Operational rules for sustainable management of dam cascades

Application to Mekong hydropower dams in Lao PDR

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TU Delft

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by

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Cover: Aerial photo of constructed Xayaburi hydropower dam in Lao PDR. Source: https://www.nationthailand.com/in-focus/30373218

TU Delft

Preface

This thesis is the final part of my Master Hydraulic Engineer at the Delft University of Technology. I would like to thank my graduation committee for the guidance, feedback and supervision during my project. Kees, thank you for the many useful, interesting and enjoyable meetings. Also I'd like to thank the colleagues of Kees at Deltares for helping me out with Delft3D-FM.

Secondly I would like to thank my family and girlfriend Emma for their unconditional support throughout my life and studies. Special thanks to papa for proof reading this report. I'd like to thank my roommates for their support during this process. Matthijs, thanks for the enjoyable times at civiel with the many coffee breaks and your feedback on this report. Finally. I'd like to thank Aike for joining me at civiel the last couple of months and for his feedback.

E. Glijnis
Delft, May

Abstract

Hydropower plants have proven to generate electricity reliably and predictably, store water to meet water demands during dry periods, improve navigability and reduce flood risk. The reservoirs of these hydropower plants face ongoing sedimentation, negatively effecting the electricity generation, water storage volume, navigability and flood risk. Obtaining an equilibrium of the in- and outgoing sediment flux reduces these negative effects.

The incentive for this report is the planned run-of-river hydropower dam cascade in the main stream Mekong river in Lao PDR. The Mekong river is characterised by the distinct low and high flow seasons and a unique ecosystem. At the location of the planned cascade, the river is located between mountains and the river bed consists of bedrock with alluvial bed forms at the banks and between rock outcrops.

Long, narrow and relatively shallow reservoirs are created due to the construction of the planned dams in the main stream Mekong. Flushing operations have proven to be an effective method to recover reservoir volume from rivers with a high season flow with long, narrow and shallow reservoirs. The Mekong river in Lao PDR has all those properties.

This report attempts to determine operational rules for a run-of-river hydropower dam cascade to increase the sediment flux by flushing operations at the dams, whilst still maximizing the electricity generation.

To do so, two steps are taken. Firstly, a set of experiments on the Mekong river and flushing events at a dam is performed in a Delft3D-FM software with the Real Time Control module. The output of these experiments are used as input for a bucket model with volume conservation to test different operational rules.

Using the Delft3D-FM software with the Real Time Control module, a one-dimensional representation of the Mekong river is made. This model is used for two purposes. First, the reduction of the sediment flux is determined by comparing the sediment flux during a representative year for the situation pre-dam and post-dam construction. Secondly, this model is used to test the influence of the draw down rate, water level set point and duration of flushing operations on the cumulative sediment flux through a dam for four different discharges. The results of the flushing experiments will then be used as input for the second step of the research, the bucket model.

Different simulations are performed using operational rules with different threshold discharges for initiating flushing events, different draw down rates and different frequencies of flushing a reservoir. Using random sampling the influence of these three variables is tested. Additionally, two predetermined strategies are tested and compared to the operational rules tested using random sampling. In the first strategy the dams in the cascade are flushing progressively from the most upstream dam towards the downstream dam. The second operational strategy flushes the reservoirs progressively starting from the downstream dam towards the most upstream dam.

Obtaining free flowing conditions during a flushing event increases the sediment flux significantly compared to flushing events that do not reach free flowing conditions, especially for lower discharges. Increasing the draw down rate proves to have limited influence on the sediment flux further upstream in the reservoir, while the flood wave released at the dam increases. Extending the duration of free flowing conditions after draw down proves to be an effective method to increase the sediment flux at the lowest reducing in electricity generation.

Performing a flushing event with 48 hours at free flowing conditions during the flood season increases the yearly cumulative sediment flux on average by a factor three. The cumulative electricity generation is reduced by just 2.5 %. Extending the duration of the free flowing conditions in a flushing event increases the sediment flux per lost GWh electricity generation.

Current operational rules at the planned cascade in the main stream Mekong do not consider flushing at all. It is recommended to include flushing events in the operational rules which are initiated if the discharge is above the design discharge of the turbines and below extreme discharges to increase the sediment flux and minimize electricity generation loss.

Contents

1
Introduction

Hydropower plants (HPP) have proven to be a reliable and predictable source of electricity generation worldwide. HPP have the capacity to contribute to the integration of new sustainable electricity generator by balancing intermittent power sources such as solar and wind (Annandale et al., 2016; Chang et al., 2013). Also dams are often used for water storage to meet water demand during dry periods or provide flood attenuation during flood events (Annandale et al., 2016; IHA, 2021).

Sedimentation in reservoirs has reduced the total reservoir volume worldwide, despite the ongoing addition of reservoir volume due to the construction of new dams (Morris, 2020) . Adverse effects due to sedimentation both occur in the reservoir and downstream. Sedimentation in a reservoir negatively effects flood risk, hydropower generation, navigation, ecology and industry. Possible downstream negative effects are bank erosion, channel incision and again negative effects on ecology and industry (Annandale et al., 2016). Applying active sediment management strategies, dam operators can either prevent, reduce or undo sedimentation in reservoirs (Hussain & Shahab, 2020; Morris, 2020).

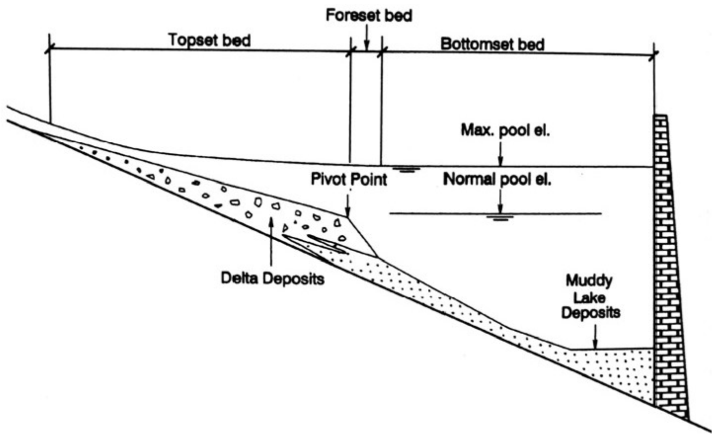


Figure 1.1: Schematized reservoir sedimentation. Depositions in delta from coarser sediment in the upper section and depositions of finer sediment in the lower section of the reservoir (Morris & Fan, 1998)

1.1. Sedimentation and sediment management in reservoirs

Reservoir sedimentation is an ongoing process and can only be stopped if the sediment fluxes in a reservoir are in equilibrium. Despite the available knowledge since the 1950s on sediment management possibilities, almost no dams are equipped either materially or operationally to prevent loss of reservoir volume. Doing so, reservoir lifetimes of existing reservoirs are limited to 50-100 years (Morris, 2020). The reservoir at the Welbedacht dam in South Africa lost 50 % of its reservoir volume in the first five years after commissioning and the reservoir at the Dashidaira dam has lost 50% of the reservoir volume after the first decade after commissioning. Both dams did not employ sediment management techniques (**ISHJA**; IHA, n.d.-b; Villiers & Basson, 2008).

1.1.1. Reservoir sedimentation

Due to the construction of a HPP in a river, a reservoir is created with increased water depth compared to the original conditions. This increased water level reduces velocities in the longitudinal direction of the reservoir, causing sedimentation in the upstream section of the reservoir. In the upper part of the reservoir the deposits will form a delta. This process is shown in Figure 1.1. Coarser sediment deposit first since they need larger flow velocities to be transported compared to smaller and finer sediment. In time this delta will migrate in the reservoir into the downstream direction.

The formation of the delta has two main negative effects at the location of the delta itself. Flood risks increase in the reservoir and also upstream of the reservoir, due to the elevated bed level at the delta. Secondly, the navigability reduces for ships traveling both in the flow direction as well as cross-sectional shipping such as ferries. Guaranteed passage for larger ships might need dredging operations as the morphology of the delta can change after severe flood events (Morris & Fan, 1998).

Downstream of the dam an erosion wave starts to migrate in the downstream direction, usually with a velocity of a few kilometers per year. Any erosion reported very far downstream just after the construction of a dam cannot be attributed to trapping of sand and gravel. Other factors such as changed land use that reduce the sediment yield into the rivers or sand mining in the river are more likely to be the reason of erosion at this time scale (Kondolf et al., 2018). Still indirect feedback effects from modified hydrographs or reduction of washload from silt and clay can contribute to more direct impacts far downstream. On a longer time scale in the order of 20-30 years, the erosion wave will reach towns, cities and the river delta at sea, which in turn causing erosion, as seen in Figure 1.2 (MRC, 2019a).

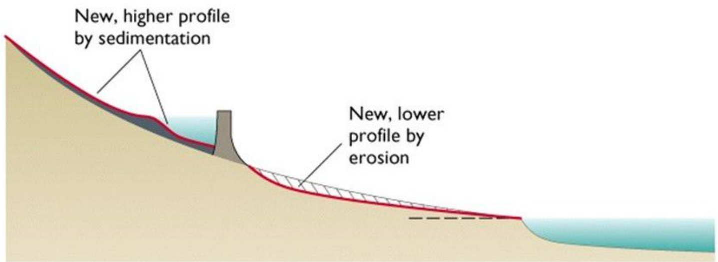


Figure 1.2: Schematized reservoir sedimentation and erosion downstream (Press & Siever, 2002)

1.1.2. Sediment management for run-of-river hydropower dams

Implementing sediment management strategies can restore the sediment equilibrium in a reservoir. A reservoir is considered to be in equilibrium if the inflow of sediment equals the outflow on annual basis. Sediment management strategies with the goal to sustainably manage a reservoir can be classified in three groups, see Figure 1.3. The first set of management techniques aims to reduce the sediment yield from the watershed of a river, whereas the second set of strategies aims to minimize the deposition of sediment in the reservoir. Finally, the third set aims to increase or recover volume from the reservoir by removing deposits in a reservoir.

Run-of-river cascades are characterized by their large spatial scale such as planned hydropower plants in the Mekong watershed (Kondolf, Rubin, et al., 2014), with lengths cascades of HPP exceeding 500 km. The large spatial scale of hydropower dam reservoirs limit the possibilities of sediment management strategies. The focus in the research is on sediment management by means of the operations of the hydropower dams. Dredging and relocation of sediment is not considered in this study, due to the large volumes of sedimentation in the reservoirs and the large spatial scale of the hydropower dam cascades. In addition, sediment bypassing by means of side channels is also not considered due to the large spatial scale of the cascade. In this research the focus will be specifically on flushing operations, which is an operational strategy aimed to re-gain reservoir volume in reservoirs by eroding previously deposited sediment.

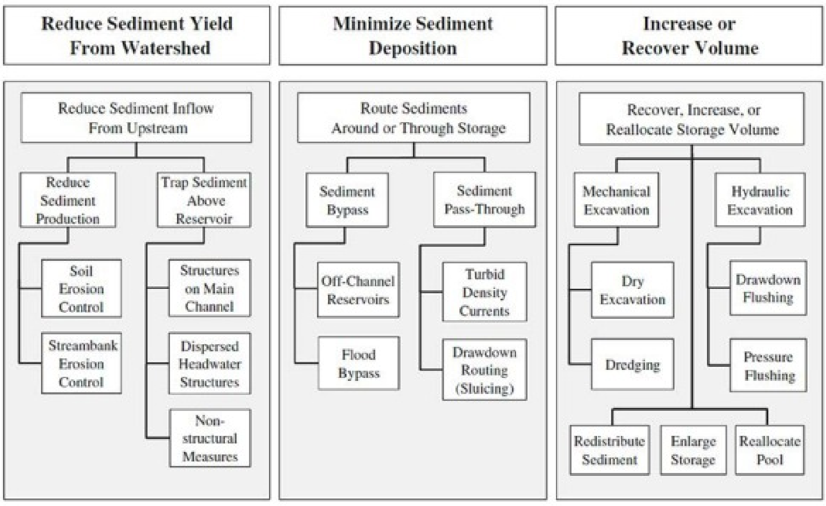


Figure 1.3: Classification of sediment management techniques for reservoirs (Kondolf, Gao, et al., 2014). The focus of this research is on recovering volume from reservoirs.

Flushing techniques

An effective way to mobilize and transport sediment in run-of-river hydropower dam induced reservoirs is hydraulic flushing for reservoirs with varying discharge and a large annual inflow to capacity ratio. The capacity to inflow ratio C/I should be at least smaller than 0.5 for effective flushing operations (Annandale et al., 2016). Flushing is best employed in narrow rivers, with a steep bed slope and seasonal varying discharge (Kondolf, Rubin, et al., 2014). The seasonal variability results in a distinct low and high flow season. During flushing riverine flow conditions that existed prior to the damming of the river are restored and even amplified in case of rapid draw down in the reservoir causing erosion of the deposited material in the reservoir and subsequent flushing of the material through the low level outlets at the dam.

For sustainable sediment management using flushing operations six important variables are to be considered. Six important operational variables are (Annandale et al., 2016; Morris & Fan, 1998):

1. **Rate of water level draw down.** High draw down rates cause strong erosive currents in the reservoir, but may also have negative consequences for the environment and bank stability in the reservoir. Higher draw down rates result in higher flood waves released into the downstream reach.
2. **Timing of the flush, relative to the river discharge.** At high discharges the currents are stronger, while also the high loads of incoming sediment are able to pass. In general the highest in flowing sediment loads occur during the rising limb of the flood wave, and particularly at the start of the wet season (Kondolf, Gao, et al., 2014; Van Binh et al., 2020).
3. **Duration of the flush.** After reaching the minimum water level the river will experience riverine conditions. Maintaining this condition for a while may be useful for extra removal of deposits.
4. **Minimum water level reached.** Lowering the water level closer to riverine conditions gives higher erosion.
5. **Rate of filling of the reservoir:** Rapid filling can be achieved by full closure of all dam outlets, at the cost of trapping all incoming sediment. For slow filling it may be possible to allow some of the sediment to be sluiced.
6. **Impact downstream** Flushing operations are notorious for the high sediment concentrations of the downstream outflow as well as the release of a flow wave with possible detrimental effects.

Based on the aforementioned minimum water level reached during a flushing operation, two types of flushing techniques can be differentiated:

1. **Free flow flushing** where the water level in the reservoir is lowered until the riverine conditions are achieved that existed prior the construction of the dam. The turbines are switched off and the water passes through low level gates and / or high located waves;

2. **Pressure flushing** during which the water level is kept close to the operational water level conditions, whilst a portion of the discharge is re-directed from the turbines to the low level gates. Free flowing conditions are not reached in the reservoir and the resulting mobilization of deposits is limited to the vicinity of the dam (Morris & Fan, 1998).

Pressure flushing does not mobilize sediment in the upper reach of reservoir at the delta, whereas free flow flushing does. Pressure flushing therefore does not increase the sediment flux through the dam to the same degree as free flow flushing. From the view point of sustainable sediment management in a reservoir free flow flushing is the preferred over pressure flushing.

Sediment management operational strategies in reservoir cascades
From literature two main operational flushing strategies for dam cascades occurs, one by MRC (2019a) and the second by Morris and Fan (1998). Both are explained below briefly.

A possible flushing strategy combined with sluicing operations for a cascade of hydropower dams is mentioned in by the Mekong River Commission (MRC, 2019a). In the proposed strategy the most downstream reservoir is flushed first, lowering the water level until free flowing conditions are reached. When the flushing operation at the most downstream dam is finished, a flushing operation is started at the next dam in the upstream direction. At the same time a sluicing operation is started at the most downstream reservoir to pass the released sediment from the upstream reservoir and thereby preventing sedimentation in the downstream reservoir. When the sediment pulse from the second dam has been sluiced through the most downstream dam, the reservoir is refilled again. This process is repeated into the upstream direction of the cascade until the most upstream dam is reached. This strategy uses the strength of the respective flushing and sluicing operations by removing sediment from a reservoir using flushing and then preventing deposition of sediment in the next reservoir.

Another view on sediment management in a series of hydropower dams is to initiate sediment management operations from the most upstream hydropower dam into the downstream direction. The rationale behind this concept is that sediment released from one reservoir deposits in the next reservoir and by flushing and sluicing from the most upstream dam the first dam in the cascade the deposition in a next reservoir is limited (Morris & Fan, 1998). Negative effects caused by this strategy are high sediment concentrations increasing for each reservoir with harmful effects to the aquatic ecosystem. In addition, the flood pulse travelling through the reservoir might be amplified by the timing of draw down operations and thereby increasing flood risks in the down stream parts of the cascade.Flushing dams in a cascade in downstream direction has been employed in the cascade in Japan (IHA, n.d.-a).

1.1.3. Operational trade-offs

The focus until now has been on sustainable sediment management in a reservoir, while the operational strategy is characterised by trade-offs. Flushing operations reduce the time a hydropower dam can generate electricity and result in a flood wave in the downstream reservoir with increased water levels. It is importance to inform communities downstream if a flood pulse is released.

In addition, ecological considerations such as the ecological flow, sediment concentrations during operational conditions and during flushing operations are important aspect to consider during operations. Flood prevention and river ice management are sometimes operational considerations (Bai et al., 2019).

Prioritizing an objective over other objectives can sometimes results in worse performance of one or more other objectives. For example, Myo Lin et al. (2020) show that reducing flood risks also reduces the hydropower generation. Bai et al. (2019) show that for maximizing sediment transport besides

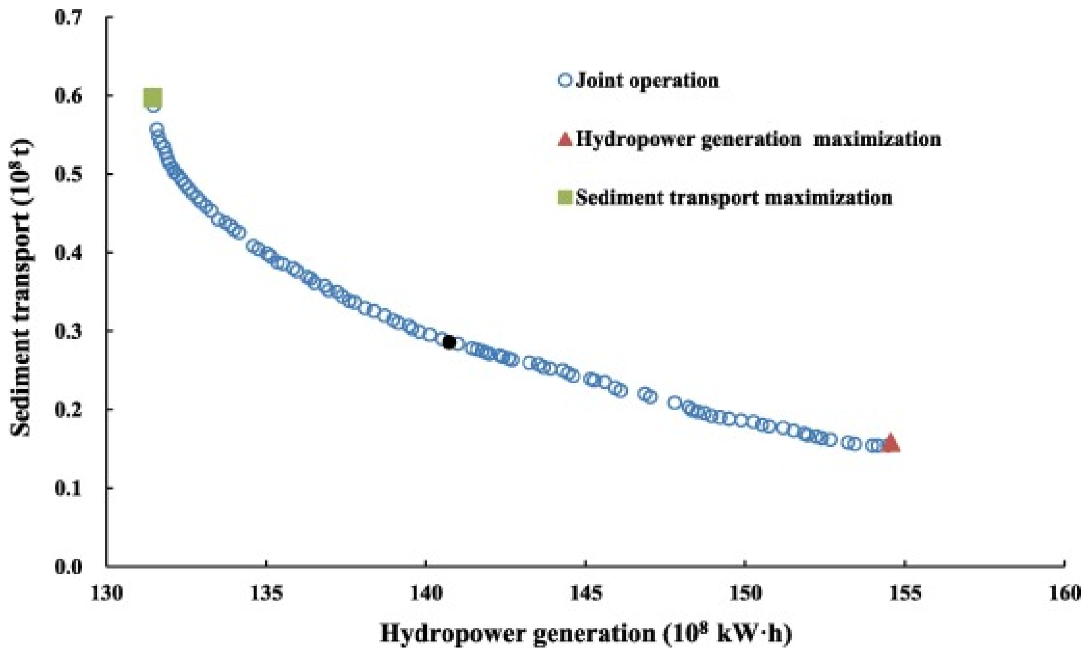


Figure 1.4: Pareto optimal front showing the trade-off between hydropower generation and sediment transport (Bai et al., 2019). Increasing electricity generation reduces the sediment transport

reduced electricity generation the water supply and flood control objectives perform worse than for either joint operation and hydropower generation maximization.

Figure 1.4 shows a set of Pareto optimal solutions for electricity generation and sediment transport for two dams. A Pareto optimal solution is a solution when the value of one variable cannot be improved without reducing the value of the other variable. To obtain a Pareto front all solutions are sorted and compared to each other.

1.2. Case study: Lao PDR hydropower dam cascade

The motivation for this study on the control of a run-of-river hydropower dam cascade originates from the development of three hydropower dam cascades in the Mekong river (MRC, 2020a). In the upper reach called the Lancang in China the first of the three cascades is partially constructed and operational. This cascade, the Lancang cascade, has 11 dams planned. Dam heights over 150 m are no exception with relatively high C/I-ratios resulting in limited possibilities for sediment flushing (Rubin et al., 2015). After the construction of all planned dams in the Lancang cascade the sediment is estimated to decrease by 80% (Kondolf, Rubin, et al., 2014; Kummu & Varis, 2007). Considering that prior to the dam construction the 50 % of the sediment load at the Mekong delta originates from the Lancang, this reduction has severe consequences for the downstream reaches. Further decreasing the sediment load in downstream direction should be prevented.

The main motivation for this research is the second hydropower dam cascade planned in the mainstream Mekong river located in Lao PDR. The planned cascade will consist of 6 run-of-river operated dams located at Pak Beng, Luang Prabang, Xayaburi, Pak Lay, Sanakham and Pak Chom. At this time only one dam at Xayaburi is constructed and fully operational, while the other 5 dams are in various stages of the planning and design process.

In this research the Pak Chom hydropower dam will not be considered, as this project is not submitted yet for the Procedures for Notification, Prior Consultation and Agreement, while all other dams have either started or finished this process. Additionally, the Pak Chom dam is planned on the border of Lao PDR and Thailand. This further complicates the process of planning and constructing.

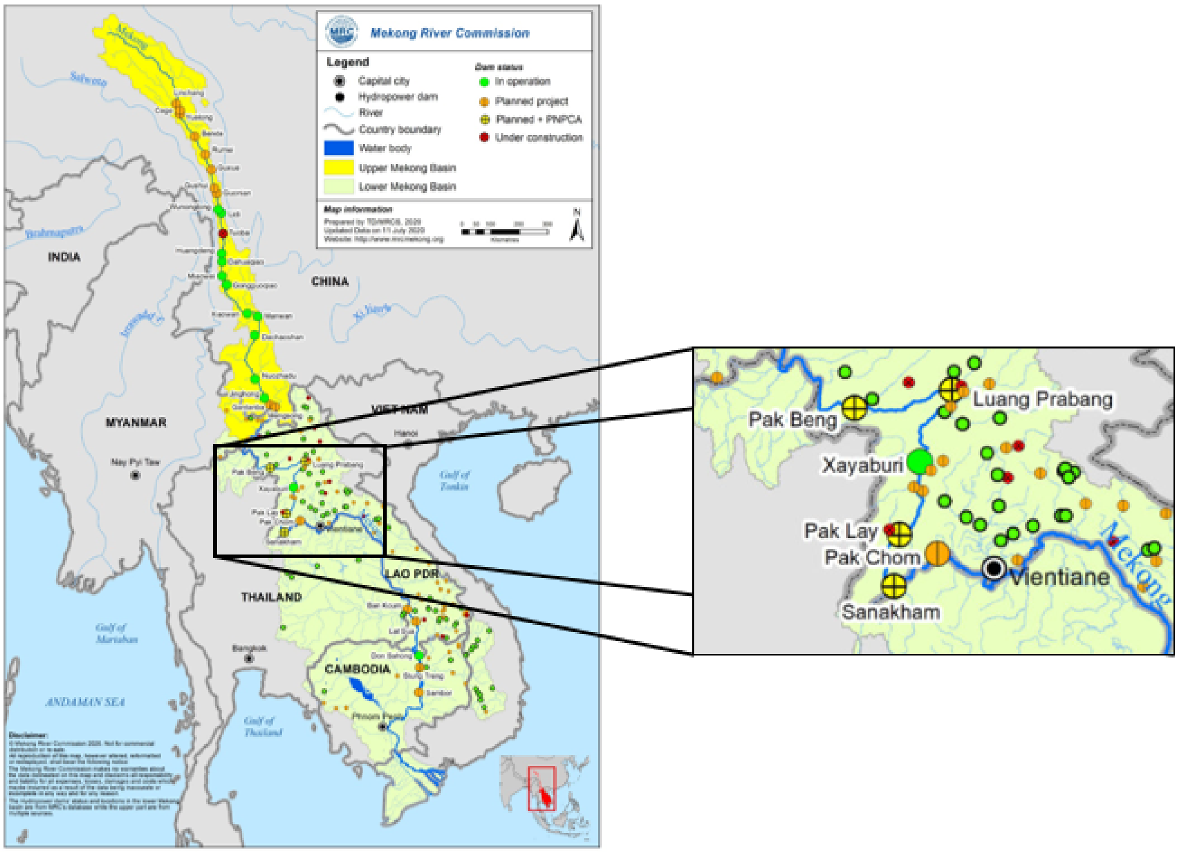


Figure 1.5: The planned hydropower cascade in Lao PDR

1.2.1. Properties and effects of hydropower dams

The planned hydropower dams are run-of-river plants with dam heights around 30 meters, creating long stretched of 40-80 km and narrow reservoirs throughout the cascade. The preliminary designs and operational rules for individual dams do account for sediment management by means of low level flood gates and flood wave sluicing for high discharges (MRC, 2019a). Sluicing is a means to prevent sedimentation a reservoir, see figure 1.3, by passing a wave of sediment laden water past the dam. However, the discharge for which sluicing operations are started has a return period of 5 years, resulting in ongoing sedimentation during intermediate periods between sluicing operation (Kondolf, Gao, et al., 2014; Morris & Fan, 1998).

The operator of the most downstream dam, i.e. Sanakham, plans to divert surplus discharge excess of the capacity of the turbines, i.e. 5,800 m^3/s, through five low level sluice gates until 11,000 m$^3/s$. The additional low level sluice gates are opened approximately 1% of the time, which is probably not every year. For 3-year flood or higher discharges all low level sluice gates are opened and the water level in the reservoir is lowered . In addition to the proposed sluicing during high flows, flushing operations for the duration of 5 to 7 days are undertaken every year in the beginning of September. No further specific details are provided. But because the dam is part of the hydropower dam cascade, further deliberation and coordination will be needed (MRC, 2021b).

In the reports on the Pak Lay hydropower dam, the designers of the project propose to execute joint and coordinated flushing operations in the entire cascade to mobilise and transport coarser sediments in the reservoirs once every 2 to 5 years (MRC, 2019c). Further elaboration on how and when to do so is not provided.

Sediment trapping due to hydropower dams in the Mekong
The Lancang cascade is the most upstream of three cascade on the mainstream Mekong River and is estimated to trap between 83-94% (Kondolf, Rubin, et al., 2014; Kummu and Varis, 2007) of the incoming suspended sediment, i.e. fine sand and clay, and will trap all coarser bedload. A study by Van Binh et al. (2020) presents the change in suspended sediment load for seven measurement stations in the mainstream Mekong river. It shows that the suspended sediment load at the first measurement station downstream of the Lancang cascade decreased with 90% compared to the predam situation. In the predam situation, approximately 50% of the total sediment load entering the South Chinese Sea originated from the Lancang basin, meaning that approximately 40% of the total sediment load to the Mekong Delta is trapped in the Upper Lancang cascade reservoirs (Walling, 2008).

In Kondolf, Rubin, et al. (2014) three scenarios for hydropower dam development are considered to determine the total trapping efficiency of sediment in each scenario. The difference in trapping efficiency downstream of the hydropower dam cascade between the scenario with all planned dams built and all planned dams built without mainstream dams is almost 25%, implying a large influence of the planned dams on basin level.

1.3. Problem statement

The sedimentation in reservoirs of hydropower dams reduces the volume of reservoir world wide by 1-2 % per year, possible resulting in situation where hydropower dams need to be decommissioned as they cannot fulfill their electricity generation function. In a time where the world is trying to divert from fossil fuels to sustainable and renewable sources to meet its energy need, this is undesirable. In addition, sediment trapping in reservoirs results in less sediment delivery downstream, resulting in erosive waves threatening infrastructure, changing habitats for aquatic life in the unique Mekong ecosystem and changing water quality parameters such as turbidity.

As the water use in the Mekong is under pressure, there is a need to ensure sediment delivery downstream of the run-of-river hydropower dam cascade using the limited water as effective as possible. Understanding how sediment can be delivered downstream of the cascade using the discharge throughout the year as effective as possible contributes to come to better operational strategies for run-of-river hydropower dams in a cascade.

Till date, the MRC has studied one operational strategy with four variations regarding the onset of flushing operation, allowing environmental flows during filling and include fish passage flow to improve the sediment flux through the Lao PDR cascade (MRC, 2019a). This strategy employs flushing and sluicing from the downstream dam, progressively moving upward through the cascade. Although this strategy is also mentioned in Morris and Fan (1998) to give the best results, as first channels are created in the deposits, enhancing the sediment flux during sluicing through the reservoir. On the contrary, Kondolf, Gao, et al. (2014) propose to guide the incoming flood and sediment pulse through a cascade by initiating flushing operations just before the sediment pulse reaches the next downstream reservoir. The question arises if and how the sediment flux through the planned hydropower dam cascade can be improved. Bearing in mind that the primary goal of the hydropower dams is to generate electricity and should therefore be included during the development of sediment management strategies. Furthermore, the various designers of the hydropower dams in the Lao PDR cascade propose to implement flushing and sluicing operations if the river discharge exceeds different threshold levels. This operational strategy resembles the strategy in which the sediment management is started at the most upstream dam. However, it remains unclear if the designers of the downstream dams have considered the fact that upstream dams employ similar operational rules and thereby possibly cause unwanted and undesirable flood pulses and sediment loads.

1.4. Objective

Sluicing and flushing techniques have been studied and successfully employed for individual reservoirs (Kondolf, Gao, et al., 2014). However the joint operation of a hydropower dam cascade with respect to sediment transport has received fewer attention, let alone also including sediment management due to flushing in combination with electricity generation interests. The main objective of this study is to find an approach to optimize sediment transport and electricity generation in a run-of-river hydropower cascade.

1.5. Research questions

The research question addressed in the research will be:

How can both sediment transport and electricity generation be optimized in a run-of-river hydropower dam cascade?

The case study in Lao PDR serves as an example to illustrate the application of the derived operational framework where the need for joint sediment management is present.

