Balancing hydropower production and fluvial connectivity in optimal large scale dam siting on the Mekong river

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Abstract

The functioning of a fluvial ecosystem is controlled by a complex mix of abiotic, biotic factors and their interactions in space and time. The condition to maintain these interactions is the fluvial connectivity, which is the functional exchange pathway of matter, energy and organisms. The construction of dams for hydropower production, flood control and water supply interrupts the fluvial connectivity, affecting in particular sediment transport, ecology and natural flow. The Se Kong, Se San, Sre Pok river system (3S river system), in south-east Asia, has the fundamental role of providing sediment to the Mekong Delta. In addition, despite being only 10% of the Mekong basin area (i.e. 81 000 km$^2$), the 3S hosts 42% of the fish species of the entire Mekong, which is the second most biodiverse river in the world. Given the rapid demographic and economic growth of Laos, Cambodia and Vietnam, the 3S has recently become a hotspot of hydropower development, the number of dams is expected to grow from the existing 14 up to 42 by 2025.

To allow a sustainable dam development, we combined the 42 dams in different portfolios, in order to analyse how their different spatial distributions affect the environmental aspects considered. To pursue our goal, we perform a multi-objective optimization analysis, considering the hydropower production as dam benefit and sediment transport, ecological connectivity and natural flow as dam impacts. To include, for the first time, the sediment transport in an optimization analysis, we developed a computationally efficient large scale sediment connectivity model, based on CASCADE framework.

If a basin scale dam planning is adopted from the beginning, most of the indicators allow to reach 65-75% of the hydropower potential (i.e. the total hydropower production of the 42 dams), limiting the impact on the environmental aspects below 35%. The inclusion of multiple environmental aspects in the optimization allowed to study how a single dam portfolio differently affects the indicators. These differences are more evident for medium hydropower productions. Even if we consider an optimal dam portfolio, developing the 60% of the 3S hydropower potential reduces by 30% the sediment connectivity within the basin. The ecological connectivity of the fish species, instead, is reduced by 70% compared to the undisturbed state. This highlights that, not only the amount of hydropower produced, but also the spatial distribution of the selected dams influences the impacts on environmental aspects. The methodology developed
in this study is an important tool to be used in decision-making processes, to analyse a large number of dams, capturing their large scale cumulative effects on multiple environmental aspects, which are differently distributed in the river network. Therefore, its application in river systems that are facing a recent hydropower exploitation, like the Amazon, Irrawaddy and Mekong, can help to adopt an environmentally sustainable dam development to protect fluvial connectivity.
Le dinamiche di un ecosistema fluviale sono controllate da un complesso insieme di fattori abiotici, biotici e dalle loro interazioni nello spazio e nel tempo. La condizione necessaria al mantenimento di queste interazioni è la connettività fluviale, ossia l’interscambio di materia, energia e organismi all’interno del fiume. La costruzione di dighe per scopi idroelettrici, di approvvigionamento e di controllo delle piene interrompe la connettività, influenzando, in particolare modo il trasporto di sedimenti, l’ecologia e il deflusso naturale del fiume. I fiumi del sud-est asiatico Se Kong, Se San e Sre Pok definiscono un sottobacino, denominato 3S, del fiume Mekong, il secondo fiume più importante al mondo per biodiversità. Il 3S rappresenta uno dei sottobacini principali per l’approvvigionamento di sedimenti al delta del fiume Mekong e, nonostante costituisca solamente il 10% (i.e. 81 000 km²) del bacino, ospita il 42% delle specie ittiche dell’intero Mekong. A seguito della rapida crescita demografica ed economica di Laos, Cambogia e Vietnam, il bacino del 3S è stato recentemente interessato da un forte sviluppo idroelettrico: il numero delle dighe presenti sul territorio è destinato a crescere dalle 14 esistenti fino alle 42 progettate per il 2025.

Per una pianificazione idroelettrica sostenibile, abbiamo combinato le 42 dighe ipotizzando diversi scenari, in modo da poter analizzare come la loro diversa posizione spaziale vada ad influenzare gli aspetti ambientali presi in esame. Per far ciò, abbiamo applicato un’analisi di ottimizzazione multi-obiettivi a scala di bacino, considerando la produzione idroelettrica come beneficio e l’alterazione del trasporto di sedimenti, della connettività ecologica e del deflusso naturale come impatti. Partendo da CASCADE, modello per il calcolo del trasporto di sedimenti a larga scala, abbiamo sviluppato una sua versione computazionalmente più efficiente, affinché per la prima volta possa essere incluso anche il trasporto di sedimenti in una analisi di ottimizzazione. La pianificazione a scala di bacino adottata, permette di raggiungere una produzione idroelettrica pari al 65-75% del potenziale totale che si avrebbe con la costruzione di tutte le 42 dighe, mantenendo gli impatti sugli indicatori ambientali al di sotto del 35%. Inoltre, l’introduzione di più aspetti ambientali nell’analisi di ottimizzazione, ha permesso di analizzare i differenti effetti provocati dal sistema di dighe; queste differenze sono più evidenti per produzioni idroelettriche medie. Alcuni scenari permettono di contenere al di sotto del 30% gli impatti sulla connettività dei sedimenti all’interno del
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Acknowledgments

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1.1 General overview

The functioning of a fluvial ecosystem is controlled by a complex mix of abiotic (e.g. temperature, lithology, geomorphology, climatic factors, etc.), biotic factors (i.e. the communities that live in the habitat like human, flora and fauna) and their interaction in space and time. Services provided by fluvial ecosystems can be divided into four broad domains: provisioning services (providing primary resources like water, food, e.g. fishes, timber and sediment for construction [Kondolf, 1994]), regulating services (e.g. climate and flood control, water quality), cultural services (e.g. spiritual, recreational, aesthetic), and supporting services (e.g. nutrient cycling, photosynthesis, soil formation) [Millennium Ecosystem Assessment, 2005]. Fluvial connectivity is a key condition for the provisioning of most of these services, with connectivity referring to the “functional exchange pathway of matter (i.e. water, sediment, nutrients), energy and organisms” [Ward and Stanford, 1995]. Sediment connectivity is a fundamental aspect directly related to ecosystem integrity and ecosystem services like: access to water resources [Trash et al., 2000], delivery of nutrients and pollutants [Walling, 1983], natural hazard risk [Bechtol and Laurian, 2005] and human livelihood [Habersack et al., 2014].

Since the very beginning, societies built settlements in the proximity of rivers to exploit river ecosystem services. In order to take as much benefits as possible from river resources, human started to build the first fluvial infrastructures like bridges, diversions and dams. Dams have contributed to human development by providing reliable sources of drinking water, irrigation, recreation, navigation, and other benefits, such as electricity [Brown et al., 2009]. Nowadays, hydropower production covers 20% of the total energy demand worldwide [Schmitt, R.J.P, 2017]; this value, however, is expected to
become even more relevant in the near future. Global energy demand is rapidly increasing and climate changes have been recognised as a relevant issue, therefore there is a growing need to fill the energy demand with renewables energies. Hydropower is considered a renewable source of energy (Rosenberg et al., 1997), which, in contrast to other renewables, can cover both the base as well as the peak energy demands (Schmitt, R.J.P., 2017). The number of dams has rapidly grown during the second half of the 20th century driven by the increase of energy and water demands. According to the World Commission on Dams (WCD), in the past half century, on average, two large dams have been built per day (Asmal, 2000).

While dams provide immediate economic benefits, they also have negative social and environmental consequences. The World Commission on Dams estimated that 40-80 million people have been displaced by large dams because they were living in areas inundated by the impoundment. Beyond that, few studies were conducted to assess the people affected downstream of dams due to changes in river flow and ecosystem conditions. Richter et al. (2010) conservatively estimated 472 million people living downstream of dams in areas that were impacted by reservoir constructions. For example, in the Lower Mekong region (Cambodia, Thailand, Laos and Vietnam) it was estimated that about 40 million people (i.e. 71% of the population) directly depend on river and flood-plain fisheries (Sverdrup-Jensen et al., 2002). From an environmental prospective, dams interrupt the fluvial connectivity and cause serious environmental consequences (Richter et al., 2010), that in many cases have led to irreversible loss of species and ecosystems (Asmal, 2000). The long-term impacts include hydrologic and water quality alterations and changes in sediment transport (Williams and Wolman, 1984; Petts and Gurnell, 2005).

The alteration of sediment delivery in the river basin caused by reservoirs, can produce negative effects upstream, within and downstream of the reservoir (Schmitt, R.J.P., 2017). In the upstream part, where most of the sediment is deposited, there is the formation of deltas, which can create flood risk hazard and increase dam backwater effects. Within the reservoir, the accumulation of sediment decreases the reservoir volume, increases maintenance cost for sediment removal from the reservoir bottom, and, finally, increases the risk of dam failure given by the greater static load on the dam. Downstream of the reservoir, the interruption of water and sediment fluxes modifies hydro-morphological and ecological processes. Sediment trapping can impact the rivers immediately downstream of the dam. The water released by the dam is characterized by sediment-starved water (or “hungry”water), which erode the river bed, inducing incision and channel degradation (Kondolf, 1997); more downstream, at the river delta, water with low sediment concentration can cause delta subsidence and costal erosion (Syvitski et al., 2009). From an ecological point of view, dams, besides preventing the fishes to migrate between different parts of the river system (Branco et al., 2014), also trap most of the nutrients necessary for the maintenance of the downstream ecosystem. To conclude, dams have impacts on many domains of fluvial system functioning. However, the magnitude of those impacts depends on the spatial distribution of the natural

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1There are various definitions of large dams. The International Commission on Large Dams (ICOLD), established in 1928, defines a large dam as a dam with a height of 15m or more from the foundation. If dams are between 5-15m high and have a reservoir volume of more than 3 million m$^3$, they are also classified as large dams (Asmal, 2000).
1.1. General overview

processes in the river basin (e.g. erosional area, migratory fishes path (Jager et al., 2015)), on the characteristics of the dam (e.g. the size of the impoundment, the height, the type of outlet), on its location and on the presence of other dams. For example, the impacts depend if a dam is located along an important fish migration or sediment transport pathway, or if other dams are present upstream or downstream (cumulative impacts of dams (Kondolf et al., 2014)).

To balance benefits and potential impacts of large dams both on people and ecosystems, a sustainable hydropower development at basin scale is necessary (Jager et al., 2015). To pursue this goal Richter et al. (2010) proposed a three-step procedure. The first step is to adopt an integrated river basin planning to avoid constructing the dams in the “wrong locations”[2]. An essential key point is to involve river communities in the planning process through stakeholders surveys, which should reveal the locations that are of critical importance to river-dependent people (Richter et al., 2010). The second is to design and operate dams in order to minimize the impacts. Important design features can include fish passage structures and sediment sluice gates, while from an operational point of view, the most important feature is the environmental flow release, which must explicitly address the flow volume, timing and quality. Since environmental and social consequences of dams cannot be assessed with complete certainty, the third step proposed is the use of an “adaptive management”, which should include a series of programmes for monitoring, evaluations and adjustments that can be modified along the entire life of the dam according to the different requirements.

Adopting a multi-objective, spatially-explicit-planning approach is an option to assess impacts of dam portfolios on different stakeholders and ecosystem services that are spatially distributed in the river basin (Jager et al., 2015). With dam portfolio we refer to a scenario composed by one or multiple dams. Multi-objective analyses have been widely applied in literature for both dam siting and dam removal problems (Kuby et al., 2005; Zheng et al., 2009; O’Hanley, 2011; Ziv et al., 2012; O’Hanley et al., 2013; Null et al., 2014). These studies consider as environmental aspect the impacts on fish species. Very few examples were explicitly considering hydro-morphology as an objective (Schmitt, R.J.P., 2017). However, none of the previous researches considers dam impacts on multiple environmental aspects at the basin scale, even though many indicators that can be derived globally are now available to assess these impacts (Grill et al., 2014).

The purpose of this thesis is to study the conflicts between hydropower production and its impacts on multiple ecosystem services in dam planning. We apply a multi-objective optimization analysis, explicitly including hydro-morphology among the objectives, based on a large-scale sediment connectivity model. Therefore, we are able to capture ecosystem services distribution within the river basin, and find the optimal dam portfolios that maximize the hydropower production, minimizing the environmental impacts.

In Section 1.2 we present the state of the art, while in Section 1.3 we go more in detail

[2] With “wrong locations”, Richter et al. (2010) is referring to the areas where the largest impacts can be produced if a dam is built.
Chapter 1. Introduction

in the different specific objectives of the thesis.
1.2 State of the art

1.2.1 Dam portfolios selection

Due to the growing energy demand and the increase in environmental concerns, many studies about sustainable river basin design have been developed to support complex decision-making processes (Jager et al., 2015).

These studies focus on selecting, from a large number of dams, the most appropriate ones, for which locations and characteristics are already available. Even though the purposes of these studies are dam siting or dam removal, the methodologies applied are the same. Kocovsky et al. (2009), using the Habitat Suitability Index (HSI), evaluates the impacts of individual dams on four fish species to prioritize dam removal in the Susquehanna River (USA). In this work, however, no optimization is performed nor cumulative dam effects are considered.

A step ahead is made by Schick and Lindley (2007); McKay et al. (2013) who represent connectivity for fish species in a model based on graph theory. The graph theory, in fluvial modelling, represents the river network as a set of nodes connected by edges, where nodes are identified by spatial information and edges represent the process linkages between nodes. This method allows to capture the spatial distribution of river services in the basin.

To analyse the trade-offs between ecological and economic objectives, an optimization approach can be adopted (Kuby et al., 2005; Ziv et al., 2012; Null et al., 2014). Given a set of objectives, the impacts of different dam portfolios is evaluated to find the optimal ones.

Adding graph theory concepts to the optimization analysis, other works are able to find the optimal dam portfolios taking into account also the river connectivity among the objectives (Zheng et al., 2009; O’Hanley, 2011; O’Hanley et al., 2013). However, these applications only consider a single environmental aspect (i.e. fishes) ignoring the multiple impacts of dams on the different river services. As mentioned in Section 1.1, sediment connectivity is one of the key condition for the maintenance of riverine ecosystem, but is rarely accounted in basin scale dam impact.

To partially fill this gap, Schmitt, R.J.P. et al. (2016) developed a graph theoretic-based sediment connectivity model (i.e. CAthment Sediment Connectivity And DELivery, CASCADE). This framework is applied in the Se Kong, Se San, Sre Pok river system (3S) to find, with an exhaustive search, the dam portfolios, amongst 14 major dam sites, which maximize the hydropower production while minimize the alteration of sediment connectivity.

To conclude, there are many studies about basin scale dam planning to capture the cumulative impact of a multi-reservoir systems on river ecosystem services. Nevertheless, so far there is a lack of studies that consider multiple environmental impacts (e.g. sediment and ecological alteration) through an optimization analysis.

\[^{3}The definition of most appropriate depends on the purpose of study (e.g. fish habitat protection, sediment delivery preservation).\]
1.2.2 Indicators for environmental performance of dam portfolios

Most studies about dam environmental impacts consider small scale impacts. Only a few studies attempt to evaluate combined effects of multiple dams on ecosystems connectivity at large scale (Segurado et al., 2013, Branco et al., 2014, Grill et al., 2014), and even fewer on sediment connectivity (Schmitt, R.J.P., 2017). To estimate the cumulative impacts of multiple dams at the large scale, we need environmental indicators that can be easily derived in data-poor settings but that are still reliable for the aim of the study. Our study includes three principal environmental aspects: sediment transport, ecological connectivity, and natural flow.

Sediment transport modelling and indicators

Hydro-morphological aspects are rarely considered in integrated water resources management (IWRM) since, modelling sediment transport is complex, computationally expensive at basin scale and the sediment data are often scarce (Merritt et al., 2003). Some hydrological models (e.g. SWAT) and hydraulic models (e.g. HEC-RAS) allow to model sediment transport. On large scale, however, these applications have high computational costs and need a large amount of input data (Merritt et al., 2003, Yalew et al., 2013).

Wild, T.B. and Loucks, D.P. (2012, 2014) developed the Sediment Simulation Screening Model (SedSim) to predict the spatial and temporal accumulation and depletion of sediment in reservoirs, evaluating the combination of three dam portfolios under three different system-wide operating policies. SedSim performs a daily time-step mass balance simulation of water discharge and sediment, however it is not able to distinguish between different sediment grain sizes (Wild, T.B. and Loucks, D.P., 2012).

Recent studies indicate that a graph theoretic approach enables the analysis of environmental connectivity (i.e. the transport of water, fishes, sediments and nutrients along the river network) at large scale (Phillips, 2014). For example, Czuba and Foufoula-Georgiou (2014) adopts a graph theoretic approach to model mud, sand and gravel transport along the Minnesota river. They represent the spatial distribution of processes and process rates in the river network in a graph-based framework in order to obtain the environmental response function for a given quantity of interest (e.g. stream flow, sediment and nutrients). In particular, they obtain the sediment flux at outlet for each time step. Their framework, however, does not consider multiple grain sizes and returns the sediment flux information only at the basin outlet and not within the basin.

Heckmann and Schwanghart (2013) and Heckmann et al. (2015) propose to apply the graph theory to analyse sediment pathways in small catchments where sediment sources, pathways and sinks are defined using a simulation model for rockfall, debris flow and fluvial processes. This approach allows to have the geomorphological information in each node of the river network, however, given the large amount of input data needed, it is applicable only in small basins.

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4It is defined as a distribution in time of a given quantity (e.g. stream flow, sediment and nutrients) at the basin outlet due to a spatially distributed input.
1.2. State of the art

Schmitt, R.J.P. et al. (2016) developed a spatially distributed modelling framework for sediment transport on large scales and in poor data river systems, CASCADE (CAthC-ment Sediment Connectivity And DELivery). In the CASCADE framework, each node has one or multiple sediment sources characterized by a specific grain size and sediment supply. Each source is the origin of a sediment “cascade” that is transported individually along the river network. In this approach, the information of sediment delivery from each source is kept separate along the pathway and, therefore, unique source sink relationship can be derived.

Two indicators are integrated in CASCADE to evaluate the sediment transport: one computes the sediment flux at the basin outlet and the other the sediment flux alteration within the basin.

Ecological connectivity

From the ecological point of view, dams are barriers that interrupt connectivity in both directions, upstream and downstream. The interruption of the ecological connectivity, in the real world, corresponds to the fragmentation of a given habitat, which can damage the local species (i.e. fragmentation creates habitat fragments that are no more connected one to the other). Some example of basic indicators for river connectivity alteration are: the number of dams, the river length upstream of each dam, the total river length with altered flow downstream (Anderson et al., 2008) or the portion of the river network accessible from the sea by migratory fishes (Nilsson et al., 2005; Anderson et al., 2008). More effective indicators, based on the graph-theoretic approach, are also available in litterature. For example, Branco et al. (2014) use the Integral Index of Connectivity (IIC) to quantify the overall connectivity in the basin. IIC is an easily computable index, however it evaluates basin fragmentation considering only the number of nodes disconnected, without considering the relative ecological importance of each disconnected node (Segurado et al., 2013). For example, it does not consider if the disconnected nodes is in main stem or in small tributaries.

