AUTHOR

Afua Owusu was born and raised in Accra, Ghana. She studied Civil Engineering at Kwame Nkrumah University of Science and Technology, Ghana, graduating with First Class Honours in 2012. She completed a Masters degree in Environmental Water Management at Cranfield University, UK in 2015, receiving the Atkins Prize for the best student on the course. After her Masters, Afua returned to Ghana and completed an internship with the Environmental Protection Agency. She also worked with the International Water Management Institute (IWMI) from on projects in the Volta Basin, first as an intern and then on a consultancy basis.

Afua moved to Delft in September 2018 to pursue a PhD. Her research looked at how e-flows are implemented through dam re-operation and also the inter-sectoral trade-offs that are identified between e-flows and conventional water uses in delivering e-flows in a unique case study. Her research was part of EuroFLOW, a European training and research network for environmental flow management in river basins. During her PhD, she successfully supervised the thesis research of four Masters students at IHE Delft and TU Delft. She finalised her PhD in July 2022 and begun a post-doctoral fellowship on Water Accounting with IWMI in September 2022.

Her research interests include hydrological modelling, environmental flows and flood recession agriculture among others. She is an avid tennis fan and also loves to play piano and read on her kindle.

Journals publications

Owusu, A.G., Mul, M., van der Zaag, P., & Slinger, J.: May the odds be in your favour: Why many attempts to re-operate dams for the environment stall. *Journal of Water Resources Planning and Management*, 148(5) doi.org/10.1061/(ASCE)WR.1943-5452.0001521, 2022.

Owusu, A., Mul, M., Strauch, M., van der Zaag, P., Volk, M., & Slinger, J.: The clam and the dam: A Bayesian belief network approach to environmental flow assessment in a data scarce region. *Science of The Total Environment*, 810, 151315. https://doi.org/10.1016/j.scitotenv.2021.151315, 2022

Owusu, A. G., Mul, M., Zaag, P. van der, & Slinger, J.: Re-operating dams for environmental flows: From recommendation to practice. *River Research and Applications*, 37(2), 176–186. https://doi.org/10.1002/rra.3624, 2021

Conference proceedings

Owusu, A.G., Zatarain Salazar, J., Mul, M., van der Zaag, P., & Slinger, J.: Multi-objective trade-off analysis in operating dams for the environment: The case of the Lower Volta River. Oral presentation at International Assembly of Hydrological Sciences (IAHS) Scientific Assembly, 2022, Montpellier, France, 2022.

Owusu, A.G., Zatarain Salazar, J., Mul, M., van der Zaag, P., & Slinger, J.: Multi-objective trade-off analysis in operating dams for the environment: The case of the Lower Volta River. Oral presentation at European Geosciences Union General Assembly, Vienna, Austria, 2022.

Owusu, A., Mul, M., Strauch, M., van der Zaag, P., Volk, M., & Slinger, J.: The clam and the dam: A Bayesian Belief Network approach to developing environmental flows in data scarce regions. Oral presentation at Ghana Water Platform Meeting: When science meets practice, online symposium, 2021.

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Owusu, A.G., Mul, M., van der Zaag, P., & Slinger, J.: May the odds be ever in your favour: Why many attempts to re-operate dams for the environment stall. Oral presentation (invited speaker) during WWF Special session at 21st WaterNet Symposium, online symposium, 2020.

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(SENSE) declares that

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born on 26th May 1989 in Accra, Ghana

has successfully fulfilled all requirements of the
educational PhD programme of SENSE.

Delft, 30 November 2022

Chair of the SENSE board

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The SENSE Research School declares that **Afua Gyamfuah Owusu** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 47.1 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2019)
- Research in context activity: 'Running of the PhD Community page of the IHE Delft PhD Source Background '(2019-2020)

Selection of Other PhD and Advanced MSc Courses

- Sampling during a controlled flood, Eawag (2018)
- Environmental Flows, IHE Delft (2018)
- PhD Start-up (2018) and PhD days, TU Delft (2019)
- Research Frontiers, TPM, TU Delft (2019)
- Data-analysis and Statistics, TU Delft (2019)
- Python for Geospatial Hydrological Applications, IHE Delft (2021)

External training at a foreign research institute

- Secondment at the Centre for Ecology and Hydrology, United Kingdom (2020)
- Secondment at the Helmholtz Centre for Environmental Research, UFZ, Germany (2021)

Management and Didactic Skills Training

- EuroFLOW ESR representative on Training Committee (2019-2020)
- Supervising 2 MSc students with theses entitled 'Influence of public participation on e-flow implementation in the context of the Water Framework Directive: A Case Study in the Acheloos River, Greece (2021) and 'The EU Water Framework Directive and environmental flow implementation' (2022)
- Teaching assistance in the MSc courses 'Introduction to Environmental Science' (2020) and 'Introduction to Water Resources Management' (2020 and 2021)

Selection of Oral Presentations

- *Re-operating dams to provide environmental flows: From recommendation to practice*. 6th Symposium of the International Society of River Science, 8-13 September 2019, Vienna, Austria
- **Invited speaker**: *May the odds be ever in your favour: Why many attempts to re-operate dams for the environment stall.* WWF Special Session at 21st WaterNet Symposium, 28 October 2020, Online
- *Multi-objective trade-off analysis in operating dams for the environment: The case of the Lower Volta River*. International Assembly of Hydrological Sciences Scientific Assembly, 30 May-3 June 2022, Montpellier, France

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IHE DELFT
Institute for Water Education
under the auspices of UNESCO

TU Delft
Delft University of Technology

Many rivers worldwide have been progressively engineered for agriculture, energy, transportation, flood control and navigation. Dams, in particular, have played a major role in controlling and harnessing large volumes of water to support these anthropogenic uses. While dams have undoubtedly contributed to human development, this has often come at a heavy price to downstream communities and the natural environment. The provision of environmental flows (e-flows), freshwater flows for the environment, is a means to restore or protect the benefits of naturally flowing rivers. Since the 1940s, e-flows science has grown, however, actual implementation remains relatively limited.

This research investigated how dams are re-operated for the implementation of e-flows. It began with a systematic literature review and survey of practical cases of dam re-operation followed by a case study of the Lower Volta River, Ghana. The research has generated knowledge on the process of dam re-operation for e-flows, the enabling factors for success and hurdles which typically stall the process, as well as inter-sectoral trade-offs inherent in delivering environmental flows in a unique case study. These insights inform attempts to scale up efforts in e-flows implementation towards the sustainable operation of dams for people and the environment.

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