To answer the research question, three sub research questions are formulated:

1. What are the impacts of the proposed dams in the Mekong river on sediment transport?
2. What is the influence of the draw down rate, set point water level and duration on the sediment flux during flushing operation?
3. How can joint operational strategies in a cascade of hydropower dams be further improved for both sediment management and electricity generation?

1.6. Reader guide

Chapter 2 presents the methodology used during the research, together with the data collection and key assumptions made. The influence of draw down rates and water level set points for flushing operations is shown in chapter 3. Results of the scenario analysis timing, frequency and cooperation for flushing events in a hydropower dam cascade are presented in chapter 4, together with the comparison between the different approaches to scenario development. In chapter 5 a reflection of the author is given on the research and its results. The conclusions of the research can be found in chapter 6, as well as recommendations for the implementation of the research and recommendations for future research.

2 Methodology

The research has three stages. First, the hydropower plant (HPP) cascade for the Mekong case study is simplified to obtain a schematized model. Although the river is simplified, it remains representative for the Mekong conditions, but essentially serves as a base for developing and testing the optimization approaches for the cascade. The second step is to model the schematized Mekong river in Delft3D-FM with RTC tools. The goal is to obtain the sediment flux in the reservoir and through the dam and to determine the influence of the ramping rates and water level set points on the sediment fluxes. In the third stage a bucket model is developed to analyse the effect of the frequency, timing and coordination of flushing events in the cascade.

2.1. Schematization Mekong river

The data used is obtained from different sources, such as the scientific papers, reports on the design of the hydropower dams, the MRC review reports and measurements reports of the MRC. The most important parameters of the schematized river are presented in Table 2.1. Explanations for the values of the parameters chosen can be found below.

Table 2.1: Overview of river and dam parameters in Delft3D-FM model

Parameter	Value	Unit
River width	375	m
River bed slope	$2.5 \cdot 10^{-4}$	m/m
Sediment grain size	200	μm
Sediment density	2650	kg/m^3
Suspended sediment fraction	0	-
Calibration coefficient EH	0.031	-
Sill height dam w.r.t. bed	0	m
Maximum gate speed	0.001	m/s

Discharge timeseries

A set of discharge series for the period 2017-2019 was obtained for the upstream part of the Mekong river and some tributaries (MRC, 2021a). Analysis of the discharge series show that 2019 is a dry year with no distinct flood season, while both 2017 and 2018 were years with the characteristic dry and flood season in the Mekong, see Figure 2.1. In this research the series for 2018 is used, since it resembles an average year closer (Van Binh et al., 2020).

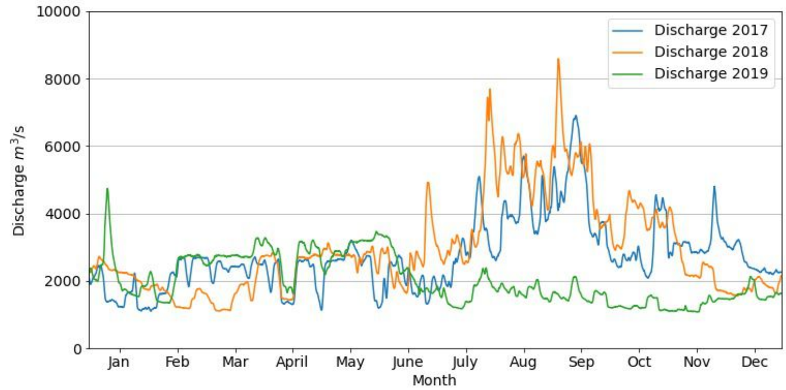


Figure 2.1: Discharge for 2017, 2018 and 2019 at the Pak Beng bridge, close to the planned Pak Bang HPP (MRC, 2021a)

River bed, roughness and sediment
The Mekong river at the planned cascade is bedrock controlled and constricted by the mountainous terrain with steep slopes. At the river banks rock outcrops are present, trapping sediment at the bank, while bed load in the middle of the river travels freely over the fixed bedrock (Gupta, 2009). At the banks the coarsest suspended sediment is deposited first when the flow velocity decreases or the roughness increase and the turbulent flow cannot support these particles. The finer particles stay in suspension and flow away, causing good sorting at the stream banks (Bravard et al., 2014).

The median grain size observed at the river banks between the most upstream dam site Pak Beng and the site in the middle of the cascade, Xayaburi, is close to 200 $/mum$. This is used as median grain size in the Delft3D-FM model.

Particles with a diameter smaller than 60 μm are distributed uniformly over the water column from the river bed to the water surface and are not a part of the bed load flux. In addition, no suspended sand has been monitored in the Mekong and therefore it is assumed that the fine to medium sand will be transported as bed load (Bravard et al., 2014). Thus only bed load transport will be considered. In the flushing experiments one grain size is chosen for the model, being fine to medium sand with a diameter of 200 μm. The roughness of the Mekong reach in Lao PDR is defined using a Manning coefficient of 0.04 $s\ m^{-1/3}$ (Sloff & Pronker, 2018; Van et al., 2012).

River slope and width
The river bed slope in the Mekong reach, where the cascade is planned, has a constant slope of approximately $2.5 \cdot 10^{-4}$ m/m (Bravard et al., 2014; MRC, 2019a).

The width of the river modelled in Delft3D-FM is based on measured cross-sections and Google Earth images. shown in Using the cross-sections shown and Google earth the river width is schematized as 375 m (Google Earth, 2019; Udomchoke et al., 2010). Figures of cross-sections at several locations are shown in appendix B.

2.2. Draw down rate and water level experiments in Delft3D-FM

To investigate the influence of draw down rates and water level set points on the sediment flux an individual reservoir is modelled. The software used is Delft3D-FM, developed by Deltares. Delft3D-FM is capable to perform hydrodynamic simulations including sediment processes and is applicable for river and reservoir systems as the modelling software is designed for large horizontal spatial scales (Deltares, 2022b). Structures such as weirs and gates can also be included in models and simulations. Additionally, the software suite offers the possibility to control structures such as weirs and sills based on flow parameters with the Real Time Control (RTC) module. Therefore, Delft3D-FM with the RTC module is a suitable modelling tool for the research.

Section 2.2.1 explains the schematization of the reservoir with a hydropower dam and simplifications and key assumptions of the reservoir and the dam. The settings of the RTC module are presented in ,

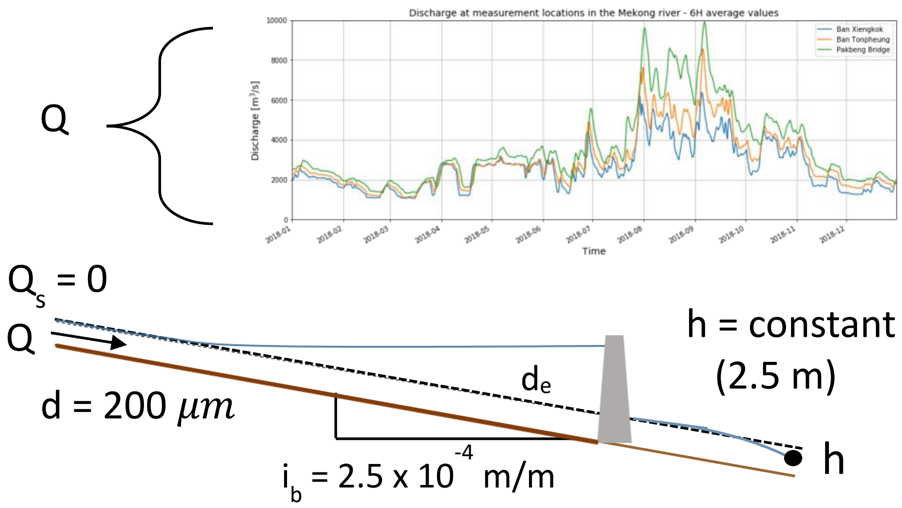


Figure 2.2: Schematized reservoir considered with the boundary conditions. The opening of the low level gates is located at the river bed

followed by the different flushing events in 2.2.4 that are modelled. Finally, the method that is used to analyse and compare the results of all the flushing events is discussed in 2.2.5.

2.2.1. Schematization, simplifications and assumptions of reservoir and dam

To determine the influence of draw down rates and water level set point during flushing events for different discharge only one hydropower dam and reservoir is modelled, as shown in Figure 2.2. The goal of the experiments is to determine the erosive force / capacity of the specific draw down events in a reservoir. Focus lays on the in-channel sediments and the possibility to mobilize the present and deposited sediment by flushing operations. This resembles two situations. Firstly, just after the construction of the dams in-channel sediment storage is still present and available to be flushed. Secondly, the situation after the formed delta in the upper section of the reservoir has migrated downstream over the course of 20 to 30 years and covered the entire river bed with alluvial deposits.

The most important parameters and settings used during the flushing experiments in the Delft3D-FM with RTC module are presented in Table 2.2. All other values of parameters are the default values of Delft3D-FM.

Table 2.2: Overview of numerical parameters in Delft3D-FM model

Parameter	Value	Unit
Grid cell width	375	m
Grid cell length	1500	m
length / width ratio grid cell	4	-
User defined time step	15	min
Maximum Courant number	0.7	-
Proportional coefficient	-1	-
Integral coefficient	$-1 \cdot 10^{-5}$	-
Derivative coefficient	0	-

Detailed explanation on the parameters and settings and also the key assumptions and simplifications in the Delft3D-FM model are:

- **1-Dimensional model:** the Mekong river is reduced to a one dimensional river. Two dimensional effects during draw down operations such as channel formation in cross-sectional direction are not included. During draw down operations flow velocities primarily increase in the stream wise direction. No relevant stratifications in the reservoir or near-field processes at the dam motive a more advanced approach. The complex sediment interaction between the channel, rock outcrops and bed forms are thus not considered. Therefore the river section considered is schematized to a one dimensional model, serving as a schematization of the channel part of the Mekong.

- **Constant and rectangular cross-section:** over the entire width of the river the cross-section is equally wide and rectangular shaped. The river width as modelled in the Delft3D-FM model is 375 m, where in reality the width varies from 250 to 650 m.

- **Constant river bed slope:** in the model, the bed level slope is modelled as a constant since the experiments that are conducted span only a short time period with a maximum of two weeks. Additionally, since the river is bed-rock controlled the river bed slope does not change on the time scale considered.

- **No bed level updates:** the formation of a delta in the reservoir due to the hydropower dam is not included, as well as the possible erosion wave downstream. The timescale of these processes is in the order of years, while the model simulates for a timescale of days to weeks. The formation of channels is also excluded from the model. With the bedrock river bed no bed level changes are expected in the time period of flushing operations.

- **One single grain size considered:** for the experiments one grain size is included in the model, instead of a grain size distribution. From the fine sediment fraction, ie. clay, silt and fine sand, the sediment flux for the fine sand fraction is trapped in the reservoir. This fine sand fraction is used in the model. The grain size chosen is fine sand predominantly found in the sand bars in the Mekong with a diameter of 200 μm (Bravard et al., 2014). These sand bars are especially import for the aquatic ecosystem functioning (Gu et al., 2020). Larger grain sizes deposit further upstream in the reservoir. This process and other grading processes are not included in the model.

- **Fully alluvial bed:** albeit the river in the case study is predominantly bedrock controlled, the river in the model is schematizes as fully alluvial. This results in an overestimation of the sediment flux during high flow conditions, as during high flows the sediment transport capacity is larger than the available sediment, resulting in supply limited conditions. These supply limited conditions is often observed in under supplied bedrock channels (Wohl, 2015).

- **Sediment formula of Engelund-Hansen:** the sediment transport in the Mekong river will be formulated using the Engelund-Hansen, which is defined as follows:

  $$s = mu^n = \frac{k}{D}u^n \tag{2.1}$$

  with the flow velocity u, n = 5, D the diameter of the grain size considered and k:

  $$k = \frac{0.05\ c_f^{3/2}}{(\Delta g)^2} \tag{2.2}$$

  with c_f the dimensionless friction coefficient, Δ the specific density and g the gravitational acceleration.

  This formula is suitable for smaller grain sizes, between 190 μm and 930 μm. Without the inclusion of a threshold Shields parameter the formula represents the stochastic nature of sediment transport, where there is no single value for onset of transport. The considered grain size of 200 μm falls within the applicable range of the formula. The Engelund-Hansen formula was derived for $0.07 < \theta < 6$ and this conditions occur in the Mekong river.

- **Simplified dam structure:** the hydropower dam is modelled as a gate with a single opening at the river bed level. The gate spans the entire width of the river. In reality, the low level gates are only located at the left and right river bank. In addition, the sill height is modelled close to the bed level to prevent backwater curves by the sill. The gate height is set to 25 meters to resemble the dam.

- **Non-erodible layer near dam:** two cells upstream of the dam and one downstream of the dam, a non-erodible layer is created in the model to prevent squeezing, i.e. reducing, the time step to prevent disproportional run times. In runs with an erodible layer the time step is reduced dramatically by Delft3D-FM to ensure a stable run. By removing the erodible layer this problem is solved. Removing the erodible layer is justified as the sediment mobilized upstream in the reservoir can pass these cells, as would happen in reality.

- **Only bed load flux in model:** the Engelund-Hansen transport formula calculates the total sediment flux and Delft3D-FM offers the possibility to assign a fixed fraction of the total sediment flux to the suspended flux. This option is not used, since it is shown that the considered fine sediment is transported predominantly as bed load (Bravard et al., 2014). A small portion of the sediment transport during flushing operations is likely to be transported as suspended material but no quantitative information is generated on the suspended sediment concentration during these flushing operations. However, increased total sediment loads also suggest increased suspended sediment loads. The benefit of this modelling choice is that the computational time is reduced by excluding the suspended sediment flux.

- **Villemonte model for weir:** the gate is defined using the default weir scheme in Delft3D-FM which is the Villemonte formula. This formula is based on a large number of measurements and expresses the discharge across the weir as function of the upstream and downstream energy heights (Deltares, 2022a).

2.2.2. PID-controller settings

In systems and control, a PID controller is used to control structure to achieve a desired state of the controlled system. In this study the control structure are the gates at the dams and the desired state is the water level at the dam. A PID controller changes the value of the controlled structure according to the observed error between the desired state of the system and the actual state of the system, by considering the error (P), the integral of the error (I) and the derivative of the error (D).

The general formulation of a PID controller is given by:

$$e(t) = x_{sp}(t) - x(t) \tag{2.3}$$

and

$$f(t) = K_p\, e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d\, e(t)}{dt} \tag{2.4}$$

where $e(t)$ is the difference between the set point $x_{sp}(t)$, the actual value of the controlled variable $x(t)$ and $f(t)$ the controller output. K_p, K_i and K_d are the proportional, integral and derivative gain factors respectively. The RTC module of Delft3D-FM uses a slightly different expression to prevent taking previous errors into account too long. In linearized and discrete form this reads:

$$f^n = f^{n+1} + K_p(e^n - e^{n-1}) + K_i \Delta t_n e^n + K_d\, \frac{e^n - 2e^{n-1} + e^{n-2}}{\Delta t} \tag{2.5}$$

The control output can be limited to match real world limitations of gates and weirs, such as minimum and maximum height and maximum speeds of the controlled structures. The values of the gain factors of the PID controller depend on the system it is used for and must be adjusted for each situation, i.e. in this case different discharges. However, the gain factors are kept constant for all flushing experiments since satisfactory results are produced.

The values and sign of the gain factors are calibrated based on the base line flushing event presented in chapter 3. The signs of K_p and K_i are negative, since an increased gate level results in a lower water level. First a smaller value of $-1 \cdot 10^{-5}$ was assigned to K_i. The proportional gain factor was increased step wise until under equilibrium conditions the water level matched the water level set point and the draw down rates where matched. This was for K_p = -1 . The derivative gain factor was kept at K_p = 0. (Deltares, 2022b)

2.2.3. Model spin up

The initial water in the reservoir is set at three meters below the water level set point at the dam, gradually filling the reservoir. The initial time step in the model is 1 second to ensure that the maximum Courant number of 0.7 is not exceeded. Within two days steady state conditions are achieved in the reservoir. Nevertheless, the time period at normal operational conditions is extended by 10 days to minimize the influence of the integral of the error in the PID-controller.

2.2.4. Draw down rates and water level during flushing experiments

The influence of the draw down rates and water level set points are tested for four different nearly constant discharges:

- **Q = 2750 m^3/s**: approximately the average discharge over a year.
- **Q = 4125 m^3/s**: 1.5 x the average discharge of a year, occurring at the rising and falling stage of the flood season.
- **Q = 5500 m^3/s**: twice the average discharge over a year and almost the design discharge of the turbines at Pak Beng.
- **Q = 6875 m^3/s**: 2.5 x the average discharge of a year and above the design discharge of the turbines.

The draw down rates considered are 0.4, 0.6, 0.8 and 1.0 m/h. These draw down rates are based on (MRC, 2019a). As the goal of the experiments is to determine the effect of the draw down rate on the sediment flux through the dam, the focus is on higher draw down rates mentioned. With higher draw down rates, the desired water level set point is reached faster. Thereby, it is likely that during the overall flushing operation with a higher draw down rate the sediment flux is higher than for lower draw down rates. Additionally, during higher draw down rates greater volumes of water are released, causing higher flow velocities as the water level is dropping in the reservoir. If the water level is lowered to the minimal water level the riverine conditions are approached.

The water level is drawn down with a constant rate, resulting in a fluctuating discharge through the dam. More complex draw down strategies are not considered, such as operations with time-varying draw down rates. The goal is first and foremost to investigate the influence of the draw down rate itself on the sediment flux.

Three water level set points are considered during the experiments to test the influence of the water level set point on the sediment flux during a flushing operation. The water level set points are defined as a deviation from the normal operational water level.

The three water level set points are -7.5 m, -10 m and -12.5 m with respect to the normal operational water level. Depending on the upstream discharge at the boundary free flow in the entire reservoir may occur.

2.2.5. Analysis flushing experiments results

The results of the flushing experiments are used during a scenario analysis which aims to determine the influence of different types, i.e. draw down rate and water level set point, frequency and timing of flushing events, as well as the result of cooperation between dam operators.

The analysis of the results focuses on two distinguishable parts. The first part of the analysis aims to show the effects of flushing operations in the reservoir. To do so, for four cross-section at 20 km intervals located upstream from the dam the flow velocity and sediment transport is presented. This way the influence length for the different flushing events is shown. In addition, the sediment flux over the longitudinal profile is plotted and analysed to determine the distance the flushing operation has influence on.

The second part of the analysis is aimed at the discharge and sediment flux through the dam into the next reservoir. These results are used for the scenario analysis as input for the control at the dams. For each run the total sediment flux is calculated, so possible relationships for the draw down rate and water level set point can be determined.

2.3. Scenario analysis method

To answer the question how the sediment flux and electricity generation both can be maximised, the reservoir cascade is schematized as a bucket model. Each reservoir is schematized as an individual bucket with a dam at the downstream end. The outcomes of the flushing experiments are used as input for this model at the out flowing flux at each individual reservoir.

First the assumptions, schematization and characteristics of the bucket model are presented in 2.3.1. The two different methods to sample operational scenarios are presented in 2.3.2

2.3.1. Assumptions, schematization and characteristics bucket model

Key assumptions, simplifications and characteristics for the bucket model are:

- **Cascade reduced to three dams:** the amount of dams is reduced to three dams with its reservoir. Three dams still provide information on cooperation of dams on a cascade level compared to two or less dams, as a combination of operations of two dams can reach a third reservoir.
- **No tributaries or additional fluxes:** the cascade system is simplified to a system without tributaries or other incoming and outgoing fluxes, such as evaporation or irrigation. During the low flow season the contribution of the tributaries is very limited, but during the flood season run off from rain this contribution increases. The Nam Ou tributary entering the Mekong in the considered section contributes 4% to annual discharge (Shrestha et al., 2018).
- **Constant water level:** it is assumed that at the dam the water level is constant, independent of the discharge upstream. This implies that under normal operational conditions the electricity generation and the sediment flux through the dam can be calculated for only the water level at the dam based on the flushing experiments executed in Delft3D-FM.
- **Dams at equal distances:** the dams in the cascade are equidistant from each other to eliminate the influence of spacing in the hydropower plant. In reality the dams are between 80 and 140 km apart (MRC, 2019a).
- **Constant travel time discharge:** it is assumed that the travel time of water fluxes between the reservoirs is constant for both normal operational conditions, as well as for flood waves released during flushing operations. In reality flood waves travel with a higher speed through the reservoirs. The model can still provide information on the timing of flushing events.
- **6 hours time step used:** the model uses a time step of 6 hours. Compared to the discharge measurement time series with 1 hour intervals the error in peak discharge is limited to 5%. The flood wave and sediment flux output of the flushing events are re-sampled to 6-hour average values so the results can be used in the bucket model.
- **No damping between two dams:** in reality damping occurs in reservoirs. However, it is assumed that this damping is negligible. This is verified in experiments, that are presented in appendix C. For a discharge of 2750 m^3/s the error of the peak of the flood wave is in the order of 3%, while for a discharge of 6875 m^3/s, the error is in the order of 10 %.
- **Sediment transport capacity:** in the model the sediment transport capacity is calculated, rather than the real sediment transport. This is inline with the alluvial bed assumption made for the flushing experiments. In the bucket model, supply limited conditions do not occur.

The resulting bucket model is shown in Figure 2.3. Three additional properties of the bucket model are important to highlight.

Calibrating sediment flux

The model should produce a similar sediment flux as the Delft3D-FM model used for the flushing experiment. To do so, the sediment flux is calibrated such that the sediment fluxes without a draw down event for both the Delft3dD-FM model and the bucket model are similar at 36 kton. For normal operational conditions the sediment flux in kg/s is presented in Equation 2.6

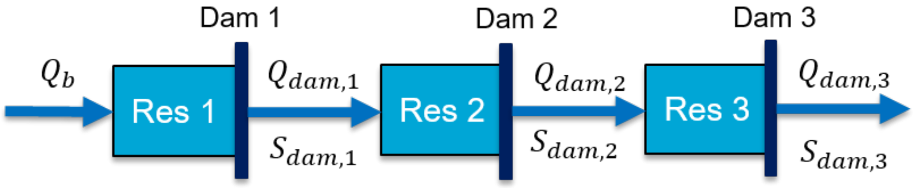


Figure 2.3: Representation of the bucket model of a cascade of three dams

$$
\begin{aligned}
S &= \left(\frac{Q_{in}}{2750}\right)^{1.75} * 0.099 \;\; for\; Q_{in} < 2750\, m^3/s \\
S &= \left(\frac{Q_{in} - 2750}{6875 - 2750}\right)^{1.75} * (10.22 - 0.099) + 0.0099 \;\; for\; 2750 < Q_{in} < 6875\, m^3/s \\
S &= \left(\frac{Q_{in}}{6875}\right)^{1.75} * 10.22 \;\; for\; Q_{in} > 6875\, m^3/s
\end{aligned}
\tag{2.6}
$$

Interpolation between discrete flushing events
The flushing events in the Delft3D-FM model are conducted for a set of four different discharges. However, at the upstream reservoir of the bucket model the measured discharge in the Mekong is applied, which is varies in time. To determine the discharge and sediment flux through the dam during a draw down event that is not started at a discharge considered in the Delft3D-FM experiments, the resulting discharge and sediment flux is determined by interpolation.

Conservation of volume
As linear interpolation is applied while the magnitudes of the flood wave through the dam are not linearly related to the discharge, a small error in the volume conservation is induced, in the range of 0.1 to 1 %. This implies that during filling the reservoir is either too much or too little water is stored. At the next time step this is corrected to obtain a closed volume balance again. The correction of the discharge through the dam is limited at 500 m^3/s to prevent sudden, undesired large corrections if they would occur.

$$Q_{correction} = \max(Q_{deviation}, 500)$$

2.3.2. Sampling scenarios

For the schematized reservoir cascade a set of scenarios are developed to determine what scenarios result in desirable outcomes for different frequencies of draw down, draw down rates and cooperation between dam operators. The first method to create scenarios uses random variables, whereas the second method uses pre-determined to investigate the effect of the draw down rates, frequency and timing of operations. Both methods consider a time period of one year to include the low and high flow season in the simulations that are distinctive for the Mekong river.

Random scenario sampling

The first method to develop operational scenarios uses random variables at each dam. For each time step a random variable is drawn from a uniform distribution. If the random variable is below a set threshold value, the dam does not start a draw down operation and the dam generates electricity. If the random variable is above the threshold value a draw down operation is started. Then again by random choice the draw down rate and the water level set point is determined. The duration at the low water level set point is fixed and follows from the results of the flushing experiments in Delft3D-FM. This procedure is visualised in Figure 2.4.

Using this scheme, five combinations of the limit on the draw down operation and the ramping rate during the operation are considered:

1. limit at $Q > 5000$ m^3/s
2. limit at $Q > 5000$ m^3/s with only high draw down rates
3. limit at $Q > 6500$ m^3/s
4. limit at $Q > 6500$ m^3/s with only high draw down rates
5. Limit at $Q > 5000$ m^3/s with reduced sediment permeability at dam 3

For the first four combinations of limit on onset of the draw down operation and draw down rates, the average number of draw down events per wet season is varied from one to three events. This will show the influence of the frequency of draw down operations per wet season.

The fifth scenario with the reduced dam permeability represents the situation of a poor dam design where the third dam in the cascade is not equipped with fit to purpose low level gates. It will show the operational costs of not including fit to purpose low level gates.

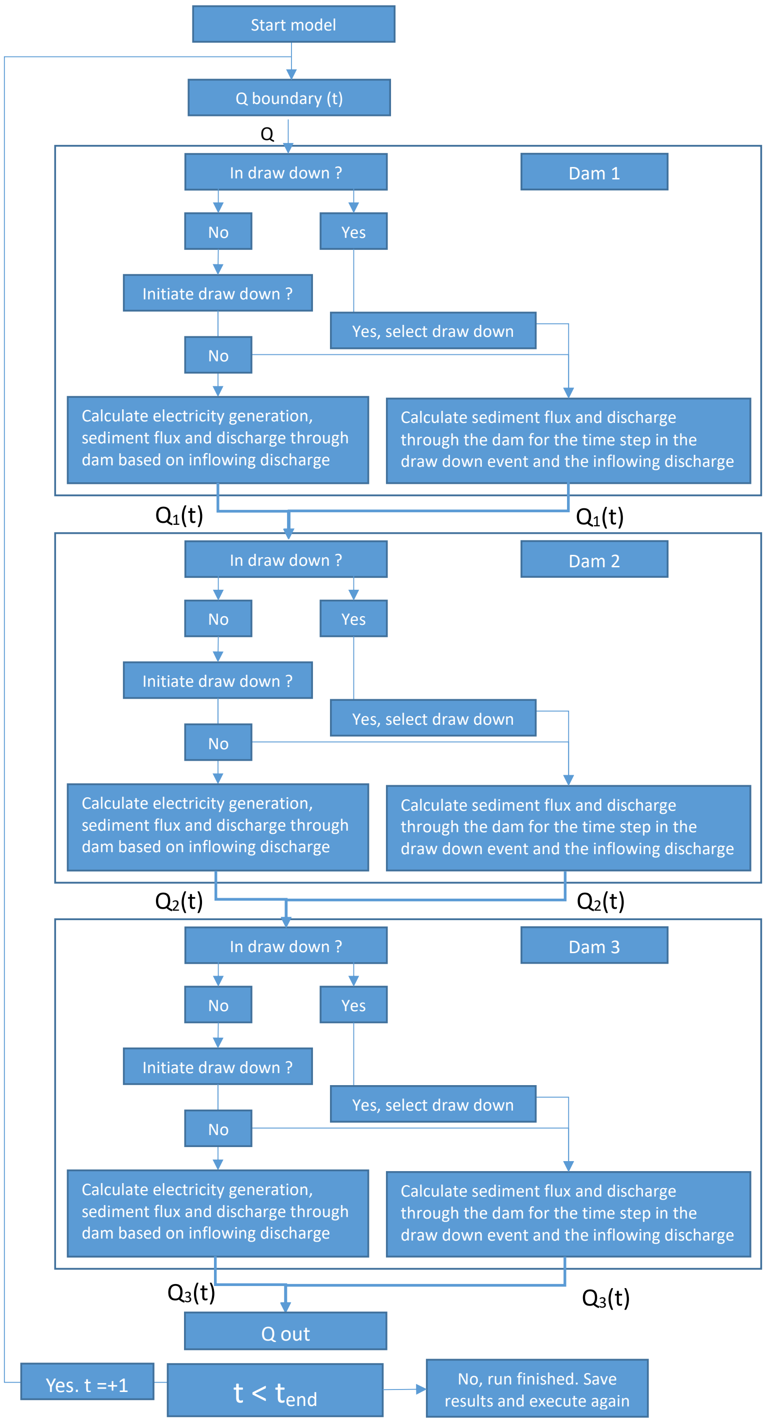


Figure 2.4: Schematized representation of the procedure used to sample. Q is the discharge of the boundary condition. Q_1,Q_2 and Q_3 are the discharges released from the dam.

Pre-determined operational scenarios
Contrary to the first method, the model is used slightly different. The second method analyses pre-determined flushing scenarios based on suggested flushing operations in cascades (Morris & Fan, 1998; MRC, 2019a), opposite to the random sampling method. The two different operations analysed are:

1. **Flushing from upstream to downstream.** The dam located most upstream in the cascade is flushed first. As this flood and sediment pulse migrates into the second reservoir of the cascade, the second reservoir is flushed as well. This continues until the most downstream dam of the cascade is reached as shown in Figure 2.5. This procedure is based on the principle that downstream dams utilize the sediment transport capacity of the arriving flood wave to erode more sediment. To determine the influence of the time between the onset of the flushing events at the dams in the cascade, four different time intervals are considered:

   - Simultaneous draw down at all dams
   - One time step difference between onset of draw down
   - Two timsteps difference between onset of draw down
   - Three time steps difference between onset of draw down

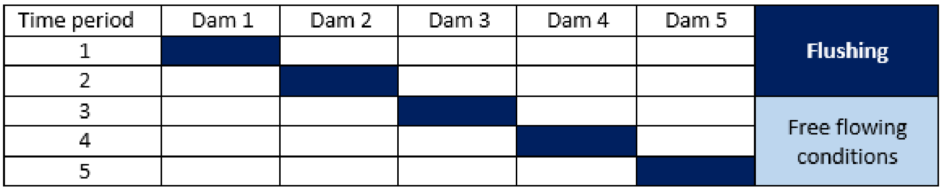


Figure 2.5: Schematized cascade flushing strategy progressively flushing downstream

2. **Flushing from downstream to upstream.** The first dam in the cascade that is flushed, is the most downstream dam. As soon as draw down is complete and a period of time has passed, the next dam in upstream direction is flushed. The discharge from this flushing event is sluiced through the downstream reservoir by maintaining free flowing conditions. After the flood wave has left the most downstream reservoir, it is refilled again. This procedure is repeated in upstream direction until the most upstream dam is reached as shown in Figure 2.6. Six different time intervals between the onset of the flushing events at the dams are considered, which are:

   - One time step difference between the onset of draw down
   - Two time steps difference between the onset of draw down
   - Three time steps difference between the onset of draw down
   - Four time steps difference between the onset of draw down
   - Five time steps difference between the onset of draw down

   One additional scenario is explored, where the reservoir are flushed progressively in upstream direction where at most two hydropower dams are not generating electricity (MRC, 2019a).