Another ecological connectivity indicator is the Dentritic Connectivity Index (DCI) by Cote et al. (2009). DCI is based on the disconnected fragment length in relation to entire network one. Considering the length, however can lead to the same problem that emerged in the IIC. It does not distinguish if a barrier is located upstream or downstream, in the network, as long as the disconnected fragments have the same length. Based on the DCI indicator, Grill et al. (2014) defined the River Connectivity Index (RCI) replacing the river fragment length with the river fragment volume. In this way, it is possible to weight more the relative impacts of dams located on larger reaches.

Natural flow alteration

Dams are regulated depending on the purpose they are built for (e.g. satisfy water demand, flood regulation, hydropower production). Dam release alters natural flow and can damage the life cycle of aquatic species and other ecosystem processes (Grill 2014). For a better understanding of sediment sources, pathway and cascades, see Section 3.3.2.
Quantifying the natural flow alteration can be fully assessed only knowing the reservoir operation rules. However, this information is rarely available. Given this lack, proxy indicators for assessing natural flow alteration have been developed. For example, the Degree of Regulation (DOR) by [Lehner et al. 2011] evaluates the percentage of river annual flow that can be stored in a system of reservoirs. A disadvantage of this indicator is that it does not compute the cumulative dam impact on the entire river network but the alteration is kept separate for each reach. For this reason, [Grill et al. 2014] developed the River Regulation Index (RRI), which takes the information coming from the DOR and weight it according to the reach volume, to get a unique indicator for the basin.
1.3 Purpose of the study

The state of the art of environmental assessment of dam development, shows a general lack of studying how different dam portfolios\footnote{We remind that a dam portfolios is a scenario composed by one or multiple dams, as explained in Section 1.1} can affect different environmental aspects on large scale, especially on sediment. Therefore, the general objective is to study sustainable dam planning through an optimization analysis, considering multiple environmental aspects.

The general objective can be divided in three specific objectives:

I An optimization analysis is a computational expensive procedure. Therefore, the first objective is to develop a computationally efficient simplified model of CASCADE framework (i.e. a large-scale sediment connectivity model), to include for the first time the sediment transport in an optimization analysis, considering a large number of dam portfolios.

II The second objective is to study via optimization the trade-offs between dam development benefits and impacts, considering as benefit the hydropower production and as impact the sediment flux alteration at the basin outlet. This objective was built on the the previous work of Schmitt, R.J.P. (2017), who applied an exhaustive search on a reduced number of dam portfolios.

III The third objective is to run an optimization, including in the previous analysis also the effects on the ecology and natural flow, using recently developed large scale indicators. In this analysis, we have considered the hydropower production as dam benefit, while the environmental impacts are measured looking at the alteration of: 1) sediment flux at the basin outlet, 2) sediment flux within the basin, 3) ecological connectivity within the basin, 4) ecological connectivity with the Mekong main stem 5) natural flow. Moreover, given the different spatial distributions of the environmental aspects within the basin, we analysed whether conflicts between different environmental indicators can emerge in the dam portfolios selection.

To reach our goals, we have developed a methodology that combines a large-scale sediment connectivity model, with an optimization engine (the general formulation is explained in the flowchart of Figure 1.1). In particular, the large-scale sediment connectivity model, returns the inputs for a simplified sediment connectivity model, which, given a vector of decision variables (i.e. a dam portfolio), compute the objectives that the optimization engine uses to evaluate if the decision variables vector is optimal or not. If it is not, the optimization engine, automatically changes the decision variable vector and repeat the procedure again, until it finds the set of optimal ones.
Chapter 1. Introduction

Figure 1.1: Flow chart that shows the general methodology adopted in the research.
Case study

The Mekong is the most important river in south-east Asia and one of the main rivers in the continent. The basin has a total surface of about 800,000 km² and it is shared between six countries, China, Laos, Cambodia, Thailand, Myanmar and Vietnam. At the mouth, the Mekong has an average discharge of 15,000 m³/s with 20-fold seasonal fluctuations from dry to wet season (Kondolf et al., 2014). Besides having the important role as food source for almost 70% of the population living in the area (Sverdrup-Jensen et al., 2002), the Mekong River Basin (MRB) is a biodiversity hotspot for fishes and large-scale fish migrations. With its 877 fish species, 484 of which are living in the delta, the MRB is the second most biodiverse river in the world (after the Amazon river) (Ziv et al., 2012). Other important data that underline its ecological importance are the great number of aquatic endemic species (106 species) (Baran et al., 2013) and the number of long-distance migratory fish species (103 species) (Ziv et al., 2012). In the past decade, due to the rapid demographic and economic growth, the countries in the MRB have been facing an increasing energy demand, leading to a relevant dam development. The hotspot of this development is the Lower Mekong River Basin (LMRB) (Kondolf et al., 2014), where 133 dams being built, planned or under construction.

The tributaries that are most involved in the recent development are the one composing the 3S sub-basin, i.e. the Se Kong, Se San and Sre Pok. The 3S sub-basin has a total area of 81,000 km² subdivided between Laos, Vietnam and Cambodia and contributes for about 20% (2,890 m³/s) to the Mekong discharge (MRC, 2005), and between 6 and 16% (10-25Mt/year) to its sediment delivery (Wild, T.B. and Loucks, D.P., 2014). Even if the 3S is the main source of sand sediment for the Mekong delta, little information on sediment distribution and composition is available for the entire basin (Wild, T.B. and Loucks, D.P., 2012). The 3S is not important only from the sediment point of view,
but also from the ecological dimension. Despite representing only 10% of the Mekong basin area, the 3S hosts 42% of the fish species of the entire basin (329 species), 17 of which are super-endemic species ([Baran et al.] 2013), meaning that they cannot be found anywhere else in the world, and are almost all present in the Se Kong. [Ziv et al.] (2012), studied how the different fish species are subdivided in the three rivers, the results of their study, in terms of total number of fish species and of migratory species, is summarized in Table 2.1.

In the near future, the total number of dams in the basin will grow from the existing 14 up to 42 (Figure 2.1). In addition to the 14 that are already built, 7 dams are under construction, while the remaining 21 are still in the planning process ([Schmitt, R.J.P. et al.] 2017). When all the dams will be completed, the hydropower production in the 3S basin could reach 30 463 GWh/year.

Dam development will further impact the fragile ecosystem of the basin, already suffering from climate changes ([Ziv et al.] 2012). The two sectors that are most impacted by reservoirs are the fish species and the sediment flux. The fishes, besides being the most important source of food for river dependent people ([Sverdrup-Jensen et al.] 2002), have also a relevant ecological value, and they will be prevented from freely traveling in the basin. The sediment flux, which is the main driver for morphologic equilibrium and delta formation (the Mekong delta is already suffering of subsidence and coastal erosion) ([Schmitt, R.J.P. et al.] 2017), will be highly altered by reservoir construction.

<table>
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<tr>
<th>Fish species</th>
<th>Migratory fish species</th>
</tr>
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<tr>
<td>Sre Pok</td>
<td>240</td>
</tr>
<tr>
<td>Se San</td>
<td>133</td>
</tr>
<tr>
<td>Se Kong</td>
<td>213</td>
</tr>
</tbody>
</table>

Table 2.1: Distribution of fish species in the three rivers of the 3S according to the study of Ziv et al. 2012}
Figure 2.1: Dam development in the 3S river basin, including existing, under construction and planned
dams. The cutout display the 3S basin location within the Mekong river basin (caption and figure
adapted from Schmitt, R.J.P. (2017)).
## Table 2.2: Dam database (first part)

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<th>Code</th>
<th>Name</th>
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<th>Latitude</th>
<th>Longitude</th>
<th>COD</th>
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<td>107.1517</td>
<td>2017</td>
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<td>106.6056</td>
<td>2019</td>
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**Table 2.3: Dam database (second part)**
Chapter 2. Case study

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Table 2.4: Dam database (third part)
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Table 2.5: Dam database (fourth part)
Models and methods

To pursue the goals of our study, we have to solve an optimization problem, in which we want to find the decision variable vector \((u)\) minimizing the indicators \((J_1, J_2, \ldots, J_6)\).

\[
\min_u (J_1, J_2, \ldots, J_6). 
\]  

(3.1)

In our application the decision variable vector \((u)\) corresponds to a dam portfolio, and is composed by 42 boolean decision variables (i.e. \(u_1, u_2, \ldots, u_{42}\)), one for each dam, which assume the value 0, if the dam is not selected in the dam portfolio, or 1, if the dam is selected. Even if only 21 dams are actually not built yet, we will suppose that all the 42 dams are subject to the decision, if they have to be built or not. This choice was driven by the fact that most of the dams on the main stem are already built or under construction, therefore most of the environmental aspects are already damaged. Starting from the current dam portfolio (i.e. 2016) would reduce too much the degree of freedom of the decision variable set, limiting the analysis.

To evaluate the dam portfolios we introduce six indicators, \(J_1, J_2, \ldots, J_6\). Two of them want to evaluate dam impacts on sediment connectivity. The model that was available to compute the sediment indicators was a large-scale sediment connectivity model, CASCADE framework. However, as previously mentioned in Section 1.3, an optimization analysis is a computationally expensive procedure, and CASCADE is too time consuming for this application. Therefore, we develop a simplified large-scale sediment connectivity model, Simplified Model (SM), which reproduces the main aspects of CASCADE, but at the same time, is more computationally parsimonious. After the development of the Simplified Model, we have all the tools to solve the optimization.
problem, which has been introduced in a general formulation in Section 1.3. In this section, instead, we will go more in detail in each step of the procedure, following the flowchart in Figure 3.1.

We started from running in the undisturbed state (i.e. without any dam) CASCADE model, which provides the information about: sediment fluxes ($\Theta_{S,e}$), dam trap efficiency ($T_{eff}$), size of the dam impoundment ($N_{inund}$), and sediment flux threshold ($t_{5\%}$). These variables, are given as input to the Simplified Model, together with the decision variables vector $u$. The Simplified Model, allows to compute the indicators $J_1, J_2, ..., J_6$, that are given to the optimization engine, Borg. Borg, is a Multi-Objective Evolutionary Algorithm (MOEA), that, from the indicators, evaluates if a dam portfolio is optimal or not. If it is not, it automatically changes the values of the decision variables $u_1, u_2, ..., u_{42}$, and restarts the procedure just described until it finds the optimal dam portfolio $u^*$.

![Figure 3.1: Flow chart showing the specific methodology and models adopted in this study.](image)

### 3.1 Decision variables

As previously mentioned, in our problem, the decision variables vector is a composed by 42 elements, one for each dam. The decision variable $u_i$, that composes the vector, is a boolean variable, that assumes the value 0 if the dam is not selected in the portfolio, and 1 if it is selected. For example, considering the dam portfolio in Figure 3.2 in which in green are represented the dams selected in the portfolio and in grey the ones not selected, the decision variables vector would be:

$$u = [1, 0, 1, 0, 0, 0, 1].$$

Where $u_{1,3,4,7} = 1$ in correspondence of the selected dams 1, 3, 4 and 7, while for the

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1The meaning and the use of each variable, will be further explained in Section 3.4.
3.2 Indicators

The inclusion of a dam in a portfolio, means that its effect on fluvial connectivity are activated in the model, through the trap efficiency and the impoundment effects.

The indicator takes into account the hydropower production of a given dam portfolio, we have to sum up all the annual hydropower productions of the dams selected in the portfolio.

Figure 3.2: In the example we consider a system composed by 7 dams. In green are represented the dams selected in the portfolio and in grey the ones not selected. The portfolio corresponds to the decision vector \( u = [1, 0, 1, 0, 1, 0, 1] \).

3.2 Indicators

To evaluate the benefits and the impacts of a dam portfolio we use a set of six indicators, one to evaluate the dam benefit as the driver for the dam development, five to evaluate the dam impacts on three main environmental aspects: sediment, ecology and natural flow. The indicators assessing the sediment aspect are model-based (i.e. based on sediment processes) while the indicators assessing the other environmental aspects (ecosystem and natural flow) are graph-based (i.e. they are proxy indicator since we do not include an ecological model).

3.2.1 Hydroelectricity

Among the dam benefits (e.g. hydropower production, flood control, water supply), we choose to focus our analysis on the hydropower production.

Hydropower production

In our case study, the annual hydropower production for each dam, expressed in GWh/year, is given by the Dam Database from the Mekong River Commission (MRC). Since the indicator takes into account the hydropower production of a given dam portfolio, we have to sum up all the annual hydropower productions of the dams selected in the portfolio.
\[ J^1 = \sum_{i=1}^{N} G_i \quad \text{[GWh/year]}, \quad (3.2) \]

where

- \( N \) is the number of dams in the portfolio;
- \( G_i \) is the annual hydropower production of dam \( i \) [GWh/year].

In the next chapters, we will refer to \( J^1 \) as “Hydropower”.

### 3.2.2 Sediment

As mentioned in Chapter 2, the 3S river system is very important for the sediment delivered to the Mekong, its contribution, in fact, is between 6-16% (i.e. 10-25 Mt/year) of the total sediment flux (Wild, T.B. and Loucks, D.P., 2014).

In this study, we have adopted two indicators, proposed by Schmitt, R.J.P. (2017), to evaluate the sediment delivery alteration: sediment flux at the river basin outlet (i.e. external sediment connectivity) and total sediment flux alteration within the river basin (i.e. internal sediment connectivity). Schmitt, R.J.P. (2017) implemented these two indicators, based on CASCADE approach (see Section 3.3), to evaluate dam impacts on sediment delivery.

#### Sediment flux at the river basin outlet

This indicator is obtained summing up, at the basin outlet, all the sediment flux coming from sediment sources spatially distributed in the basin (developed by Schmitt, R.J.P. (2017)). The sediment flux (\( \Theta_{S,\Omega} \)) for a given dam portfolio is calculated using the Simplified Model (see Section 3.4)

\[ J^2 = \sum_{i=1}^{N} \Theta_{S,\Omega}^i \quad \text{[kg/year]}, \quad (3.3) \]

where

- \( N \) is the number of sediment sources;
- \( \Theta_{S,\Omega}^i \) is the sediment flux of the sediment source \( i \) at the basin outlet \( \Omega \) [kg/year].

This indicator considers only the sediment flux at the basin outlet. Comparing the value of the indicator obtained with a given dam portfolio with the one obtained in the undisturbed state, we can evaluate the reduction of sediment flux coming from the basin. However, this indicator does not take into account the impacts on the local sediment flux (i.e. in each reach).

In the next chapters, we will refer to \( J^2 \) as “SedimentOutlet”.
3.2. Indicators

Total sediment flux alteration in the river basin

This indicator evaluates the difference in each reach between the sediment flux in the undisturbed state and the one with the dam portfolio considered (developed by [Schmitt, R.J.P. (2017)]). Then the difference in each reach is weighted by the corresponding reach length to aggregate the impacts in just one value for the entire basin. Considering the total sediment flux alteration, it is possible to evaluate the dam impacts on sediment flux within the river basin.

\[ J^3 = \left( \sum_{i=1}^{N} \Delta \Theta_{S,e}^i \right) \times L \quad [\text{kg*L/year}], \quad (3.4) \]

where

\[ \Delta \Theta_{S,e}^i = \Theta_{S,e}^i (bd) - \Theta_{S,e}^i (pd) \quad [\text{kg/year}], \]

where \( \Delta \Theta_{S,e}^i \) is a matrix containing the difference between sediment fluxes before and post dam construction for each reach \( e \) and for each sediment source \( \varsigma \) [kg/year];

\( \Theta_{S,e}^i (bd) \) is a matrix containing the sediment flux of each source \( \varsigma \) in each reach \( e \) in the undisturbed state (bd=before-dams) [kg/year];

\( \Theta_{S,e}^i (pd) \) is a matrix containing the sediment flux of each source \( \varsigma \) in each reach \( e \) with the dam portfolio selected (pd=post-dams) [kg/year];

\( \Delta \Theta_{S,e}^i \) is a vector containing the difference between sediment fluxes before and post dam construction for each reach \( e \) [kg/year];

\( L \) is a vector containing the reach lengths [m].

In Equation 3.4, the first term \( \left( \sum_{i=1}^{N} \Delta \Theta_{S,e}^i \right) \) sums for each reach, \( e \), all the differences in sediment fluxes coming from different sediment sources \( i \). Therefore, the result of this term is a row vector, with a length equal to the number of reaches, that has to be multiplied (i.e. vector product) by the vector of the reach lengths.

The higher is the indicator value, the higher is the sediment alteration inside the river network.

In the next chapters, we will refer to \( J^3 \) as “SedimentAlteration”.

3.2.3 Ecology

The 3S river system is very rich in fish biodiversity. In fact, although the 3S watershed represents only 10% of the Mekong one, the 3S hosts 329 fish species, 42% of the total species existing in the entire Mekong area.

In this study, when we will refer to ecology, we will consider the impact only on the fish species. The following indicators are not based on a model but on the graph theory, so they are proxy indicators and not process based as the two for the sediment.

We will consider two different indicators to assess impacts on internal and external

\[ \text{To have a better understanding of how the matrix is structured see Figure 3.9} \]
connectivity: the River Connectivity Index (RCI) and the Migratory fishes connectivity, respectively. With these two indicators, we will account for the barrier effect of dams, which prevents the fish species to migrate in the river basin. Dams will be considered completely impermeable to the fish species in both directions, from upstream to downstream and vice versa (i.e. no fish passage).

River Connectivity Index (RCI)

In order to evaluate the fish habitat fragmentation within the river basin, we used the RCI by [Grill et al.] (2015). This indicator is designed to evaluate dam cumulative impact on fish species. The basic concept of the RCI is that a dam, as a barrier, partition the river network into fragments that are not connected anymore one to the other (Figure 3.3).

The river connectivity index is the sum of the ratios between the volume of the fragment $i$ squared, over the total basin volume squared.

\[
J^4 = \frac{\sum_{i=1}^{N} V_i^2}{V_{tot}^2} \cdot 100 \quad [\%], \quad (3.5)
\]

where

- $N$ is the number of fragments;
- $V_i$ is the river volume of fragment $i$ [m$^3$];
- $V_{tot}$ is the volume of the entire river network [m$^3$].

Both volumes are calculated multiplying the reach length by its width and depth. The channel is assumed to be prismatic, therefore, width and depth are constant along each reach. The length is extracted from the river network, the width is computed using a scaling law based on the drainage area and the energy slope (see Equation 3.29), the depth is computed using the 1.5 year return period discharge, which corresponds to the bankfull conditions (its computation is included in CASCADE framework, see Section 3.3.6).

The RCI measures the ecological connectivity of the river network, if the RCI value is 100%, the river basin connectivity is undamaged.

In the next chapter, we will refer to $J^4$ as “EcologicalConnectivity”.

Migratory fishes connectivity

This indicator has been developed on the same idea of the RCI. Since, we want to assess the dam impacts on long-distance migratory fishes coming from the Mekong, the indicator considers only the most downstream fragment volume, that is the only river portion accessible from the Mekong.
3.2. Indicators

\[ J^5 = V_\Omega \ [m^3], \]  

where

\( V_\Omega \) is the volume of the most downstream fragment (i.e. the fragment connected with the outlet \( \Omega \)) [m\(^3\)].