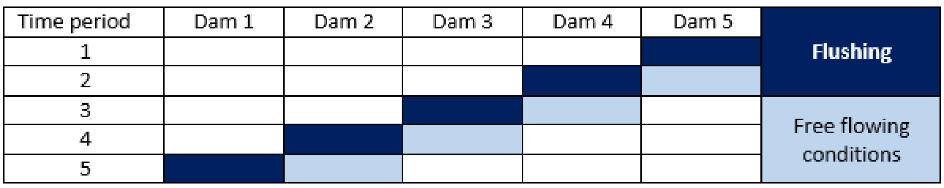


Figure 2.6: Schematized cascade flushing strategy progressively flushing upstream

2.3.3. Evaluation of simulation results

The results of the simulations are used to construct a Pareto optimal front. The bucket model calculates and returns the electricity generation and sediment flux per dam per for every time step as well as the total electricity generation and sediment flux for each dam. To construct the Pareto optimal fronts for each dam and simulation the total electricity generation and sediment flux for all runs in a simulation are sorted in a list. The elements in the sorted list are element wise compared to each other to determine if a run is part of the Pareto optimal front.

3

Flushing experiments in Delft3D-FM

The influence of the draw down rate and water level set point for multiple discharges on the sediment flux through the dam is determined in a set of experiments, explained in chapter 2. A total of 48 flushing experiments have been performed. The goal is to quantify the amount of sediment that is mobilised during an operational action for different cross-section in the reservoir.

During the flushing experiments a snippet of the hydrograph of 2018 is used where the discharge is almost constant. This is also done to observe the effect of (small) variations in discharge during the minimal water level. The influence of the discharge at which the flushing event is performed is tested for four discharges, varying from 2750 m^3/s to 6875 m^3/s.

The Delft3D-FM model will be run twice for the time period of a year with the hydrograph of 2018 at Chiang Saen as boundary condition at the upstream end of modelled river segment. First, the model will be run without a dam to determine the sediment transport at the conditions prior to dam construction. Secondly, a schematized dam is included in the model, to determine how the sediment transport in the reservoir is affected by the construction of a dam, again with the hydrograph of Chiang Saen of 2018 as boundary condition at the upper end.

This chapter first presents the sediment flux through the river prior to the construction of the dam in section 3.1. The hydraulics and sediment flux under normal operational conditions through the dam as well as in the reservoir are shown in section 3.2. Thirdly, the base line flushing event is analysed in 3.3. An overview of the results of all experiments can be found in 3.4. The analysis on the draw down rate, water level set point and duration at the water level set point is given in 3.4.1, 3.4.2 and 3.4.3 respectively.

3.1. Reference conditions: free flow without dam

To understand the implications of the construction of hydropower dams in the Mekong river and the effects of flushing operations, the river first is modelled without the inclusion of a hydropower dam first. This results is the reference level for the sediment flux and can compared to the flushing operations.

As mentioned before, the model will be run for the time period of one year with the hydrograph of Chiang Saen at the boundary. All assumptions, simplifications, model settings and model variables (see chapter 2) for the flushing experiments are also applied and used to determine the reference conditions.

3.1.1. Hydraulics

The flow velocity at the proposed dam location is plotted together with the discharge in Figure 3.1. As the discharge increases from about 2000 m^3/s in the dry season to approximately 8000 m^3/s in the wet season, the flow velocity doubles from 1 to 2 m/s.

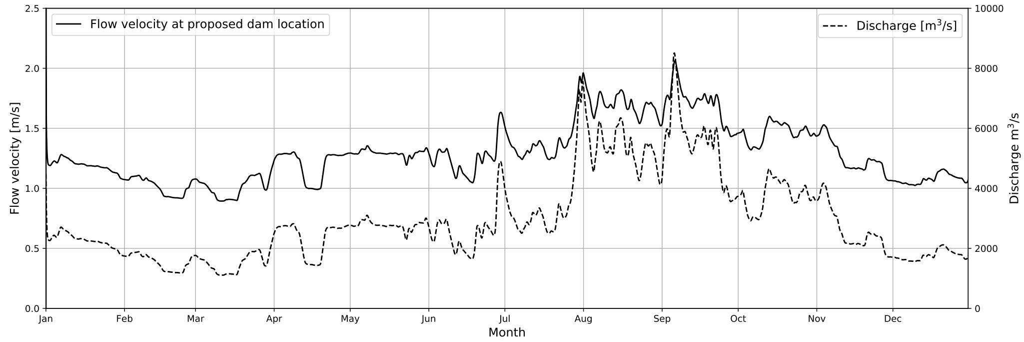


Figure 3.1: Flow velocity and discharge at the proposed dam location from the Delft3D-FM model for free flowing situation without dam

3.1.2. Sediment transport

During the run time of the Delft3D-FM model, the sediment transport for all cross-sections is equal and the total sediment transport is 3.5 Mt/year, similar to the sediment transport of fine sand in this section of the Mekong (Koehnken, 2014). This is achieved by calibrating the model with Figure 3.2 presents the cumulative sediment flux and the discharge as a function of time, showing that the majority of sediment transport takes place during the high flow season.

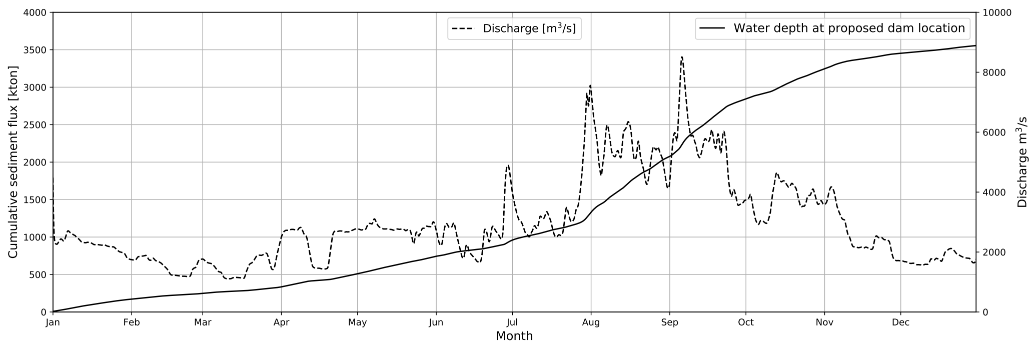


Figure 3.2: Cumulative sediment flux and discharge at the proposed dam location from the Delft3D-FM model for free flowing situation without dam

3.2. Normal operational conditions

At normal operational conditions the water level is kept constant in the reservoir by the PID controller. To compare the results of the flushing experiments with the situation without flushing, the discharge and sediment flux through the dam during normal operational conditional are determined first. In addition, sediment transport over the longitudinal profile is also shown in order to compare it to the situation during the draw down operations.

3.2.1. Water level and flow velocities in the reservoir

The water levels near the dam are almost constant, resulting in decreasing flow velocities along the reservoir in downstream direction towards the dam. At 60-70 km upstream of the dam, where the backwater of the reservoir is starting to appear, this reduction in flow velocity becomes increasingly significant. From 20-30 km upstream of the dam, the flow velocity is almost constant due to the backwater curve.

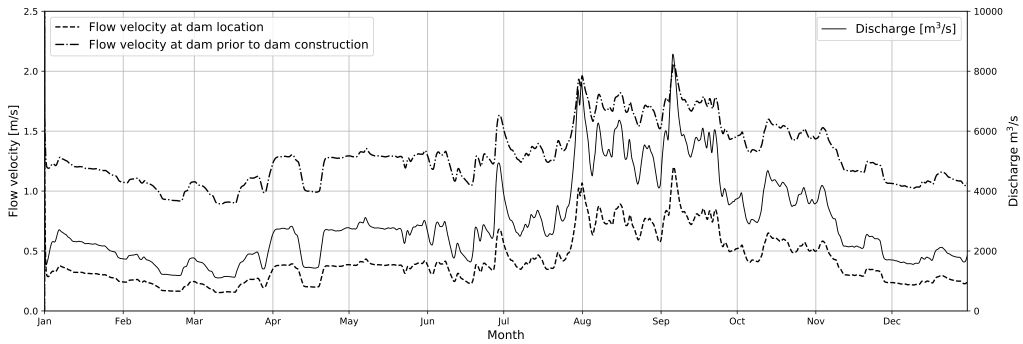


Figure 3.3: Flow velocity and discharge at the proposed dam location from the Delft3D-FM model for the situation with dam

3.2.2. Discharge and sediment flux through the dam

As expected, the discharge through the dam follows the inflow at the reservoir as the water level in the reservoir is kept constant. The sediment transport capacity at the dam is reduced by almost 99 % compared to the situation without a dam. Figure 3.4 indicates that virtually no sediment is transported until the onset of the wet season in July.

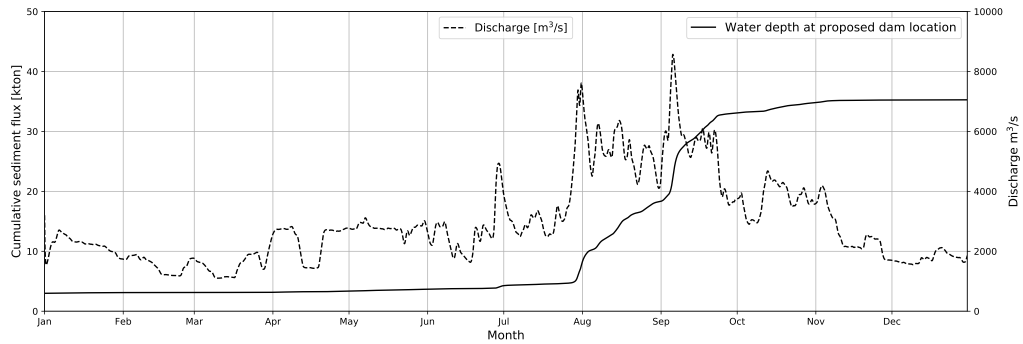


Figure 3.4: Cumulative sediment flux and discharge at the proposed dam location from the Delft3D-FM model for the situation with dam for the year 2018.

3.2.3. Sediment flux along the reservoir

Under normal operational conditions, the backwater curve in the model extents some 60-70 km upstream in the reservoir. From there on, the water depth increases and the flow velocity reduces, reducing the sediment transport capacity and resulting in sediment deposits. The cumulative sediment flux at the dam is shown in Figure 3.4 as a function of time together with the discharge at the dam, showing that the sediment flux is again largest at high flows.

Using the Exner principle, the bed level change over time can be determine by taking the derivative of the sediment flux over the downstream distance x:

$$c_b \frac{\partial s}{\partial x} = -\frac{\partial z_b}{\partial t} \tag{3.1}$$

with c_b the sediment concentration in the bed, s the volume sediment transport per unit width and z_b the mean elevation of bed surface. Doing so, roughly three sections in the model can be discerned: 1.) the upstream reach without influence of the dams on the sediment transport, 2.) the middle reach where the sediment flux reduces to the point where the sediment flux almost reduces to zero and 3.) the final reach until the dam where the sediment transport is reduced to virtually none. Figure 3.5 presents both $\frac{\partial s}{\partial x}$ and $\frac{\partial z_b}{\partial t}$. It show delta formation in the upstream part of the reservoir at 80 to 50 km from the dam.

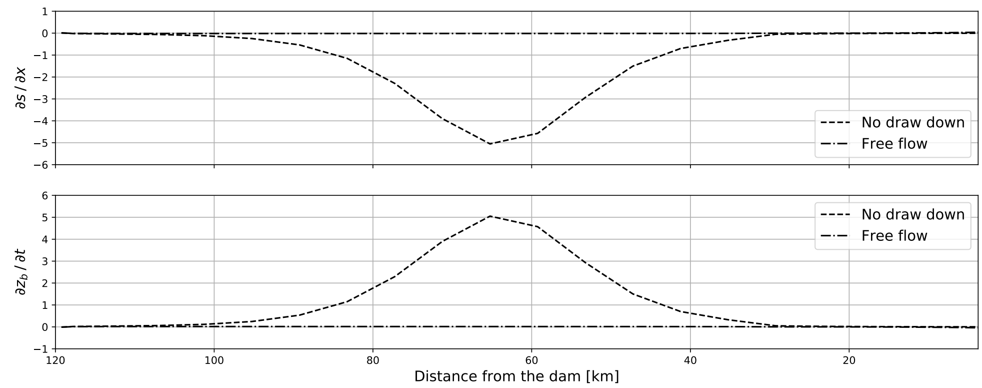


Figure 3.5: The upper panel shows $\frac{\partial s}{\partial x}$ and the lower panels $\frac{\partial z_b}{\partial t}$, indicating the formation of a delta in the upper reach of the reservoir

3.3. Base line flushing event

To highlight key results of the draw down events, the base line flushing event is analysed in this section. The reference flushing event has a draw down rate of 0.4 m/h until free flow conditions are reached with 2750 m^3/s entering the reservoir at the upstream boundary. The water level set point as a function of time is shown in Figure 3.6. In this experiment only the sediment flux during the draw down operation and time of free flowing conditions is considered. It is assumed that during the filling of the reservoir the sediment flux through the dam is negligible.

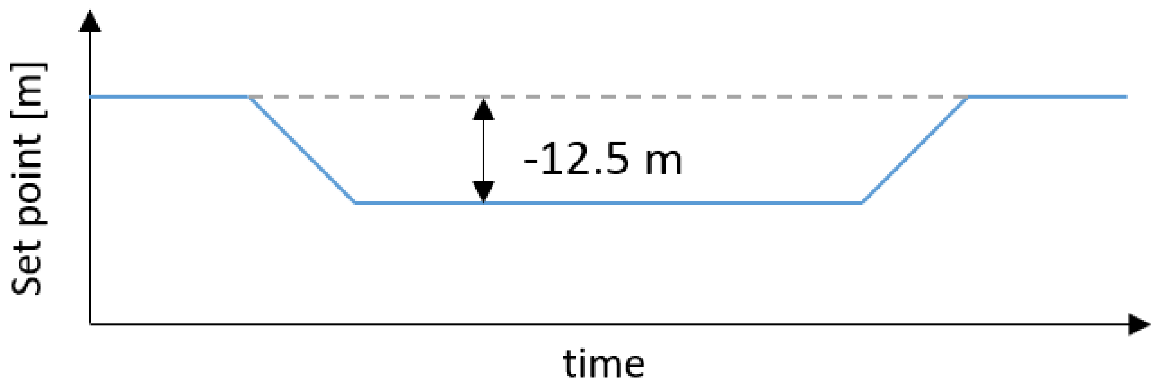


Figure 3.6: Schematized water level set point for the PID controller

3.3.1. Hydraulic parameters in the reservoir and at the dam

Firstly, the influence of the draw down operation throughout the reservoir is presented in longitudinal direction and also at four cross-sections as a function of time. The upstream influence for the four cross-section, at 20, 40, 60 and 80 km upstream of the dam will be reviewed for the water level, the flow velocities and sediment transport.

Retrogressive wave

To lower the water level in the reservoir, the discharge through the dam is increased and a flood wave is released at the downstream end of the dam. As a result, a retrogressive wave migrates in the reservoir, lowering the water level. At the cross-sections 20 km upstream of the dam the discharge is increased from approximately 2750 to 3754 m^3/s, which is the only location with a major increase of the discharge for about 12 hours. Further upstream damping occurs, reducing the height of the retrogressive wave.

After this wave has passed, the discharge at all cross-sections is constant again when the water level has reached its set point.

Flood wave through the dam
At the dam a flood wave is released into the downstream reservoir. The properties of the flood wave, i.e. peak discharge and duration, depend on the discharge in the upstream reservoir, the draw down rate and the water level set point. For the baseline flushing event, the discharge at the dam increases from ± 2750 m^3/s to ± 4600 m^3/s at the peak of the flood wave. This is one of the aspects of draw down operations that deserves attention, as this wave results in elevated water level in the downstream reservoir and possibly increased flood risks.

Water level
As seen in section 3.2, the influence of the backwater curve due to the dam extents up to 60 to 70 km upstream in the river. For the reference draw down scenario, the water level is restored to free flowing conditions for the entire river reach. Since the difference between the free flowing conditions and the water level due to backwater curve is smaller in the upper section of the reservoir, the free flowing conditions persists longer in the upper reach of the reservoir than in the lower reach of the reservoir. To mobilize sediment and in turn transport the sediment through the reservoir and pass the dam utilizing the free flow conditions, a flushing event should have a long enough duration at the lower water level.

Flow velocities
After the onset of the draw down operation at the dam, the flow velocities throughout the reservoir approach the free flowing levels prior to the construction of the dam. As expected, it takes some time for the retrogressive wave to travel in the upstream direction of the reservoir. Figure 3.7 shows that 20 km upstream of the dam the flow velocity almost doubles and at 40 km of the dam the flow velocity increases by approximately 30-40 %. Further upstream in the reservoir, 60 km from the dam the influence of the draw down is limited as the flow velocity is only increased by 5-10 %, since the difference between backwater conditions and free flowing conditions is limited. Closer to the dam, there is still a small influence of the dam, increasing the water level and reducing the flow velocity.

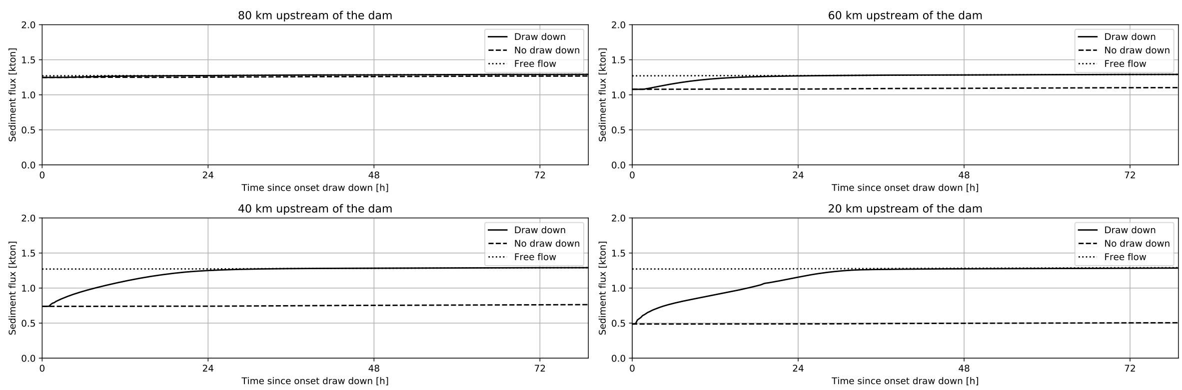


Figure 3.7: Increase in flow velocity in the reservoir, compared to free flowing conditions and normal operational conditions

3.3.2. Sediment transport in the reservoir and at the dam

The sediment transport capacity at different cross-sections will be shown for the duration of the experiment, both the instantaneous as well as the cumulative sediment flux. The sediment flux for the original situation without dam and the situation with dam but without draw down will be included as well for comparison. The cross-sections considered are located at 20, 40, 60 and 80 km upstream of the dam and at the dam itself.

Instantaneous sediment flux

During flushing operations the water level is lowered at the dam and a retrogressive wave travels through the reservoir. This retrogressive wave increases the flow velocity and the sediment flux. At the cross-sections 80, 60, 40 and 20 km upstream of the dam the sediment flux approaches the original sediment flux of free flowing conditions, while at 20 km upstream of the dam a small effect of the backwater effect is noticed. Figure 3.8 shows the instantaneous sediment flux at the different cross-sections. Due to the increase in transport capacity, erosion takes place in the reservoir at the locations with deposits.

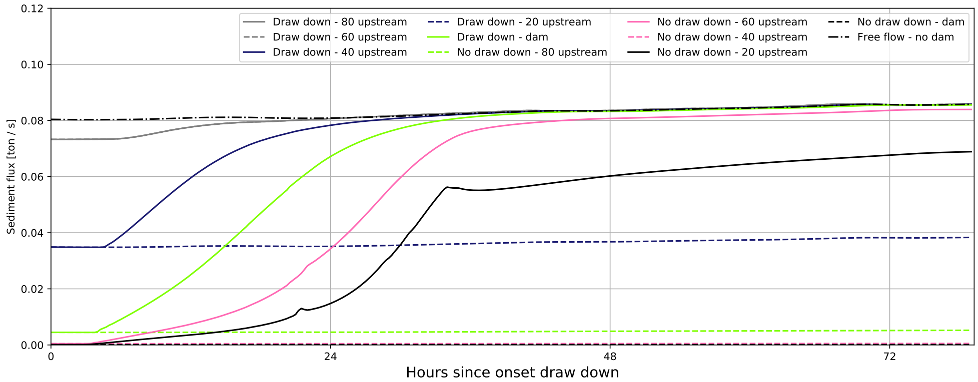


Figure 3.8: Sediment flux as a function of time at four cross-sections in the reservoir and at the dam. Closer to the dam the flow velocity increases earlier in time, while further upstream flow velocities increase later in time.

At the downstream cross-sections the sediment flux increases earlier than at the upstream cross-sections as the retrogressive wave is migrating in the upstream direction. However, as the difference between the water depth during normal operational conditions and the equilibrium depth is smaller in the upper section of the reservoir than for the lower section of the reservoir, more time is needed at the lower section of the reservoir to achieve free flowing conditions. This emphasises the need for sufficient time during draw down operations.

Cumulative sediment flux

The cumulative sediment flux for the reference flushing event is shown in Figure 3.9 for the four cross-sections in the reservoir. The cumulative sediment flux for both free flowing conditions without dam and normal operational conditions are included as reference. Especially close to the dam, i.e. at 20 km upstream of the dam and at the dam itself, the cumulative sediment flux increases significantly resulting in release of sediments through the dam. The largest increase in sediment flux is observed closest to the dam. The water level increase due to the backwater curve is larger closer to the dam compared to further located cross-sections. Only at the cross-section located 20 km upstream of the dam the riverine flow conditions are not fully restored due to a small backwater effect of the dam.

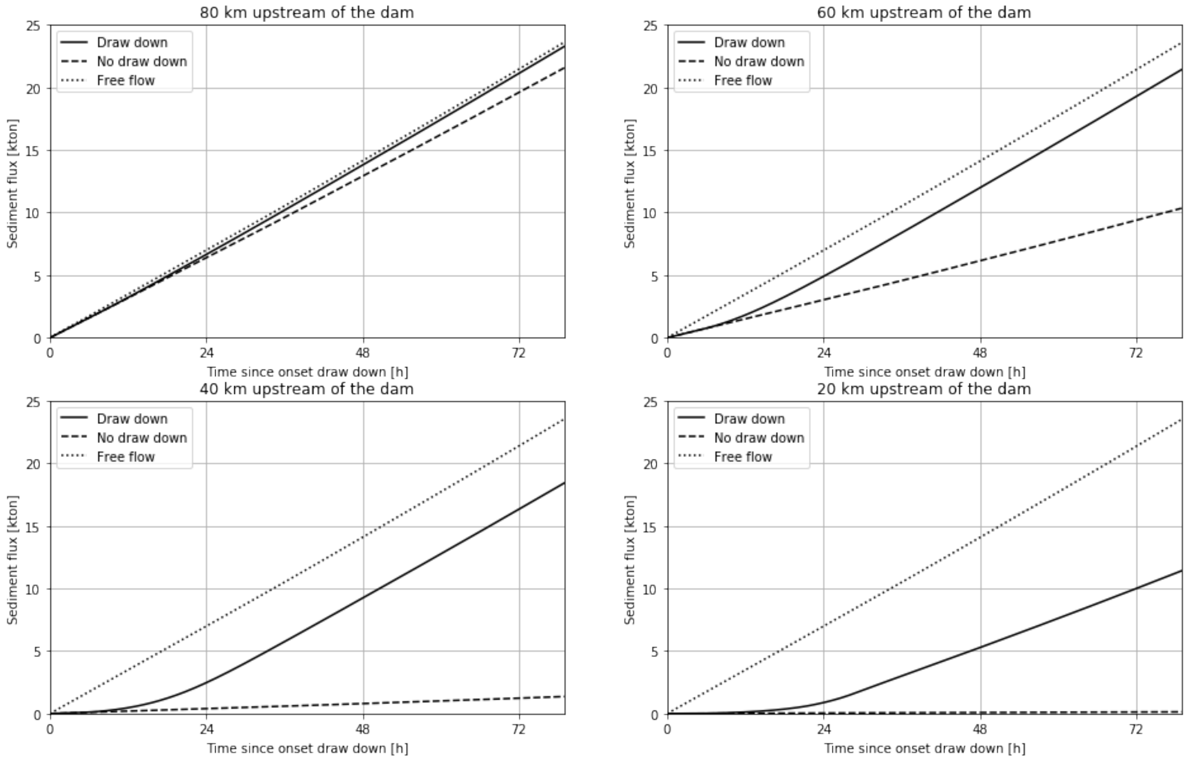


Figure 3.9: Cumulative sediment transport as function of time for four cross-sections in the reservoir, compared to no draw down and free flowing conditions

3.4. Overview results

The cumulative sediment flux after 24 hours at the water level set point through the dam for all the flushing experiments are presented in Tables 3.1 and 3.2, subdivided for the different discharges imposed at the boundary. Findings on the influence of the draw down rate, water level set point and duration at low water level set point are given below in the sections 3.4.1, 3.4.2 and 3.4.3 respectively.

Table 3.1: Cumulative sediment flux after 24 hours at the water level set point for the different combinations of water level set points and ramping rates for discharges of 2750 m^3/s and 4125 m^3/s

	Q = 2750 m^3/s				Q = 4125 m^3/s			
$\Delta h_{set}[m]$ / r [m/h]	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
- 12.5 m	6.0	8.5	10.1	11.2	16.0	20.6	23.1	24.8
- 10 m	1.4	2.3	2.8	3.3	10.5	13.4	15.2	16.5
- 7.5 m	0.5	0.8	1.0	1.1	3.2	3.8	4.2	4.6

Table 3.2: Cumulative sediment flux after 24 hours at the water level set point for the different combinations of water level set points and ramping rates for discharges of 5500 m^3/s and 6875 m^3/s

	Q = 5500 m^3/s				Q = 6875 m^3/s			
$\Delta h_{set}[m]$ / r [m/h]	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
- 12.5 m	30.6	37.2	40.7	42.9	50.6	59.0	63.4	66.1
- 10 m	27.6	33.5	37.8	38.9	49.4	57.5	61.7	64.4
- 7.5 m	12.5	14.3	15.4	16.2	33.8	38.57	40.9	24.6

3.4.1. Influence draw down rate

The influence of the draw down rate on the sediment flux is considered for the distance from the dam and the discharge at which the flushing event is started:

- **Distance from the dam:** the closer to the dam, the more influence the draw down rate has on the total sediment flux during a draw down event. This is because the water level difference between the reservoir water level and the free flowing water level is higher closer to the dam.
- **Discharge into reservoir:** the relative influence of the draw down rate is largest for flushing events at low discharge than for flushing events at high discharge. The absolute difference in cumulative sediment flux during a flushing operation at 40 and 60 km upstream from the dam for all discharge increases with approximately 5%. At high discharges the free flowing conditions are faster reached and therefore the influence of the draw down rates is limited. Again, closer to the dam the influence of the draw down rate combined with the discharge into the reservoir is larger than further upstream in the reservoir.

Figure 3.10 shows that for all water level set points the sediment flux increases. The initial increase in draw down rate from 0.4 m/h to 0.6 m/h results in the greatest increase in sediment flux for all discharges and water level set point. Increasing the draw down rate from 0.6 m/h to 0.8 m/h leads to a smaller increase in sediment flux compared to increasing the draw down rate from 0.4 m/h to 0.6 m/h.

In addition, the relative increase in sediment flux is lower at high discharges than at lower discharges. For example, by increasing the draw down rate from 0.4 m/h to 0.6 m/h at Q = 4125 m^3/s and lowering the water level to free flow conditions results in an increased sediment flux of 29%, while for the same increase in ramping rate and free flowing conditions but at Q = 6875 m^3/s the increase in sediment flux is only 17 %. One explanation might be that for higher discharges the free flowing conditions are reached faster, i.e. in the order of 5 to 10 hours, compared to lower discharges and that therefore the relative contribution of the draw down phase decreases.

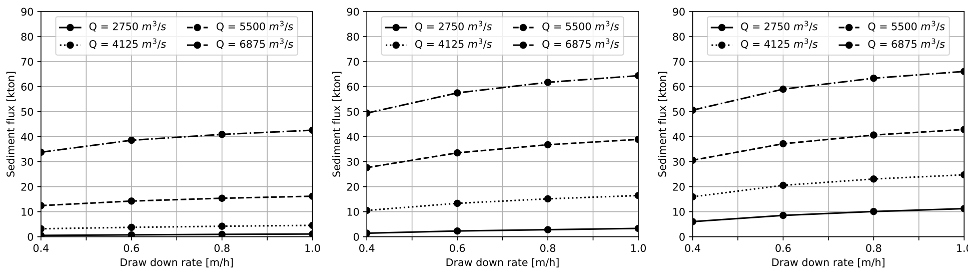


Figure 3.10: Influence of the draw down rate on the cumulative sediment flux after 24 hours at the water level set point

3.4.2. Influence water level set point

The influence of the water level set point on the sediment flux is considered for the distance from the dam and the discharge at which the flushing event is started:

- **Distance from the dam:** the influence of the water level set point is negligible for the cross-sections located 80 and 60 km from the dam. Closer to the dam the influence of the water level set point increases. For the runs where free flowing conditions where not reached the influence of the water level set point is greater than for runs where free flowing conditions were reached.
- **Discharge into reservoir:** For the lowest discharge, 2750 m^3/s, a backwater curve is still present 20 km upstream of the dam for both flushing event where the water level is lowered by 7.5 and 10.0 m, resulting in a fraction of the total sediment flux compared to free flowing conditions. Lowering the water level below limits of free flowing conditions merely moves the sediment in the upper part of the reservoir slightly downstream in the reservoir than enabling the sediment to pass the dam.

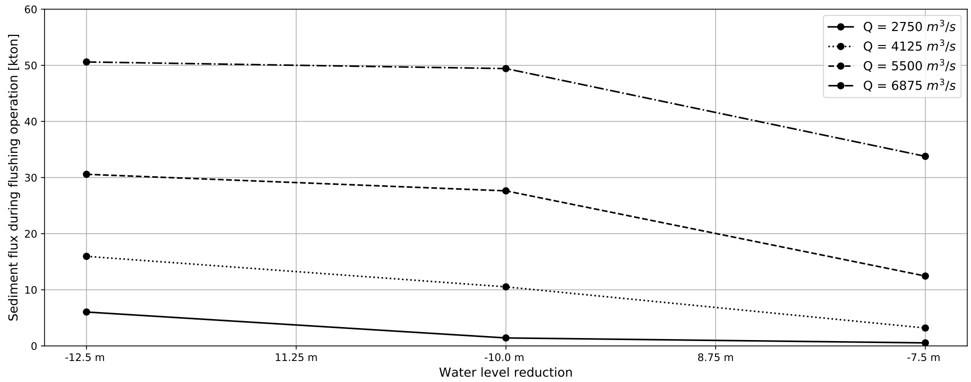


Figure 3.11: Influence water level set point on the cumulative sediment flux after 24 hours at the water level set point

Figure 3.11 shows the influence of the water level set point on the cumulative sediment discharge during flushing events for all flushing events with a draw down rate of 0.4 m/h. Especially at lower discharges lowering the water level set point increases the sediment flux. For all discharges and ramping rates at with a lowering of the set point by -7.5 m the water depth near the dam does not reach free flowing conditions. Obtaining free flowing condition increases the sediment flux significantly and is most effective for removing sediment from the reservoir. For the other draw down rates the same is true. An overview of graphs for the other draw down rates can be found in appendix C.

3.4.3. Duration low water level set point

Finally, a short analysis is done on the duration of the low water level during the flushing operation, using the baseline flushing event as an example. The cumulative sediment flux for the different cross-sections is calculated after 24, 48 and 72 hours at the water level set point. For each duration and cross-section the ratio between the sediment flux during flushing and the sediment during no flushing is presented. This indicates the relative increase in sediment flux due to the flushing operation. The filling of the reservoir, when the sediment flux through the dam is assumed to be zero, is included.

The cumulative sediment flux during draw down operations for different cross-sections is calculated for the time it takes to reach free flowing conditions with an additional 24 hours at free flowing conditions. These cumulative sediment fluxes are compared to free flowing conditions and the situation without a draw down operation. The results are shown in Table 3.3. Closer to the dam the draw down operation has more influence on the sediment flux than at the most upstream cross-section, increasing the sediment flux 335 times with respect to no draw down operation. On a yearly basis, a short draw down operation at low flows can increase the annual sediment flux by 20 % or approximately 6.7 kton through the dam.

Table 3.3: Ratio sediment flux at the 5 cross-sections for the reference draw down event with 24 hours of free flowing conditions as well as the gain in sediment transport capacity due to draw down.

	Ratio sediment flux [-]	
Distance from dam	Draw down / Free Flow	Draw down / No draw down
0	0.41	335
20	0.60	106
40	0.73	13
60	0.90	2.1
80	0.99	1.1

In Table 3.4 the relative effect of the reference draw down operation with 48 hours at free flowing conditions compared to free flowing conditions without the dam and the situation with no draw down at the dam. Again the biggest influence of the draw down operation is at the downstream part of the reservoir. Compared to maintaining free flow for 24 hours, maintaining free flow for 48 hours results in sediment fluxes closer to free flowing conditions. The additional time needed is 28 %, while the sediment flux at the dam almost doubles from 6.7 kton to 12.7 kton.

Table 3.4: Ratio sediment flux at the 5 cross-sections for the reference draw down event with 48 hours of free flowing conditions as well as the gain in sediment transport capacity due to draw down.

	Ratio sediment flux [-]	
Distance from dam	Draw down / Free Flow	Draw down / No draw down
0	0.54	423
20	0.73	123
40	0.84	15
60	0.94	2.1
80	1.0	1.1

Again increasing the duration at free flowing conditions by 24 hours increases the sediment flux at all cross-section, but the increase is largest at the lower cross-sections. Compared to maintaining free flow for 24 hours, the duration of the entire flushing event increases by 35 % whilst increasing the sediment flux at the dam by approximately 280 %. It therefore beneficial for the sediment flux to maintain free flowing conditions for a longer period of time. This effect however reduces for higher draw down rates and for higher discharge. At the same time, for higher draw down rates free flowing conditions are obtained faster and for higher discharges the free flowing conditions are also obtained faster since the free flowing conditions have greater water depths.

Table 3.5: Ratio sediment flux at the 5 cross-sections for the reference draw down event with 72 hours of free flowing conditions as well as the gain in sediment transport capacity due to draw down.

	Ratio sediment flux [-]	
Distance from dam	Draw down / Free Flow	Draw down / No draw down
0	0.60	456
20	0.79	136
40	0.88	15
60	0.96	2.2
80	1.0	1.0

4

Operational scenarios: frequency, draw down rate, timing, and coordination

The influence of timing, frequency and coordination of flushing operations within a hydropower dam cascade is determined using the bucket model described in chapter 2. The results of the flushing experiments in chapter 3 are used as input for the bucket model. The bucket model will be used to determine operational rules for sustainable sediment management considering both the sediment flux and electricity generation at cascade level.

4.1. Draw down settings during scenarios

To determine operational rules for sustainable sediment management, the bucket model will be used. During the evaluation of the imposed operational rules three variables will be kept constant amongst all scenarios.

First, the bucket model will only use flushing events that lower the water level in the reservoir to free flowing conditions, since this proved to be best strategy in the flushing experiments performed in Delft3D-FM. Secondly, the free flowing conditions are maintained for 48 hours in all scenarios, after which the reservoir is refilled again. Finally, the time steps used is kept constant and set at 6 hours, as mentioned in chapter 2.

All flushing experiments in chapter 3 were executed using a discrete set of constant discharges at the upstream boundary of the reservoir. Since the measured discharge of 2018 is imposed at the upper reservoir in the bucket model, there is a need to determine the sediment flux for draw down events that occur at other discharges than the discrete set used in chapter 3. This is done by interpolation between the sediment fluxes obtained for the experiments with a discharge of 2750 m^3/s and 6875 m^3/s. This is explained in chapter 2

In this chapter two methods are used to test operational rules in the cascade. In the first method, the random sampling method, there is an user defined probability that at a give time step a dam will initiate a flushing event. In the second method, flushing events will be initiated at pre-determined moments in time.

For the random sampling method 10,000 runs are executed per applied operational rule. This number of runs proved to show satisfactory conversion, as can be seen in appendix D. For the method using pre-determined operations, 200 runs are performed to test the influence of the starting moment of these operations during the wet season. These 200 runs follow from the that fact that all operational rules are focused on initiating draw down operations during the high flow season. With the used settings, the duration of the wet season is approximately 250 days.

4.2. Overview random sampling for draw down and fixed scenarios

The operational rules considered for the random sampling method are explained in section 4.2.1. The pre-determined operations are explained in section 4.2.2. The random sampling method will be applied to a cascade of three dams, while the pre-determined operations are applied to a cascade of five dams.

4.2.1. Random sampling for draw down

The random sampling method is used to determine the influence of four variables on both the electricity generation and sediment flux:

1. **Frequency of draw down operation:** the amount of times a draw down operation is conducted during a year
2. **Draw down rate during operation:** the draw down rate used during flushing events
3. **Timing of draw down operation:** the threshold value of the discharge at which flushing operations can be initiated
4. **Sediment permeability at a dam:** to what extend sediment can pass the dam

During the random sampling method, three scenarios are considered, which are:

- **Simulations on frequency and timing of draw down operations.**

  The average frequency of flushing events considered is varied between one, two and three times per year. This is done to determine the influence of the frequency of flushing events on the sediment flux and electricity generation.

  To assess the influence of the timing of a flushing event during the flood season, two threshold values for initiating a flushing event are considered. The first threshold value is at a discharge of 5000 m^3/s. This threshold value is below the design discharge of the turbines, which is 6000 m^3/s. The second threshold value is 6500 m^3/s, which is above the design discharge of the turbines. Initiating flushing operations only if the threshold value is exceeded, mimics the pre-dam situation of the dam where the majority of the sediment flux is transported during high flows in the wet season.

  Combining the three considered average frequencies of draw down and the two threshold values result in six different sampling scenarios, which will all be executed.

- **Simulations on draw down rate during flushing**

  The results of the flushing experiments in chapter 3 showed that high draw down still increase the sediment flux at the dam considerably at high discharges, even though this effect is smaller than for low discharges.

  All six simulations with the different threshold and frequency of flushing events are executed again, but this time only using draw down rates of 0.8 m/h and 1.0 m/h. The sets of simulations can be compared to determine the influence of the draw down rate on the resulting electricity generation and sediment flux at each dam.

- **Simulation on reduce sediment permeability of a dam**

  One simulation is made for the situation where the sediment permeability of the third dam and final dam in the cascade has a sediment permeability of 80% compared to the other dams. This simulation is included because it was found that for two consecutive dams the size of the low level gates differed a factor four (MRC, 2019b, 2019c). This simulation will show the consequences of a design of low level gates that is not fit for purpose.

4.2.2. Pre-determined operations

For the pre-determined operations, only a subset of all possible scenarios is considered, focusing on two orders of flushing (Morris & Fan, 1998; MRC, 2019a). In the first variant, the flushing operations is started at the upstream dam in the cascade, progressively moving towards the most downstream dam in the cascade. In the second variant, the order of flushing in the cascade is just opposite, where the flushing operation in the cascade is started at the most downstream dam and progressively moving in upstream direction.

For both variants the draw down rate is fixed at 0.8 m/h to eliminate the influence of different draw down rates, as this is already covered in the simulations using the random sampling method. All scenarios with pre-determined cooperative flushing strategies take place in the wet season of the used hydrograph, from July 27th to September 29th.

In these experiments the influence of timing of the flushing events during the flood season is explored, as well as the influence of the time between the onset of flushing events for the dams. The influence of the onset of the cascade flushing is varied from the onset of the wet season to 50 days after the onset of the wet season.

Cascade flushed in downstream direction

Flushing the cascade in downstream direction is based on the idea that the operators utilize the released flood wave at upstream reservoirs. The released flood wave increases sediment transport capacity. Additionally, drawing down the water level of the downstream reservoir prior to the arrival of the flood wave prevents the deposition of sediments the reservoir.

The pre-determined operations are tested for a cascade of five dams, contrary to the three dams for the scenarios developed using random sampling. The cascade with five dams resembles the planned cascade of the case study in the mainstream Mekong river. Using five dams is possible due to the limited amount of scenarios that are considered in the fixed scenarios and thereby limiting the computational time.

To determine the influence of the time between the onset of the flushing events in the cascade on the electricity generation and sediment flux, four different scenarios are considered:

1. **Simultaneous draw down.**

   The onset of the flushing operations at all dams is equal. The peaks of the flood waves released at the dams are not enhanced, but the flood waves reach the next dam before the draw down is complete, resulting in elevated discharge levels at the end of the draw down operation.

2. **Draw down prior to arrival flood wave.**

   The flushing operation at a downstream dam is started at the moment the flood released from the upstream dam is halfway the reservoir. The released flood wave from the upstream dam arrives at the next dam at the second time step of the draw down operation. This enhances the discharge through the dam at that time step and thereby increase the sediment transport capacity.

3. **Draw down at arrival flood wave.**

   Flushing in a reservoir starts at the moment the flood wave from the dam upstream reaches the downstream dam. This results in an amplification of the flood wave.

4. **Draw down as flood wave passes dam.**

   The flushing operation is started as the peak of the flood wave released by the upstream dam just arrives at the downstream dam. Doing so amplifies the discharge and sediment transport capacity of the flood wave in downstream direction in the cascade.

Cascade flushed in upstream direction
The second strategy uses the free flowing conditions after draw down to increase the sediment flux through a reservoir (MRC, 2019a). As the water level in a reservoir has reached free flowing conditions, the reservoir upstream will start a draw down operation. The released flood and sediment pulse flows through the reservoir will increase due to the free flowing conditions.

Similar to the situation where the cascade is flushed in downstream direction, different time intervals between the onset of the flushing operations are considered. The different time intervals considered between the onset of flushing operations are:

1. **Arrival flood wave as draw down has finished.**

   The flood wave released at the upstream dam arrives at the next dam at the moment the minimum water level is reached. The flood waves released from the dams migrate through the next reservoir while free flowing conditions persist. The most downstream dam starts the refilling of the reservoir just after the flood wave from two dams upstream has passed.

2. **Arrival flood wave just after draw down has finished.**

   The interval between draw down events is gradually increased to reduce the time no hydropower dam is generating electricity. Under this scenario where the reservoirs are flushed with a time interval of 12 hours the cascade is producing no electricity for 36 hours.

3. **Draw down after free flowing conditions reached.**

   The reservoir upstream of a dam initiates a flushing event at the moment the downstream reservoir obtains free flowing conditions. In addition, only for a period of 12 hours no electricity is generated in the entire cascade.

4. **Always one dam generating electricity.**

   The draw down of the last reservoir in the cascade is initiated at the moment the downstream dam has finished its draw down operation and is generating electricity again. Doing so ensures a base electricity generation of one dam at all times.

In addition to the described scenarios above, two extra scenarios are considered with a longer draw down period to extend the duration of the entire flushing event to 5 days per dam. This is first done for the scenario where all dam initiate a draw down operation simultaneously. In the second scenario the reservoirs in the cascade will be flushed from the downstream dam in the upstream direction again, but while doing so ensuring that at most two dams are not generating electricity. This scenario resembles the proposed operation by the MRC closest (MRC, 2019a).

Finally, the boundary condition at the upstream reservoir is changed from 2018 to 2019, which was a year without a distinct flood pulse in the wet season. The operation where three dams are always generating electricity is applied to assess the outcome of flushing the cascade anyway despite the lack of high discharges.

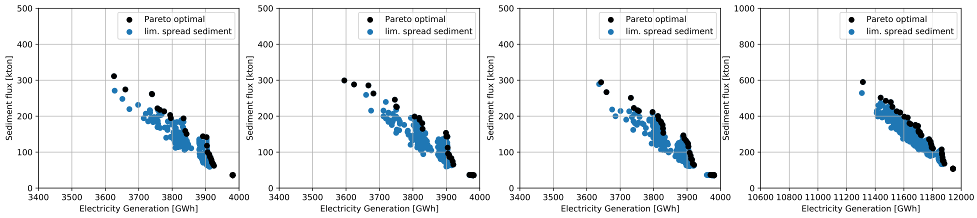
4.3. Results random sampling for draw down

The results of the randomly sampled runs for different operational rules are first refined before they are presented. Since the goal is to combine electricity generation with sustainable sediment management throughout the reservoirs in the cascade, the runs with limited differences in sediment flux between the different dams are identified. Large differences in sediment flux between the reservoirs results in excess deposition or erosion the reservoir.

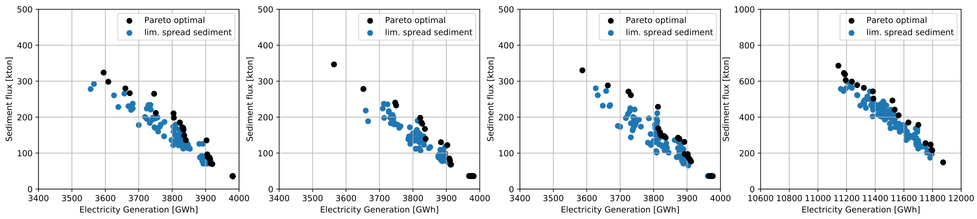
To only obtain runs with limited difference in sediment flux between the dams, only the results with a limited spread of 2 percent point at each dam are considered. In other words, the results of a run are only included if the contribution of the individuals dams is between 31% and 35 % of the cumulative sediment flux. For the remaining runs, the Pareto optimal front is determined for each dam and on cascade level.

4.3.1. Influence frequency flushing operations

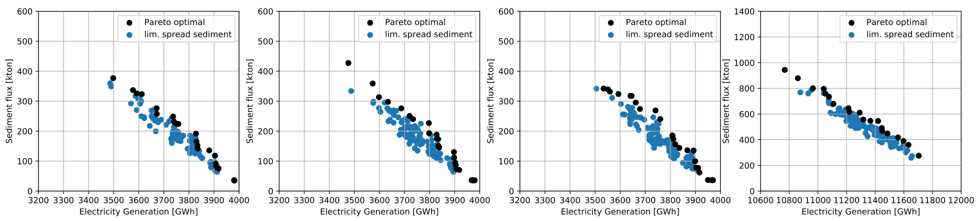
The influence of the frequency of a flushing event in the wet season is evaluated for the runs with on average one, two or three flushing events per wet season, with the limitation that no flushing operation is initiated if the discharge below 5000 m^3/s. The results of these simulations are shown in Figure 4.1. Enlarged figures of the results can be found in Appendix D.



(a) Electricity generation versus sediment flux. Flushing onset limit: > 5000 m^3/s, with on average one flushing event in the wet season.



(b) Electricity generation versus sediment flux. Flushing onset limit: > 5000 m^3/s, with on average two flushing events in the wet season



(c) Electricity generation versus sediment flux. Flushing onset limit: > 5000 m^3/s, with on average three flushing events in the wet season. Note the different scale w.r.t. Figures 4.1a and 4.1b

Figure 4.1: Electricity generation versus sediment flux for each dam (panel 1-3) and the total cascade (panel 4).

The results for the different settings show clusters in the solutions, representing the number of flushing events during the wet season. The panel for dam 1, the left panel of Figure 4.1a, shows at least four distinct clusters of no, one, two and three flushing events during the wet season. The single dot at the bottom right of the diagram at approximately 4000 GWh and 36 kton represents the scenario without a flushing event taking place in the flood season. Moving up and left the second cluster is distinguished with all runs with exactly one flushing event during the flood season. Performing an additional flushing operation increases the sediment flux by approximately 70 kton, which is twice the sediment flux if no flushing operation is initiated. The electricity generation however reduces by approximately 80 GWh.

4.3.2. Influence flushing at higher discharge

The discharge limit for onset of a draw down operation is increased from 5000 m^3/s to 6500 m^3/s. This increase in the limit for the onset of flushing operation explores the situation where dam operators wait for higher discharges to initiate a flushing event. Moreover, this shows the effect of executing flushing operations at discharges either below or above the design discharge of the turbines at 6000 m^3/s.

Limiting the onset of flushing events to discharge values over 6500 m^3/s highlights the effect of clustered results as seen in Figure 4.2. At most two flushing events can be initiated during the flood season if the initiation of flushing operations is limited to discharges over 6500 m^3/s. Compared to the limit at 5000 m^3/s, especially better results for the sediment flux for almost similar electricity generation are obtained. This is due to two factors. First, at higher discharges the sediment flux increases for a flushing event with the same or similar draw down rate. The second reason is that for discharges over 6000 m^3/s the water cannot be used to generate electricity as the design discharge of the turbines is exceeded. Performing flushing operations at these discharges utilizes this excess discharge.

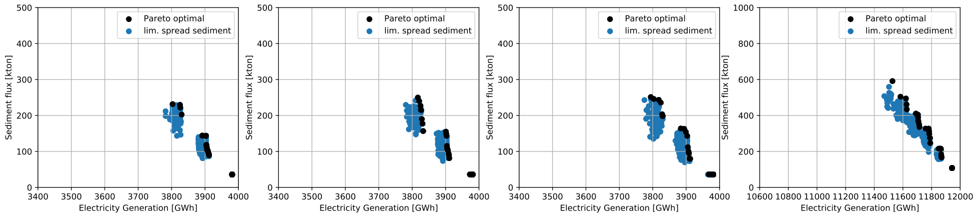


Figure 4.2: Electricity generation versus sediment flux, with on average one flushing event in the wet season. Flushing is only initiated at discharges above 6500 m^3/s. (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

4.3.3. Influence draw down rates

The draw down rates used during flushing events are limited to high draw down rates of 0.8 m/h and 1.0 m/h, while the limit on draw down operations is kept at 5000 m^3/s. In theory, this should lead to solutions with increased electricity generation and sediment flux results due to the shorter duration and higher draw down rate.

Figure 4.3 shows the results for the operational rules where only the high draw down rates of 0.8 m/h and 1.0 m/h are used. The Pareto optimal results shift up and to the right compared to Figure 4.1a, implying a higher sediment flux and more electricity generation compared to the scenarios using also 0.4 m/h and 0.6 m/h as draw down rate. This is due to two reasons. The first reason is that the duration of the considered flushing event is shorter, thus a dam has more time to generate electricity. Secondly, more sediment is transported at the dam due to the use of higher draw down rates.

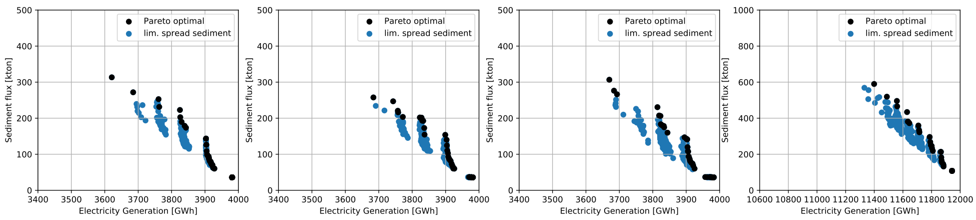


Figure 4.3: Electricity generation versus sediment flux, with on average one flushing event in the wet season, while only use draw down rates of 0.8 m/h and 1.0 m/h. (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

Limiting the draw down rates to 0.8 m/h and 1.0 m/h, while increasing the discharge limit for initiation of a flushing event to 6500 m^3/s, results in further conversion of the results as seen in Figure 4.5. Especially for electricity generation the spread is very limited, compared to runs with the same frequency of draw down operations. For the sediment flux on the other hand, the increased discharge threshold to start a draw down event and the application of only high draw down rate can significantly increase the sediment flux at the dam.

As the difference in sediment flux at the dam for flushing operations with draw down rates of 0.8 m/h and 1.0 m/h is in the order of 2 to 3 kton per flushing event, the increase in sediment flux can be partially attributed to the increased discharge threshold of the flushing event. Since at 6000 m^3/s the design discharge of the turbines is reached, a similar amount of electricity generation is lost for either flushing at for example 6000 m^3/s and 7000 m^3/s. The incoming discharge after the initiate of the flushing events also partially contributes to the total sediment flux

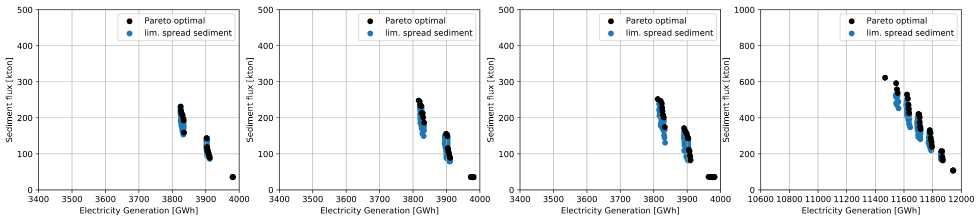


Figure 4.4: Electricity generation versus sediment flux, with on average one flushing event in the wet season, while only use draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

4.3.4. Influence reduced sediment permeability

This section considers the influence of reduced sediment permeability at a dam by a flawed design of the low level gates and shows the extra effort needed to pass sediment through the dam. The reduced sediment permeability of 20% is applied to the most downstream dam of the cascade. Flushing operations are only initiated at discharges above 5000 m^3/s and on average occur once per flood season. This way, the results can be compared to the runs shown in Figure 4.1a.

Due to the reduction in sediment permeability of dam 3, the average sediment flux for a single flushing event reduces. Whereas previously almost 150 kton of sediment could be passed through dam 3 during a single flushing event (see Figure 4.1a), this reduces to approximately 120 kton. To achieve 150 kton an additional flushing event is needed at the costs of about 60 GWh.

On cascade level, the cumulative sediment flux reduces for equal electricity generation compared to the situation without reduced sediment permeability.

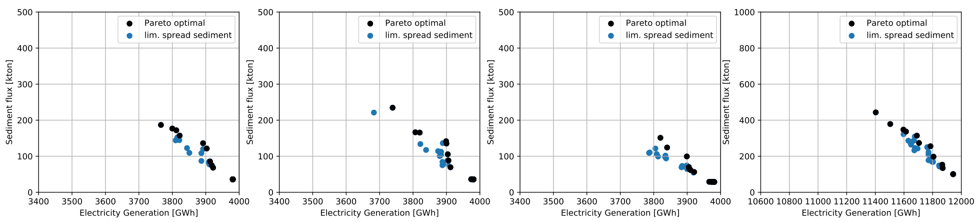


Figure 4.5: Electricity generation versus sediment flux, with on average one flushing event in the wet season, while the sediment permeability of most downstream dam in the cascade is reduced. (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

4.4. Results fixed scenarios for draw down

The experiments for fixed scenarios are conducted for a cascade existing of five dams. All dams use a draw down rate of 0.8 m/h to eliminate the effect of the draw down rate on the results.

4.4.1. Flushing cascade in downstream direction

In these scenarios each reservoir is flushed once during the flood season. The reservoirs are flushed progressively in downstream direction starting from the most upstream located reservoir. As mentioned before, the time difference between the onset of the flushing operation at the dams is varied to see the effect of starting the flushing operations at different time intervals.

The time difference for initiating the draw down operation appears to be an important parameter when flushing progressively in the downstream direction for two variables.

First, the sediment flux passing the dams varies amongst runs using a different time interval between the start of flushing events. The largest observed sediment flux at the dams and cascade level occurred when a downstream reservoir started the flushing operation just prior to the arrival of the flood wave. Increasing the time interval of onset between the dams decreased the total sediment flux.

The second effect of varying the time interval between the onset of flushing operations is the relative contribution of each dam to the total sediment flux through the cascade. For time intervals of zero, one and two time steps between the start of flushing operations, the most upstream dam has the lowest contribution to the sediment flux and the most downstream dam in the cascade the highest, see Figure 4.6. The difference in relative contribution is the smallest for a time interval of 2 time steps.

At a time interval of 3 time steps the pattern of the relative contributions of the dams to the total sediment flux changes. For this time interval the most upstream dam has the largest contribution to the total sediment flux and the most downstream dam in the cascade the lowest. The most upstream dam results in the same absolute sediment flux and electricity generation across all runs with different time intervals. Thus from a time interval of 3 time steps or larger, the sediment flux through the cascade reduces progressively downstream. Progressively flushing downstream with time intervals between flushing events of 2 time steps or smaller results in an increasing sediment flux through the cascade.

For the different time periods between the onset of the flushing operation, the total electricity generation does not change significantly.

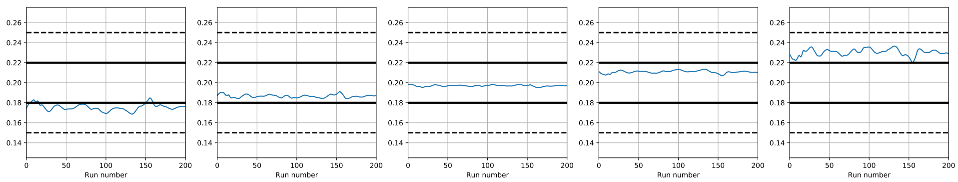


Figure 4.6: Relative contribution of each dam to the total sediment flux at the dam

Compared to the random sampling scenario where draw down operations are initiated above 5000 m^3/s, only one pre-determined operational scenario showed improvements for the total sediment flux. This is the scenario where the flushing operation is initiated just prior to the arrival of the flood wave from the upstream reservoir. Especially for the second and third dam in the cascade this is increase is largest, while at the same time the electricity generation is equal or slightly reduced.

For the runs where the draw down coincided with the arrival of the flood wave from an upstream reservoir, no single run produced results where the sediment flux at each dam was approximately the same. The runs where a part of the flood wave has passed the dam before a flushing event is started, resulted in similar sediment fluxes at each dam. But the sediment flux passed through each dam was smaller than for the runs where the draw down was started prior to the arrival of the flood wave.

4.4.2. Flushing cascade in upstream direction

The scenarios where the cascade is flushed from the downstream reservoir progressively in upstream direction shows very different results compared to progressively flushing downstream.

The maximum sediment flux that can be passed at all dams in the cascade by progressively flushing in upstream direction is smaller than the situation where the cascade is flushed progressively in downstream direction. However, timing the operation so that the flood wave reached the next dam as the free flowing conditions are just reached or so a time period later produces results with slightly higher electricity generation for similar sediment fluxes at the dams. The difference in electricity generation between dams is again insignificantly small.

The difference in sediment flux between the dams shows the same pattern for all scenarios, where the most downstream dam has the largest sediment flux. The time at which the progressive upstream flushing operation is started in the cascade is more important compared to the pre-determined operations progressively flushing downstream. The difference in sediment flux between dams varies more based on the in flowing discharge at the upper boundary.