The larger is the volume accessible, the larger is the habitat the migratory fishes have available.

In the next chapters, we will refer to \( J^5 \) as “MigratoryFishes”.

![Diagram of river network with 4 fragments and 3 dams](image)

**Figure 3.3:** The 3 dams partitioned the river network in 4 fragments with specific volumes (Figure adapted from [Grill et al. 2014](#)).

### 3.2.4 Natural flow

In the previous Section 3.2.3 we presented two indicators to assess the barrier effect of dams. In this section, instead, we will present an indicator, based on the graph theory, to evaluate dam impact, on ecosystem processes, resulting from natural flow alteration. We adopted the RRI by [Grill et al. (2014)](#), who expanded the Degree of Regulation (DOR) indicator in order to take into account the natural flow alteration in a multi-reservoir system.
\[ J^6 = \sum_{i=1}^{N} DOR_i \cdot \frac{rv_i}{V_{tot}} \% \],

(3.7)

where

\[ DOR_i = \frac{\sum_{j=1}^{M} s_j}{D_i} \cdot 100 \% \],

\[ s_j \] is the storage capacity of dam \( j \) [m\(^3\)];
\[ D_i \] is the total annual discharge flowing through the reach \( i \) [m\(^3\)];
\[ DOR_i \] is the potential effect of dams \( j = 1, \ldots, M \) on natural flow of reach \( i \) [%];
\[ rv_i \] is the river volume of reach \( i \) [m\(^3\)];
\[ V_{tot} \] is the volume of the entire river network [m\(^3\)].

The first step is to calculate the DOR, summing up the storage volume \( (s_j) \) of all the reservoirs upstream of a reach \( i \) and dividing it by the total discharge \( (D_i) \), flowing through the reach in one year. The \( DOR_i \), therefore, measures how much water the reservoirs subtract from the natural flow of reach \( i \). Usually 10% is the threshold to mark evident changes in the natural flow regime (Lehner et al., 2011).

To obtain the RRI, the DOR is multiplied by the volume of reach \( i \) in percentage \( (rv_i/V_{tot}) \). Using the river volume as weight, it allows to consider also if the altered flow regards a small or a large volume.

The total annual discharge \( D_i \) has been computed as the annual average of the hydrographs available in each reach, that for the 3S is a 20 years record. The hydrograph is extracted from the pre-processing of CASCADE (to see the extraction of the hydrograph, see Section 3.3.6).

In the next chapters, we will refer to \( J^6 \) as “FlowAlteration”.

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CASCADE modelling framework

CASCADE (CAtchment Sediment Connectivity And DElivery) is a large-scale sediment connectivity model recently developed by Schmitt, R.J.P. et al. (2016). This approach combines graph theory concepts with sediment transport modelling. The sediment delivery coming from multiple sources is described through individual transport processes, called “cascades”. This allows to keep the information about provenance and destination, of a single sediment source, disaggregated along the river network. In our application, the sediment indicators, i.e. SedimentOutlet \((J^2)\) and SedimentAlteration \((J^3)\), have to be computed using a large-scale sediment connectivity model. CASCADE is too computationally expensive for an optimization analysis. Therefore, the indicators cannot be computed through this model. CASCADE, however, is used as the starting point for the development of a simplified large-scale sediment connectivity model, the Simplified Model (SM). Moreover, a preliminary run of CASCADE in the undisturbed state (i.e. without dams) provides the variables \(\Theta_{S,e}, T_{eff}, N_{inund}\) and \(t_{5\%}\) (introduced in Figure 3.1 and further explain in Section 3.4), which are the inputs used by the Simplified Model to compute the sediment fluxes in the basin.

In Sections 3.3.1, 3.3.2, 3.3.3, 3.3.4, 3.3.5, we go through the main procedures implemented in CASCADE framework, while in Section 3.3.6 we describe the implementation of CASCADE in the 3S basin by Schmitt, R.J.P. et al. (2016).

3.3.1 CASCADE approach

In Figure 3.4 are summarized the main aspects, used by CASCADE framework, to model sediment delivery in a river basin. The starting point is the river network (Figure 3.4(A)), that has to be transformed in a directed acyclic graph (Figure 3.4(B)), composed by nodes (identified by arabic numbers), representing river confluences or connections, and edges representing river reaches. For each reach, one or multiple sources (indicated with roman numbers) are identified (Figure 3.4(C)). For instance, in correspondence of the reach 2 we have sources II and III. Each source is characterized by a grain size, visualized with the dot size, and a sediment supply. To keep track of each sediment source along the river network, the graph from Figure 3.4(B) has to be expanded into the one in Figure 3.4(D), so that, the information of different cascades is kept separate. The expanded graph represents the possible path of each sediment source in the river network (i.e. the possible connected nodes). For each reach and for each sediment source, the transport capacity, which is the energy available for sediment entrainment, is computed using standard sediment transport formulas, based on the source grain size, on local geomorphology and on local hydraulic conditions. In Figure 3.4(E), the transport capacity is visualized by the line width. As we can notice, the transport capacity can change along the cascade path, and, since it depends on the grain size, it is different for cascades active in the same reach. For example, in reach number 2, source number III has a higher transport capacity than source number II, since it is characterized by a smaller grain size. However, in Figure 3.4(E), the transport capacity does not consider yet the presence of multiple cascades in a reach, therefore, the actual energy available for each cascade, is smaller than the one computed at this step. CASCADE considers the presence of multiple active cascades in a reach.
through the “competition”. The competition corrected transport capacity is displayed in Figure 3.4(F). The differences between the two transport capacities, can be seen, for example, in reach 5, where all the sources IV, V and VI experienced a lower energy available. As displayed in Figure 3.4(G), along a cascade, no additional sediment is taken up, but only deposition can be observed, otherwise no unique connectivity information could be derived. Sediment of a cascade can deposit if the sediment input in the reach is greater than the local transport capacity, or if the cascade has to be routed through a reservoir, in which we have a drop in the energy available for entrainment. A sediment cascade is interrupted if all his initial supply has deposited, for example sources I and II are both interrupted in reach 3. The reaches in which deposition is observed, are defined as sinks. In Figure 3.4(G) it can be observed that reach 2 is a sink for cascade I, reach 3 for sources I, II and III, and reach number 5 is a sink for cascades III, IV and V. Therefore, we can conclude that, a reach can have the function of sink for multiple sediment cascades. The peculiarity of CASCADE framework is that the information is kept disaggregated for all the sediment sources and for all the reaches, as a consequence, sediment provenance and connectivity information can be derived in any node. In particular the output of the model is a matrix, that we further refer as $\Theta_{S,e}$, in which the sediment flux for each cascade $\gamma$ in each reach $e$ is stored.

3.3.2 Conventions and symbols

In this section, we introduce some of the conventions and symbols that are used in the following chapters. As previously mentioned, the river network has to be split in a directed acyclic graph composed by edges (indicated with $e$ in the set of all the edges $E$) and nodes (indicated with $n$ in the set of all the nodes $N$). In this case study, we have one source for each reach (i.e. no multiple sources like it was presented in Section 3.3.1) indicated with $\varsigma \in S$, where $\varsigma$ indicates the single source and $S$ is the total number of active sources. Each source $\varsigma$, has a characteristic grain size $d_\varsigma$, and is the origin of one and only one sediment cascade $\gamma \in \Gamma$. Where $\gamma$ is the single cascade, and $\Gamma$ is the total number of cascades, which has cardinality $g$, and, in this case, it is equal to the number of active sources $S$. Each sediment source, is the starting point of a pathway $\kappa \subseteq E$, which is the set of the edges from the source $\varsigma$, till the basin outlet $\Omega$ (if it is not interrupted because of deposition or by the presence of a reservoir). Therefore, a general path of a source, is indicated as $\kappa_{\varsigma}$. Some examples of connectivity information that can be derived from CASCADE are the total cascades connected to a certain edge $e$, which will be expressed as $\Gamma_e \in \Gamma$, and the sources that are connected to the edge $e$, that can be written as $S_e \in S$. Some more variables that will be used in the following sections, and that can be useful to introduce at this point are: the transport capacity $Q_S$, which, if referred to a general cascade $\gamma_\kappa$ in the edge $e$, will be expressed as $Q_{S_\gamma_\kappa}$, and the sediment flux $\Theta$, which, if referred to a cascade $\gamma_\varsigma$ in the edge $e$, is written as $\Theta_{\gamma_\varsigma}$.

\[\text{Since between cascades and sources there is a unique relationship, we can identify the cascade } \gamma \text{, with the index of its correspondent source } \varsigma.\]
3.3. CASCADE modelling framework

Figure 3.4: Graphical representation of CASCADE framework. A: river network subdivision in reaches. B: graph representation of the river network by nodes and edges. C: sediment sources identification. D: graph expansion in the possible connected nodes. E: representation of the transport capacity for each grain size and for each reach, indicated by the line width. F: competition corrected transport capacity (smaller than the one from panel E, given by the presence of multiple grain sizes). G: routing of sediment cascades along the river network. H: each edge receives sediment from multiple cascades, defining sediment flux, provenance, and sorting; and thereby connectivity of an edge. (Figure and caption adapted from Schmitt, R.J.P. et al. [2016])
Chapter 3. Models and methods

3.3.3 Transport capacity calculations

The sediment can be mobilized and transported downstream if the local energy (i.e. transport capacity) exceeds a certain threshold for sediment entrainment, as previously mentioned in Section 1.1. The main factors that influence the transport are the magnitude and frequency of flow events, the local river morphology and the grain size. This latter quantity influences the type of transport that can occur. Finer grain sizes, like silt and clay, are transported in suspension, coarser fractions, like gravel, as bed-load and intermediate grain sizes, like sand, can be transported both in suspension or as bed-load, depending on hydraulic conditions. CASCADE model includes two empirical formulations for the calculation of the transport capacity, one for sand (Engelund and Hansen [1967]) and another for gravel (Miguel Wong and Gary Parker [2006]). The first step is to derive the dimensionless transport capacity $q_{S* e}$ for the grain size $d_e$ in the edge $e$, with two different formulations:

$$q_{S* e} = \begin{cases} 0.05 \cdot \tau_{* e}^{5/2}, & \text{if } d_e < 2 \times 10^{-3} \text{ m} \quad (\text{Engelund and Hansen}); \\ \alpha \cdot (\tau_{* e} - \tau_{* e c})^\beta, & \text{else} \quad (\text{Wong and Parker}). \end{cases}$$

(3.8)

Where:

- the constant parameters $\alpha = 3.97$ and $\beta = 1.5$ are derived from Miguel Wong and Gary Parker (2006);

- $C_{f* e}$ is the local friction factor

$$C_{f* e} = \frac{2 \cdot g \cdot I_e \cdot h_e}{v_e^2};$$

(3.9)

- $v_e$ is the flow velocity in the reach, [m s$^{-1}$], $g$ is the gravitational acceleration [kg m s$^{-1}$], $I_e$ and $h_e$ are respectively the channel gradient [m m$^{-1}$] and the flow stage [m] in the reach $e$;

- $\tau_{* e}$ is the the dimensionless shear stress

$$\tau_{* e} = \frac{I_e \cdot h_e}{R \cdot d_e};$$

(3.10)

- $R$ is the relative density of sediment;

- $\tau_{* e c}$ is the critical shear stress, assumed constant, equal to 0.047, under fully turbulent flow conditions (Miguel Wong and Gary Parker [2006]).
The volumetric value of the transport capacity $q_{S\varsigma e}$, for a given grain size $d_\varsigma$, in the reach $e$, per unit of channel width, is obtained by inverting the equation:

$$q_{S\varsigma e} = \frac{q_{S\varsigma e}}{\sqrt{R \cdot g \cdot d_\varsigma^3}}.$$  \hspace{1cm} (3.11)

To calculate the transport capacity, CASCADE needs for each reach $e$ a hydrograph $Q_e$, from which the flow stage $h_e$ and the flow velocity $v_e$ are derived. To make the code more computationally efficient, instead of calculating the transport capacity for each observation of the hydrograph, $Q_e$ has been divided in $p$ percentiles, using $\sigma$-intervals (i.e. also rare but high magnitude events are considered), derived from a normal distribution (i.e. 0.1\%, 2.3\%, 15.9\%, 50\%, 84.1\%, 97.7\% and 99.9\%). From the mean discharge value in each percentile $Q_e(p)$, the correspondence transport capacity ($q_{S\varsigma e}(p)$) has been calculated with equation 3.11. The transport capacity is, then, multiplied by the number of observations in the percentile ($n_{pe}(p)$) in order to get the total transport capacity of the $p$-th percentile ($q_{S,tot\varsigma e}(p)$) through the following equation:

$$q_{S,tot\varsigma e}(p) = q_{S\varsigma e}(p) \cdot n_{pe}(p).$$ \hspace{1cm} (3.12)

The total transport capacity of the $p$-th percentile is then converted in mean annual transport capacity for a given grain size $d_\varsigma$ in the edge $e$ as:

$$q_{S,annual\varsigma e} = \frac{\sum_{k=1}^{p} q_{S\varsigma e}(k) \cdot n_{tot e}}{n_{tot e}} \cdot 365,$$ \hspace{1cm} (3.13)

where $n_{tot e}$ is the total number of observations in the edge $e$. Finally, to obtain the transport capacity ($Q_{S\varsigma e}$) in kg year$^{-1}$, and not per unit channel width, the value obtained from equation 3.13 has to be multiplied by the channel width $W_{AC e}$ and by the sediment density ($\rho_S$), that is assumed to be constant and equal to 2600 [kg m$^{-3}$]:

$$Q_{S\varsigma e} = q_{S,annual\varsigma e} \cdot W_{AC e} \cdot \rho_S.$$ \hspace{1cm} (3.14)

### 3.3.4 Competition options

The formula presented in Section 3.3.3 computes the transport capacity if only one cascade is active in each reach. However, as explained in Section 3.3.1, in most
of the reaches multiple cascades are active, therefore, a correction is needed to take into account this process. In literature are available some empirical formulations, which describe the simultaneous movement of different grain sizes. In the CASCADE framework, instead, a competition factor has been introduced, so that the competition-corrected transport capacity considers the redistribution of the energy available in the reach among the different cascades. The corrected transport capacity ($Q_{S_e}'$) can be obtained through the following equation:

$$Q_{S_e}' = F_{e}^c \cdot Q_{S_{ref}},$$

(3.15)

where, $F_{e}^c$ is the competition factor and $Q_{S_{ref}}$ is the reference transport capacity, as calculated in Section 3.3.3. In this formulation, two different competition factors and two reference transport capacities have been used. The combination of these two variables gave four different scenarios for competition. For scenarios 1 and 2, the reference transport capacity is the one calculated for the median grain size ($d_{50e}$) in reach $e$ ($Q_{S_e}(d_{50e})$), where, the median grain size is the one estimated from all the cascades originating in the upstream sources of reach $e$:

$$Q_{S_e}' = F_{e}^c \cdot Q_{S_e}(d_{50e}).$$

(3.16)

In scenarios 3 and 4, instead, the competition corrected transport capacity ($Q_{S_e}'$) is proportional to the sediment supply ($Q_{S,in_e}$) of the cascade $\gamma_\varsigma$:

$$Q_{S_e}' = F_{e}^c \cdot Q_{S,in_\varsigma}. $$

(3.17)

Regarding the two competition factors, in the scenarios 1, 3 and 4, cascades with higher local transport capacity compete more effectively, getting a higher share of the energy available. The competition factor can be expressed as:

$$F_{e}^c = \frac{Q_{S_e}^{\varsigma}}{\sum_{k \in \Gamma_e} Q_{S_e}^k}.$$

(3.18)

Equation (3.18) is the ratio between the transport capacity of a single cascade $\gamma_\varsigma$ and the sum of the transport capacities of all the other cascades present in reach $e$. The second competition factor implemented, used in scenario number 2, postulates that cascades with a higher supply get a larger amount of energy for entrainment:
3.3. CASCADE modelling framework

\[ F_e^c = \frac{Q_{S,in_e}}{\sum_{k \in \Gamma_e} Q_{S,in_k}}. \]  \hspace{1cm} (3.19)

To summarize:

- **Scenario 1**: in which

\[ Q_s e' = F_e^c \cdot Q_{S,e}(d_{50e}), \quad \text{where} \quad F_e^c = \frac{Q_{S,in_e}}{\sum_{k \in \Gamma_e} Q_{S,in_k}}; \]  \hspace{1cm} (3.20)

Finer sediment particles are transported preferentially, since, smaller grain sizes, for fixed morphologic and hydraulic conditions, have a higher transport capacity.

- **Scenario 2**: in which

\[ Q_s e' = F_e^c \cdot Q_{S,e}(d_{50e}), \quad \text{where} \quad F_e^c = \frac{Q_{S,in_e}}{\sum_{k \in \Gamma_e} Q_{S,in_k}}; \]  \hspace{1cm} (3.21)

the transport capacity assigned to each cascade is strongly influenced by the initial sediment supply, therefore the sediment fractions with a higher supply are preferentially transported.

- **Scenario 3**: in which

\[ Q_s e' = F_e^c \cdot Q_{S,in_e}, \quad \text{where} \quad F_e^c = \frac{Q_{S,in_e}}{\sum_{k \in \Gamma_e} Q_{S,in_k}}; \]  \hspace{1cm} (3.22)

if in a reach there are multiple cascades with the same supply, the ones that obtain the larger share of energy are the one with a finer grain size \( d_e \).

- **Scenario 4**: uses the same formulation for the reference transport capacity \( Q_{S,in_e} \) and the competition factor \( F_e^c \), as the scenario 3. Cascades, however, compete only with the ones that have a similar grain size. Therefore, two cases are distinguished, one for sources with a grain size smaller than 2\( m \)m (e.g. sand), and the other for \( d_e > 2 \text{mm} \) (e.g. gravel).

\[ Q_s e' = F_e^c \cdot Q_{S,in_e}, \quad \text{where} \quad F_e^c = \begin{cases} \frac{Q_S^c}{\sum_{k \in \Gamma_e} d_k \leq 2 \times 10^{-3} m} Q_{S,k}^c, & \text{if} \ d_e \leq 2 \times 10^{-3} m \\ \frac{Q_S^c}{\sum_{k \in \Gamma_e} d_k > 2 \times 10^{-3} m} Q_{S,k}^c, & \text{if} \ d_e > 2 \times 10^{-3} m \end{cases}. \]  \hspace{1cm} (3.23)
The idea is that, if both sediment classes are active in a reach, the transport of one does not affect the transport of the other.

### 3.3.5 Reservoir routing

In literature, a common approach to model sediment through reservoir is using empirical relationships, which allow to calculate the trapping efficiency as a function of some reservoir characteristics ([Kondolf et al., 2014](#)). In CASCADE, instead, a component for the in-reservoir sediment routing is integrated, and allows to recalculate the transport capacity for each incoming grain size in each reservoir compartment. The number of compartments is equal to the number of edges inundated by the reservoir impoundment. For example, in Figure 3.5, the dam submerges three edges on the main stem and one on the tributary.