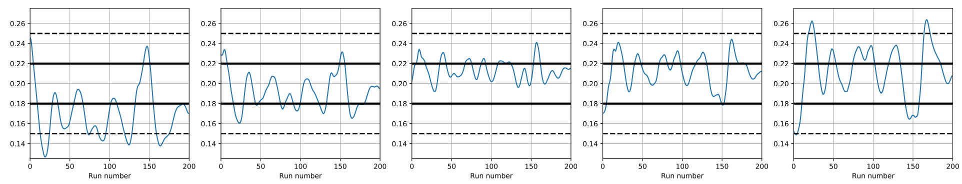


Figure 4.7: Relative contribution of each dam to the total sediment flux at the dam, progressively flushing in upstream direction with a time interval of two time steps (12 hours)

Flushing with three dams generating electricity
To test the operational strategy where at least three dams are generating electricity whilst flushing the cascade in upstream direction, the duration of the free flowing conditions at the flushing events is extended from 48 hours to 72 hours. To be able to compare the obtained results to the previous runs, the pre-determined strategy where all dams are flushed simultaneously is executed again. Doing so enables to compare the runs with a shorter and long duration at free flowing conditions.

Comparing the results of two simulations shows that generating electricity with three dams at all time reduces the sediment flux through the dam significantly compared to the operational strategy where all dams are flushed simultaneously. Keeping a part of the cascade operational comes thus at a cost with respect to the sediment flux. The electricity generation and sediment flux at the third dam of the cascade is shown for both scenarios in Figures 4.8 and 4.9

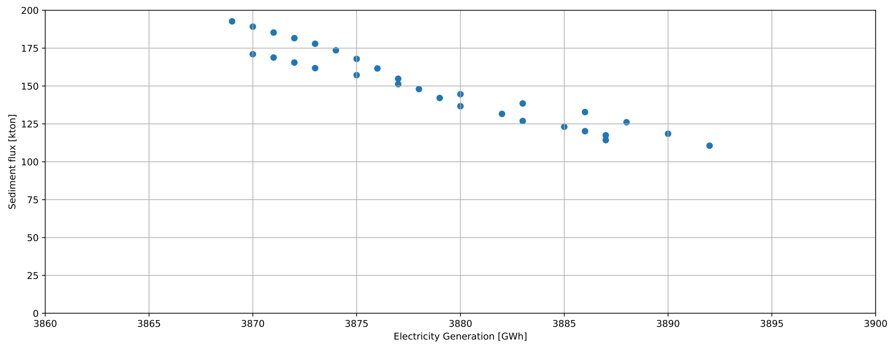


Figure 4.8: Electricity generation versus sediment flux for the scenario with simultaneous flushing at all dams.

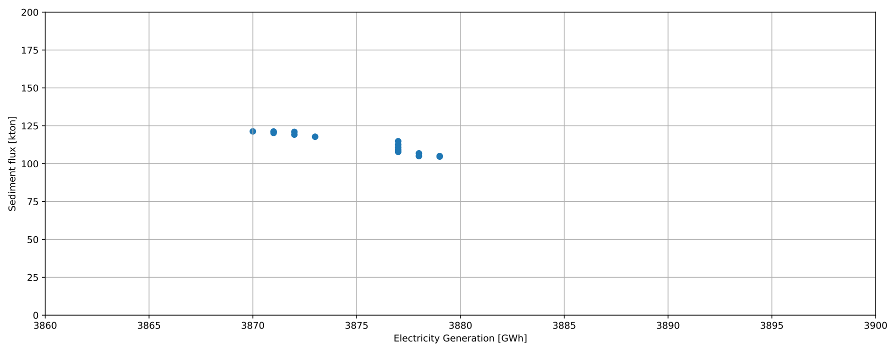


Figure 4.9: Electricity generation versus sediment flux. Flushing cascade in upstream direction, whilst generating electricity at three dams simultaneously

Increasing the duration of the free flowing conditions by 24 hours increases the sediment flux at each dam by approximately 50 kton. The electricity generation on the other hand is reduced on average by 25 GWh per dam. From the random sampling method it was observed that an additional flushing event increased the sediment flux by 70 kton, while reducing the electricity generation by 80 GWh. This shows that extending the duration of free flowing conditions is a better trade-off than flushing more frequently with a short duration at free flowing conditions.

Flushing at low flows

The final simulation explores what would happen if a flushing operation is initiated every year during, even in the absence of high discharges. To do so, the hydrograph of 2019 is imposed at the upstream boundary, which was a year without high discharges in during the wet season.

The operational strategy for which this is tested, is the strategy where at least 3 dams generate electricity while flushing the reservoirs in upstream direction. The resulting sediment fluxes at the dams are compared to the sediment fluxes at the dam without starting a flushing operations.

Without draw down events, the sediment flux is approximately 3 kton for all dams. Applying the operational strategy results in a sediment flux at all dam of about 15 kton. For reference, the sediment flux in 2018 for the situation without draw down events was approximately 36 kton.

5 Discussion

The discussion will be divided into two sections. First, the schematization, assumptions and simplifications for the flushing experiments on the draw down rate and the water level set point from chapter 3 will be discussed, as well as the results of these flushing experiments. Secondly, the schematization, assumptions and simplifications as well as the results for the scenarios on the operational scenarios of chapter 4 are discussed.

5.1. Discussion on flushing experiments

The discussion on the flushing experiments is divided into two parts. The first part discusses the simplification made for the Delft3D-FM model and the possible effects on the results. Secondly, results from the flushing experiments are discussed.

5.1.1. Discussion on model settings, assumptions and simplifications

- With the one-dimensional river and reservoir section considered in the Delft3D-FM model, the complex two-dimensional sedimentation and erosion processes are not accounted for, both during normal operational conditions as well as during flushing events. Additionally, lateral sediment transport interactions, such as lateral channel formation in the coarse in-channel sediment, during flushing events are not taken into consideration. By doing so, only the in-channel sediment flux over the bed rock section in the middle of the river is accounted for. This results in an overestimation of the sediment flux.
- The Delft3D-FM model with RTC tools developed in this study considers one grain fraction, namely fine to medium sand of 200 μm. In reality gravel, larger sand, silt and clay fractions are present in the reservoir and these fraction mix with the sand fractions. Therefore a sorting effect of the sediment in longitudinal direction is expected, with the larger grain sizes settling at greater distance from the dam than sediment with a smaller grain size.
- During the calibration of the sediment transport the sediment transport is reduced by a factor 30 to match the observed sediment flux of the considered sand fraction. Writing out the Engelund-Hansen formulation for the grain size diameter results in:

  $$s = mu^n = \frac{k}{D}u^n \tag{5.1}$$

  with the flow velocity u, n = 5, D the diameter of the grain size considered and k:

  $$k = \frac{0.05\ c_f^{3/2}}{(\Delta g)^2} \tag{5.2}$$

  The sediment diameter is related to the sediment flux by D^{-1}, meaning that the found sediment flux can mobilise sediment with a diameter 30 times larger. The flushing operations as modelled in the used Delft3D-FM model indicate that even sediment up to gravel can be mobilised in the reservoir.

- A limitation with respect to the erosive capacity of the flushing events is the use of a fixed bed level without morphodynamic bed level updates (Morris & Fan, 1998). In reality the dam and subsequent reservoir cause the formation of a delta in the upper reach of the reservoir, resulting in little to none sediment reaching the influence area of the flushing operations. After several years the in-channel storage and outcrop storage of sediment is deprived and little to no sediment is available to be transported through the dam due to flushing operations. Only after the delta migrates downstream in the reservoir, flushing experiments will be able to restore the sediment flux through the dam. Therefore this research is applicable for the initial situation when sediment is still available in the form of in-channel storage and for the situation with a fully alluvial bed due to depositions in the reservoir.

- The dam in the Delft3D-FM model is modelled as a sill with a gate over the entire river width, which moves vertically to control the discharge through the schematized dam. The schematized gate opening is on the level of the river bed. The result is that all bedload can immediately pass the dam, without initial sedimentation close to the dam. This differs from reality on at least two aspects:

    1. In reality the low level gates are not located at the river bed level (MRC, 2019c). Since a fraction of the sediment flux is transported as bedload, low level gates are needed to pass this fraction through the dam. Without low level gates at the river bed level initial sedimentation at the toe of the dam will occur before all bedload is able to pass the dam.
    2. The model has no limitation on the discharge passing through the low level gates, whereas questions have been raised on the design of the low level gates for the planned dams in the Mekong river. The total surface area of the low level gates between two consecutive dams differs by a factor 4. Either the low level gates at one dam are oversized or undersized at the other dam (MRC, 2019b, 2019c).

- As only the fine sand load is added to the model (and not the fine silts and clay and coarse sediment and gravel), the model only provides information on the sediment flux for this portion of the load. The high suspended sediment concentration related to flushing operations are not included in the model. However, once can consider the other sediment fraction qualitatively, based on the sediment flux realised during flushing operations.

- In the model, the fixed water level boundary condition should be replaced in future studies with a Q-H relationship to better represent the water level at the downstream reach. Preferable this downstream boundary condition also considers the possible back water curve of a downstream dam if it is nearby.

- In the experiments, the draw down rate is assumed constant, thereby reducing the water level linearly. The influence of time varying draw down rate is not considered, which might be better at mobilizing sediment in the reservoir (Omer et al., 2020). The result is that the used draw down rates are not optimized for any variable such as sediment flux or flood wave mitigation.

5.1.2. Discussion on results of flushing experiments

- **Limited increase in flow velocity:** during flushing operations in reality the flow velocities increase, even above flow velocities occurring during free flowing conditions. However, for the flushing events considered this was not observed for the set of draw down rates from 0.4 m/h to 1.0 m/h. This might be due to the schematised shape (i.e. rectangular) in the model, rather than a more natural trapezoidal shape or triangular shape. Compared to real life flushing events the flow velocities in the reservoirs might be underestimated and therefore the sediment transport during flushing as well.
  A more extreme flushing event with a draw down rate of 1.5 m/h was also modelled as a test and for this draw down rate the flow velocity near the dam slightly exceeded the flow velocity occurring during free flowing conditions. The results of this extreme draw down event is included

in appendix C.

- **Duration flushing events free flow:** for all four different discharges in which the water level is decreased to free flowing conditions with an equal ramping rate, the duration of the total flushing operation is equal. The fact that for high discharges the free flowing conditions are obtained quicker than for low discharges is not included in the model. The model thus compared the total time of the flushing operations, rather than the time needed to draw down the water level to free flowing conditions, maintain free flowing conditions and refill the reservoir.
- **Duration free flowing conditions:** in the analysis of all flushing experiments only three durations, i.e. 24, 48 and 72 hours, at the draw down water level are considered. Since the majority of the sediment flux is transported during free flowing conditions, it might be better to extend the duration of free flowing conditions beyond 72 hours from two perspectives. First, the sediment flux per flushing event increases while the relative time spent on filling during a flushing operation is reduced. Secondly, at each flushing event a flood wave with high discharge is released into the downstream reservoir with adverse effects on the flood risk and the (aquatic) ecosystem, as well as the mentioned upstream adverse effects such as possible bank instabilities (Hui, 2015; Mohammed-Ali et al., 2021).

5.2. Scenario analysis

For the scenario analysis the settings, assumptions and simplifications for the model are discussed first, followed by the discussion of the results found.

5.2.1. Discussion on model settings, assumptions and simplifications

Considering the bucket model to analyse scenarios, the following must be noted:

- **Constant travel time of discharge:** as the model has relatively large time steps of 6 hours to facilitate shorter run times, subtle changes in travel time of flood waves cannot be taken into account. The consequence is that some flood waves travel too slow in the model and that the resulting absolute timing of flushing events is not entirely correct. However, conclusions based on the relative timing, that is initiating the flushing event just prior to the arrival or passing of a flood wave, for flushing events are still possible.
- **No damping of flood waves:** the model passes the flood waves on from one dam to the other, without calculating the damping that would normally occurs in the reservoirs. The sediment transport capacity in downstream reservoirs after the release of a flood wave is thus an overestimation, since the damping observed in the Delft3D-FM model was between 2 and 10 % depending on the flushing event. On the contrary, in reality tributaries discharging in the mainstream Mekong also increase discharges, which is not considered in the model.
- **No notion of suspended sediment or retention time of sediment:** the model does not consider suspended sediment that might be able to be sluiced through during high flows in combination with a water level reduction. Rather than the actual sediment transport the model calculates the potential mobilization of sediment since it does not take into account the availability of sediment. However, by focusing on the high discharge events, for which it is know that sediment is present especially in the rising limb of the flood pulse, implicitly the potential flushing capacity is more or less aligned with the supply of sediment into the reservoirs.
- **No tributaries of Mekong or lateral inflow:** at the schematized section of the Mekong several tributaries join the Mekong river, of which the Nam Ou is the most important. It delivers 6-7 Mt/yr into the mainstream especially during high flows, which would end up just downstream of the second dam at Luang Prabang (Shrestha et al., 2018). The hydropower dam, and all other downstream dams, located below Luang Prabang should pass more sediment through the dam than the dams upstream of the Nam Ou. If tributaries such as the Nam Ou would have been included, the dams downstream of the Nam Ou would have to increase the sediment flux through the dam to achieve equal sediment fluxes into and out of the reservoirs.

- **Only discrete flushing events:** the model is only equipped with a range of four draw down rates to lower the water level to free flowing conditions. Flushing events with lower or higher draw down rates are not considered. This limits the range of solutions.

- **Interpolation between discrete flushing events:** since the flushing events in chapter 3 are only executed for a discrete set of constant discharges at the upstream boundary of the reservoir, the sediment flux for flushing events exposed to time-varying and discharges outside the used set are interpolated. It is noted that this will result in an underestimation at high discharge for the sediment flux, while it will lead to over-estimations of the sediment flux for low discharges.

- **Limited operational alternatives:** the model only has two modes of operation, which are maintaining the water level at operational water level or executing a flushing event. Real sluicing operations, where the water level is lowered to the minimum operational water level to both pass incoming sediments through the dam as well as generate electricity at the same time, are not included in the model. The sluicing events are an effective method to prevent deposition of sediment released from an upstream reservoir.

- **Constant water level difference:** the electricity generation at a dam is calculated assuming a constant water level difference over the dam. This neglects the elevated water level due to high discharges at the downstream end as well as possible back water effects of a downstream dam reaching the toe of the dam. This results in an overestimation of the electricity generation, especially during high flows and higher tail water level caused by the downstream dam.

- **Calibration sediment flux:** the sediment flux through the cascade is calibrated for the situation that the dams do no start a flushing operation. For the situation that free flow is assumed throughout the cascade, the sediment flux is approximately 70 % of the sediment flux observed in the Delft3D-FM model. This means that the obtained increases in sediment flux due to flushing operations is lower than it would be in reality.

For the two different methods to develop operational scenarios, i.e. random sampling or pre-determined combinations of flushing in a specific order, some additional limitations are discussed. Three additional limitations for the random sampling method are:

1. **Limited number of simulations:** albeit the simulation is carried out for only one year and with a time step of 6 hours for a limited part of the hydropower dam cascade and only focusing on the high flows during the wet season, the resulting simulations are only a small part of the entire solution space. With approximately 200 discharge values over 5000 m^3/s in the used hydrograph and three dams considered, there are in the order of tens of million combinations of either one or two flushing event per dam.

2. **Sampling same or very similar scenario twice:** due to the stochastic nature of the method equal or very similar scenarios might be generated during random sampling. This reduces the amount of new information provided for a run.

3. **A posteriori method:** the chosen method does not include preferences of an individual dam operator or governing body with respect to either electricity generation and sediment flux at both dam and cascade level. A wide range of possible operational alternatives is created, from which the decision maker can select the preferred option. However, it might be that the decision makers are only interested in a sub set of the presented operational alternatives.

The method to run simulations for fixed pre-determined scenarios has also two limitations:

1. **Limited number of simulations:** only the scenarios given as input to the model are run. It is up to the user to feed the model with pre-determined scenarios.

2. **Dependent on model user:** it is up to the user of the model to initially use its knowledge to generate scenarios that might prove to have good properties for both electricity generation as well as the sediment flux through the dams.

5.2.2. Discussion on results of scenarios

This section of the discussion on the results of the different scenarios is divided into three parts. The first parts covers some general remarks on all experiments. The second section discusses the experiments on the influence of the frequency, discharge limit for flushing operation onset and the draw down rate used. Finally the results of the pre-determined scenarios are discussed.

Only flushing at high discharge events

For all random sampling scenarios and the majority of the fixed scenarios considered a flushing operation is only initiated if the discharge exceeds a threshold of at least 5000 m^3/s, with the possibility that the threshold discharge is not exceeded. This might happen during years with low flows, such as in 2019 and 2020. Due to lower than normal rainfall and an exacerbating effect of dam operations in the Lancang cascade, the flood pulse normally migrating through the Mekong between June and October did not occur (Eyler et al., 2022; Van Binh et al., 2020).

If discharge values do not exceed 5000 m^3/s, no flushing event will take place. This reduces the sediment flux through the dams again to approximately 36 kton, which is determined first as reference situation. The scenario analysis indicates that for one flushing event in the wet season between 60 to 150 kton of sediment can be mobilized at each dam. If for the hydrograph of 2019 the reservoir would be flushed according to the proposed strategy by the MRC with draw down rates of 0.4 m/h, the average sediment flux would increase from 36 kton to approximately 50 to 60 kton.

Influence of frequency, limit and draw down rate

Even though more frequent flushing increases the sediment flux through the reservoir, it also creates frequent flood waves in the cascade that might be enhanced by the dams downstream. As the flushing events are planned by the operators, villages and downstream dams can be informed.

Limiting the onset of flushing events above the design discharge of the turbines instead of discharges below the design discharge of the turbines, provides better solutions with respect to electricity generation and the sediment flux than initiating flushing events for discharges above 5000 m^3/s. However, the flood waves released at higher initiation limit are also greater. This has negative implications for communities downstream, as well as the aquatic ecosystem (Annandale et al., 2016).

Again, the operators are faced with the dilemma to either wait for increased discharges for which they initiate the flushing operation or initiate the flushing operation nonetheless at a lower discharge than initially desired.

Pre-determined flushing in upstream direction

The initial idea behind the operational strategy where three dams are always generating electricity at full capacity is that the flood released from an upstream dam is sluiced through the downstream reservoir. During the sluicing operation the water level is lowered from the normal operational water level to the minimum operational water level. At this water level the dam is still able to generate electricity, given that the concentration of sediment is with acceptable limits to be passed through the turbines, while at the same time passing discharge and sediment through low level gates.

The results from the bucket model are different from the original proposed operation, as the dams in the bucket model can either generate electricity or initiate a flushing event after which the free flowing conditions are maintained. Now, the model returns a higher sediment flux and lower cumulative electricity generation.

6
Conclusion

6.1. Conclusions

The construction of the hydropower dams in the mainstream of the Mekong river in the Laos will provide electricity generation and revenue for the dam operators. This comes at the cost of interrupting the sediment delivery from the upstream Mekong river basin to the delta. Without sediment management, the dam cascade will interrupt practically all coarse-grained sediment, i.e. gravel and sand. Although the dam cascade will pass through most of the fine sediment, i.e. clay and silt, the fine sediment are trapped temporarily in the impoundments at low and medium flows, and are then mostly released and passed during floods.

For effective flushing operations the water level should be lowered until free flowing conditions are achieved throughout the reservoir. Lowering the water level partially, proves to be an ineffective measure to transport sediment throughout the entire reservoir. For all draw down rates at 2750 m^3/s, for which the water level is lowered partially thus free flowing conditions are not reached, the sediment flux at the dam is a factor 6 lower for a reduction in water level of 10 meter at the dam. For a reduction in water level of 7.5 m at the dam the sediment flux is a factor 10 lower than for free flowing conditions.
The relative influence of increasing the draw down rate on the sediment flux is largest for lower discharges than for higher discharges. Increasing the draw down rate at 2750 m^3/s from 0.4 m/h to 0.6 m/h increases the sediment flux after 24 hours of free flowing condition by 42 % from 6.0 to 8.5 kton. The same increase in draw down rate at 5500 m^3/s yields an increase in sediment flux by 22 % from 30.6 to 37.2 kton.
Extending the duration of the free flowing conditions proves to be an effective method to increase the sediment flux through the cascade. Additionally, with a longer duration the eroded sediment can migrate further downstream in the reservoir.

Using flushing operations at cascade level can increase the sediment flux be a factor 3 to 5, whilst the electricity generation reduces by approximately 2.5 %. Initiating flushing operations only at discharges above 6500 m^3/s, rather than above 5000 m^3/s increases the sediment flux. On the other hand, the loss in electricity generation is similar with the design discharge of the turbines at 6000 m^3/s. Since all discharge above the design discharge cannot be used for electricity generation and is diverted to flood gates anyway.

Combining the Delft3D-FM with RTC tools and the bucket model provides a technique to investigate different operational rules within a dam cascade with respect to electricity generation and sediment flux. The model can be adjusted and extended for different cascades by changing river parameters, adding tributaries and changing dam parameters.

6.2. Recommendations

The recommendations are divided into three parts for clarity and are made with respect to model use, model development and further research and implementation of the found results into dam cascades experiencing sedimentation.

6.2.1. Further model development

The Delft3D-FM model can be further expanded to a 2D or 3D-model to better represent the river properties of the Mekong river and include a more detailed dam design. This will better represent the interaction of the river banks with the main river channel and better represent the sediment flux under flushing operations.

Also using different grain size fractions, including a suspended sediment fraction and including the bedrock outcrops better represent the sediment transport process in the Mekong river. Combining this with at least a second dam in the Delft3D-FM model can prove useful to investigate combinations of flushing and sluicing events in a dam cascade.

The bucket model should be improved by incorporating a more elaborate river routing method that is capable of representing the river flow more accurately. Additionally, more variables than electricity generation and the sediment flux at the dam should be included whilst determining the Pareto front. Examples of additional variables might be flood risk or suspended sediment concentration.

Another alteration to the model might be to include a more sophisticated algorithm to acquire the Pareto front, preventing the sampling of outcomes that are far off the Pareto optimal front.

6.2.2. Future studies

For the smaller sediments such as clay, silt and fine sand, combinations of flushing and sluicing events might prove to be an effective method to first erode sediment from a reservoir and then be passed through the next reservoir. Such combinations might be interesting for future studies since during sluicing operations electricity generation can continue.

Secondly, the actual sediment trapping and mobilization in the created reservoirs in the cascade for different grain sizes should be further investigated using a more advanced Delft3D-FM model or a similar model. This will provide insight in the exact sediment deposition for different grain sizes. Ideally, this model will is also used to investigate the influence of different sediment management strategies.

6.2.3. Application of findings in dam cascades

Cooperative sediment management on a cascade scale has proven to be able to increase the sediment flux through the dams at a small loss of electricity generation.

In recent years still, dam designers and operators have designed dams and proposed operational rules from the paradigm of the ‘economical lifetime of a dam’. However, constructed dams are not easily decommissioned and removed after full-out sedimentation in the reservoir, nor are these costs included during the design of the project. To this end, it is advised that dam designers and operators include sediment management strategies on cascade level early on in the design process to achieve a sustainable sediment management strategy.

Additionally, initiating the flushing of the cascade above the design discharge of the turbine but below extreme discharge values proves to utilize the available water best. The sediment fluxes at all dams and electricity generation are very similar, preventing excess sedimentation or erosion in either of the reservoirs.

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A

Mekong basin HPP development

This appendix describes the context in which the hydropower dam cascade is planned. Secondly, properties of the planned dams are highlighted.

A.1. Mekong River Basin

The Mekong River Basin spans six countries from its origin in China, moving down along the border of Myanmar and Lao PDR to the border of Thailand and Lao PDR. After flowing through Lao PDR the Mekong enters Cambodia to finally enter the Southern Chinese Sea in Vietnam. The Mekong can be divided into an upper basin and a lower basin, where the Upper Mekong Basin (UMB) spans China and a fraction of Myanmar. The Lower Mekong Basin (LMB) spans Thailand, Lao PDR, Cambodia and Vietnam, where the Mekong enters the South Chinese Sea.

A.1.1. Upper Mekong River Basin

The Mekong river originates from the Tibetan Plateau, flowing through narrow and steep gorges in China. The Upper Mekong River has the most substantial main stream hydropower development of the Mekong, with 12 completed and operational hydropower plants, 1 under construction and at least 10 planned projects being a part of the Lancang cascade (MRC, 2020a). The Lancang cascade is the most upstream of three cascade on the main stream Mekong River and estimation to trap between 83-94% (Kondolf, Rubin, et al., 2014; Kummu and Varis, 2007) of the incoming suspended sediment, i.e. fine sand and clay, and will trap all coarser bedload. A study by Van Binh et al. (2020) presents the change in suspended sediment load for seven measurement stations in the main stream Mekong river and shows that the suspended sediment load of the first measurement station downstream of the Lancang cascade decreased with 90% compared to the predam situation. In the predam situation, approximately 50% of the total sediment load entering the South Chinese Sea originated from the Lancang basin, meaning that approximately 40% of the total sediment load to the Mekong Delta is trapped in the Upper Lancang cascade reservoirs (Walling, 2008).

A.1.2. Lower Mekong River Basin

People in the Lower Mekong Basin depend on the Mekong River by means of two industries: agriculture and fisheries, both providing food and income. Of the agricultural production, 80 % of the production is rice, which is the most important part of the diet in the lower Mekong basin. People in the lower Mekong basin depend between 47 - 80 % of their protein intake on fish and other aquatic life caught from the Mekong, depending on the country considered (Hortle, 2007). Substantial changes in the river therefore might affect large parts of the population in the lower Mekong basin.

A.2. Hydropower cascade development in Lao PDR

The river flow in the Mekong is subject to seasonal and intra-seasonal fluctuations with a distinct flood pulse and low flow season and rapid, short term variations in river discharge caused by run-off from monsoon rains and tropical storms (MRC, 2015). This fluctuation has resulted in a unique ecosystem and an abundance of natural resources for the entire Mekong river basin for water, food and energy providing income for many. Human activities such as water extraction for irrigation, settlements with hard structures in and at river banks and the construction of hydropower dams put pressure on the ecosystem and climate change adds additional stress on the ecosystem. The impacts of all these stresses combined possibly lead to unforeseen and cumulative effects (MRC, 2019a).

The entire Mekong River Basin has a large hydropower potential which remained largely untouched during the 20th century due to limited economical development in the remote provinces of China and ongoing wars and political instability in the lower basin countries. Since the stability in the region and the economical development in the basin countries the development of hydropower plants has gain interest as a means to produce electricity to enable economic growth and generate income by selling electricity to neighbouring countries. In the upper Mekong basin in China, where the Mekong is also called the Lancang, 11 main stream hydropower dams are planned with large reservoirs, reducing the outflow of sediment by 83% with respect to the pre-dam situation, which equals a reduction of total sediment load of approximately 40 % (Kondolf, Rubin, et al., 2014). An additional consequence of the Lancang cascade is the reduction the level and variability of high flows and increasing the low flows and variability which is estimated to be observed in as far as Cambodia in a situation without hydropower dams on the main stream lower Mekong (Van Binh et al., 2020).

The government of Lao PDR has set the goal to become the ‘battery of Asia’ by constructing hydropower plants in the country, generation income from selling the generated electricity to neighbour countries. Lao PDR is the least developed country in the Mekong Basin with 18% of the population living below the national poverty line, with a declining trend between 1993 and 2019 (Lao Statistics Bureau & World Bank, 2020).

A.2.1. Main stream hydropower dam cascade

Lao PDR has a total utilizable hydropower potential of 26,500 MW and the planned cascade in the main stream Mekong has a potential of 5,051 MW, thus the planned cascade will utilize a fifth of the total potential in Lao PDR (IHA, 2016). The Lao government already agreed on electricity supply to the neighbouring countries of Thailand, Cambodia and Vietnam, totalling 15,500 MW by 2030 available for export. Needless to say, the planned cascade plays an important role in achieving the set goal to become the battery of Asia. All dams in the cascade will be operated as run-of-river hydropower plants, meaning that the inflow at the reservoir equals the outflow and thereby maintaining a constant water level in the reservoir within some operational limits to anticipate for changing incoming discharge.

The hydropower cascade in the main stream Mekong in Lao PDR is still in development and planning phase, with only the Xayaburi hydropower plant being commissioned and operation till date. This research is limited to the cascade of five hydropower plants consisting of hydropower dams at Pak Beng, Luang Prabang, Xayaburi, Pak Lay and Sanakham. The most downstream dam, i.e. Pak Chom, is not considered in this research. Pak Chom is still in a preliminary phase, i.e. the project has not been submitted for Prior Consultation and Agreement (PNPCA). Moreover, the dam is located at the border between Lao PDR and Thailand, complicating the process as both Lao PDR and Thailand have to agree with the project, whereas the dams considered in this research are all fully located in Lao PDR. It remains uncertain if and when the Pak Chom hydropower project will be constructed.

Pak Beng

The most upstream planned hydropower plant is located near Pak Beng, approximately 450 km downstream of the last main stream dam in the Lancang cascade in China. The sedimentation of all reservoirs is expected to be large here due to the fact that the sediment load is highest (MRC, 2019a). With 16 bulb turbines, 57 MW each, the operation of the hydropower plant can be adjusted flexibly to the incoming discharge. The dam is also equipped with low gates and openings below the water intake for the turbines to accommodate sediment sluicing and flushing and enabling transport of deposited material just in front of the intakes of the turbines (MRC, 2017).

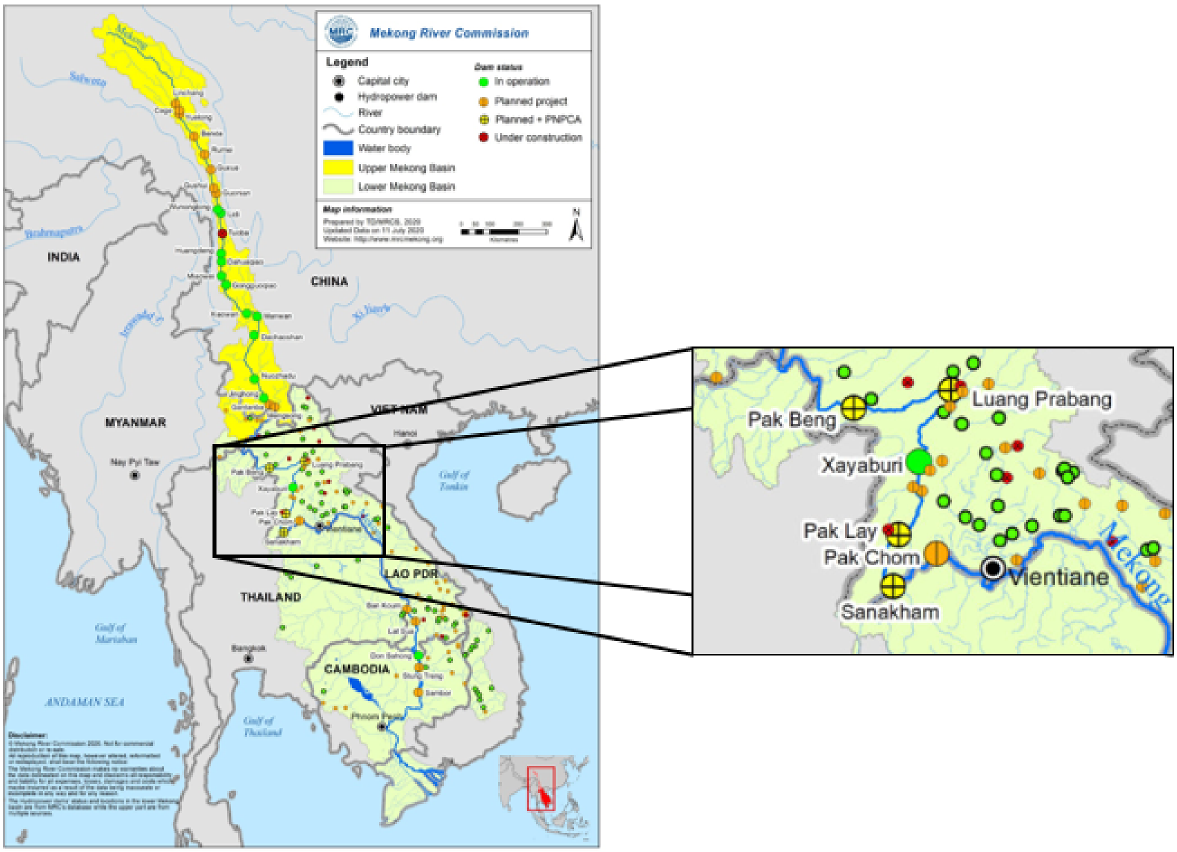

Figure A.1: The planned hydropower cascade

Luang Prabang

Luang Prabang hydropower dam is located 143 km downstream of the HPP of Pak Beng, just some 20 kilometers upstream of the town Luang Prabang. The rated discharge over the 7 turbines is 5,355 m^3/s with an installed capacity of 1,400 MW, being the largest hydropower plant in the cascade in terms of capacity. The spillway structure both has surface level outlets as well as low level gates suited for sediment management techniques such as sluicing and flushing (Pöyry, 2019). However, sediment management operation are not included in operational stratey and the low level gates will only be employed when the discharge exceeds 5,355 m^3/s. Using the Brune curve based on the reservoir volume and annual inflow, the reservoir is expected to trap at least 35 % of the incoming sediment, as the active storage volume of the reservoir is used instead of the total storage volume (Kummu et al., 2010).

Xayaburi

The hydropower plant at Xayaburi is the first dam in the hydropower cascade that is completed. The rated power amounts to 1,285 MW, generating 7,405 GWh per year and supplying electricity to 3 million inhabitants in Thailand and 1 million inhabitants of Lao PDR. The run-of-river hydropower plant has a height of 32 meter, and has put great effort in a transparent HPP for fish migration, with four options for fish migration in the upstream direction and two options for the downstream migration (MRC, 2019b).

The Mekong river, especially the reach where the cascade is planned, is characterised by the deep pools in the river stream, used by aquatic life as shelter during the dry season (Poulsen et al., 2002). These pools are potentially endangered by filling due to sedimentation of coarse sediment. In the far upstream part of the reach upstream of Xayaburi, close to the Luang Prabang HPP, several very deep pools with depths up to 35 meters are found.

Pak Lay

The fourth hydropower project in the Lao PDR cascade is located 110 km downstream of the Xayaburi project operated as a run-of-river project. The 14 turbines, each with a production capacity of 55 MW

Figure A.2: Aerial view of the Xayaburi Hydropower plant Nation Thailand, 2019

and rated discharge per turbine of about 435 m^3/s, have a total capacity of 770 MW and a rated discharge of 6,101 m^3/s. Prior to expected high discharges the water level is lowered to convey the flood wave through the dam and promote sediment transport and routing through the reservoir. The dam is equipped with surface spillways, two bottom outlets and outlets in between the surface spillway and the bottom outlets to facilitate sediment transport operations. The operator also proposed to flush the coarse sediment every 2 to 5 years in coordination with the other dams in the cascade. However, it unclear how this should be implemented and what the expected results of such flushing operations are for the Pak Lay hydropower dam and other dams (MRC, 2019c).

Sanakham

The most downstream project is located close to the border between Lao PDR and Thailand, with 12 turbines with a capacity of 57 MW at 414 m^3/s (MRC, 2020b). As the Sanakham project is located close to the border with Thailand the trans-boundary effects of the project should be preferentially be avoided, minimized where possible and at least mitigated. This in particular applies to the sediment transport at the dam. The Mekong river becomes the border between Thailand and Lao PDR after the Sanakam dam, where also the characteristics of the river change. The river changes from a bed rock controlled river with characteristic deep pools to an alluvial section of the Mekong. As the sediment transport in blocked in the cascade, the sediment supply in the alluvial reach reduces and an erosive wave from Sanakham is expected to travel downstream up to the capital of Vientiane of Lao PDR over the years (MRC, 2019a).

A.2.2. Nam Ou cascade

In the reach between the Luang Prabang and Xayaburi HPP, the Nam ou tributary enters the main stream Mekong. Together with the 3S system downstream in Cambodia, Vietnam and Lao PDR, joining the Mekong river in Cambodia, the Nam Ou is one of the major tributaries of the Mekong river, as the discharge amounts to 4 % of the annual discharge. Although the sediment influx in the Nam Ou increases under various climate change models (Shrestha et al., 2018), the planned cascade is expected to reduce the sediment flux by approximately 70 - 80 % from 4.8 - 6.7 Mt/yr to 1.1 - 2.0 Mt/year (Meynell, 2016).

B

Mekong river system in Lao PDR

This appendix is intended to provide background information on the Mekong river.

To understand the impact of the planned hydropower dam cascade, understanding the current system where the projects are planned is indispensable. The current river system in Lao PDR is undergoing continues changes due to construction of upstream hydropower dams as well as climate change, which has to be understood for the analysis on the impacts of the hydropower dams. Data regarding discharge and sediment characteristics are scarce for the Mekong, with the Discharge Sediment Monitoring Project (DSMP) in the period 2009 - 2013 as one of the few available studies on the sediment flux and characteristics in the Mekong river (Koehnken, 2014). Three measuring points are especially relevant for the planned Lao PDR cascade. The first location of interest is at Chiang Saen, upstream of the cascade, where both the suspended sediment load as well as the bedload were measured. The second location location where measurements were carried out is at Luang Prabang where only the suspended sediment load was measured. The final location of interest from the measurement campaign is Chian Khan, located just downstream of the planned cascade, where the suspended sediment concentration was measured.

B.1. Hydrodynamics

The river discharge in the Mekong at the planned cascade has been changed and is changing primarily under the influence of the construction of the Lancang cascade in China and climate change. This section explains the influence of both the Lancang cascade and climate change, which in theory have an opposite effect on the river discharge (Wang et al., 2017).

The Mekong river is characterised by a distinct dry season, followed by a flood pulse in the wet season. Water in the reach of the planned cascade originates primarily from the Tibetan Plateau, attributing up to 75 % of the discharge in the dry season and up to 50 % of the discharge in the flood season at Vientiane, downstream of the planned cascade (Adamson et al., 2009). At the location of the planned cascade the share of water originating from the Tibetan Plateau will be higher, as it is some 150 - 500 km closer to the Lancang cascade. The mean discharge at Chiang Saen in the period between 1960-2009, based on MRC data, is 2,611 m^3/s (Lu et al., 2014), with dry season flows around 1000 - 1500 m^3/s (90-days minimum flow equals 1240 m^3/s for the period 2009 - 2014), whilst the discharge during the flood pulse (90 days maximum) reaches approximately 4200 m^3/s (Li et al., 2017). The seasonality of the Mekong at Chiang Saen is seen in Figure B.1 showing the distinct flood peak arriving at June and lasting till November.

The hydrology of the Mekong river is complex, undergoing continues change due to changes in land and water use, climate change, variability in time and space of precipitation, changes in monsoon and construction and operation of hydropower dams. To make an attempt to understand the hydrology, the hydrology of the Mekong at the proposed hydropower dam cascade will described for different periods of time, based on construction of hydropower dams in the upstream Lancang cascade, comparable to previous studies. Firstly, there is a period of measurement prior to the completion and filling of the first large mainstream dam in the Lancang cascade, with measurements starting in 1960 till 1991. A transitional period is defined from 1992 onward until 2009 and a post - impact period from 2009 - 2014. Additionally

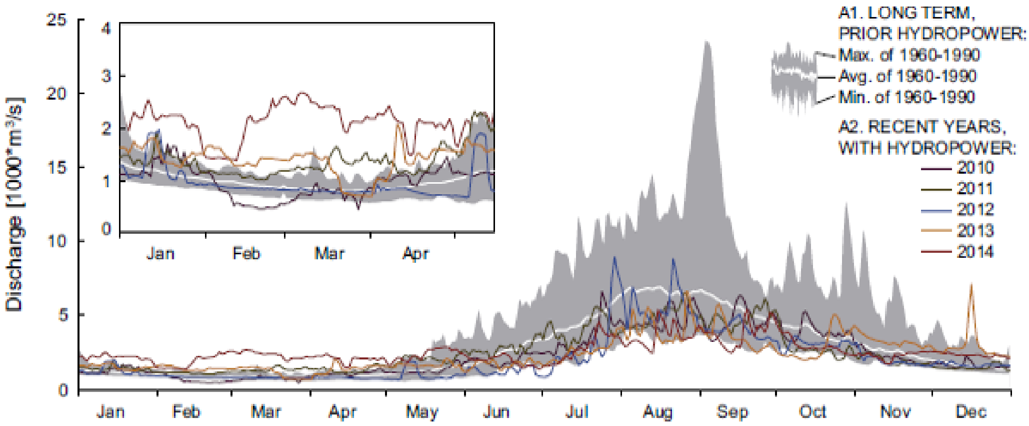

Figure B.1: Observed discharge at Chiang Saen for the period 2010-2015 in colour compared with the maximum, average and minimum discharge for the pre-hydropower dam period 1960-1990 (Räsänen et al., 2016)

Although the Mekong is often referred to as a river with high discharge variability, this is mainly true for the reach downstream of the planned cascade. For the five years of data collection in the DSMP, the variation of the discharge at especially Chiang Saen is low in comparison the reach downstream of the cascade. Defining the variability of the discharge as the ratio of the 80th percentile and 20th percentile, the ratio upstream of the cascade at Chiang Saen was between 2.3 and 3.6, whereas the variability increases through the rest of the Mekong is 3.7 to 6.4. The increasing variability in discharge in the downstream direction of the Mekong is visualised in Figure B.2. This can be attributed to the fact that the majority of the water originates from the UMB, which provides a relative continues discharge. The increased variability in the lower Mekong can be mostly attributed to the inflow of rainfall run-off from the left bank of the Mekong in Lao PDR. This area, east and downstream of the planned mainstream cascade, is exposed to the monsoon rains and drains to the Mekong river (Adamson et al., 2009).

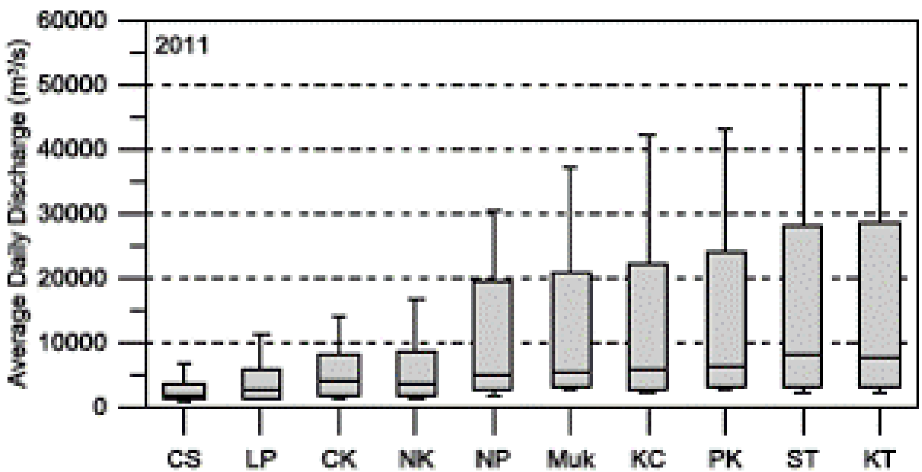

Figure B.2: Visualisation of the increasing discharge variability in the downstream direction (Koehnken, 2014)

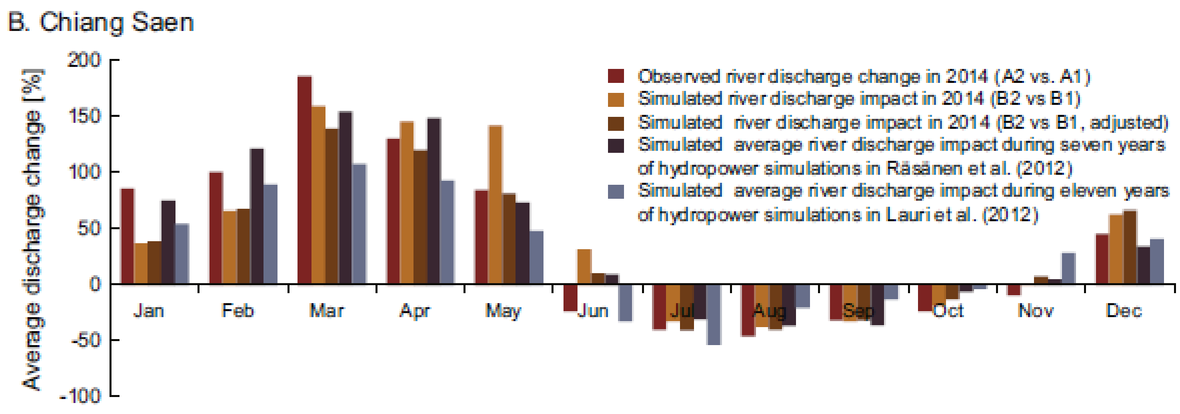

Figure B.3: Relative change of the average discharge showing an increase in flow for the dry season (December - May) and a decrease in flow during the flood season (June - November) (Räsänen et al., 2016)

Influence Lancang Cascade

The construction and commissioning of hydropower dams in the Lancang cascade has been ongoing since 1993,starting with the Manwan dam. There are multiple effects of the dams in the Lancang cascade on the hydrology at Chiang Saen. After the construction of the dams in the Lancang cascade, water from the flood season is diverted to the dry season due to the storage in the reservoirs in the Lancang cascade for constant electricity generation. After the construction of the cascade, the dry season flows slightly increased with respect to pre-dam values and the discharge in the flood season slightly decreased (Lu et al., 2014). At Chiang Saen an increase in the discharge in June of 15% is observed after the construction of the dams in the Lancang cascade and a decrease of 9% in discharge in August (Lu et al., 2014). This effect became more apparent after the completion and filling of the Xiaowan dam, a 292 m high dam with an installed capacity of 4,200 MW. Prior to the completion of Xiaowan dam, the influence of the Lancang cascade on the hydrology was low with only small changes in discharge in June and August (Lu et al., 2014). The influence of the planned Lancang cascade on the other hand is described and modelled to be noticeable (Adamson et al., 2009; Fan et al., 2015; Li et al., 2017; Räsänen et al., 2016).

An increase of flow was noticed at Chiang Saen in June of 15 % and a decrease in August of 9%, which can be related to the operation of the hydropower plants in the Lancang cascade (Lu et al., 2014). In the study it is suggested that the power generation increased in July and that the reservoirs are refilled again in August. Another explanation might be that the changes can be attributed to sediment management operations in the Lancang cascade, where the operators of the dams in the Lancang employed sluicing of water in the first part of the flood season to discharge sediment laden water and refill the reservoirs with ‘clear water’.

The shift of discharge from the flood season to the dry season has been modelled and compared to the observed discharge in the Mekong (Räsänen et al., 2016). The dry season flow from December to May was estimate to increase by 81 - 92%, whereas the average discharge in the period between June and November is estimated to decrease by 24 - 26 % at Chiang Saen. Figure B.3 shows the change in average discharge for each month. For the same time period, estimations based on daily discharge time series analysis show a similar trend, with an increase of discharge in the period December - May and a decrease in discharge June to November (Li et al., 2017). The changes are in line with the general effects of hydropower dams (Morris & Fan, 1998).

Based on the discharge time series for the period 2009 - 2014, a significant decrease in the 1-, 3-, 7-, 30- and 90-days maximum discharge has been observed , as well as a significant increase in the 1-, 3-, 7-, 30- and 90-days minimum discharge. These changes in hydrology might be caused by the Lancang cascade, but the considered time period of 5 years is too short to draw definite conclusions.

In the pre-dam period in the Lancang cascade, the arrival of the flood pulse is very regular, with the arrival with the same period of weeks each year (Adamson et al., 2009). Prior to the construction of the dams in the Lancang cascade the arrival of the flood pulse was around June 14^{th} (± 36 days) (MRC, 2019a). With the construction of the Lancang cascade and the mainstream dam development the arrival of the flood pulse is expected to be delayed to June 26^{th} (± 39 days), with the expected duration decreasing from approximately 152 days to 142 days (MRC, 2019a).

All in all, the Lancang cascade might alter the hydrology of the Mekong river by reducing the discharge in the flood season and increasing the discharge at low flows. However, only as years pass the influence of the Lancang cascade on the hydrology becomes apparent.

Influence climate change

Besides the construction and management of the hydropower dams in the Lancang cascade, climate change potentially alters the river flow. Firstly, the precipitation patterns might alter both in space and time. The amount of precipitation in the UMB is predicted to increase during the wet season (Binh et al., 2020; Hoang et al., 2016; Wang et al., 2017). On the other hand, due to the increased temperature, both evaporation and transpiration will increase as well, increasing the annual river discharge slightly, whilst the variability on shorter time scale increases. It must be noted that the uncertainty in the predicted changes for the effect of climate change are rather high (Manh et al., 2015).

The flood pulse in the upper Mekong basin can be predominantly attributed to the snow melt in the Tibetan Plateau.Due to the increased temperatures, the snow melt starts earlier in the year and more discharge will flow into the Mekong (Wang et al., 2017).

Observed discharge in recent years (2019-2021)

Recent years are characterised by particularly low discharge during the flood season. During the last three years no characteristic flood pulse was observed at the location of the planned cascade. In the 2020 flood pulse season, the peak of the flood pulse reached discharge levels just shy of 3,500 m^3/s, with a lower volume of water compared to historic discharges. This was caused by historically low rainfall in the basin and was exacerbated by the Lancang cascade (Basist & Williams, 2020; Eyler et al., 2022)

B.2. Morphodynamics

At the location of the planned mainstream cascade the river bed is bedrock controlled and characterised by deep pools in the river bed. The river cross-section is gorge like, with relatively steep banks and constricted by the surrounding topography, shown in Figure B.4. Deep pools in the section of the planned cascade can reach depths over 30 meters, providing shelter for the migrating large fresh water fish species, unique for the Mekong river.

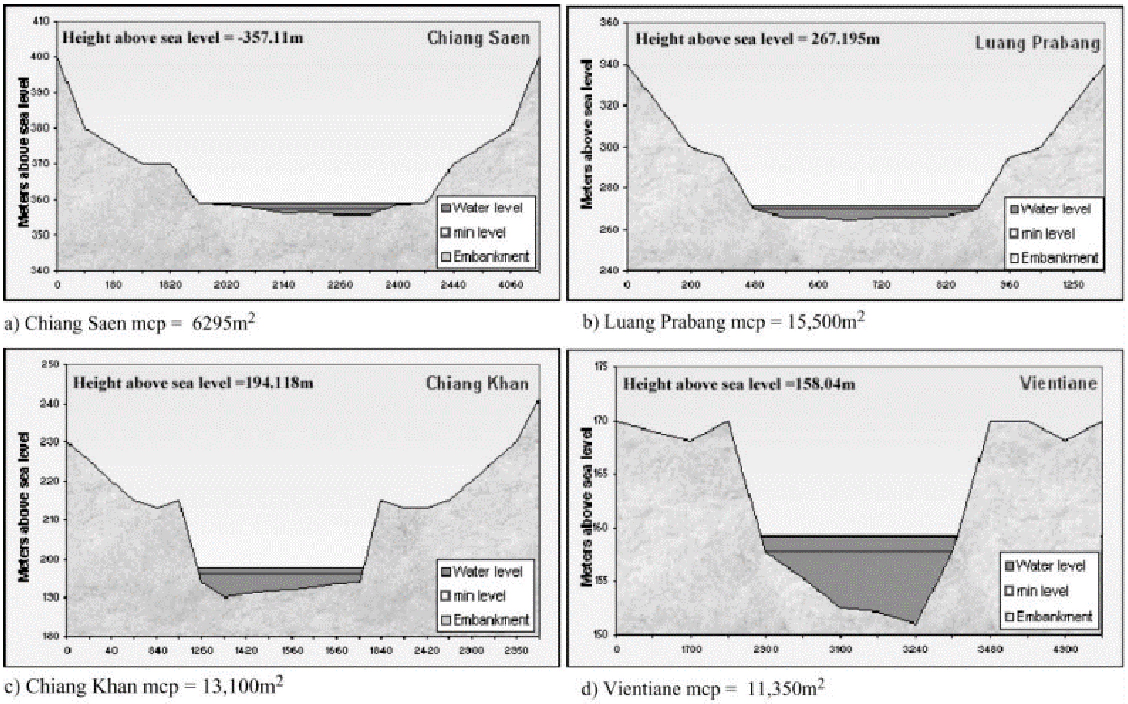

Figure B.4: Cross-section of river section at Chiang Saen, Luang Prabang, Chiang Khan and Vientiane. Note the distorted scale on the x-axis (Udomchoke et al., 2010)

Sediment transport through deep pools

The sediment flux through a deep pool in the Mekong has been observed from the low flow season in May 2006 until the next low flow season in April 2007, during 11 different periods during the year. The study located was the forced deep pool Ang Nyay, in the reach downstream of the planned mainstream cascade, located 20 km upstream of Vientiane.

Contrary to previous assumptions, the deep pools rather act as a conduit of the sediment flux during the flood season than as a sediment storage zone. At the onset of the wet season, with the increasing discharge and flow velocity, sediment enters the pool and travels through the pool during the flood pulse. With increasing discharge and water depth, the wavelength and height of the dunes increase. Dune heights increase from 1-2 m in June at the onset of the flood pulse to 4-8 m at the end of August, meaning that the height of the dunes can reach up to 20 - 30 % of the water depth at low flow flows (Conlan et al., 2008).

The maximum volume of sediment in the pool is reached around the peak of the flood pulse, after which a flat bed is formed in the centre of the pool. After the peak of the flood pulse has passed, the sediment in the pool is rapidly eroded from the pool. In bedrock-alluvial reaches, i.e. bedrock reaches with sediment overlaying the bed, it is expected that a sediment wave travels on average one or two deep pools during one flood pulse (Conlan et al., 2008).

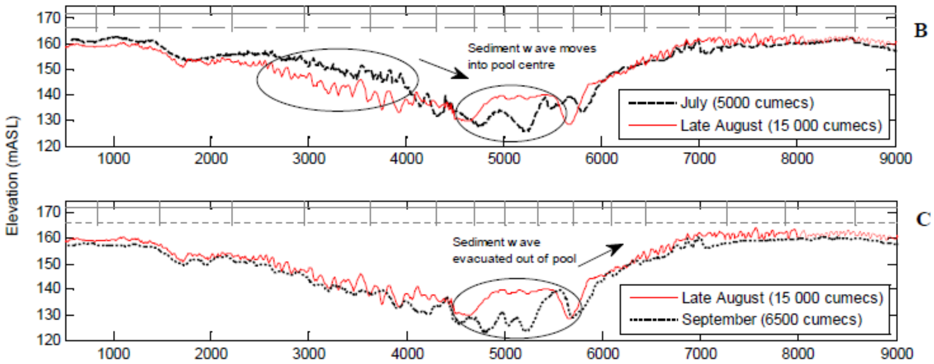

Figure B.5: Longitudinal cross-section of river section showing a sediment pulse migrating through a deep pool during the flood season

B.3. Sediment Flux

The timing of sediment delivery in the LMB is important for the maintenance of the river channel, ecological habitats and nutrient delivery to floodplains, the Tonle Sap and Mekong Delta. In the pre-dam situation about 80 %, of the sediment flux is transported during the wet season in the flood pulse. With the decreased river discharge at during the flood pulse and increased dry season flow, the percentage of sediment transported during the flood season is expected to decrease (MRC, 2019a).

The average suspended sediment load at Chiang Saen, just upstream of Pak Beng, in the period 2009-2013, was approximately 10.8 Mt/year and the bedload is estimated at 1.6 Mt/year. The suspended sediment load at Chiang Saen is mostly medium to fine sand, whereas the bedload consists of coarse sand, gravel and cobbles. The sediment load varied over the years between 7.3 and 14.9 Mt/year. Compared to historic values before the construction and commissioning of the Lancang cascade (1960 - 2002), the sediment load entering from China has decreased with approximately 85 %. There are of course other contribution to the change of sediment load such as sand mining and land and water use changes (Koehnken, 2014; Kondolf et al., 2018).

The suspended sediment flux at Chiang Saen depends highly on the river flow and the operation of the Lancang cascade. The suspended sediment concentration and the suspended sediment flux both increase with increasing flows for the Chiang Saen, Luang Prabang and Chiang Khan measurements. Moreover, a clear influence of the hysteresis is observed also with respect to the sediment loads. The water in rising limp of the flood pulse transports more sediment than the falling limp of the flood pulse, noticeable at all location in the cascade (Koehnken, 2014).

In the undisturbed situation, the sediment flux increases from 10.8 Mt/yr at Chiang Saen to 22.3 Mt/yr at the Luang Prabang measurement station. The measured increased sediment flux originates from the sub-catchment North of the planned cascade. Further downstream the measured sediment flux reduced to an average 18.8 Mt/yr at Chiang Khan, located near the proposed location of the Sanakham (Koehnken, 2014).

Due to the smoothing of the hydrograph, i.e. a decrease in mean discharge during the flood season and increase in dry season discharge, the delivery of sediment over the year becomes more uniform, with a shift from the flood pulse to the dry season (MRC, 2019a).

The grain size distribution of the incoming sediment at the Pak Beng hydropower plant can be estimated using the grain size measurements at Chiang Saen reported in the DSMP 2009 - 2012. It must be noted that the number of measurements is limited to two years (2010 and 2012), of which the measurements from 2010 should be handled with care, as they show some inconsistencies. Therefore it is opted to only use the data retrieved from the 2012 measurement campaign for suspended sediment (Koehnken, 2014).

In the period from July 5th un till August 30th, eight grain size measurements of the suspended sed-

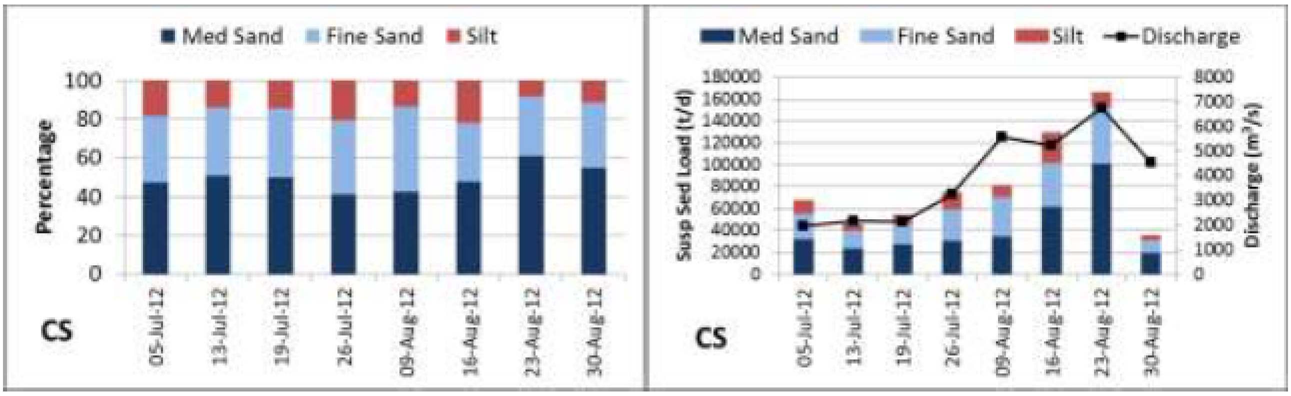

Figure B.6: The sediment fractions (left) and sediment fractions combined with discharge and sediment flux (left) at Chiang Saen, located upstream of the planned cascade (Koehnken, 2014)

iment were conducted at Chiang Saen. It is observed that the percentage of the respective medium sand, fine sand and silt fraction seems to be rather independent of the discharge. The total amount of sediment however increases with increasing river discharge. The bedload was dominated by gravel, pebbles and coarse sand at Chiang Saen, fine and medium sand at Nong Khai, which is located in the downstream reach of the cascade at the Lao PDR - Thai border (Koehnken, 2014).

Effect of Lancang Cascade

From the boarder of China the channel is predominantly characterised by bedrock, meaning that the channel has little capacity to provide or store sediment (Rubin et al., 2015). The sediment load in this section of the Mekong originates from sediment transported from tributaries draining into the main river and the Upper Mekong Basin. The Lancang cascade and the accompanying sediment trapping has been studied extensively. It is estimated that 83 % of the pre-dam sediment load to the planned cascade in Lao PDR is trapped in the Lancang cascade. Depending on the scenario of hydropower dam development the reduction varies between 77 % and 91 % (Kondolf, Rubin, et al., 2014).