For each of these reaches, we need to extract its depth and width. Both variables are obtained overlapping the Fully Supply Level (FSL), available in the dam database (Table 2.3), with the terrain elevation, extracted from the Digital Elevation Model (DEM) (Figure 3.5A). The average hydraulic conditions of the river reach are assigned to the corresponding compartment (Figure 3.5B). CASCADE recalculates the transport capacity in each compartment \( k \), using the Engelund Hansen formula presented in Section 3.3.3 ([Engelund and Hansen, 1967](#)).
3.3. CASCADE modelling framework

Before being able to calculate the transport capacity, information about the energy slope ($I_k$), flow stage ($h_k$), flow velocity ($v_k$) and width ($W_k$) are needed for each compartment. The energy slope can be calculated as:

$$I_k = \frac{v_k^2}{2g}, \quad (3.24)$$

where

- $v_k$ is the average flow velocity in the compartment:

$$v_k = L_k \frac{V_k}{Q_k}; \quad (3.25)$$

- $L_k$ is the inundated length of $k$ [m];
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- \( \frac{V_k}{Q_k} \) is the residence time in the compartment (being \( V_k \) the compartment volume and \( Q_k \) the water inflow) [s].

In the calculation of the flow velocity some simplifications are introduced, the compartment is assumed to be rectangular, therefore, the depth \( h_k \) and the width \( W_k \) are uniform along the section. The FSL is kept constant in the calculations, which means assuming reservoirs are always maintained full. This assumption is not always true, however, most reservoirs in the 3S are for hydropower purposes, therefore, it can be considered reasonable. Once the new transport capacity is calculated, the one previously calculated in the undisturbed state is replaced. Since, in most cases, the flow velocity in a reservoir is very low, the newly calculated transport capacity is drastically smaller than the previous one. Therefore, most of the sediment deposits in the impoundment. CASCADE applies the same sediment routing scheme to reaches and reservoirs. In the general scheme, two cases can occur: in the first one, all the sediment input from the upstream reach is routed downstream, since the local energy available (\( Q_{S,e}^\varsigma \)) is enough to entrain all the sediment downstream; in the second case, instead, the sediment input is greater than the local transport capacity, therefore, only a fraction of sediment is transported downstream and deposition occurs:

\[
\Theta_{S,e}^\varsigma = \begin{cases} 
\Theta_{S,e-1}^\varsigma, & \text{if } \Theta_{S,e-1}^\varsigma < Q_{S,e}^\varsigma \text{(case 1)} \\
Q_{S,e}^\varsigma, & \text{else (case 2)}
\end{cases}
\]  

(3.26)

The sediment deposited by each cascade can be calculated as the difference between the sediment outgoing from \( e - 1 \) (\( \Theta_{S,e-1}^\varsigma \)) and the one outgoing from \( e \) (\( \Theta_{S,e}^\varsigma \)) (reaches \( e \) and compartments \( k \) are treated in the same way):

\[
\Delta_{S,e}^\varsigma = \Theta_{S,e-1}^\varsigma - \Theta_{S,e}^\varsigma.
\]  

(3.27)

\( \Delta_{S,e}^\varsigma \) is a deposition rate [kg/year], and can be transformed in the absolute value of all the sediment deposited in reach \( e \) [kg], summing up all the cascades \( \gamma_{\varsigma} \) passing through \( e \) and multiplying by the time step \( \delta t \):

\[
\Delta_{S,e} = \sum_{i=1}^{n} \Delta_{S,e}^i \delta t.
\]  

(3.28)

In Figure 3.5(C) is displayed how the sediment deposition within reservoir can reduce the impoundment volume, therefore, all the hydraulic parameters should be recomputed for the new bottom profile.

\(^4\)For the mass balance, the sediment outgoing from reach \( e - 1 \) is equal to the one entering in reach \( e \).
The dams in the 3S are assumed to be equipped with bottom outlets. Therefore, the portion of sediment that has not deposited in the impoundment can be routed downstream of the dam, otherwise also the sediment fraction that reaches the dam would be trapped.

### 3.3.6 Implementation of CASCADE model in the 3S basin

The 3S case study was already implemented in CASCADE by Schmitt, R.J.P. (2017) during a previous study on dam portfolios evaluation. To apply CASCADE in the 3S basin, the morphologic and hydrologic input data has to be derived first.

The river network has been obtained starting from a void-filled digital elevation model (DEM) with a 90 m resolution (Jarvis et al., 2008). After applying a minimum drainage area of 75 km\(^2\) for channel initialization, the river network has been split in reaches in correspondence to the confluences. In total 1422 reaches were obtained, with an average length of 6.3 km. To each reach has been assigned the corresponding channel gradient \(I_e\) and the value of the drainage area calculated for its most upstream point \(AD_{e}\). The last morphologic characteristic needed is the active channel width \(W_{AC,e}\). This parameter has been determined for 200 random reaches, while for the remaining a scaling law, that compute the width as function of the drainage area \(AD_{e}\) and the gradient \(I_e\), has been used:

\[
W_{AC,e} = AD_{e}a\cdot I_{e}b. \tag{3.29}
\]

The two parameters \(a\) and \(b\), in Equation 3.29, have been calibrated in a previous work of Schmitt, R.J.P. et al. (2016) and are assumed equal to \(a = 0.47\) and \(b = -0.12\).

Since, for the hydrologic data, a limited number of discharge records were available, the results from the work of T. Piman et al. (2013) were used. They developed a Soil & Water Assessment Tool (SWAT) calibrated on the period from 1987 to 2006, that gave as output 20-year hydrographs in 39 different reference locations in the 3S. Through an embedded component in CASCADE, the discharge corresponding to the bank-full conditions was computed for these locations (i.e. approximated with the 1.5 year return period discharge \(Q_{1.5,RL}\)). For all the other reaches, the \(Q_{1.5,e}\) was computed using a power law fitted to the bank-full conditions and the drainage area. For the sediment routing, CASCADE requires to have, for each reach, an hydrograph \(Q_{e}\), which can be obtained multiplying the hydrograph in the downstream reference location \(Q_{RL}\) by a scaling factor \(J_e\):

\[
Q_{e} = J_{e} \cdot Q_{RL}. \tag{3.30}
\]
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The scaling factor \( J_e \) is the ratio between the bank-full discharge in the reach \( e \) \((Q_{1.5e})\) and the same condition in the downstream reference location \((Q_{1.5RL})\):

\[
J_e = \frac{Q_{1.5e}}{Q_{1.5RL}}.
\] (3.31)

Another input necessary to the model is the information about the sediment sources (i.e. grain size and sediment supply). One of the strengths of CASCADE is that, in poor data basins, sediment information is derived using some equilibrium considerations for the grain size while the sediment supply is set equal to the local transport capacity. However, for 3S, a previous inverse modelling study gave a better approximation for the sources initialization (Schmitt R.J.P. et al., "in Review"). In the inverse modelling, 7500 random initializations of the grain size were performed using a Monte Carlo approach. The grain size was sampled in the sand range \((0.0625 - 2 \text{ mm})\), and no \(a\text{-priori}\) assumption was made on the sediment probability distribution. The sediment supply of source \( \varsigma \) was set equal to the minimum downstream transport capacity. The results of this random approach gave a wide variability both in the sediment flux \((4 \cdot 10^9 - 2 \cdot 10^{11} \text{ kg/year})\) and in the median grain size \(d_{50}\) \((0.065 - 2 \text{ mm})\) at the basin outlet \(\Omega\). However, only 65 initializations out of 7500 (i.e. 0.8%) were matching the observations available at the Mekong confluence. Therefore, for our application, the average of these 65 sediment source initializations was used as input for the sediment sources (Figure 3.6).

As explained in Section 3.3, to take into account the presence of multiple sediment cascades in a reach, CASCADE introduces a competition factor that can be computed in the 4 different ways presented in Section 3.3.4. However, the inverse modelling gave as result the initialization of the sources already considering the competition. Therefore, when CASCADE is run, with this sediment sources initializations, the competition does not have to be performed again, otherwise it would be considered twice. In Figure 3.7 we show the sediment flux resulting from a CASCADE run in the undisturbed state (i.e. no dams). Analyzing the provenance of sediment flux at the basin outlet, we can state that the most important river for the sediment transport is the Sre Pok, producing 51% of the 3S sediment flux. The Se Kong and the Se San produce 26% and 23% respectively.

To evaluate dam impacts on the 3S sediment delivery, dams information are required for the basin. This information is available from the Mekong River Commission (MRC), which reports the dam characteristics for all the 42 dams: built, under construction or planned for the near future. For the majority of dams the information is complete and it includes, for example, location, year of construction, full supply level, storage capacity, inundated area, installed capacity, expected yearly production and type of reservoir (i.e. reservoir or run-of-river). The details of the 42 dams are presented in Tables 2.2, 2.3, 2.4 and 2.5. 38
Figure 3.6: The dots represent the sediment sources computed in the inverse modelling. The colors represent the $\log_{10}$ of the sediment supply expressed in kg/year.
Figure 3.7: The sediment flux, computed with CASCADE, in the undisturbed state (i.e. no dams), expressed in kg/year. The Se Kong, Se San, Sre Pok produce 26%, 23% and 51% of the total sediment flux respectively.
3.4 Simplified Model

The Simplified Model (SM) is a computationally efficient version of the large-scale sediment connectivity model, CASCADE. To have a more clear idea why we developed the SM, we present an approximated computational time if the optimization would have been performed combining CASCADE with Borg (i.e. the Multi Objective Evolutionary Algorithm used in our analysis, see Section 3.5).

Depending on the dam portfolio, the computational time for a CASCADE run is between 3-4 seconds. Usually, with Borg MOEA, to obtain the optimal solutions, the model as to be run between 100 000 and 1 000 000 times. With CASCADE this would require between 4 and 45 days, just for one Borg run. In addition, a sensitivity analysis on the results should be performed which would increment exponentially the computational time. Therefore, we developed the SM, which is able to capture the main processes modelled in CASCADE and to reduce drastically the computational time (up to 50 times less).

CASCADE, every time a dam portfolio has to be evaluated, performs the sediment routing for each sediment source $\varsigma$, and derives the sediment flux $\Theta_{\varsigma,e}$ in each reach $e$ of the pathway. Furthermore, in this application, the sediment sources parameters (i.e. grain size and supply) are the results of a previous inverse modelling exercise, which includes cascades competition calculation ($\text{Schmitt R.J.P. et al., “in Review”}$). Therefore, the competition analysis does not have to be computed again when routing the sediment downstream. As a consequence, the reach by reach analysis integrated in CASCADE (i.e. sediment routing), add very little information about sediment fluxes against a considerable increment in the computational effort.

The SM starts from a preliminary run of CASCADE in the undisturbed state. Then, every time a new dam portfolio has to be evaluated, it applies matrix operations, instead of the computationally expensive routing scheme used by CASCADE.

In Figure 3.8 we show a flow chart to represent the SM processes.
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Figure 3.8: Flow chart representing the main steps and variables of the Simplified Model.

\[ \Theta_{S_{5\%},e}^c = \Theta_{S^r_{1},e}^c \]

Figure 3.9: Matrix containing the input sediment fluxes of each sediment source \( \varsigma \) in each reach \( e \).
3.4. Simplified Model

The SM requires four main input coming from CASCADE:

- $\Theta_{S,e}^\varsigma$: is a matrix containing the input sediment fluxes of each source in each reach ($\Theta_{S,e}^\varsigma$), where $\varsigma$ identify the source and $e$ the reach (Figure 3.9). The number of rows of the matrix, is equal to the number of sources $\varsigma$, the number of columns is equal to the number of reaches $e$. The matrix has been obtained performing the sediment routing without dams in a preliminary run of CASCADE, to obtain the sediment fluxes expressed in kg/year in each reach in the undisturbed state of the system.

- $T_{eff}$: is a vector of 42 elements containing the trap efficiency for each dam, ranging from 0 (i.e. all the sediment pass through the dam) to 1 (i.e. all the sediment is trapped in the reservoir). It has been calculated running CASCADE 42 times, using as dam portfolio a vector of zeros, except the element corresponding to the dam which trap efficiency has to be calculated, that assume the value 1. In Figure 3.10, we present an example to compute the trap efficiency; we refer to the scenario before dam construction as “bd”, and to the one post dam construction as “pd”. After a dam is built, the sediment flux downstream of the dam ($\Theta_{S,2}^\varsigma$) decreases comparing to the one computed in the undisturbed state, i.e. $\Theta_{S,2}^\varsigma(pd) < \Theta_{S,2}^\varsigma(bd)$.

The trap efficiency is then calculated as the percent reduction between the flux in the reach 2 before the dam construction and post dam construction (Figure 3.10):

$$T_{eff} = \frac{\Theta_{S,2}^\varsigma(bd) - \Theta_{S,2}^\varsigma(pd)}{\Theta_{S,2}^\varsigma(bd)}. \quad (3.32)$$

![Figure 3.10: Sediment flux alteration given by the construction of a dam.](image)
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- $N_{\text{inund}}$: contains for each dam the nodes that are inundated by the impoundment. This information is obtained in the pre-processing part of CASCADE, in which the full supply elevation of the dam is overlapped with the elevation of the river network.

- $t_{5\%}$: is a column vector with a number of elements equal to the number of sources, containing the 5% value of the initial sediment supply for each source. The use of this vector will be better explained in the next paragraph.

Once the input for the Simplified Model are obtained, CASCADE will not be run anymore. As previously mentioned, the Simplified Model applies matrix calculation on the sediment flux matrix ($\Theta_{\varsigma S,e}$).

The SM matrix operations are shown in Figure 3.11. The first step is to insert in $\Theta_{\varsigma S,e}$, the dam in the corresponding reach (Figure 3.11(B)), stored in the 3S dam database. At this point, the first effect, that has been considered, is the reduction of the sediment flux downstream of the dam because of its trapping effect. In particular, in the SM, we multiply by the trap efficiency the cascades originating upstream of the dam, in the nodes $e$ that are downstream of the dam. For example, if a dam is located in the reach 3 (Figure 3.11(B)), the cascades, originating from the sources $\varsigma_1, \varsigma_2, \varsigma_3$, experience a reduction in the downstream reaches 4, 5 and 6; the modified sediment flux has been indicated as $\Theta_{\varsigma S,\text{trap}}$ (Figure 3.11(C)).

The second effect is the one produced by impoundment on the inundated nodes. Since, in the reservoir there is a drop in the hydrodynamic forces given by the low water velocity, the sediment produced in the submerged sources is negligible comparing to the order of magnitude of the total sediment flux. Therefore, a good assumption is to set to zero the sources in the inundated nodes. Comparing to the trap efficiency, the effect of the inundated nodes, can be seen along all the cascades originating in the inundated nodes. In Figure 3.11(D) the sources affected by the impoundment are $\varsigma_2$ and $\varsigma_3$, once they are set to zero, they will not be active anymore along all their pathway (e.g. if the source $\varsigma_2$ is zero, also $\Theta_{\varsigma S,e}$ will be zero in the reaches 3,4,5 and 6). This new sediment flux is indicated with $\Theta_{\varsigma S,\text{inund}}$ (Figure 3.11(D)).

In CASCADE framework, if a cascade along its pathway deposits 95% or more of the initial supply, it is considered extinguished. Consequently, in the reaches in which the deposition is above this threshold, the sediment flux $\Theta_{\varsigma S,e}$ is set to zero. This approximation is reproduced in the SM, and it is explained in Figure 3.11(E), where, after applying the trap efficiency, the cascade $\varsigma_1$ exceeds the specified threshold. Therefore, in the reaches 4, 5 and 6, the sediment flux is set to zero. In Figure 3.11(E), the modification is referred as $\Theta_{\varsigma S,5\%}$.

The final output of the Simplified Model is the sediment fluxes matrix ($\Theta_{\varsigma S,'e}$). This matrix will then be used to compute the different indicators for the dam portfolios optimization.

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3In Figure 3.11, we refer with $\Theta_{\varsigma S,\text{trap}}, \Theta_{\varsigma S,\text{inund}}, \Theta_{\varsigma S,5\%}$ to the sediment fluxes that have been modified in the matrix by the corresponding processes: trap efficiency, application of the inundated nodes and sediment flux below the 5% of the initial flux. For example in Figure 3.11(D), the reaches inundated by the impoundment are the number 2 and 3. However, we have marked with the notation also reaches number 4, 5 and 6, since their sediment fluxes have been modified because of the inundated nodes process and not because the reaches are actually inundated.
3.4. Simplified Model

Figure 3.11: Representations of the matrix calculations operated by the Simplified Model to obtain the final sediment fluxes matrix that is used to compute the indicators. The different panels show: A): the input sediment flux matrix in the undisturbed state; B): in which reach the dam is located; C): how the matrix is modified after applying the trap efficiency; D): how the matrix is modified after applying the inundated nodes; E): how the matrix is modified after applying the 5% threshold.
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3.5 Multi-Objective Evolutionary Algorithms

The decision variable vector (i.e. dam portfolio) is composed by 42 Boolean variables. Therefore, if we want to evaluate each dam portfolio \( u \in U \), where \( U \) is the decision variable space, we should run the model \( 4.4 \times 10^{12} \) times (see the Equation (3.33)).

\[
C_{tot} = \sum_{k=1}^{n_{sites}} \frac{n_{sites}!}{(n_{sites} - k)! \cdot k!} \tag{3.33}
\]

where

- \( C_{tot} \) is the number of possible combination (i.e. the number of possible dam portfolios);
- \( n_{sites} \) is the number of dam siting, in our case study \( n_{sites} = 42 \).

Even though, the Simplified Model takes only 0.08 seconds to calculate the impacts of a dam portfolio, evaluating the entire decision variable set \( U \), would require a computational time that is in the order of \( 10^4 \) years. Adopting an optimization algorithm, we are able to find the optimal dam portfolios \( (u^*) \), exploring only a portion of the dam portfolios set, \( U \).

Given the characteristics of the problem (i.e. the model is not linear and the indicators are nor linear nor differentiable), we adopted an heuristic method to perform the optimization analysis. Common heuristic methods, for solving water resources problems, are the Multi-Objective Evolutionary Algorithms (MOEAs) (Maier et al., 2014).

In this paragraph, we will briefly describe the MOEAs procedure. Before the MOEA method is explained, it is important to define what is the meaning of “population” and “individual” in this type of algorithms. The population is a set of individuals, where every individual represents a decision variable vector (i.e. an individual corresponds to a dam portfolio, \( u \), and a population is composed by \( N \) dam portfolios, \( u_1, u_2, \ldots, u_N \)).

To better describe the algorithm procedure, we will use the example in Figure 3.12, in which two decision variables \( u_1, u_2 \) and two indicators \( J_1, J_2 \) to be minimize are considered.