In addition to the reduction of the total amount of sediment, the relationship between increasing discharge and increasing suspended sediment concentration changed at Chiang Saen. During the measuring campaign, the results indicate a decoupling between the relation between high flows and high sediment flux, especially in dry years. Historically, the bedload sediment flux increased during high flows and almost reduced to almost zero during low flows in the dry season. Even though the river flow was higher at Chiang Saen in the 2012 and 2013 dry season, the sediment flux was lower than expected, likely to be caused by the upstream dam operation in the Lancang cascade. Furthermore, the variability of the sediment flux over the year reduced during the measurement campaign, also likely caused by the upstream hydropower cascade (Koehnken, 2014).

C

Overview reservoir Flushing results

This chapter first presents the damping and travel time of the flood waves released during flushing. Secondly, an overview is given of the cumulative sediment flux as a function of time for all combinations of draw down rate, duration and water set point level.

C.1. Damping and travel time of the flood waves

In the bucket model the assumption is made that the travel time of the all flood waves through the reservoirs is constant and the assumption is made that damping will not occur in the reservoir. Experiments are executed to determine the error that is introduced in the bucket model due to these assumptions. To do so, the flood waves created for the flushing experiments with a reduction of the water level set point by 10 meters using a draw down rate of 0.4 m/h and 1.0 m/h for the four discharges. The results of these experiments are presented in Table C.1 for the draw down rate of 0.4 m/h and in Table C.2 for a draw down rate of 1.0 m/h.

Table C.1: Damping of flood wave and travel time for flood waves released for a draw down rate of 0.4 m/h and Δh_{set} of - 10m

Q	$Q_{max,up}$	$Q_{max,dam}$	error (%)	Δt
2750	4864	4531	3.3 %	12
4125	5853	5732	2.0 %	11
5500	7086	6909	2.5 %	10
6875	8347	8055	3.5 %	10

Table C.2: Damping of flood wave and travel time for flood waves released for a draw down rate of 1.0 m/h and Δh_{set} of - 10m

Q	$Q_{max,up}$	$Q_{max,dam}$	error (%)	Δt
2750	7080	5900	16 %	10
4125	7920	6869	13 %	9
5500	8829	7872	11 %	9
6875	9864	8931	8 %	9

An example of the observed damping and travel time of flood wave is shown in Figure C.1 together with the re-sampled 6-hours average discharge that will be used as input for the bucket model.

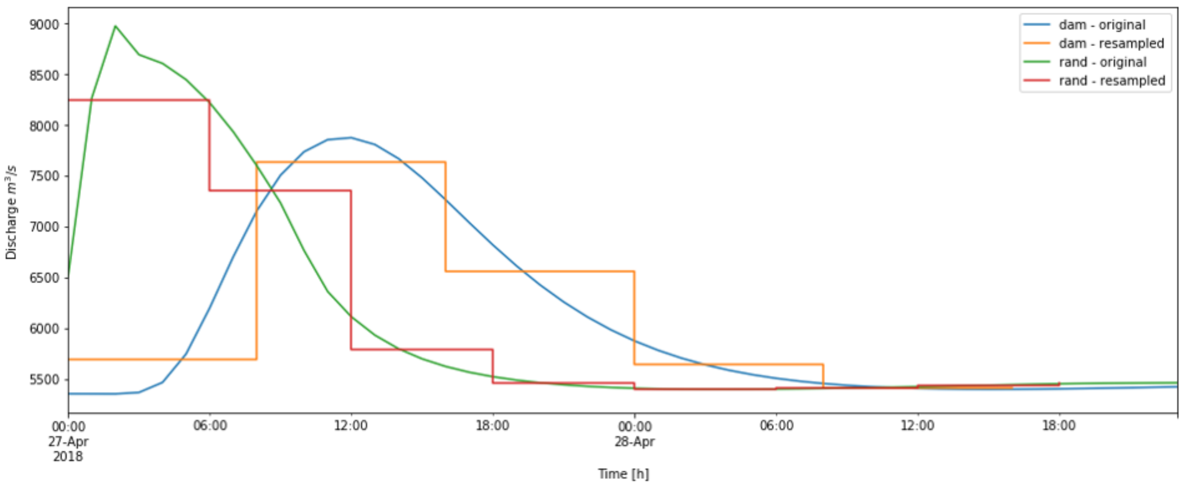

Figure C.1: Damping and travel time of the flood wave released by a flushing event with a draw down rate of 1.0 m/h to achieve a reduction in water level set point of Δh_{set} = - 10m at a discharge of 5500 m^3/s

C.2. Results flushing experiments

The cumulative sediment flux as a function of time is plotted for all combinations of draw down rate, water level set point and input discharges. Prior to this overview, the discharge boundary conditions used during the flushing experiments are shown in Figure C.2. All discharge operations are initiate at 2018-04-27 00:00.

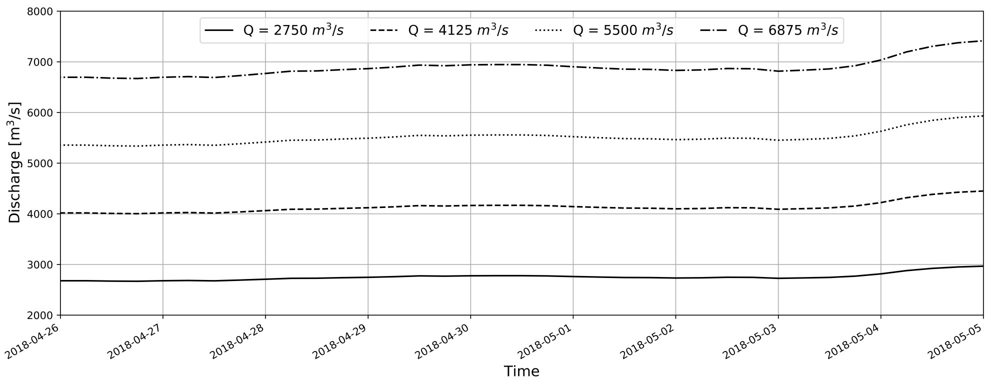

Figure C.2: The four different discharge boundaries used during the flushing experiments

The results of all combinations of flushing operation are presented for the same discharge at the boundary and same draw down rate, while the results of three different water level set points are plotted in the same figure.

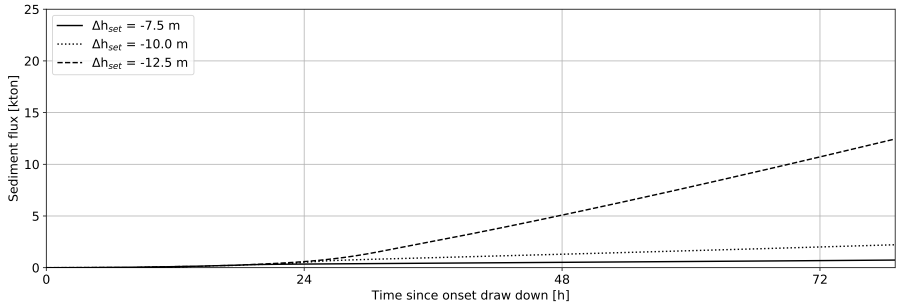

Figure C.3: Cumulative sediment flux at the dam for Q = 2750 m^3/s and r = 0.4 m/h

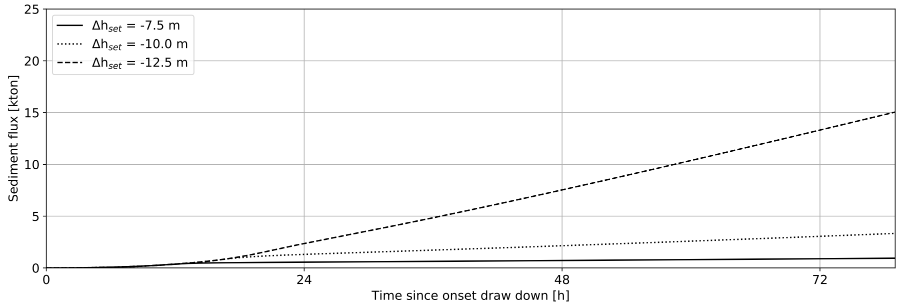

Figure C.4: Cumulative sediment flux at the dam for Q = 2750 m^3/s and r = 0.6 m/h

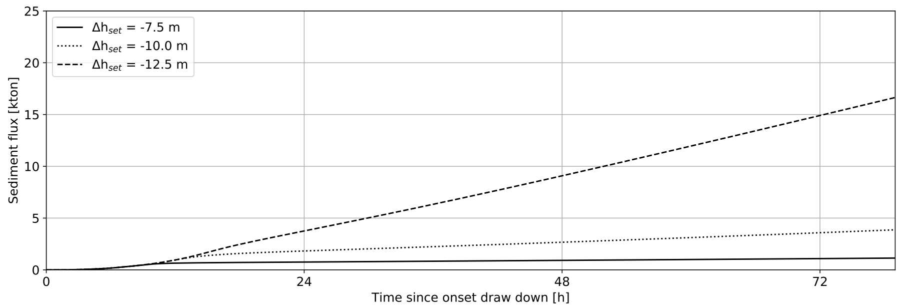

Figure C.5: Cumulative sediment flux at the dam for Q = 2750 m^3/s and r = 0.8 m/h

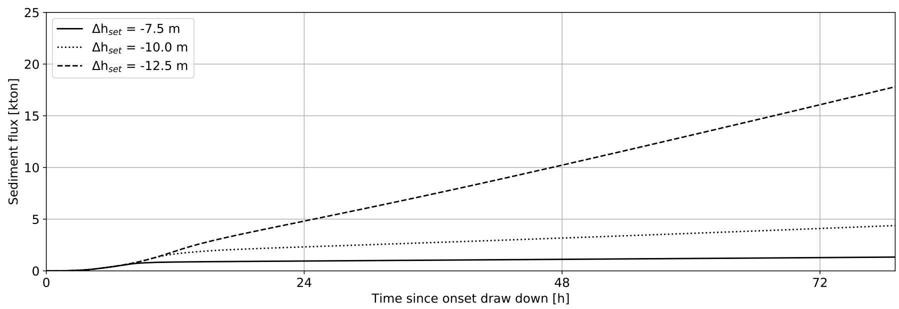

Figure C.6: Cumulative sediment flux at the dam for Q = 2750 m^3/s and r = 1.0 m/h

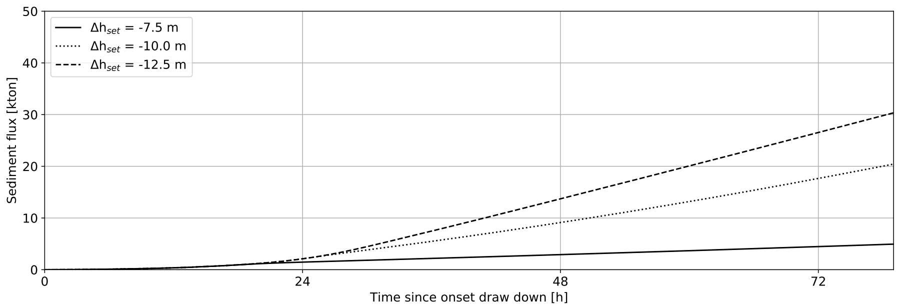

Figure C.7: Cumulative sediment flux at the dam for Q = 4125 m^3/s and r = 0.4 m/h

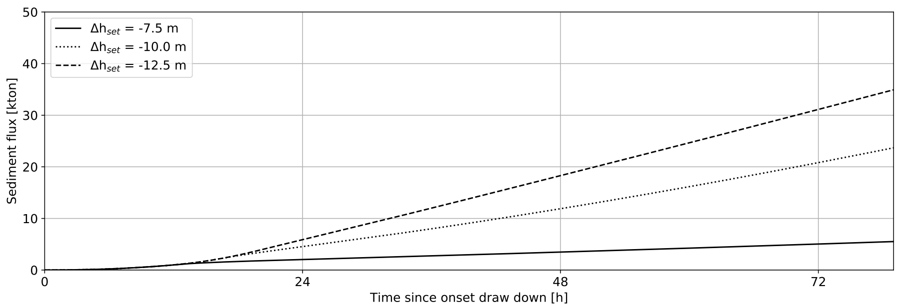

Figure C.8: Cumulative sediment flux at the dam for Q = 4125 m^3/s and r = 0.6 m/h

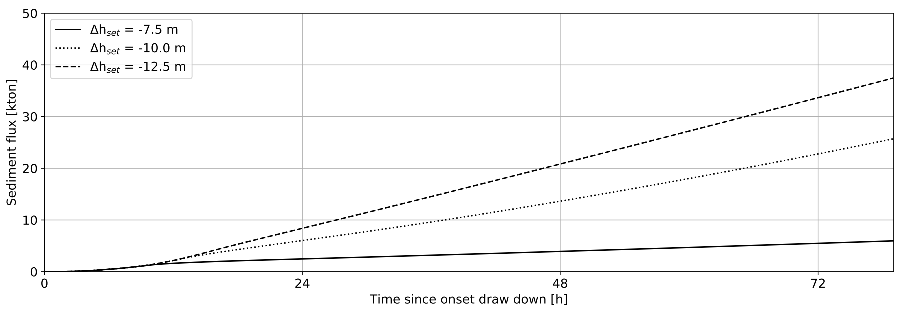

Figure C.9: Cumulative sediment flux at the dam for Q = 4125 m^3/s and r = 0.8 m/h

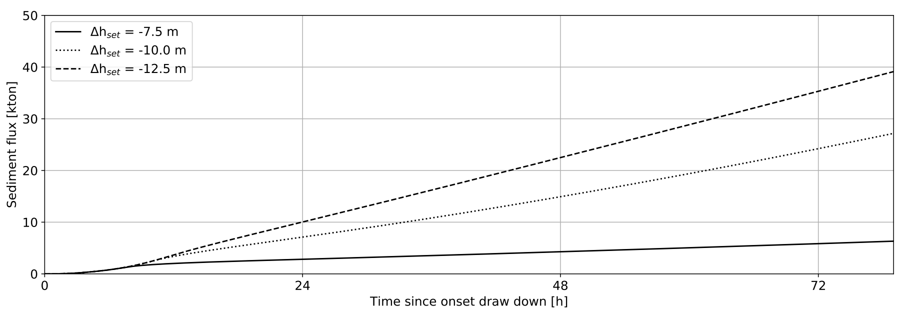

Figure C.10: Cumulative sediment flux at the dam for Q = 4125 m^3/s and r = 1.0 m/h

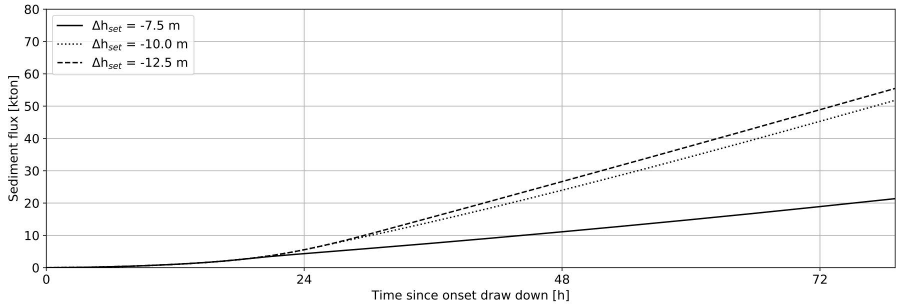

Figure C.11: Cumulative sediment flux at the dam for Q = 5500 m^3/s and r = 0.4 m/h

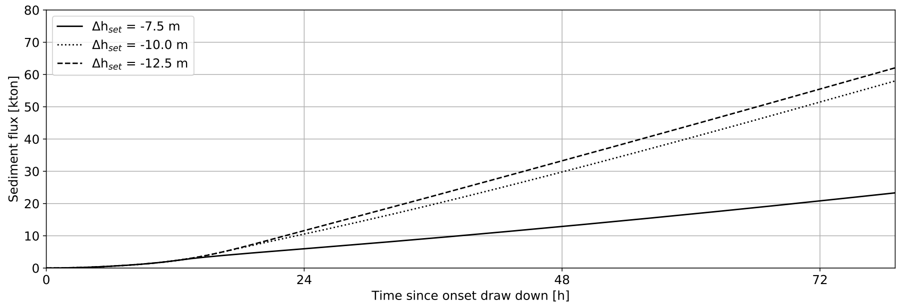

Figure C.12: Cumulative sediment flux at the dam for Q = 5500 m^3/s and r = 0.6 m/h

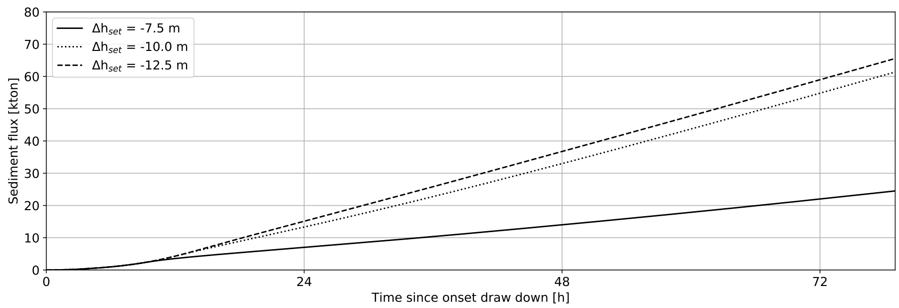

Figure C.13: Cumulative sediment flux at the dam for Q = 5500 m^3/s and r = 0.8 m/h

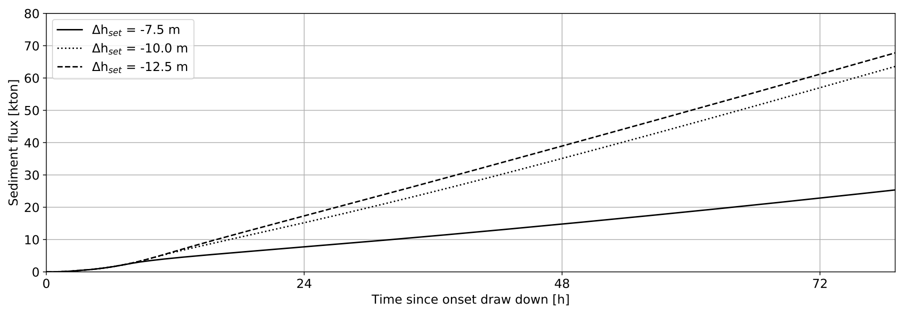

Figure C.14: Cumulative sediment flux at the dam for Q = 5500 m^3/s and r = 1.0 m/h

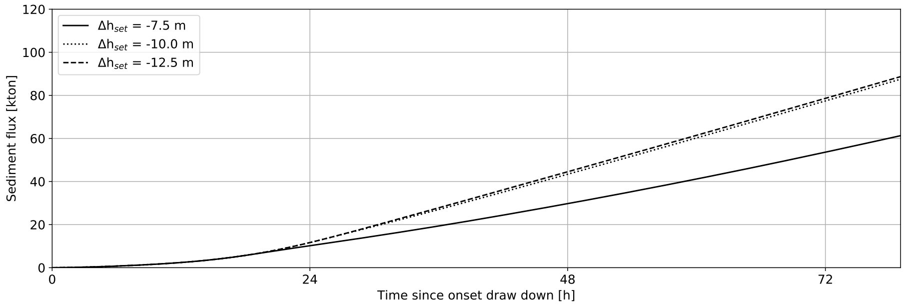

Figure C.15: Cumulative sediment flux at the dam for Q = 6875 m^3/s and r = 0.4 m/h

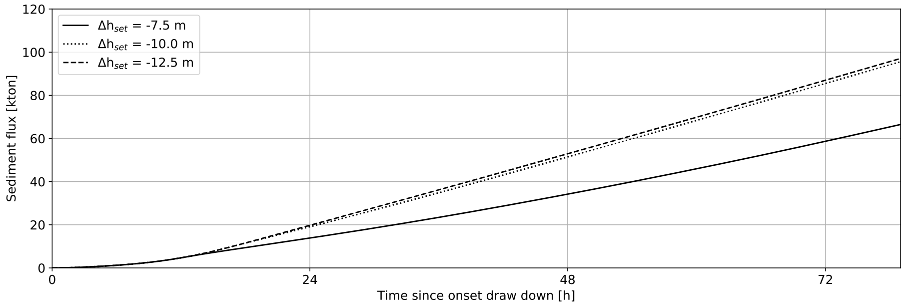

Figure C.16: Cumulative sediment flux at the dam for Q = 6875 m^3/s and r = 0.6 m/h

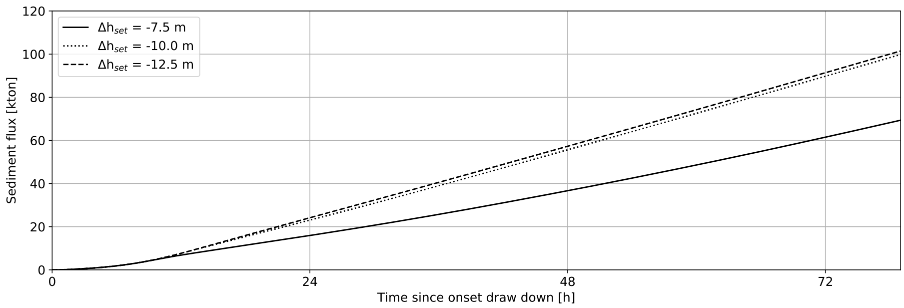

Figure C.17: Cumulative sediment flux at the dam for Q = 6875 m^3/s and r = 0.8 m/h

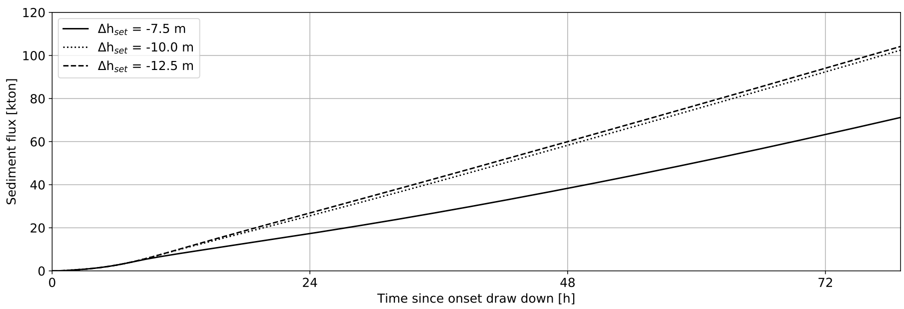

Figure C.18: Cumulative sediment flux at the dam for Q = 6875 m^3/s and r = 1.0 m/h

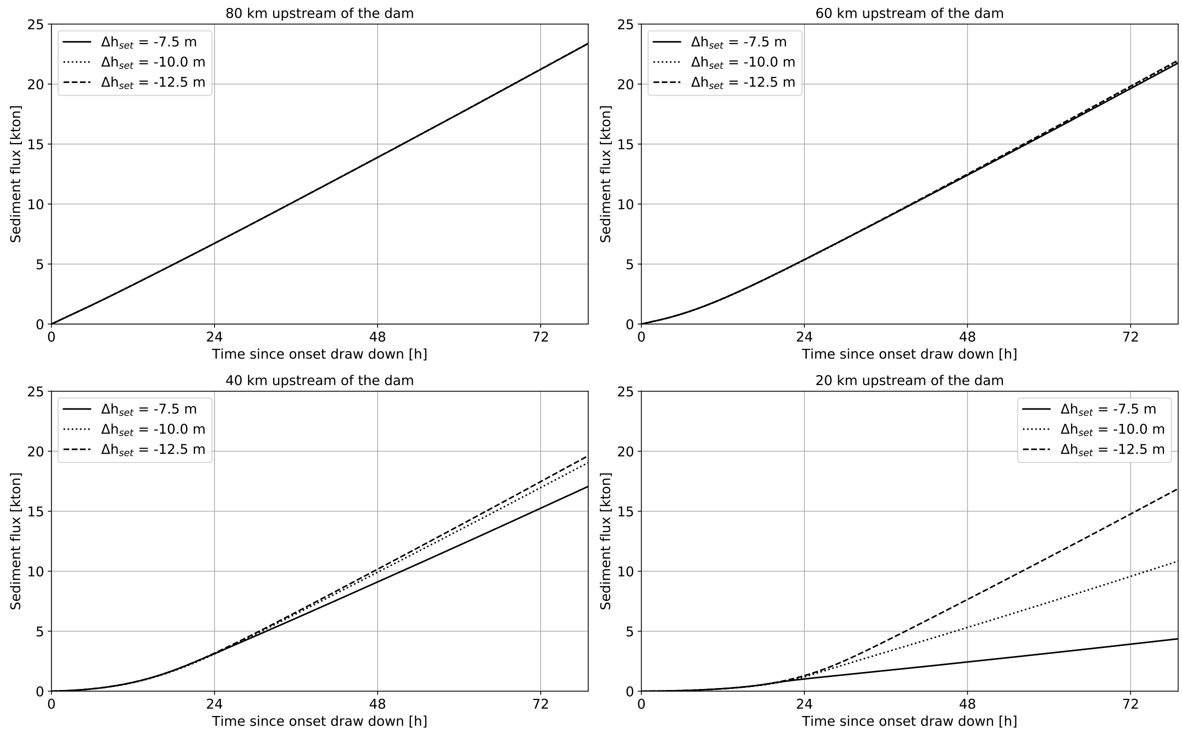

Figure C.19: Cumulative sediment flux at four cross-sections for Q = 2750 m^3/s and r = 0.4 m/h

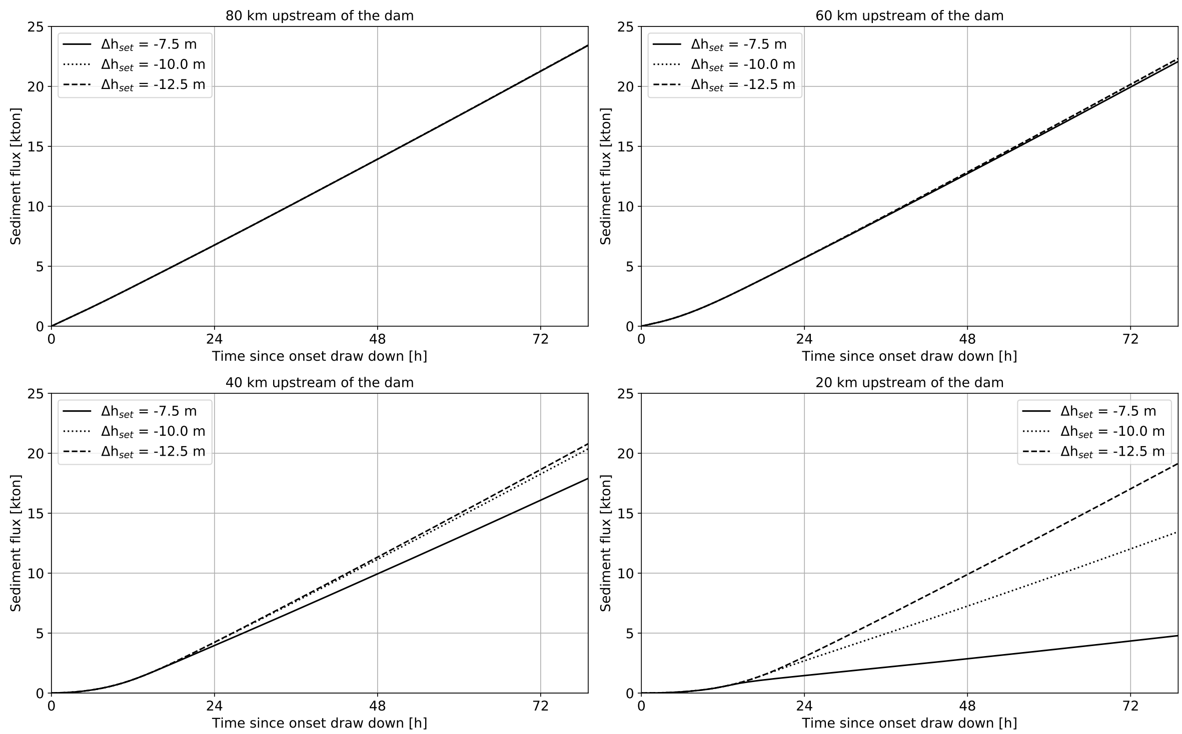

Figure C.20: Cumulative sediment flux at four cross-sections for Q = 2750 m^3/s and r = 0.6 m/h

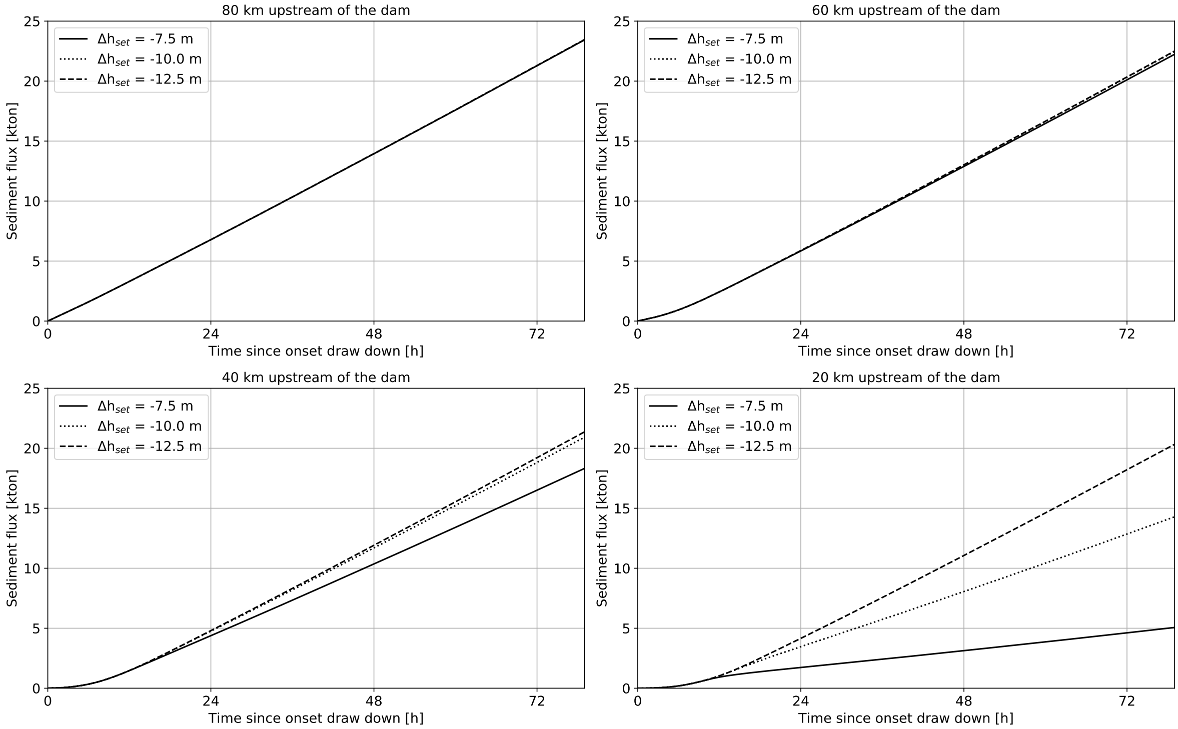

Figure C.21: Cumulative sediment flux at four cross-sections for Q = 2750 m^3/s and r = 0.8 m/h