In the initialization process, the algorithm choses a random group of individuals to assemble the initial population. Then, the individuals are evaluated in the indicators space, simulating the model (Figure 3.12(A)). The individuals that fit better the selection criteria (i.e. the ones that minimize the indicators values), are chosen to produce the next generation (Figure 3.12(B)). To generate the new population (offspring), genetic operators (i.e. cross-over, mutation and replacement) are applied to the best individuals identified at the previous step (parents) (Figure 3.12(C)). This new generation is evaluated (Figure 3.12(D)) and the previous steps are repeated until a termination condition is achieved (Figure 3.12(E)). At the end of the procedure, the algorithm returns the population that minimize the indicators values.

For this study, we adopted the Borg MOEA. This algorithm handles many-objective
problems, as the one considered in this study, it allows to avoid local minima and is computationally efficient. One of the main advantages of Borg, is that uses multiple genetic operators, therefore, it is not required to select *a-priori* which will be used in the optimization process. In addition, Reed et al. (2013) conducted a diagnostic assessment of ten MOEAs for water resources applications, concluding, that among all the algorithms tested, Borg MOEA had the best performances.

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6A further explanation of genetic operators is given at the beginning of Section 3.5.1
Figure 3.12: MOEA general procedure: (A) the MOEA algorithm select a random initial population, in the space of the decision variables, and evaluate its individuals; (B) the algorithm select the individuals that fit better the criteria (i.e. to minimize the objective); (C) the genetic algorithm is applied to the best individuals of the first population to generate offspring; (D) the new population is evaluated; (E) the previous step are repeated until the termination condition is achieved, than the algorithm return the optimal solutions.
3.5. Multi-Objective Evolutionary Algorithms

3.5.1 Borg MOEA

Borg MOEA is an Multi-Objective Evolutionary Algorithm develop by Hadka and Reed (2013) to solve optimization problems. Borg procedure is composed by a main lopp and a restar procedure. In the main loop the algorithm evaluates, a certain number of times, a population (Figure 3.16). The main loop is interrupted and the restart mechanism activated if some criteria are no more satisfied. The restart procedure is used to generate a new population that will be evaluated in the main loop.

Before explaining more in details how the algorithm works, it is necessary to present some of its components.

In the main loop there are 4 main components:

1. **Adaptive multi-operator procedure**
   
   At each step, the algorithm produces a new population (offspring) starting from the previous one, applying crossover and mutation through genetic operators (Figure 3.12(C)).
   
   The issue, in most MOEAs, is the necessity to select a-priori which genetic operator will be used in the problem. Most of the times, however, in real-world problems, it is unknown which is the best genetic operator. To solve this problem, Borg introduces a novel component that allows to discover, during the procedure, which genetic operator performs better. At the beginning, all the operators can be applied with the same probability, then the pobability is updated according to the number of successful offspring generated by each operator.

   The operators used by Borg MOEA are listed below:

   - Simulated binary crossover (SBX)
   - Differential evolution (DE)
   - Parent-centric crossover (PCX)
   - Unimodal normal distribution crossover (UNDX)
   - Simplex crossover (SPX)
   - Uniform mutation (UM)
   - Polynomial mutation (PM)

   The operators used for the crossover are SBX, DE, PCX, UNDX, SPX, while for mutation UM and PM are used.

   In Figure 3.13 are displayed the distributions of the offspring produced by SBX, DE, UM, PCX, UNDX, SPX. The different distributions show that SBX and UM generate solutions along a single axis while DE, PCX, UNDX and SPX do not show this trend.

2. **ε-Dominance Archive**

   Borg divides the indicators space into hyperboxes with side length ε. If two or more solutions reside in the same hyperbox, the algorithm keeps only the non-dominated one (i.e. the one minimizing the indicators) and adds it to the archive. The Archive is where Borg stores the non-dominated solutions.
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This tool guarantees converge and diversity during the search of the optimal population, avoiding deterioration.

![Image](image.png)

**Figure 3.13:** In the six panels are represented the distributions of the parent and the offspring produced by the following operators: SBX, DE, UM, PCX, UNDX, SPX. The black dots (●) indicate the parents, while the smaller dots the offspring (Figure adapted from [Hadka and Reed (2013)]).

3. \( \varepsilon \)-Progress

It is an extension of the \( \varepsilon \)-Dominance Archive to measure search progression, where \( \varepsilon \) is the minimum threshold for improvement. During the evaluation process, the algorithm must produce find at least one solution whose improvement is larger than \( \varepsilon \). If this condition is not satisfied, the restart mechanism is activated to avoid stagnation (i.e. local minima).

4. Tournament selection

The Tournament selection is a procedure adopted by MOEAs, in which the algorithm randomly selects a set of individuals that are evaluated through a tournament. The winner of each tournament is selected to apply the crossover with one of the genetic operators described above. An example of a tournament is presented in Figure 3.14 in which, from the initial population composed by 10 individuals, 4 of them are randomly selected for the tournament. The winner \( I_T \) is the one selected to apply the crossover. The number of individuals in the tournament determines the selection pressure. In fact, if the population size is large, weak individuals have a small chance to be selected, so the selection pressure is stronger.
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![Diagram of tournament selection procedure](image)

**Figure 3.14:** The tournament selection procedure. From the initial population composed by 10 individuals, 4 of them are randomly selected for the tournament ($I_2$, $I_7$, $I_9$, $I_5$). The winner $I_7$ is the one selected to apply the crossover.

When the restart mechanism is activated, Borg combines three techniques to generate the new population:

1. **Adaptive Population Size**
   Borg uses a fixed population-to-archive ratio ($\gamma$) to maintain the population size proportional to the archive size (Figure 3.15).

   \[ \gamma = \frac{\text{population size}}{\text{archive size}} \geq 1. \]  

   (3.34)

   If the difference between the population-to-archive ratio, computed at that step, and $\gamma$ is larger than 25%, the population size has to be adapted.

   An example of **Adaptive Population Sizing** is presented in Figure 3.15 in which after Run 1 the new population size depends on the size of the archive $A_1$ and the ratio $\gamma$. This technique helps to avoid local minima ([Tang et al., 2006](#)).

2. **Adaptive Tournament Size**
   Borg uses the adaptive tournament size in order to maintain the same selection pressure after every restart. The innovation of this method is that, it does not keep the tournament size constant, but it adapts it to the population size, maintaining fixed $\tau$, a fixed percentage of the population size.
3. **Injection**

During the restart, the new population is filled with the individuals from the archive of the previous population \( (A) \). The remaining slots, instead, are filled with individuals obtained mutating archive individuals selected randomly. Some experiments, conducted by Hadka and Reed (2013), proved that the injection technique improves the quality of the results.

An example of injection is presented in Figure 3.15. During Run 1, the initial population is evaluated and the archive \( A_1 \) is filled with non-dominated solutions. When the restart procedure is activated, the new population is filled with the individuals from archive \( A_1 \), the remaining slots (i.e. the portion coloured in grey) is filled with individuals obtained mutating \( A_1 \) individuals selected randomly. The portion coloured in grey has a size equal to \((\gamma - 1)\) times the size of archive \( A_1 \). This procedure is repeated at each restart.

![Figure 3.15](image)

Figure 3.15: The figure displays, during the restart, how the new population is filled starting from the archive of the previous one. The new population is composed by individuals from the previous archive (i.e. portion in white) and by individuals obtained applying mutation on archive individuals (i.e. the portion in grey). The size of the new population depends on the size of the archive and on the ratio \( \gamma \).

Once the main components of Borg are defined, we can present a short description on how it works.

In the main loop (Figure 3.16), Borg selects \( k \) parents to generate a new offspring. One parent is randomly selected from the archive, while the remaining \( k - 1 \) are the winners of tournaments. The parents are recombined with the genetic operators to generate the offspring. At this point, Borg evaluates this new individuals and updates the population and the archive. Periodically, two conditions to exit from the main loop are checked (Figure 3.17): the


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\(\varepsilon\)-Progress and the Population-to-Archive Ratio. It is sufficient that one of the two conditions is not satisfied to activate the restart mechanism, in which Adaptive Population size, Adaptive Tournament Size and Injection are applied. When the new population is generated, the main loop starts again. The algorithm is stopped when the maximum number of function evaluation (NFE) is reached.

Figure 3.16: Borg main loop (Figure adapted from [(Hadka and Reed, 2013)](http://example.com))

Figure 3.17: Borg, periodically, checks if the restart mechanism has to be activated. If yes, the Adaptive Population Size, the Adaptive Tournament Size and the Injection are applied (Figure adapted from [(Hadka and Reed, 2013)](http://example.com)).
To run Borg we need to define some key parameters that must be given as input:

- **Nvars**: is the number of decision variables considered in the optimization problem;
- **Nobjs**: is the number of objectives (i.e. indicators) evaluated in the optimization problem;
- **Nconstrs**: is the number of constraints applied in the optimization problem;
- **objectiveFcn**: is the function that compute the indicators;
- **Number of Function Evaluation (NFE)**: defines how many times Borg can evaluate the objective function. Once the NFE is reached, the algorithm terminates and returns the results. It is necessary to tune the NFE value, testing the problem convergence;
- **LowerBounds**: defines the lower value that decision variables can assume;
- **UpperBounds**: defines the higher value that decision variables can assume;
- **Epsilons (\(\varepsilon\))**: is the resolution used by Borg to find new solutions, as explained in the paragraph \(\varepsilon\)-Dominance archive and \(\varepsilon\)-Progress, above. Smaller epsilon values result in a fine-grained Pareto sets, and larger epsilons in a coarse-grained sets. It is required to define and tune an epsilon value for each objective;
- **Parameters**: are all the parameters already defined by Borg MOEA with default values. It is possible to modify the default values but it is not necessary to run the algorithm.

Since in Borg, the results can be affected by the randomization included in the framework, to filter the problem uncertainty, it is recommended to run the optimization process more than ones, according to the problem sensitivity (i.e. run Borg with different initial seeds).
In this chapter, we introduce the setting for the analysis conducted during our research, on the 3S river basin. In Section 4.1, we introduce how we tuned Borg parameters to run the optimization analysis; in Section 4.2, we introduce Borg setting for the two-objective problem and the analyses conducted on the results; in Section 4.3, we introduce Borg setting for the six-objective problem and the analyses conducted on the results. Each of the sections below reflects the section subdivision of Chapter 5.

4.1 Borg parameters tuning and sensitivity analysis

As explained in Section 3.5.1, the Borg algorithm requires the tuning of a certain number of parameters, which are problem dependent. In particular, a preliminary analysis has to be made to set properly:

- epsilon ($\varepsilon$);
- number of initializations (i.e. seeds);
- number of function evaluations (NFE).

The tuning of these three parameters is a key point for obtaining reliable results, therefore a sensitivity analysis was conducted on the two objectives optimization, the starting point of our thesis. The indicators considered were the hydropower production on one
Chapter 4. Experiment setting

hand, and the sediment flux at the basin outlet on the other.

The selection of the $\epsilon$ parameter can influence the resolution and the quality of the results obtained in an optimization exercise. To evaluate the sensibility of the problem to this parameter, we tested 30 different settings with 10 initializations each, for a total of 300 evaluations. We applied the Latin Hypercube Sampling method (LHS) to generate the 30 initializations (Zatarain Salazar et al., 2016). The LHS is a statistical method which allows to generate quasi-random samples of parameter values from a multidimensional distribution. First of all, we have to define a domain for epsilon. We started from the results of a previous work of Schmitt, R.J.P. (2017) in which, a Pareto front was obtained with an exhaustive search considering the same two indicators. These results gave as output a range in the sediment flux from $8.76 \cdot 10^8$ up to $1.31 \cdot 10^{10}$ [kg/year] and for the hydropower from $9.6 \cdot 10^3$ to $3.05 \cdot 10^4$ [GWh/year]. The resulting difference between the minimum and the maximum was than divided by 10, this value was assumed to be the domain in which the epsilon values could range. Therefore, the boundaries for the domain result to be $0 - 2.08 \cdot 10^3$ [GWh/year] for the hydropower production and $0 - 1.22 \cdot 10^{10}$ [kg/year] for the sediment flux. To be sure that also low values of one parameter were combined with high values of the other one, we applied the LHS three times in different portions of the domain:

- first sample: 10 points in all the domain (Figure 4.1(A));
- second sample: 10 points considering all the domain along the sediment axis, the lower 1/3 of the domain along the hydropower axis (Figure 4.1(B));
- third sample: 10 points considering all the domain along the hydropower axis, the lower 1/3 of the domain along the sediment axis (Figure 4.1(C)).

Moreover, we obtained a higher density of points in the area with low values of both the epsilons. In this portion of the space is were the best performance is expected to be obtained. For large values of epsilon, in fact, Borg does not recognize as improvement quantities that are relevant comparing to the magnitude of the variable.

The performances of the 300 evaluations have been assessed using the hypervolume. This metric has been selected since, usually, is the most challenging performance test in the evaluation of evolutionary algorithms. It requires high performance for convergence and diversity (Zatarain Salazar et al., 2016), which are two key characteristics that have to be satisfied.

The results of this analysis are presented in Section 5.1.1.

The second parameter to be set is the number of initial seeds. The initializations considered can affect the final solution, different initializations, in fact, can lead to different Pareto optimal solutions. For this evaluation, we run Borg with 10 different initializations, fixing the value of the two epsilons (i.e. $\text{epsilon}_{\text{Hydropower}}$ and $\text{epsilon}_{\text{SedimentOutlet}}$). The 10 different Pareto fronts have then been compared.

The results of this analysis are presented in Section 5.1.2.

The last parameter, that should be tuned, is the number of function evaluations (NFE).
4.1. Borg parameters tuning and sensitivity analysis

This parameter is the one that allows to obtain a Pareto front which gets as close as possible to the theoretical optimal Pareto front (i.e. convergence problem). The NFE suggested value, in evolutionary algorithm literature ([Hadka D. et al., 2012]), is at least 10,000. In our analysis, we calculated the Pareto front for six different values of NFE: 200, 500, 1,000, 5,000, 10,000 and 100,000. The results were compared to verify when the problem reaches the convergence.

The results of this analysis are presented in Section 5.1.3.

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Figure 4.1: Latin hypercube sampling for the ε parameters. A: First sampling. B: Second sampling. C: Third sampling. D: Total ε sampling, which is the union of the three previous panels.
Chapter 4. Experiment setting

4.2 Two-objective optimization

In the first step of this analysis, we want to obtain the Pareto front for a two objectives optimization problem. The indicators considered in this section are, the hydropower production, to take into account dam benefits, and the sediment flux at the basin outlet, to evaluate the possible impacts of dams construction on sediment delivery. As will be explained in Section 5.1, the analysis on Borg parameters gave their configuration in order to reach the best compromise between accuracy and computational cost. Parameter settings for this analysis are:

- $\varepsilon_{\text{Hydropower}} = 573 \ [GWh/year]$,
  $\varepsilon_{\text{SedimentOutlet}} = 9.05 \times 10^7 \ [kg/year]$;
- Number of initializations = 4;
- NFE = 100 000.

After deriving the Pareto front, an analysis on the dam spatial distribution in the 3S basin is conducted, to examine which are the most impacting dams on the natural sediment flux at the basin outlet (i.e. the less selected ones). This results are also compared with the historical dam development of the 3S. The analysis is presented in Section 5.2.1.

At this point, we use the two objectives optimization problem to validate the Simplified Model, the results are presented in Section 5.2.2. The validation has been performed on two levels. The first one consists in verifying the ability of the Simplified Model to reproduce CASCADE. For this purpose, we run CASCADE with the optimal dam portfolios obtained from the optimization performed with the Simplified Model. The validation has been conducted considering the two sediment indicators implemented in CASCADE framework: the sediment flux at the basin outlet (i.e. SedimentOutlet) and the sediment alteration in the basin (i.e. SedimentAlteration).

In the second type of validation, instead, we run the optimization algorithm with CASCADE model, to analyse if there are any relevant differences in the spatial pattern of the dams selected in the optimal portfolios. Running Borg with CASCADE was possible since all the parameters for the optimization have been previously tuned with the Simplified Model. Without knowing this parametrization a-priori, the computational time would have been prohibitive.
4.3 Six-objective optimization

As presented in Chapter 2, the 3S river basin has a relevant importance for the sediment delivered to the Mekong and for the great number of fish species living in the basin. In order to consider multiple environmental aspects, we have expanded the two-objective optimization problem into a six-objective one. In particular, we will consider: two objectives for sediment delivery (SedimentOutlet and SedimentAlteration, see Section 3.2.2), two for ecological aspects (MigratoryFishes and EcologicalConnectivity, see Section 3.2.3), one for the flow regulation (FlowRegulation, see Section 3.2.4) and one for the hydropower production (Hydropower, see Section 3.2.1). We used two different indicators for the sediment and the ecology, one is interested in maintaining the external connectivity with the Mekong river, the other the internal state of the 3S basin (i.e. internal connectivity). Four indicators, i.e. SedimentOutlet, MigratoryFishes, EcologicalConnectivity and Hydropower, has to be maximized; while the others, i.e. SedimentAlteration and FlowRegulation, has to be minimized. Also for this analysis, we need to tune the parameters to apply Borg. The problem structure was unchanged comparing to the two-objective, i.e. the decision variables and the fuction which calculates the objectives are the same, and, as will be explained in Section 5.1.1, the problem is not sensitive to the setting of the $\varepsilon$ parameter, we can conclude that also the six-objective problem can be considered not sensitive to the epsilon parameter. Therefore, we have decided to set the parameter in a way that is common in the literature, but do not require to evaluate multiple epsilon parametrizations. We evaluated all the 6 objectives for the 43 optimal two-objective portfolios, to have a reference interval for each indicator. Then, we divided, for each indicator, the interval by the total number of solution $n_{tot} = 43$.

$$\varepsilon_{J_i} = \frac{\max(J_i) - \min(J_i)}{n_{tot}},$$

where $\max(J_i)$ and $\min(J_i)$ are respectively the maximum and the minimum values of the indicator $J_i$. Thus, the parameters used in the optimization exercise will be:

- $\varepsilon_{Hydropower} = 521 \ [GWh/year],$
- $\varepsilon_{SedimentOutlet} = 2.95 \cdot 10^8 \ [kg/year],$
- $\varepsilon_{SedimentAlteration} = 7.56 \cdot 10^{13} \ [kg \cdot m/year],$
- $\varepsilon_{EcologicalConnectivity} = 1.7 \ [%],$
- $\varepsilon_{MigratoryFishes} = 6.31 \cdot 10^7 \ [m^3],$
- $\varepsilon_{FlowAlteration} = 0.08 \ [%];$

- Number of initializations = 4;
- NFE = 100 000.
Chapter 4. Experiment setting

After obtaining the Pareto front for the six-objective problem, we focus the first part of the analysis on capturing the main conflicts between the different objectives using a seven-dimensions space\(^1\) and the parallel plot. The next step consists in projecting the seven-dimensions space in a two-dimensions one. In this analysis, we plot each environmental indicator with the hydropower production, to analyse how much each indicator is sensible to the hydropower development (Section 5.3.1). In Section 5.3.2 we consider the two main conflicts that are expected to occur in the dam distribution of the environmental indicators considered:

1. Sediment versus ecological indicators:
   - SedimentOutlet versus MigratoryFishes (i.e. both external connectivity);
   - SedimentAlteration versus EcologicalConnectivity (i.e. both internal connectivity).

2. Internal versus external connectivity:
   - SedimentAlteration versus SedimentOutlet (i.e. both assessing impacts on sediment)
   - EcologicalConnectivity versus MigratoryFishes (i.e. both assessing impacts on ecology)

\(^1\)Two dimensions have been used to plot the hydropower production to make the results more intuitive.
CHAPTER 5

Results

5.1 Borg parameters tuning and sensitivity analysis

5.1.1 Epsilon tuning

As explained in Section 4.1, to select the $\epsilon$ parameters for the optimization, we tested 30 epsilon values with 10 initializations each, to check the sensitivity of the problem. The Pareto fronts obtained with each parametrization are displayed in Figure 5.1 with colored dots, the red circles are the $\epsilon$ setting selected for the 2-objective optimization analysis.

Looking at the Pareto fronts, the only differences between the 30 $\epsilon$ parametrizations are: the points density and the extension of the frontiers. For example, it can be noticed that the Pareto front in purple is more extended than the others for low hydropower productions. However, for medium and high yields, the density of the pareto points is not satisfactory and there is a general lack of solutions.

For a more rigorous selection of the best epsilon, all the 30 settings have been evaluated according to the hypervolume performance. In Figure 5.2, the hypervolume performances of the 300 evaluation (i.e. 10 initializations for each of the 30 settings) are plotted, represented by a bar. The height and the colour of the bar are the percentage of hypervolume reached by each experiment, while the red dots in the background are the maximum hypervolume performances reached by each epsilon setting. This analysis is
Chapter 5. Results

conducted to assess if all the initializations, for a given $\varepsilon$, have a satisfying hypervolume performance, in order to avoid selecting an epsilon setting that results in a good performance only in one initialization (Zatarain Salazar et al., 2016).

From the results obtained, we can conclude that the problem is not sensitive to the calibration of epsilon, since all the calibrations reach almost the same maximum and average performance for the hypervolume (Figure 5.2). The $\varepsilon$ parameters that were selected, to be more suitable for the two-objective optimization analysis, are:

- $\varepsilon_{\text{Hydropower}} = 573 \text{ [GWh/year]}$
- $\varepsilon_{\text{SedimentOutlet}} = 9.05 \cdot 10^7 \text{ [kg/year]}$.

Figure 5.1: Pareto fronts for different $\varepsilon$ settings are represented with coloured dots. The Pareto front represented with red circles, corresponds to the $\varepsilon$ setting chosen for the optimization analysis.
5.1. Borg parameters tuning and sensitivity analysis

5.1.2 Initialization comparison

The number of initializations is the second parameter which has to be tuned. For the following analysis, we run Borg 10 times, with different initial seed, using the epsilon setting identified in Section 5.1.1. Each panel of Figure 5.3 shows with red dots the solutions obtained with a single initialization, with black circles the Pareto front resulted combining the solution of the 10 initializations considered. The black circles frontier has been obtained selecting only the Pareto efficient solutions from all the different initializations. For example, if a point is dominated by another one from another initialization, it will not be present in the black circles frontier.

In Figure 5.3, it can be noticed that, except for low hydropower productions, the shapes of the Pareto fronts are similar in all cases. Also looking at the hypervolume, in Figure 5.2, it can be seen that on average there is a negligible difference of performances among the initializations of the same epsilon setting.

From this analysis, we can conclude that the problem is not very sensitive to the number of initializations. Therefore, for the optimization analyses the number of initializations is set equal to 4 to reduce the computational costs.

**Figure 5.2:** Plot of the hypervolume performance in percentage, for each of the 10 initializations of the 30 epsilon settings, represented by the bar height and colour. The red dots on the background are the maximum hypervolume performance for a given epsilon calibration.
Figure 5.3: Plot of the optimal solutions obtained for each initialization in red, compared to the total optimal solutions of the $\varepsilon$ setting, represented with black circles.
5.1.3 Convergence analysis

The number of function evaluations (NFE) is the last important parameter that must be given as input to Borg algorithm. In fact, in order to get a reliable result, the algorithm must have reached the convergence to the theoretical optimal solution. In Figure 5.4, with different symbols and colours, we present Pareto fronts obtained for different settings of NFE. Given the nature of the problem, where each decision variable can be just 1 or 0, the Pareto front moves quite rapidly toward the convergence. Already with an NFE = 5 000, the solutions can be considered Pareto efficient. Incrementing the number of function evaluation above 100 000 increas exponentially the computational costs, without giving any improvement in the quality of the solutions.

Therefore, for the optimization analyses, the NFE is set equal to 100 000. A NFE equal to 5 000 would have been suitable for the problem, but, since the computational costs were still reasonable, we preferred to perform a greater number of function evaluation.

![Figure 5.4: Plot of the Pareto fronts for six different values of NFE to analyse the convergence of the two-objective optimization problem.](image-url)
Chapter 5. Results

5.2 Two-objective optimization

5.2.1 Pareto front and dam distribution

The goal of the two objectives optimization is to find which is the optimal trade-off considering just one indicator for dam benefits, the hydropower production [GWh/year], and one for the environment, the sediment flux at the basin outlet [kg/year]. Running the optimization algorithm with the parameters introduced in Section 4.2, we have obtained the set of Pareto efficient solutions (blue dots in Figure 5.5), where each solution corresponds to a dam portfolio. However, given an optimal dam portfolio, not in all the cases we can move to the next point, since, every dam portfolio is not related to the others. Therefore, some dams selected in the first portfolio might not be chosen in the second one. In Figure 5.5 on the main $x$ and $y$ axes, are displayed the absolute values of the two objectives, while on the secondary axes the values are converted in percentage. The star on the top-right corner represents the Utopia, which coordinates are the best values (i.e. maximum) for both indicators. The utopia $x$ value is the one obtained with the portfolio in which all the dams have been selected, therefore, the hydropower corresponds to the total hydropower potential and it is equal to 30 463 [GWh/year]. The utopia $y$ coordinate is the one corresponding to the undisturbed state, where no dam has been selected and the sediment flux at the outlet is $1.38 \cdot 10^{10}$ [kg/year]. The black squares represent the historical hydropower development in the basin, the correspondent sediment fluxes have been computed using the Simplified Model.

The optimization problem returns 43 optimal dam portfolios. In the first part of the Pareto front, for low hydropower productions, there is apparently a lack of information, since, the first solution already produces 8 041 [GWh/year]. However, we can be satisfied with this Pareto front, since, for the first point, the reduction in the sediment flux is just in the order of the 2%. Therefore, it is not interesting searching for solutions for lower hydropower productions, because the sediment loss would be almost negligible. Up to 74% of the 3S hydropower potential, the reduction in the sediment flux at the outlet is less than proportional than the increase in the electricity production. Therefore, the hydropower development affects the sediment delivery only partially. After this break point, for a small increment in the hydropower production, big drops can be observed in the sediment flux at the basin outlet. The reason of this larger decreases, is that the last dams selected in the portfolios are the most downstream ones or the ones in the Sre Pok. The first ones can produce a large decrease in the sediment flux since they trap a high number of cascades in their impoundment, the seconds, instead, are located in the river that produces most of the sediment delivered to the basin outlet (i.e. the Sre Pok produces 51% of the 3S sediment flux, see Figure 3.7).

The break point, previously identified, can be seen as the system capacity, for which 74% of the hydropower is produced, reducing only the sediment flux by 23% of the undisturbed supply (Figure 5.5).

The historical dam development in the 3S, displayed in Figure 2.1, includes dams that are already built, under construction and planned for the near future (i.e. 2025). The dams built until 2016 have a cumulated hydropower production of 12 000 [GWh/year] (point identified with 1 in Figure 5.5). For hydropower productions lower than this
value, we can notice that, if a basin scale planning would have been adopted from the beginning, the sediment flux at the outlet could have been 20% higher. The largest sediment flux decrease, in the historical development, is given by the Lower Se San 2 (LSS2), which is currently under construction. The LSS2 is considered the most impacting dam of the 3S because it will trap both the discharge coming from the Se San and the Sre Pok. When LSS2 will be completed, the sediment flux at the basin outlet will drop from 70% (point 2 in Figure 5.5) down to 20% (point 3 in Figure 5.5), while the hydropower will increase just by 6.5% of the total potential. After the construction of LSS2, the impact on sediment delivered to the outlet, for not considering a basin scale planning from the beginning, get even larger. For an hydropower production of 16 590 GWh/year (point 3 in Figure 5.5), in fact, the historical development has already reduced the sediment flux to 20% of the natural state. With a basin scale planning, instead, the sediment flux could be 79% (i.e. difference between blue dots and black squares in correspondence of point 3 in Figure 5.5). This higher value of sediment flux is obtained, since LSS2 can be replaced by less impacting dams with the same hydropower production.

Comparing the Pareto front obtained in the optimization with the historical development, we can conclude that lower impacts can be generated adopting a basin scale dam planning, in particular for medium-high hydropower productions.

Figure 5.5: Plot of the Pareto front for the two objectives problem in blue, and the historical dam development in black. The star on the top-right corner is the Utopia point. The four points identified in the historical development are: 1: the current dam development, 2: the dam development before the construction of LSS2, 3: the dam development after the construction of LSS2, 4: the dam development considering the dams already built and the ones under construction. The point shown on the pareto front represents the System Capacity (SC).
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Each point of the pareto front is a dam portfolio, therefore, we can analyse the probability of each dam to be selected in a portfolio. Figure 5.6 shows the probability, according to the colour bar, considering all the 43 portfolios of the Pareto front. The most selected dams are the ones in the Se Kong, in particular, if located on the tributaries and not on the main stem. The dams in the Sre Pok basin, instead, are almost never selected. All of them, except the Buon Kuop dam (Figure 5.6), have a probability smaller than 30% to appear in a dam portfolio, since the Sre Pok delivered to the basin outlet 51% of the total sediment flux (Figure 3.7). The reason why the Buon Kuop dam appears always in all the scenarios can be identified in its high hydropower production and negligible sediment trapping (Table 5.1). Also the most downstream dams, i.e. Lower Se San 2 and Sekong (Figure 5.6), have a very low probability to be selected (i.e. < 10%), because they have high trap efficiencies and they intercept a high sediment flux (Table 5.1). O Chum 2 dam, (Figure 5.6), is rarely selected since its hydropower production is almost null (Table 5.1).

<table>
<thead>
<tr>
<th>Dam</th>
<th>Trap efficiency</th>
<th>Hydropower [GWh/year]</th>
<th>Natural Sediment flux [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buon Kuop</td>
<td>0.01</td>
<td>1 459</td>
<td>2.00 · 10^9</td>
</tr>
<tr>
<td>Lower Se San 2</td>
<td>1.00</td>
<td>1 954</td>
<td>1.02 · 10^{10}</td>
</tr>
<tr>
<td>Sekong</td>
<td>0.59</td>
<td>558</td>
<td>3.51 · 10^9</td>
</tr>
<tr>
<td>O Chum 2</td>
<td>1.00</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5.1: Trap efficiency, hydropower production and natural sediment flux (i.e. sediment flux in the undisturbed state) of the following dams: Buon Kuop, LSS2, Sekong and O Chum 2
5.2. Two-objective optimization

Analysing the dam distribution of the 43 optimal portfolios, we identified a spatial pattern in the dam selected. Therefore, we divided the Pareto front in three main groups (Figure 5.7(A)):

- **Group 1**: low hydropower production, in which most of the dams selected are located in the Se Kong basin (Figure 5.7(B));
- **Group 2**: medium hydropower production, in which most of the dams selected are located both in the Se Kong and Se San river basins (Figure 5.7(B));
- **Group 3**: high hydropower production, in which the dams are selected also in the Sre Pok basin (Figure 5.7(B)).
In Figure 5.7(B), in Group 1, can be observed that all the dams selected are in the Se Kong basin, except two dams, which appear in all the portfolios. The first one, the Upper Kontum dam (Figure 5.8, Table 5.2), in the Se San sub-basin, is selected, since it has a high hydropower production and a low sediment flux, despite its trap efficiency is equal to 1. The other one, the Buon Kuop dam (Figure 5.8, Table 5.2), in the Sre Pok sub-basin, has a probability equal to 1 to be selected, since it has a negligible trap efficiency against a high hydropower production. In the Se Kong basin, we can identify two groups of dams that are always selected in the portfolios. The first one, which is composed by Xekaman 3, Xe Kaman 4B, Xe Kaman 4, Xe Kaman 2B and
5.2. Two-objective optimization

Figure 5.8: In figure are displayed the names of the main dams in the Se Kong, Se San and Sre Pok.

Xe Kaman 2A, has a total hydropower production of 2 281 [GWh/year], and a natural sediment flux\(^1\) at the most downstream dam\(^2\) of \(2.2 \cdot 10^8\) [kg/year](Figure 5.8, Table 5.2). The second group, which is composed by Houayho and Xepian-Xenamnoy, has a total production of 2 235 [GWh/year] and a natural sediment flux equal to \(1 \cdot 10^8\) [kg/year](Figure 5.8, Table 5.2). Therefore, considering both groups, we can produce 15% of the total 3 0463 GWh/year potential hydropower production, limiting the impact to 2.3% of sediment flux at the outlet. This is the reason why all the dams, in the two groups, have probability 1 to appear in a dam portfolio.

<table>
<thead>
<tr>
<th>Dam</th>
<th>Trap efficiency</th>
<th>Hydropower [GWh/year]</th>
<th>Natural Sediment flux [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Kontum</td>
<td>1.00</td>
<td>1 056</td>
<td>(1.42 \cdot 10^7)</td>
</tr>
<tr>
<td>Buon Kuop</td>
<td>0.01</td>
<td>1 459</td>
<td>(2.00 \cdot 10^9)</td>
</tr>
<tr>
<td>Xekaman 3</td>
<td>0.85</td>
<td>983</td>
<td>(1.07 \cdot 10^8)</td>
</tr>
<tr>
<td>Xe Kaman 4B</td>
<td>1.00</td>
<td>301</td>
<td>(1.25 \cdot 10^7)</td>
</tr>
<tr>
<td>Xe Kaman 4</td>
<td>0.24</td>
<td>375</td>
<td>(7.56 \cdot 10^6)</td>
</tr>
<tr>
<td>Xe Kaman 2B</td>
<td>1.00</td>
<td>381</td>
<td>(2.22 \cdot 10^8)</td>
</tr>
<tr>
<td>Xe Kaman 2A</td>
<td>0.81</td>
<td>242</td>
<td>(2.24 \cdot 10^8)</td>
</tr>
<tr>
<td>Houayho</td>
<td>0.81</td>
<td>487</td>
<td>(2.83 \cdot 10^7)</td>
</tr>
<tr>
<td>Xepian-Xenamnoy</td>
<td>0.98</td>
<td>1 748</td>
<td>(1.01 \cdot 10^8)</td>
</tr>
</tbody>
</table>

Table 5.2: Trap efficiency, hydropower production and natural sediment flux (i.e. sediment flux in the undisturbed state) of the main dams in Group 1

\(^1\)With natural sediment flux we consider the one in the undisturbed state.

\(^2\)We have considered the undisturbed sediment flux at the most downstream dam, since it is the maximum impact that the system of dams can have, i.e. if the trap efficiency of the most downstream dam has trap efficiency equal to 1.
Chapter 5. Results

<table>
<thead>
<tr>
<th>Dam</th>
<th>Trap efficiency</th>
<th>Hydropower [GWh/year]</th>
<th>Natural Sediment flux [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plei Krong</td>
<td>0.52</td>
<td>417</td>
<td>5 · 10^9</td>
</tr>
<tr>
<td>Yali</td>
<td>1.00</td>
<td>3,659</td>
<td>1.1 · 10^9</td>
</tr>
<tr>
<td>Se San 3</td>
<td>0.94</td>
<td>1,224</td>
<td>1.1 · 10^9</td>
</tr>
<tr>
<td>Se San 3a</td>
<td>0.95</td>
<td>479</td>
<td>1.2 · 10^9</td>
</tr>
<tr>
<td>Prek Liang 2</td>
<td>1.00</td>
<td>259</td>
<td>1.8 · 10^8</td>
</tr>
<tr>
<td>Prek Liang 1</td>
<td>0.77</td>
<td>324</td>
<td>2.1 · 10^8</td>
</tr>
</tbody>
</table>

Table 5.3: Trap efficiency, hydropower production and natural sediment flux (i.e. sediment flux in the undisturbed state) of the main dams in Group 2

In Figure 5.7(B), in Group 2, Borg starts to select dam portfolios which include dams located also in the Se San. It can be noticed that, there are four dams on the main river stem, which are always selected in all the portfolios, while two, located on a tributary, appear in less than 20% of the portfolios in Group 2. This behaviour is unexpected, so a deeper analysis on the dam characteristics is needed.

The 4 main stem dams in the Se San are: Yali, Plei Krong, Se San 3 and Se San 3a (Figure 5.8, Table 5.3). Analysing the data from Table 5.3 we can see that, even though Yali traps all the sediment flowing through the reach (8% of the total sediment flux), it has the highest hydropower production of all the 3S river basin (12% of the total hydropower potential). However, the other 3 dams, are located very close to Yali. The short distance implies that, a small number of sources can provide sediment, therefore, these dams can be added to the portfolio incrementing the sediment impact at the outlet by less than 1%. On the contrary, the total hydropower potential can be increased by 7%. Considering the benefit and the impacts of this 4 dams, we can produce 5,779 GWh/year (19%) trapping only 1.2 · 10^9 kg/year (9%) of sediment.

In Figure 5.7(B), in Group 3, the dams on the Sre Pok and the ones that impact the most are selected in the portfolios, since the hydropower production has to reach the maximum potential of 30,463 GWh/year. The dams in the upper Sre Pok: Duc Xuyen, Buon Tua Srah, Dray Hlinh 1&2, Sre Pok 3 and Sre Pok 4 (Figure 5.8, Table 5.4), have a probability close to one to be selected in a portfolio of Group 3. Buon Kuop dam has not be included since its already selected (i.e. 100% probability) in all the portfolios of the Pareto front. The total hydropower production of these dams is 2,198 GWh/year (7%), while the reduction of the sediment flux at the basin outlet is 2.43 · 10^9 kg/year (17%). The impacts of these dams are more than the double of benefits (i.e. Hydropower), while for the dams analysed in Group 1 and 2, the benefits were more than the double of the impacts.

The most downstream dams, i.e. Lower Sre Pok 3, Lower Se San 2 and Sekong, are the least selected, since are the most impacting dams of the basin. Lower Sre Pok 3 can reduce by 38% the total sediment flux at the outlet, Lower Se San 2, since is located after the confluence between Se San and Sre Pok, can trap 74% of the total sediment flux at the outlet, while Sekong would intercept more than a half of the sediment coming from the Se Kong basin (Figure 5.8, Table 5.4). Moreover, the increment in the hydropower production, given by these dams, is not worth the impacts produced.
5.2. Two-objective optimization

<table>
<thead>
<tr>
<th>Dam</th>
<th>Trap efficiency</th>
<th>Hydropower [GWh/year]</th>
<th>Natural Sediment flux [kg/year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duc Xuyen</td>
<td>0.84</td>
<td>181</td>
<td>$5.98 \cdot 10^8$</td>
</tr>
<tr>
<td>Buon Tua Srah</td>
<td>1.00</td>
<td>359</td>
<td>$9.55 \cdot 10^8$</td>
</tr>
<tr>
<td>Buon Kuop</td>
<td>0.01</td>
<td>1459</td>
<td>$2.00 \cdot 10^9$</td>
</tr>
<tr>
<td>Dray Hlinh 1 and 2</td>
<td>0.07</td>
<td>179</td>
<td>$2.37 \cdot 10^9$</td>
</tr>
<tr>
<td>Sre Pok 3</td>
<td>1.00</td>
<td>1060</td>
<td>$2.38 \cdot 10^9$</td>
</tr>
<tr>
<td>Sre Pok 4</td>
<td>0.20</td>
<td>329</td>
<td>$2.65 \cdot 10^9$</td>
</tr>
<tr>
<td>Lower Sre Pok 3</td>
<td>0.96</td>
<td>1201</td>
<td>$5.51 \cdot 10^9$</td>
</tr>
<tr>
<td>Lower Sre Pok 4</td>
<td>0.99</td>
<td>221</td>
<td>$3.18 \cdot 10^9$</td>
</tr>
<tr>
<td>Lower Se San 2</td>
<td>1.00</td>
<td>1954</td>
<td>$1.02 \cdot 10^{10}$</td>
</tr>
<tr>
<td>Sekong</td>
<td>0.59</td>
<td>558</td>
<td>$3.51 \cdot 10^9$</td>
</tr>
</tbody>
</table>

Table 5.4: Trap efficiency, hydropower production and natural sediment flux (i.e. sediment flux in the undisturbed state) of the main dams in Group 3

From this analysis, we can conclude that in the optimal dam portfolios, the initial development should be focused in the Se Kong basin, where the total sediment supply is 25% of the 3S (Figure 3.7) and the dams are mainly located on tributaries. If additional hydropower production needs to be exploited, also the dams in the Se San can be developed. The dams in the Sre Pok and the most downstream ones (e.g. Lower Se San 2, Lower Sre Pok 3, Lower Sre Pok 4 and Sekong) should not be built, unless the maximum hydropower potential wants to be reached. Their impacts, in fact, would completely destroy the sediment delivery in the basin.

The historical development, instead, follows almost the opposite trend. The first dams to be built were in the Sre Pok and Se San basins, and the construction of LSS2 is in the middle of the hydropower development.
5.2.2 Simplified model validation

The validation of the Simplified Model (SM) has been performed on two levels, as explained in Section 4.2. The first one aims to evaluate the ability of the SM to reproduce the sediment indicators computed with CASCADE. The second one wants to verify if the two models interact in the same way with Borg (i.e. if the two models select the same optimal dam portfolios).

In the first part of the validation process, we verify the performance of both indicators:

![Figure 5.9: Comparison between the Simplified Model and CASCADE, computing for the same dam portfolios the two indicators: Hydropower and SedimentOutlet.](image)

sediment flux at the outlet (i.e. SedimentOutlet) and sediment alteration in the basin (i.e. SedimentAlteration). The scenarios used for the first part of the analysis are the ones obtained from the two-objective optimization. However, random dam portfolios could be used, since we are interested in comparing the objectives values and not if dam portfolios are optimal or not. In Figure 5.9, where the SedimentOutlet is displayed, the red dots represent the results of the optimization using the Simplified Model, while the blue circles are the results of running CASCADE with the same portfolios.

Since the indicators are computed based on the same dam portfolio, the difference in the objectives values can be seen only along the sediment flux axis. The difference between the two models is less than 1% in all the portfolios performed, therefore we can conclude that the Simplified Model reproduces well the sediment flux at the outlet computed with CASCADE model.
5.2. Two-objective optimization

The second indicator considered, in the analysis, is the SedimentAlteration, computed as the difference between the sediment fluxes in the undisturbed state and in a given dam portfolio, multiplied by the reach length \[3.2.2\]. In Figure 5.10, the red dots are the values obtained with the Simplified Model, while the blue circles are the one obtained running CASCADE. The Simplified Model underestimates the dam impacts on SedimentAlteration. The difference, between the two models, increases with the number of dams selected in the portfolio and, therefore, with the Hydropower. The maximum difference, that can be observed, is 8%, when all the 42 dams are selected. To analyse the spatially distribution of the error, we have plotted, on the river network, the difference between CASCADE and the Simplified Model in the fluxes reduction, expressed in percentage:

\[
\frac{\sum_{i=1}^{N} \Delta \Theta_{s,e}^i (CASCADE) - \sum_{i=1}^{N} \Delta \Theta_{s,e}^i (SM)}{\text{NaturalFlux}_{e}},
\] (5.1)

In Equation (5.1) the first term (\(\sum_{i=1}^{N} \Delta \Theta_{s,e}^i (CASCADE)\)) sums for each reach, \(e\), all the differences in sediment fluxes coming from different sediment sources \(i\). The \(\text{NaturalFlux}_{e}\) is the natural sediment flux in the basin, for each reach \(e\).

The differences between the two models are divided in 9 classes represented with different colours, while in grey are identified the reaches where no difference has been observed (Figure 5.11). Negative values of the percentage means that the SM overestimates the impacts comparing to CASCADE, while positive values means that the SM underestimates them. The error is concentrated in reservoir impoundments, since the SM does not recalculate the transport capacity in the inundated reaches of a reservoir. In the SM, cascades originating upstream of a reservoir can be entrained until its most downstream reach, i.e. where the dam is located. CASCADE, on the contrary, recomputes the transport capacity in the inundated nodes, which results close to zero. Therefore, most of sediment deposits in the upstream part of the impoundment and cannot reach the dam.
Chapter 5. Results

Figure 5.10: Comparison between the Simplified Model and CASCADE, computing for the same dam portfolios the two indicators: Hydropower and Sediment Alteration.

Figure 5.11: On the river network, are displayed the differences in sediment alteration between the Simplified Model and CASCADE, expressed in percentage.
In the second type of validation, we compare the dam portfolios obtained running the optimization algorithm once with the Simplified Model, and once with CASCADE. The indicators used for this analysis are Hydropower and SedimentOutlet.

In Figure 5.12 the red dots are the Pareto points for the Simplified Model, while the blue circles are the ones for CASCADE. The shapes of the Pareto frontiers in the two cases are similar. Even if in the indicators space the two models seem to have the same performances for all the Pareto points, some differences may appear in dam distributions. Portfolios with different dam distributions, in fact, can have the same objectives performances. Therefore, we compare dam distributions of all the optimal portfolios, Figure 5.12, obtained with the two models. The comparison was made taking the portfolios corresponding to the same hydropower production. In Figure 5.13 we show an example of the comparison between two portfolios. On the left, with the red triangles, are displayed the dams selected by the Simplified Model, while, on the right in blue are displayed the ones selected by CASCADE. Since we are interested in the dam distribution pattern, the few differences in the dam selected are considered relevant for our purpose. The coordinates of the two dam portfolios are respectively:

- **Simplified model**: Hydropower = 17 958 GWh/year; SedimentOutlet = 1.16·10^{10} kg/year,
- **CASCADE**: Hydropower = 17 785 GWh/year; SedimentOutlet = 1.16·10^{10} kg/year.

From the validation analysis, we proved that the Simplified Model is able to reproduce, in a satisfying way, both the sediment indicators which are based on CASCADE framework and that no relevant differences can be observed in the dam distribution pattern running the optimization analysis with the two models.

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3The two portfolios will not have exactly the same hydropower production because they are the results of two separate optimization exercises. Therefore, the couple of points selected, is the one with the closest hydropower production to the fixed one.
Chapter 5. Results

Figure 5.12: Plot of the two Pareto fronts obtained running the two-objective optimization once with the Simplified Model (red dots), and once with CASCADE (blue circles).

Figure 5.13: Plot of two dam portfolios, one obtained running the two-objective optimization with the Simplified Model and the other with CASCADE, corresponding to the same hydropower production.
5.3 Six-objective optimization

To assess how the inclusion of multiple environmental aspects can affect the dam development and if there are conflicts among different environmental indicators, we performed a six-objective optimization. Introducing new objectives has exponentially increased the number of optimal solutions, which has grown up to 3,482, comparing to the 43 obtained in the two-objective problem. To visualize the results, in a first step, we have used the AeroVis visualization software, developed by Kollat (2012). The software allows to explore efficiently the results of complex multi-objective problems. The objectives values differ in order of magnitude and some of them have to be minimized (i.e. SedimentAlteration and FlowAlteration) while others maximized (i.e. Hydropower, SedimentOutlet, EcologicalConnectivity and MigratoryFishes). Therefore, to make the results visualization more intuitive, the objectives have been normalised between 0 and 1, where 0 is the worst case for each indicator and 1 is the best one (i.e. the utopia).

In Figure 5.14 we display: the hydropower production on the \( x \) axis and by the colour of the cone, the sediment flux at the outlet on the \( y \) axis, the sediment alteration on the \( z \) axis, the ecological connectivity by the cone orientation (\( O \)) (i.e. the top of the cone is down-oriented for the worst case, up-oriented for the best), the migratory fishes by the cone size (\( S \)) (i.e. small cones for low values of the indicator, large cones for the best values) and the flow alteration by the cone transparency (\( T \)) (i.e. the more transparent the cone is, the lower the value of the indicator).

![Figure 5.14: Plot of the Pareto efficient dam portfolios for the six objectives problem in a seven dimensions space (two dimensions have been used to display the hydropower production).](image)

4Two dimensions have been used to plot the hydropower production to make the results more intuitive to understand.
To better analyse the Pareto front in the seven-dimension space, we show 8 different views of Figure 5.14 in which the cube has been rotated by 45° (Figure 5.15). From the six-objective optimization, the conflict between hydropower production and all the environmental indicators emerges(Figure 5.14). In Figure 5.15(H), in which the $x$ and $y$ axes are the SedimentOutlet and SedimentAlteration respectively, we can observe that all the solutions have a value of the SedimentAlteration that is at least equal (in percentage) to the value of the SedimentOutlet. Therefore, if a solution is good for the SedimentOutlet, it cannot be bad for the SedimentAlteration. The opposite is not true, in fact for a given value of SedimentAlteration we can have a great difference in the performance for the SedimentOutlet. Moreover, we can separate the optimal solutions in two groups. The first one (on the left side of Figure 5.15(H)) has almost constant low values of: SedimentOutlet, EcologicalConnectivity (visible in Figure 5.15(H,D,A)) and MigratoryFishes (visible in Figure 5.15(H,E)); the other three indicators, Hydropower (visible in 5.15(A)), SedimentAlteration (visible in Figure 5.15(H)) and FlowAlteration (visible in Figure 5.15(A,G)), instead, have a great variability. In the second group (on the right of Figure 5.15(H)) no indicator has constant values.
Figure 5.15: Each panel is a different view of the cube, presented in Figure 5.14 rotated by 45°.
Chapter 5. Results

To analyse the differences between the two groups just described, we have used the Interactive Parallel Axis Plots by Trindade and Herman [Trindade 2015]. This visual tool, for multidimensional analysis, plots each solution (i.e. dam portfolio) with a line which intersects the axes in the corresponding values of the indicators.

Figure 5.16: The Parallel axis plots each portfolio with a line, which intersects the axes in the corresponding values of the indicators. In figure are presented three parallel axis for different values of hydropower: (A) solutions that have an hydropower production between 30% and 40%; (B) solutions that have an hydropower production between 50% and 60%; (C) solutions that have an hydropower production between 90% and 100%. The parallel axis allows to see the performance of a given dam portfolio for all the six objectives, expressed between 0 (worst performance) and 1 (best performance).
In Figure 5.16(B), we have plotted all the dam portfolios with a hydropower production between 50% and 60%. The trajectories of the solutions confirm the findings of the previous analysis. Even considering a small range of hydropower production, we can observe that the SedimentAlteration and the FlowAlteration have a limited range in the objective values. The SedimentOutlet, EcologicalConnectivity and Migratory Fishes indicators, instead, cover a wide range of the objectives values. The reason why some portfolios give a low performance for the SedimentOutlet and for the MigratoryFish while has a good performance for the SedimentAlteration, is that the most downstream dams are selected. In fact, these dams, represent a barrier for the MigratoryFish and they trap almost the entire amount of sediment that, in the natural state, should reach the basin outlet. At the same time, the alteration of sediment flux, caused by downstream dams, is visible only on a limited river length, therefore the SedimentAlteration indicator is not influenced that much.

From this analysis, we can state that for low hydropower productions we have high values of the environmental indicators for all the portfolios 5.16(A), while for high hydropower production we have low values of all the environmental indicators 5.16(C). For medium hydropower production, instead, the environmental indicators can experience large differences in their values 5.16(B). Therefore, we can conclude that, if we want to exploit around 50% (15 000 GWh/year) of the 3S hydropower potential, more attention is need in the dam siting, since major impact can be avoided without affecting the hydropower production.

In Figure 5.17 we show the dam probability to be included in a dam portfolio for all the 3 482 optimal solutions obtained in the six-objective optimization. The probability of each dam is displayed with the different colours. The panel on the bottom left corner displays the dam probability previously obtained in the two-objective optimization (Figure 5.6). It can be observed that the inclusion of spatially distributed indicators, i.e. SedimentAlteration and FlowAlteration, has modified especially the probability of the dams which were selected least in the two-objective analysis, since they were the most impacting for the SedimentOutlet. The probability of system of dams in the upper Sre Pok, for example, in the two-objective was smaller than 30%, while in the six-objectives the probability of dams like Sre Pok 3, Sre Pok 4, Dray Hlinh 1&2 has grown up to 40%, 50% and 60% respectively. Also the most downstream dams like Sekong and LSS2, have increased their probability from below 10%, up to 30% and 50%. On the contrary, the probabilities of dams in the Se San, that previously were grater than 70% to be selected in a portfolio, like Xe Kong 3up, Xekaman 1 and Xekong 4 have decreased to 50%, 40% and 30% respectively.

The increment of the probability of downstream dams like LSS2 and Sekong is attributed to the portfolios presented in Figure 5.16(B) which, since they include the two dams mentioned, have low performances for the SedimentOutlet indicator, and high for SedimentAlteration. These dams were almost never selected in the two-objective optimization since they have large impacts on the SedimentOutlet indicator, which was the only one assessing dam impacts in the analysis.
Figure 5.17: In Figure we show the dam probability to be included in a dam portfolio for all the 3482 optimal solutions obtained in the six-objective optimization. The probability of each dam is displayed with the different colours. The panel on the bottom left corner displays the dam probability previously obtained in the two-objective optimization (Figure 5.6)
To study the conflicts emerged between hydropower production and environmental indicators, we have projected the solutions of the six-objective optimization into 5 two-dimension plots (Figure 5.18), which have on the x-axes the Hydropower, and on the y-axes the five environmental indicators, in absolute values. The utopia is always on the top right corner, therefore, the axes of SedimentAlteration and FlowAlteration (i.e. the ones which were minimized) have been flipped upside-down. Each blue dot corresponds to a different dam portfolio.

The concept of system capacity, introduced in the two-objective optimization, can be expanded to the six-objective one. In all the panels in Figure 5.18 we can identify a point which splits the pareto front in two parts (i.e. red dots in Figure 5.18): the first one in which the environmental indicator is less sensitive to the dam development, and a second one, where the decrease of the environmental indicator is more than proportional than the increase of the hydropower production. We remind that, with system capacity, we refer to the point up to which it is worth it to exploit the system, since the marginal benefits are greater than the marginal impacts.

We analyse, in particular, which are the indicator performances in correspondence of the system capacities. For each environmental indicator, the system capacity corresponds to a different hydropower production and a different impact on the environmental indicators. In Figure 5.18(A, C, D), where are displayed the SedimentOutlet, EcologicalConnectivity and MigratoryFishes, the system capacities allow to reach an hydropower production around 75-80% of the total potential (i.e. 22 847 - 24 370 GWh/year), limiting the environmental impacts below 35%, since, for medium-low hydropower the indicators are not very sensitive to the dam development. The FlowAlteration is the one with the lowest hydropower production for the system capacity (62%), however the indicator is almost unaltered comparing to undisturbed state (10%) (Figure 5.18(E)). The SedimentAlteration, even though, has a system capacity with the highest hydropower production (84%), it is the one with the largest impact, with 48% reduction. In Figure 5.18 we can observe that the SedimentAlteration indicator is more affected by the dam development, for medium-low hydropower productions, comparing to the SedimentOutlet. Downstream dams have large impacts on sediment delivery on small portions of the river network (i.e. limited reach length) while the upstream ones alter a small quantity of sediment flux but affect a longer part of the network. The SedimentAlteration depends on both the flux alteration and the river length affected. The SedimentOutlet, instead, is influenced only by the magnitude of the sediment trapped. Therefore, even if, before the system capacity the marginal benefits are larger than the marginal impacts, the damages produced in correspondence of this point may have altered in a irreversible way the environmental aspect.

The dam portfolios are the same in each panel of Figure 5.18 they have different positions in the two-dimension spaces since they assume different values of the environmental indicators.
Figure 5.18: In each panel, the six objectives Pareto front is projected in a two-dimension space, and is plotted with blue dots. On the x-axes, for all the panels, is displayed the hydropower production, while on the y-axes are displayed the different environmental indicators, in particular A: the SedimentOutlet, B: the SedimentAlteration, C: the EcologicalConnectivity, D: MigratoryFishes, E: FlowAlteration. The red dots identify the system capacities of each environmental indicator.
5.3. Six-objective optimization

5.3.1 Pareto front of single indicators and common solutions

In this section, we want to analyse which is the hydropower production achievable, fixing the impacts on the different environmental indicators, in this case, the 20% value is chosen. We start from the six-objective Pareto front projections of Figure 5.14 converting the axes from absolute values into percentages. In Figure 5.19, where the x-axis is the hydropower production and the y-axis the environmental indicators, are displayed with grey circles the optimal dam portfolios and with the filled circles we have highlighted the ones that satisfy the constraint, EnvironmentalIndicator > 80%. The black triangle on x-axis is the maximum hydropower produced by the highlighted solutions.

We can observe that each indicator has a different number of solutions that satisfy the constraint and a maximum hydropower production achievable. In each group, we are interested in the portfolio that maximizes the hydropower production. The Migratory-Fishes indicator allows to produce the highest hydropower production (80%) while the SedimentAlteration is the one that has the smallest number of solutions as well as the lowest hydropower production (47%).

As we observed in the parallel axis (Figure 5.16B), for a small range of one indicator (i.e SedimentAlteration, FlowAlteration), we can have a great variability in the others. For example in the parallel axis in Figure 5.20, we considered all the portfolios where the SedimentAlteration impact is less than 30%. Among these portfolios, we highlighted the one characterized by the highest hydropower production. This dam portfolio allows to preserve the 70% of the Sediment within the basin but it shows values of SedimentOutlet, EcologicalConnectivity and MigratoryFishes below the 70% threshold.

Therefore, if we want to avoid producing large impact on these indicators, we have to look for the portfolios, which are common to all the highlighted solutions of the indicators (i.e. portfolios with the same dam distribution).

In Figure 5.21 we plot with black dots only the common portfolios that satisfy the 80% constraint for all the indicators. On the x-axis we represent the hydropower production and on the y-axis we have selected the SedimentOutlet as reference. The grey circles in Figure 5.21 are all the optimal portfolios and the black triangle on x-axis indicate the maximum hydropower production achievable by the solution highlighted.

The number of solutions has decreased comparing to the panels in Figure 5.19 in which the constraint was satisfied by only one indicator per panel. Also the hydropower production is smaller by 5% than the worst case, the SedimentAlteration.

Footnote: For the y-axis every indicator could be selected as reference since the choice of the y-axis determines only the position of the points in the space and not the solutions selected.
Figure 5.19: In each panel the six-objective Pareto front is projected in a two-dimension space that has on the x-axis the hydropower production, and on the y-axis the different environmental indicators, on both axes the indicators are expressed in percentage. The optimal solutions are plotted with gray circles. In particular, on the y-axis are displayed in panel A: the SedimentOutlet, B: the SedimentAlteration, C: the EcologicalConnectivity, D: MigratoryFishes, E: FlowAlteration. The solutions highlighted with the different colours, are the ones that satisfy the constraint $\text{EnvironmentalIndicator} \geq 80\%$. The black triangle on the x-axis represents the maximum hydropower production for the group of coloured solutions.
5.3. Six-objective optimization

Figure 5.20: The Parallel axis plots each portfolio with a line, which intersects the axes in the corresponding values of the indicators. In figure are shown the dam portfolios which allow to preserve 70% of the SedimentAlteration indicator. Among these portfolios, we highlighted the one characterized by the highest hydropower production. This dam portfolio keep the sediment alteration within the basin below the 30%, affecting significantly SedimentOutlet, EcologicalConnectivity and MigratoryFishes indicators.

Figure 5.21: Plot in the Hydropower versus SedimentOutlet space all the optimal dam portfolios with gray circles, with black dots are plotted the solutions that are common to all the indicators of Figure 5.19 and satisfy the constraint EnvironmentalIndicator $>80\%$ for all the indicators. The black triangle on the x-axis represents the maximum hydropower production for the group of common solutions.
If we extend the previous analysis, changing the values of the constraint from 100% to 0%, selecting the solution that maximize the hydropower production, we obtain the trajectories of the different Pareto fronts for each indicator, which are represented in solid lines in Figure 5.22. The black dashed line, instead, is the trajectory for the common solutions.

Comparing to the dashed line, the solid lines show that the single indicators are less affected by the dam development for hydropower production lower than 70-75%. After this percentage, the indicator values rapidly decrease down to 0%. The trajectory of the common solution, instead, starts to decrease for lower hydropower production (60%) but more gradually.

The plot, in Figure 5.22, can be read in two ways: in the first one, if we fix a certain percentage of environmental indicators that we want to preserve, on the x-axis we can see which are the different hydropower productions that can be generated; in the second one, if we fix the hydropower production on the y-axis we can read the impacts on each indicator. The first one is the analysis conducted already in Figure 5.19 and 5.21. In the second one, if we fix the hydropower production to 80%, can be noticed that there is a large difference between the impacts for the common solution and the ones for the single indicators. While the indicators experience a reduction between 22% (i.e. MigratoryFishes) and 45% (i.e SedimentAlteration and EcologicalConnectivity), the impact on the common solution has already grown to 70%.

The six-objective optimization returned the optimal dam portfolios for the hydropower production and the five environmental indicators considered. However, among the portfolios, some of them can relevantly impacts some indicators to preserve the others. To avoid this drawback, different preferences can be expressed for each indicator. In our case, for example, we decided to select the portfolios that equally impact all the environmental indicators. However, if in a river basin an environmental aspect is more important than another one, different percentages can be chosen for each indicator.

**Figure 5.22:** The solid lines are the Pareto front of each environmental indicator, the black dashed line is the one of the common solutions. The x-axis is the hydropower production, the y-axis is the environmental integrity.
5.3.2 Environmental indicators comparison

For this analysis, we want to prove if there are any relevant differences in dam distribution, considering different environmental indicators. As mentioned in Chapter 1, different ecological aspects have different spatial distributions in the river network, which can lead to major variability in the dam site selected in the optimal portfolios. We want analyse, in particular, the conflicts between two groups:

1. Sediment versus ecological indicators:
   - SedimentOutlet versus MigratoryFishes (i.e. both external connectivity);
   - SedimentAlteration versus EcologicalConnectivity (i.e. both internal connectivity).

2. Internal versus external connectivity:
   - SedimentAlteration versus SedimentOutlet (i.e. both assessing impacts on sediment)
   - EcologicalConnectivity versus MigratoryFishes (i.e. both assessing impacts on ecology)

With the analysis of the first group, we want to assess how the different spatial distributions of the two fluvial aspects considered (i.e. sediment and ecology) affect the dam sites selected in the portfolios.

In the second group, we are interested in analysing if different points of view of the same environmental aspect have contrasting dam distributions. In our study, the two points of view are represented with external and internal connectivity. The internal connectivity “looks” at the internal state of the 3S basin (i.e. SedimentAlteration and EcologicalConnectivity). The external connectivity, instead, is interested in maintaining the connection with the Mekong river (i.e. SedimentOutlet and MigratoryFishes).

Each panel in Figure 5.23 shows the dam portfolios, if we want to preserve a percentage equal to 70% of the indicators.

\[\text{To avoid the randomness of the scenario selected, we have compared the single dam portfolio with the ones within a range of } \pm 2.5\% \text{, for each indicator. The analysis has proved that the dams selected are the results of a pattern and not of randomness. However, this analysis will not be displayed in this thesis.}\]
Figure 5.23: A: Dam portfolio for SedimentOutlet=70%. B: Dam portfolio for SedimentAlteration=70%. C: Dam portfolio for MigratoryFishes=70%. D: Dam portfolio for EcologicalConnectivity=70%.
5.3. Six-objective optimization

*Sediment versus ecological indicators*

If we compare the optimal dam distributions of sediment and ecological indicators that look at the external connectivity, SedimentOutlet and MigratoryFishes (Figure 5.23(A,C)), we can observe that the main differences occur in the Sre Pok river. As mentioned in Section 3.3.6, the Sre Pok delivers to the outlet 51% of the sediment produced by the 3S basin, for this reason, in the SedimentOutlet, the dams in the Sre Pok are selected last. The MigratoryFishes, instead, aims to have the largest river fragment connected to the outlet without reservoirs, therefore the upstream dams are selected first, also in the Sre Pok. Despite, the five dams selected in the Sre Pok, this river is still the most important for the migratory fishes. The Se Kong and Sre Pok rivers have the largest volume, so they weight the most in the computation of the MigratoryFishes indicator.\(^8\) If we look at the possible dam sites in the two rivers, it can be noticed that in the Se Kong the dams are mainly located in the upstream tributary reaches (i.e. small volume per unit length). In the Sre Pok, instead, most of the dams are located on the main stem or downstream (i.e. large volume per unit length). For this difference in the spatial distribution of the dam sites, the ones in the Sre Pok are selected last.

Figure 5.23(B) and Figure 5.23(D) show the dam distributions associated to sediment and ecological indicators that consider the internal connectivity. The SedimentAlteration is built on the reduction of the sediment flux in a reach, given by the construction of a dam, and it is then weighted by the length of the reach itself. It can be noticed that, for this indicator also the most downstream dams are selected in the portfolio. Even if, the variation in the sediment flux is greater, in absolute value, comparing to the upstream dams, the effect of the downstream ones is visible on a small reach length. The EcologicalConnectivity, instead, is based on the river volume, therefore, it avoids to build dams on downstream reaches or on main stems. Since, they provide a larger habitat per unit length for fish species, comparing to tributaries.

If we look at the external connectivity indicators, we can conclude that there is not a clear difference in the dam spatial distribution, since, both prefer to build upstream dams, and avoid the downstream one. If we look at the internal connectivity indicators, instead, the SedimentAlteration built also downstream dams which are avoided by the EcologicalConnectivity. This difference reflects the spatial distribution of the two services within the basin.

\(^8\) The Se Kong and Sre Pok are both deeper rivers than the Se San, therefore, their habitats are preferable for fishes (Baird I. and Shoemaker B. 2008)
Chapter 5. Results

**Internal versus external connectivity**

In the second type of comparison, we compare for each of two environmental aspects (i.e. sediment and ecology), the external connectivity indicators with the internal ones. Comparing the indicators defined as SedimentAlteration and SedimentOutlet (Figure 5.23(A,B)), can be noticed that in general, both of them avoid to build dams in the Sre Pok, which is consistent with the 51% of the sediment flux delivered by this river. However, as explained in the previous paragraph, SedimentAlteration selects also LSS2 (Figure 5.23(B)), which is the most impacting dam if we consider the SedimentOutlet indicator. In fact, for the SedimentAlteration, the LSS2 effect is smaller than the one of upstream dams on the Se Kong main stem, like Xekong 4, Xe Kong 3 up and Xekaman 1 (Figure 5.23(A)). The impact on the sediment alteration, for this latter dams, can be seen almost on the entire length of the Se Kong.

Considering the two fish species indicators (Figure 5.23(C,D)), the main difference between the dam spatial distribution is in the Sre Pok. The EcologicalConnectivity is interested in maintaining the volume of one fragment as large as possible, the Migratory Fishes, in addition, requires that this fragment is connected with the basin outlet. Even if, the EcologicalConnectivity could select downstream dams in the portfolio maintaining intact a large fragment in the upstream reaches, in this application, this does not occur, since the volume contribution of the downstream portion of the basin is the most relevant for both indicators.

We can conclude that, even if we are interested in preserving one environmental aspect (e.g. sediment), we have contrasting dam spatial portfolios, depending if we are considering the internal or external connectivity (i.e. SedimentOutlet and SedimentAlteration respectively).
Conclusions and future research

Main findings

We based our research on the previous work of Schmitt, R.J.P. (2017), in which he applied an exhaustive search, on a reduced number of dam portfolios, to minimize the trade-off between hydropower production and sediment connectivity in the 3S river basin. In our study, instead, we applied for the first time a two-objective optimization, at basins scale, to obtain the optimal trade-off between the hydropower production and the sediment connectivity with the Mekong. To run the optimization, we developed a computationally efficient large-scale sediment connectivity model which was able to reproduce well CASCADE model results and, at the same time, could decrease by 50 times the computational time. Nevertheless, to have a more rigorous estimate of the sediment delivery, it is recommended to run CASCADE once the optimal dam portfolios are obtained.

The solutions obtained implementing the optimization analysis dominate the one obtained by Schmitt, R.J.P. (2017), especially for medium-high hydropower productions. However, no relevant differences, in the dam distribution pattern, were found. The Pareto front obtained with the two-objective analysis suggests which should be the optimal temporal dam development in the 3S to impact the least on sediment flux at the basin outlet, and, as a consequence, on the Mekong river. In this analysis, we found that, the dam development should be focused first in the Se Kong, where reservoirs are located on the upstream tributaries and the sediment contribution to the basin outlet is 25% of the total. This conclusion is consistent with the finding of Schmitt, R.J.P. (2017). On the contrary, the historical dam development was concentrated in the Sre Pok and in the Se San basins, considerably reducing the sediment flux at the 3S outlet. Adopting an optimal dam planning, it is possible to explore the “system capacity”. The
system capacity is the point, on the Pareto front, up to which the impact on sediment is limited comparing to the increment of hydropower production. After this point, for a small increase of hydropower production, large impacts are produced on sediment. In the two-objective optimization, the system capacity corresponds to a 23% reduction of the sediment flux at the basin outlet and an hydropower production of 74% of the 3S hydropower potential. Therefore, following a susitainable dam development, we can still exploit most of the hydropower potential, keeping limited the impacts on the sediment delivered to the Mekong. Looking at the historical dam development (Figure 5.5), the same sediment impact was already achieved in 2010 with an hydropower production of 28%, less than a half of what could be produced adopting a basin scale dam planning.

To assess if the inclusion of multiple environmental aspects can affect the dam development, we performed a six-objective optimization. Moreover, we analysed if there are any conflictual dam portfolios between different environmental aspects. With the optimization, we obtained the optimal dam portfolios considering the five environmental indicators (i.e. SedimentOutlet, SedimentAlteration, EcologicalConnectivity, MigratoryFishes and FlowAlteration) and the hydropower production. The concept of system capacity, introduced in the two-objective optimization, can be extended to all the five environmental indicators considered in this second analysis. For each indicator, in fact, it is possible to identify a point after which the increment of environmental impacts is larger than the increment in the hydropower production. Four out of five indicators (i.e. SedimentOutlet, EcologicalConnectivity, MigratoryFishes and FlowAlteration) have system capacities which allow to have an hydropower production of at least 19 000 GWh/year (62%), keeping the impacts below 35%. The SedimentAlteration, instead, achieves the 85% (24 000 GWh/year) of the hydropower potential, but the reduction in the indicator is almost 50%. The finding that multiple environmental indicators have similar system capacities is consistent with the works of Schmitt, R.J.P. (2017), who studied the trade-off between hydropower production and sediment flux at the basin outlet, and Ziv et al. (2012), who assessed the trade-off between hydropower production and migratory fishes in the Mekong.

Each environmental aspect has its own spatial distribution within the basin. From a physical point of view, the spatial distribution of sediment flux depends on the distribution of sources, supplies and transport capacities. The spatial distribution of ecological aspects, instead, depends on how the river volume is distributed within the basin. This can result in two types of conflicts. In the first one, given a single dam portfolio, conflicts can emerge among different environmental indicators. In particular, in our analysis, we observed that, for medium values of hydropower, an individual dam portfolio can lead to high values for SedimentAlteration and FlowAlteration, and low performances for SedimentOutlet, EcologicalConnectivity and MigratoryFishes (Figure 5.16). In the second one, optimal dam portfolios have contrasting dam distributions for different environmental indicators. In our study, in particular, we have considered two indicators for both sediment and ecology, one for internal and the other for external connectivity. Therefore, we were able to analyse if between the two indicators, considering the same environmental aspects, there were differences in the impacts. Analysing the results, we proved that for sediment indicators there are different optimal dam portfolios, if we consider the sediment delivery to the Lower Mekong (i.e. exter-
nal connectivity) or if we are interested in maintaining the sediment delivery within the 3S (i.e. internal connectivity). The main downstream dams are the ones for which the differences in the marginal impacts are more evident between the two sediment indicators. Lower Se San 2 (LSS2), for example, traps almost all the sediment flowing to the basin outlet, therefore, it considerably reduces the value of the SedimentOutlet indicator. This finding is consistent with the studies conducted in the Mekong basin, about sediment delivery (Wild, T.B. and Loucks, D.P. [2014]; Schmitt, R.J.P. [2017]). If we consider the SedimentAlteration indicator, instead, Lower Se San 2 does not significantly impact its value. Since it is close to the basin outlet, it affects only a limited length of the downstream reaches. In the 3S, however, the SedimentAlteration indicator is less relevant than the SedimentOutlet, since the basin has a fundamental function in the maintenance of the Mekong Delta, which is the major habitat to protect. In another context, in which the internal sediment connectivity is the aspect to preserve, the SedimentAlteration indicator would be more relevant than the SedimentOutlet one.

**Limitations and future development**

This work was an attempt to find the optimal dam portfolios considering dam impacts on multiple environmental aspects. Given the complexity of the problem and the multitude of aspects to consider, some limitations can be identified. These limitations can be the guidelines for future developments that can be added to the analysis.

One problem of considering large scale dam planning, is that the basin can be shared between different countries, which are interested in their own profit. In our study, we considered only one indicator for the hydropower production, without considering the national borders. Analysing the results, the dams in Cambodia are selected last, since they are the most downstream ones and they impact the most the aspects considered. Therefore, the optimal dam portfolios that we found, in the real world are feasible only if there is a strong international cooperation between the three countries, that allows to take agreements on the dam development. In most cases, this is an ideal situation, and each country look at its own interests. Therefore, using one indicator for the hydropower production of each country would be more appropriate.

The natural flow alteration, deriving from dam regulation, can affect the ecological aspects and sediment delivery. While the barrier effect of dams is included in CASCADE, their effect on the natural flow is not assessed yet. To fulfil this lack, in our analysis, we adopted the RRI indicator. This proxy indicator considers the potential storage capacity of a dam portfolio compared to the natural flow of the river, on annual temporal scale. However, the inclusion of dam management in CASCADE framework could improve the understanding of the impacts coming from this effect.

The two indicators that assess the ecological aspects are based on the river connectivity. In our application, we have considered that in the undisturbed state the river is 100% connected. This is a simplification, since some natural or anthropical disconnections might be present in the basin and not detected by the Digital Elevation Model.
(DEM). Including this information in the analysis could improve the results quality, but would require a higher definition DEM or detailed database on natural and anthropical disconnections.

Deeper analysing the results obtained from the indicators EcologicalConnectivity and MigratoryFishes, the information provided, about the dam pattern, can be considered redundant. In fact, the dam portfolio obtained with the EcologicalConnectivity for a given percentage of the indicator is the same given by the MigratoryFishes but with a higher percentage (i.e. smaller impacts). The reason can be identified in the formulation of the indicators. Both of them are based on the river volume, the MigratoryFishes takes into account only the river volume of the most downstream fragment connected to the outlet, and in the EcologicalConnectivity the volume of the most downstream fragment is the one that affects the most the value of the indicator. Therefore, they are considering the same aspects even if they are aggregated in a different way. We can conclude that if we are interested in doing an optimization exercise to select the dams that have less impacts on the three environmental aspects (i.e. sediment, fish species and flow alteration), the six objectives sediment problem can be reduced to a five-objective one, in which the MigratoryFishes will not be considered. However, after the optimal portfolios are selected, the indicator previously deleted can be recomputed to have an estimate of the impacts also on that aspect.

When we have computed the common solutions (Figure 5.22), we have implicitly given the same weight to all the indicators. Another option would be to assign a different weight to each of them, according to the evaluation of some experts or with a participatory process in which each country decides the relative importance of each indicator.

Besides the limitations, our analysis can be an important tool to be used in decision-making processes. The methodology developed during our study, in which we combined a spatially distributed sediment model with an optimization algorithm, allowed us to consider, for the first time, the cumulative dam effects at network scale, on multiple environmental aspects, including sediment. From the analysis of the results, it is possible to: identify the dam distribution pattern for a sustainable dam development, identify the system capacity for each indicator and explore the conflicts between different environmental aspects.

For these reasons, our methodology can be extremely useful to screen dam portfolios in river basins which risk to experience multiple environmental impacts given by dam development, like the Amazon, the Irrawaddy and the Mekong river basins (Latrubesse et al., 2017).


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