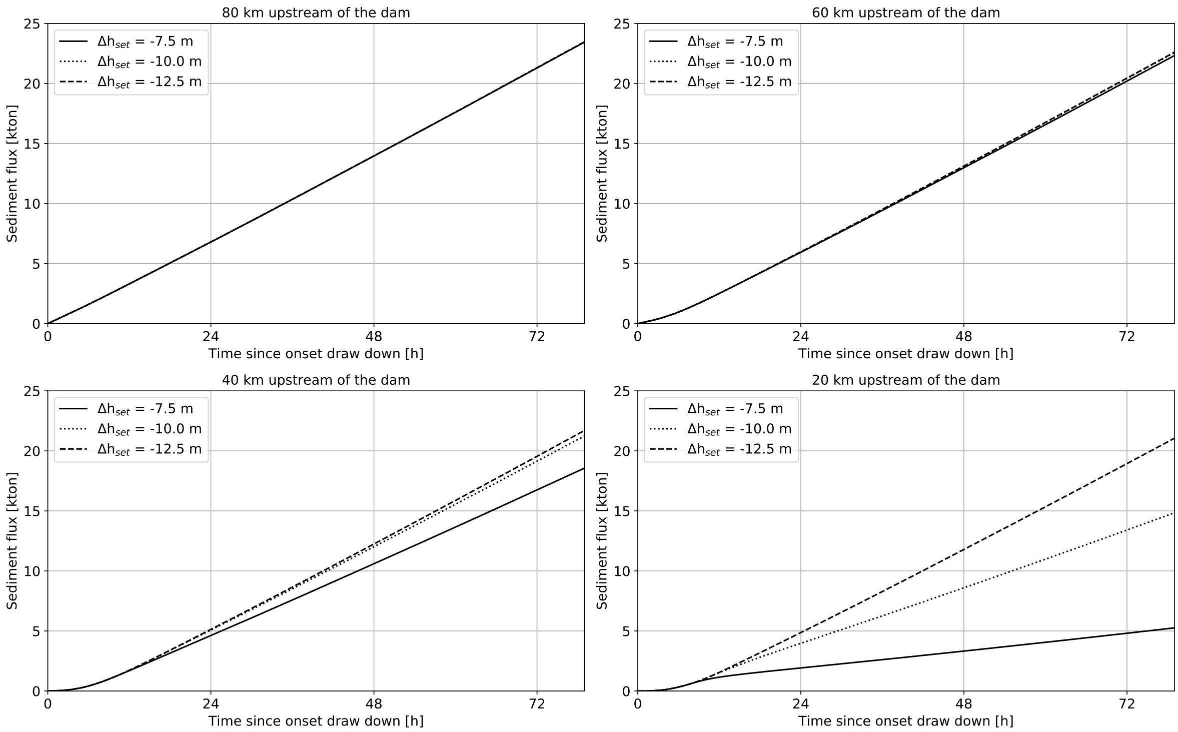

Figure C.22: Cumulative sediment flux at four cross-sections for Q = 2750 m^3/s and r = 1.0 m/h

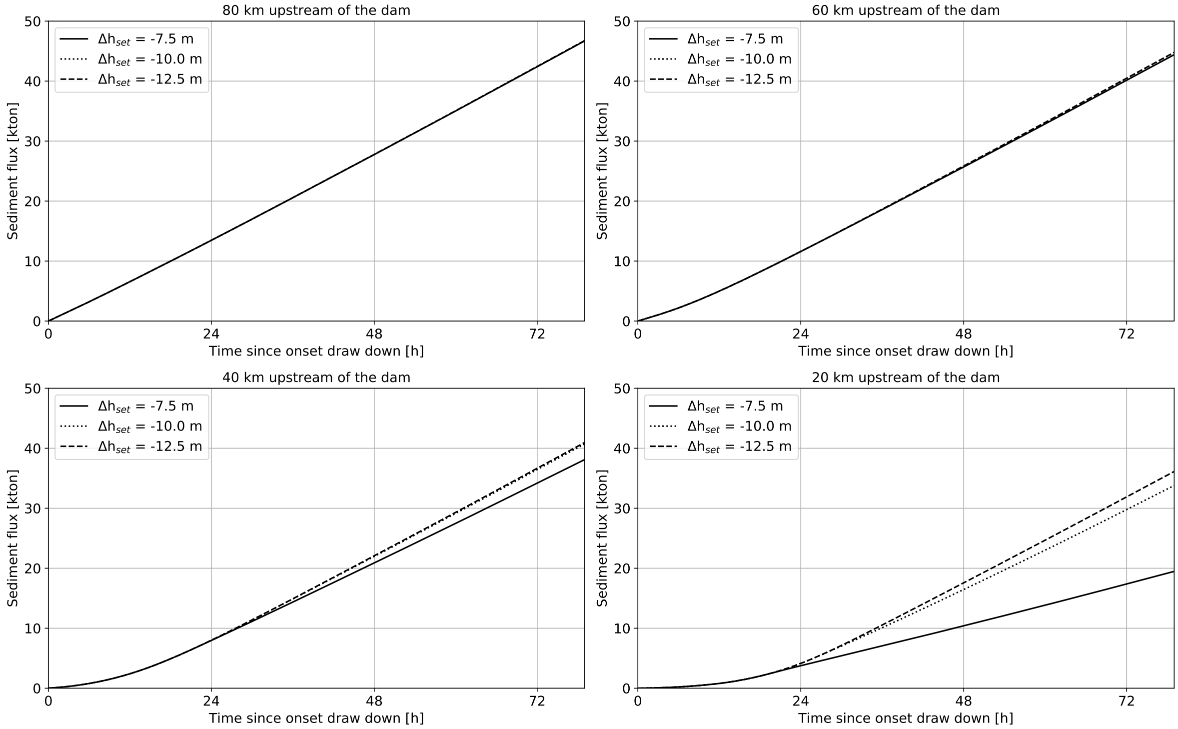

Figure C.23: Cumulative sediment flux at four cross-sections for Q = 4125 m^3/s and r = 0.4 m/h

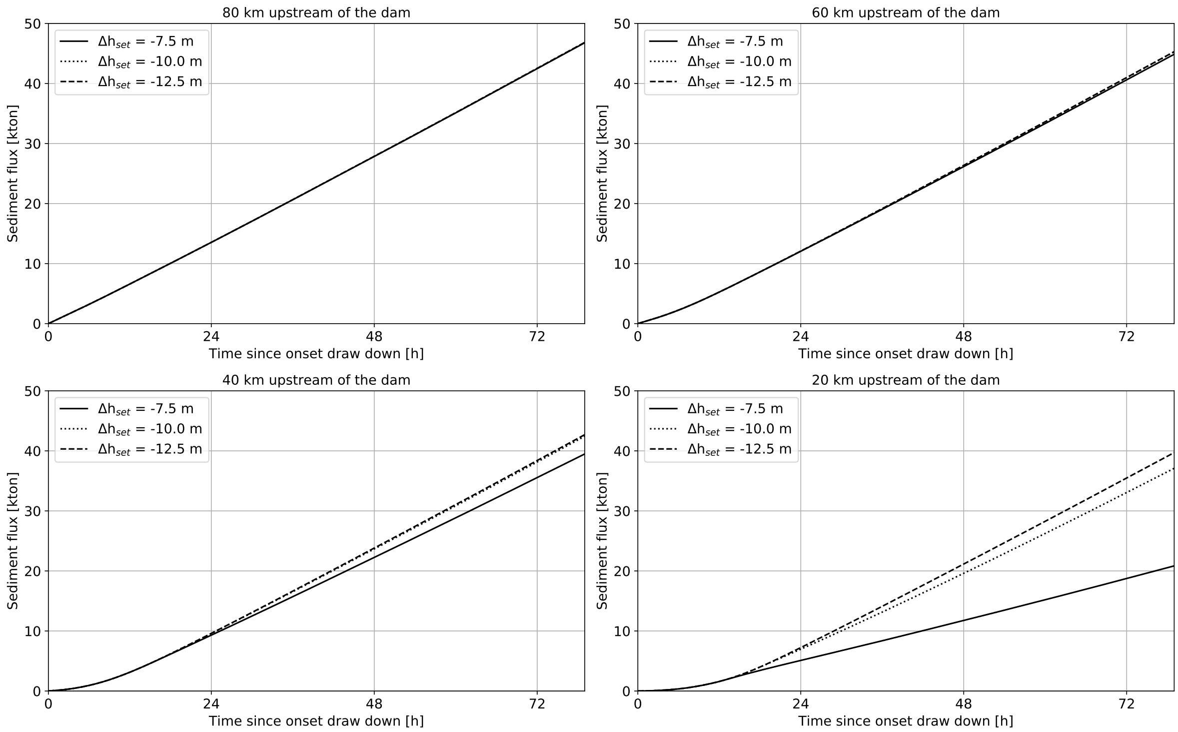

Figure C.24: Cumulative sediment flux at four cross-sections for Q = 4125 m^3/s and r = 0.6 m/h

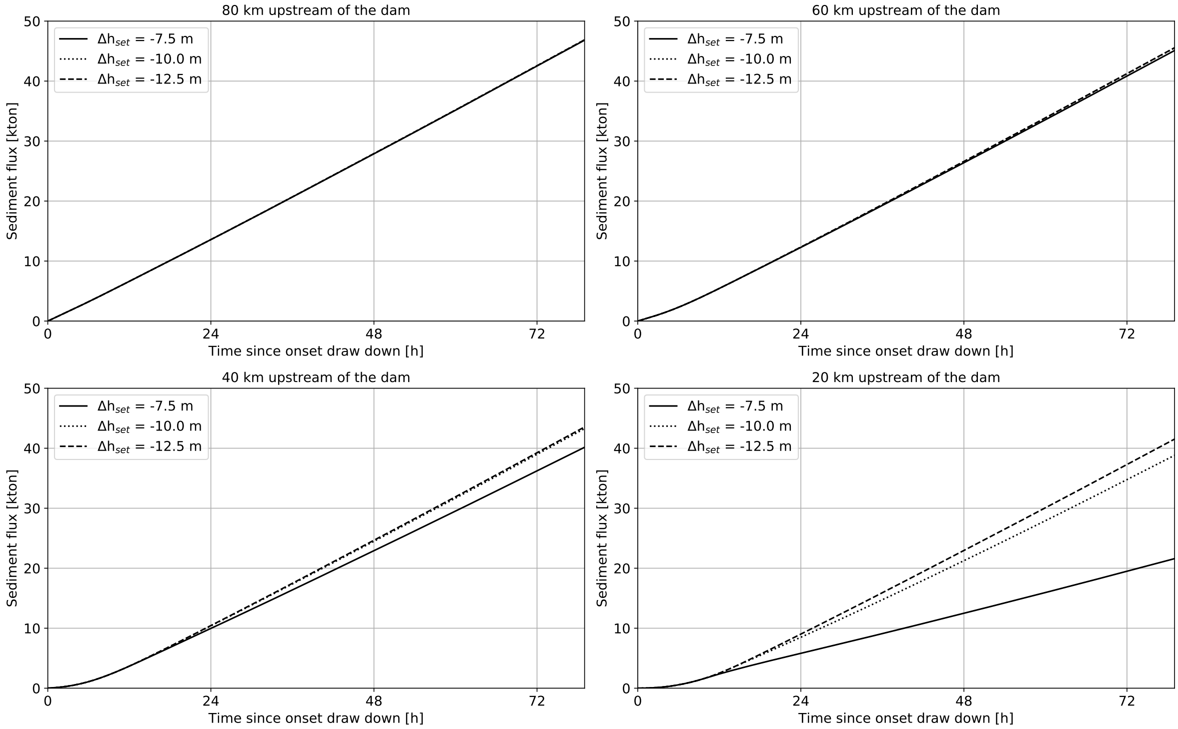

Figure C.25: Cumulative sediment flux at four cross-sections for Q = 4125 m^3/s and r = 0.8 m/h

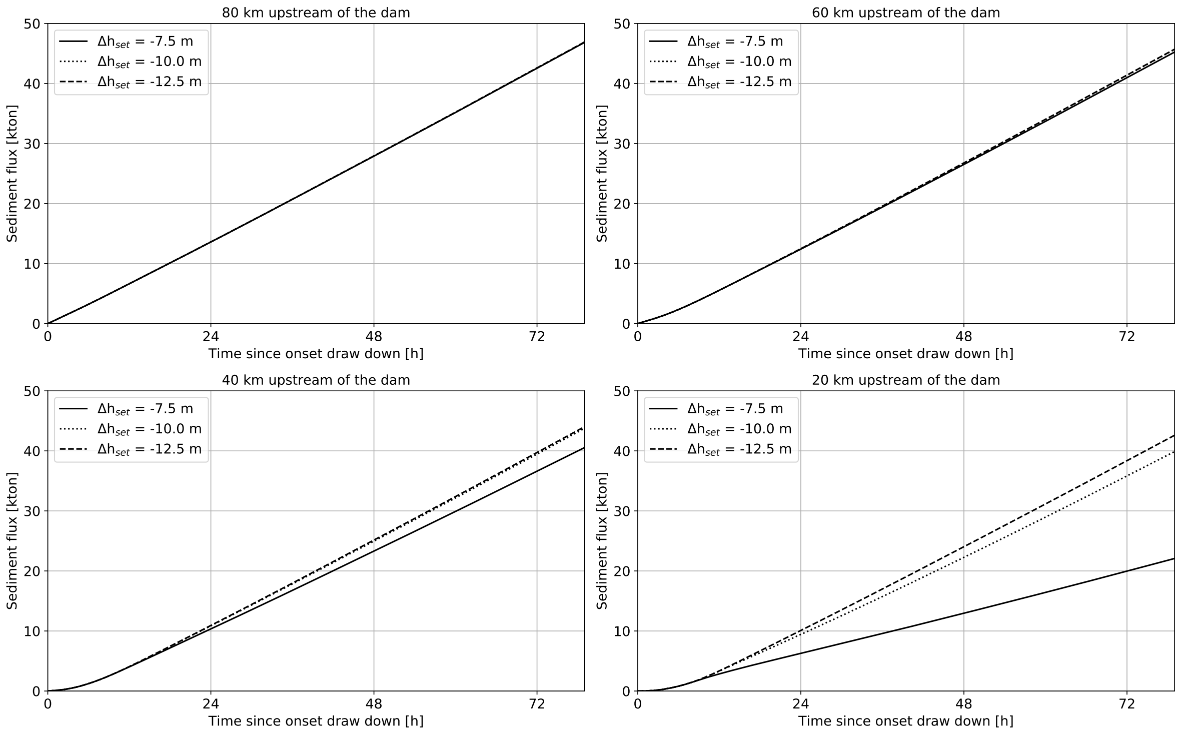

Figure C.26: Cumulative sediment flux at four cross-sections for Q = 4125 m^3/s and r = 1.0 m/h

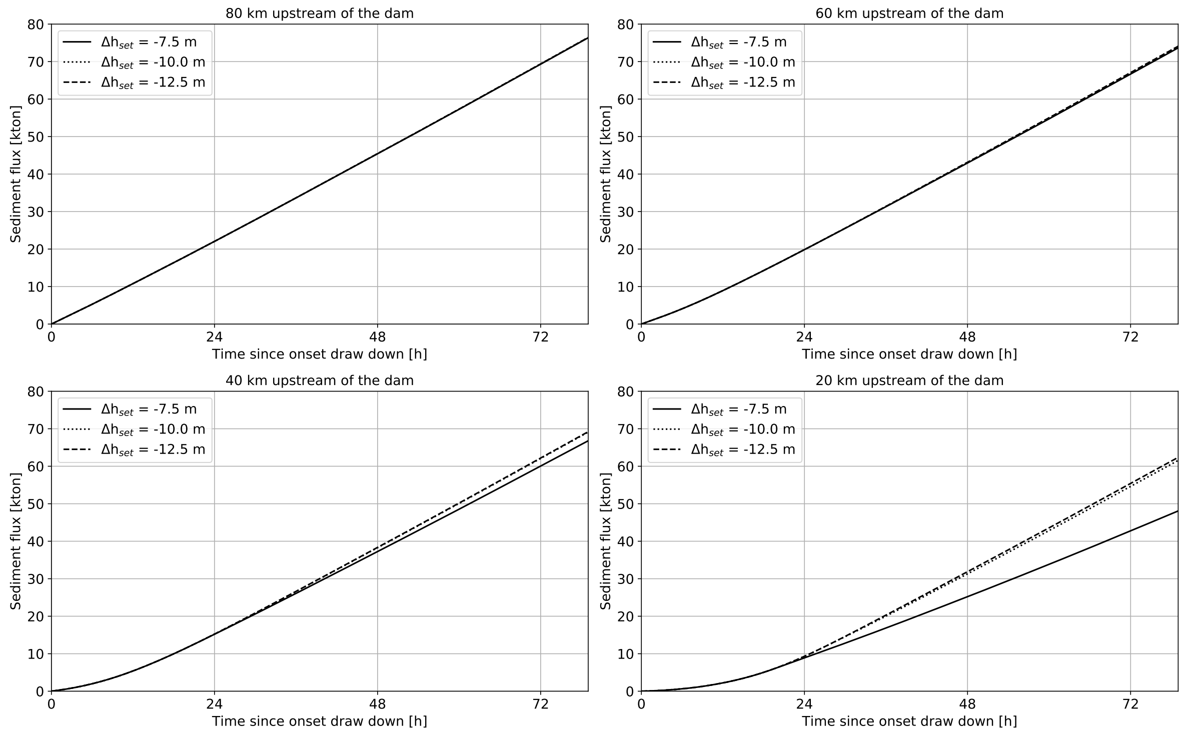

Figure C.27: Cumulative sediment flux at four cross-sections for Q = 5500 m^3/s and r = 0.4 m/h

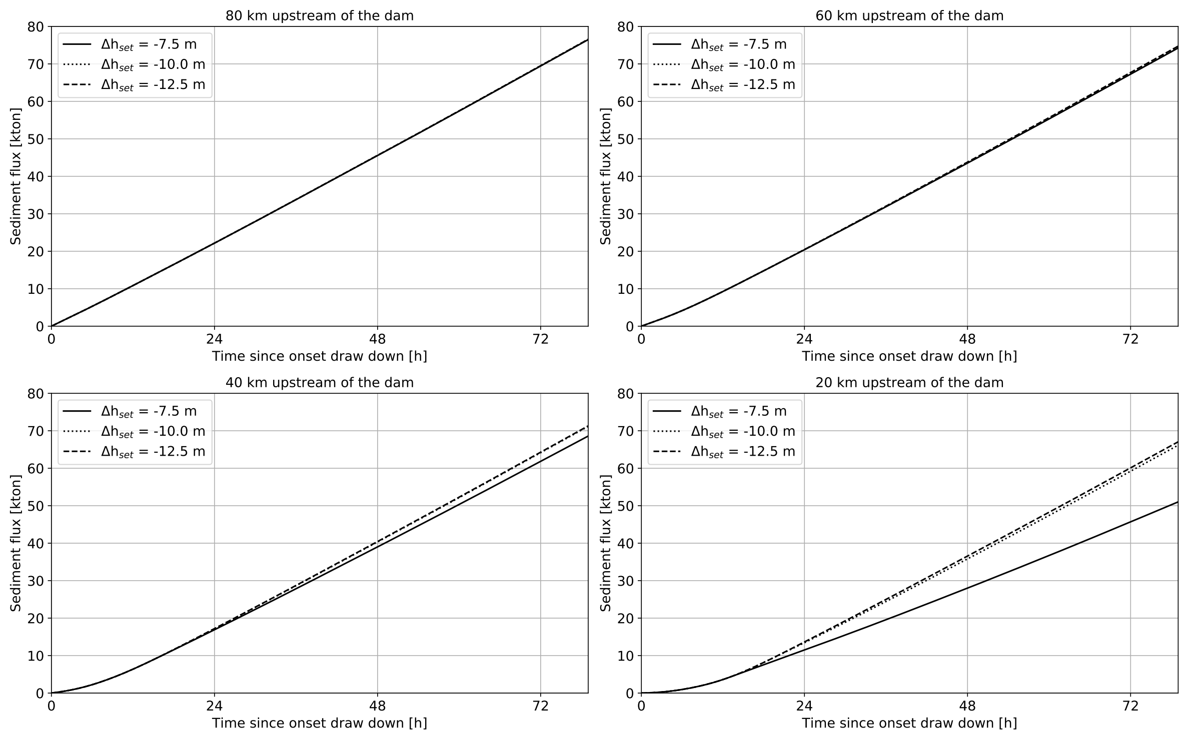

Figure C.28: Cumulative sediment flux at four cross-sections for Q = 5500 m^3/s and r = 0.6 m/h

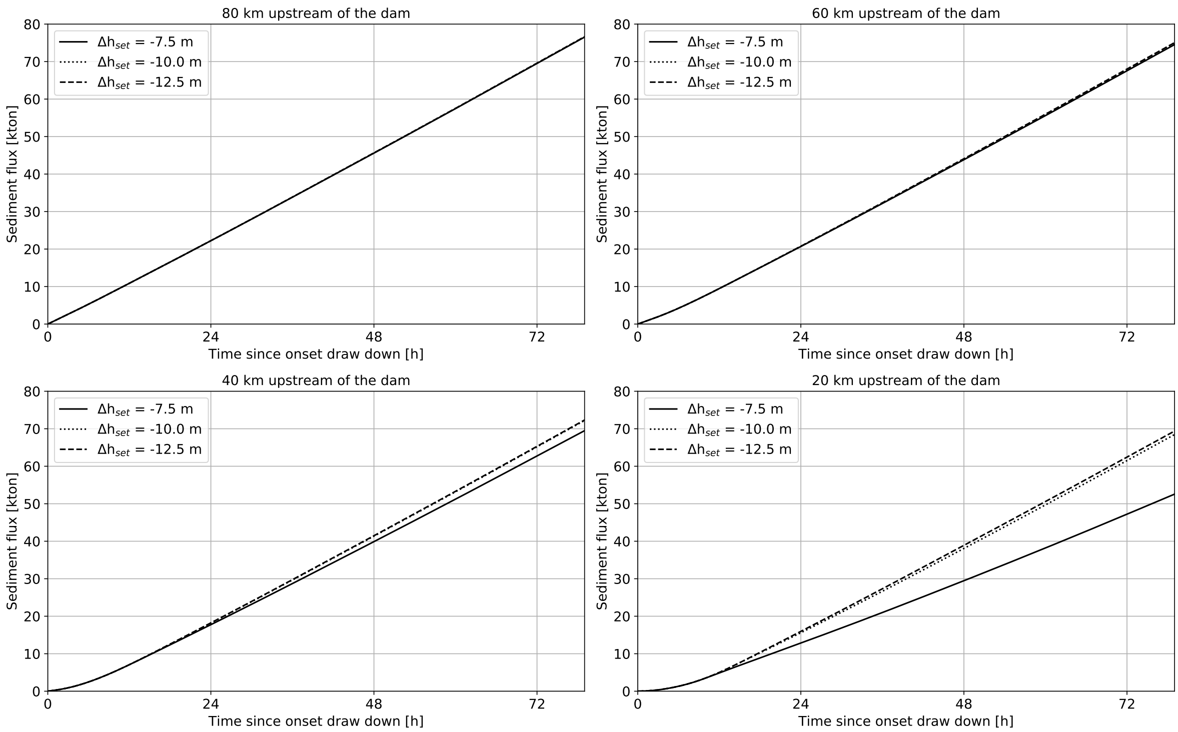

Figure C.29: Cumulative sediment flux at four cross-sections for Q = 5500 m^3/s and r = 0.8 m/h

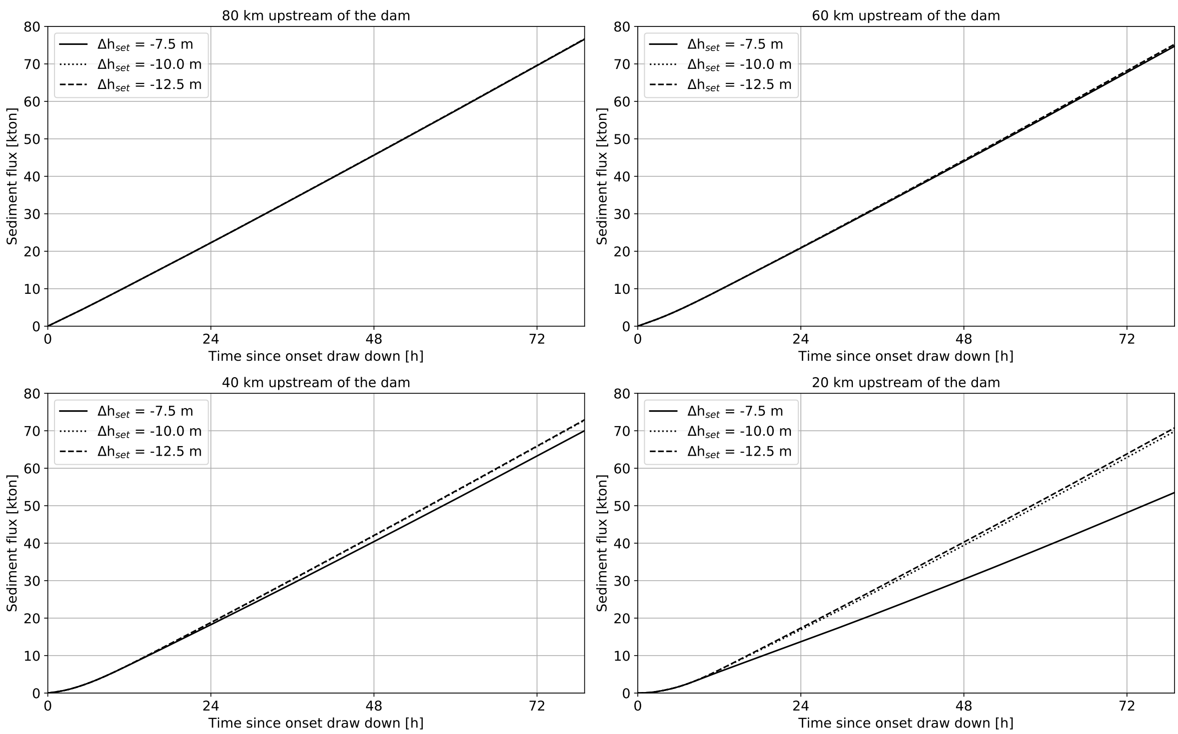

Figure C.30: Cumulative sediment flux at four cross-sections for Q = 5500 m^3/s and r = 1.0 m/h

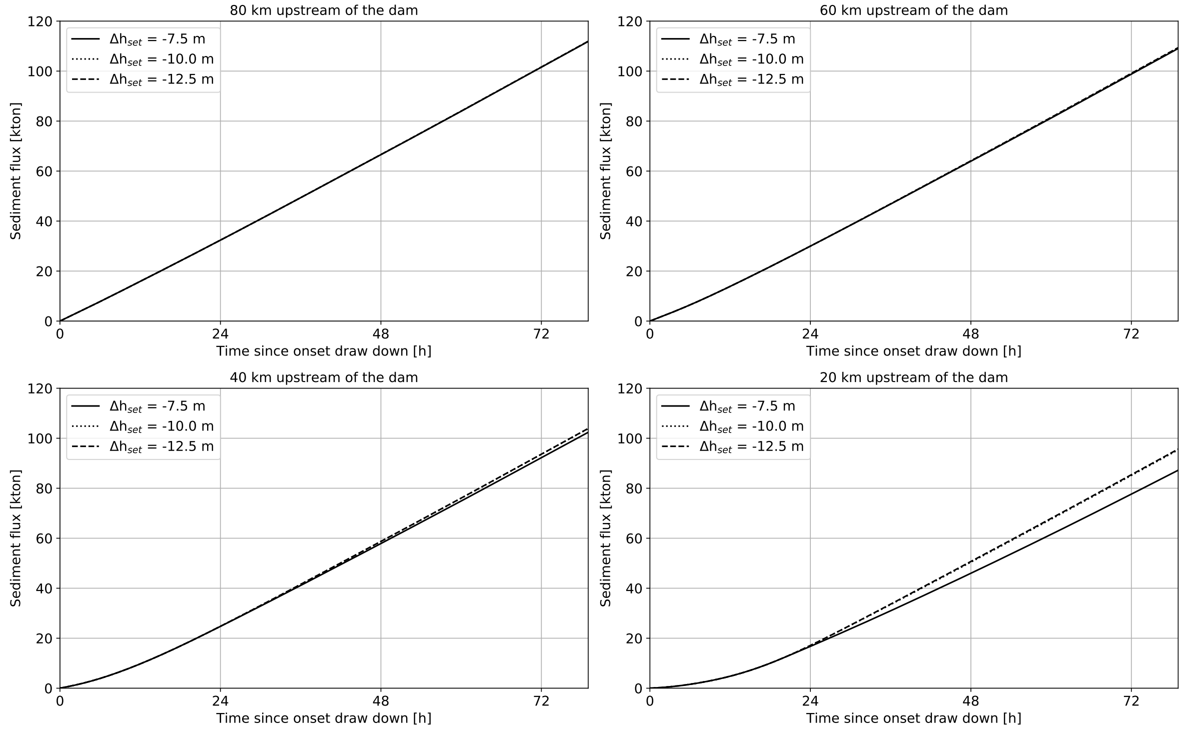

Figure C.31: Cumulative sediment flux at four cross-sections for Q = 6875 m^3/s and r = 0.4 m/h

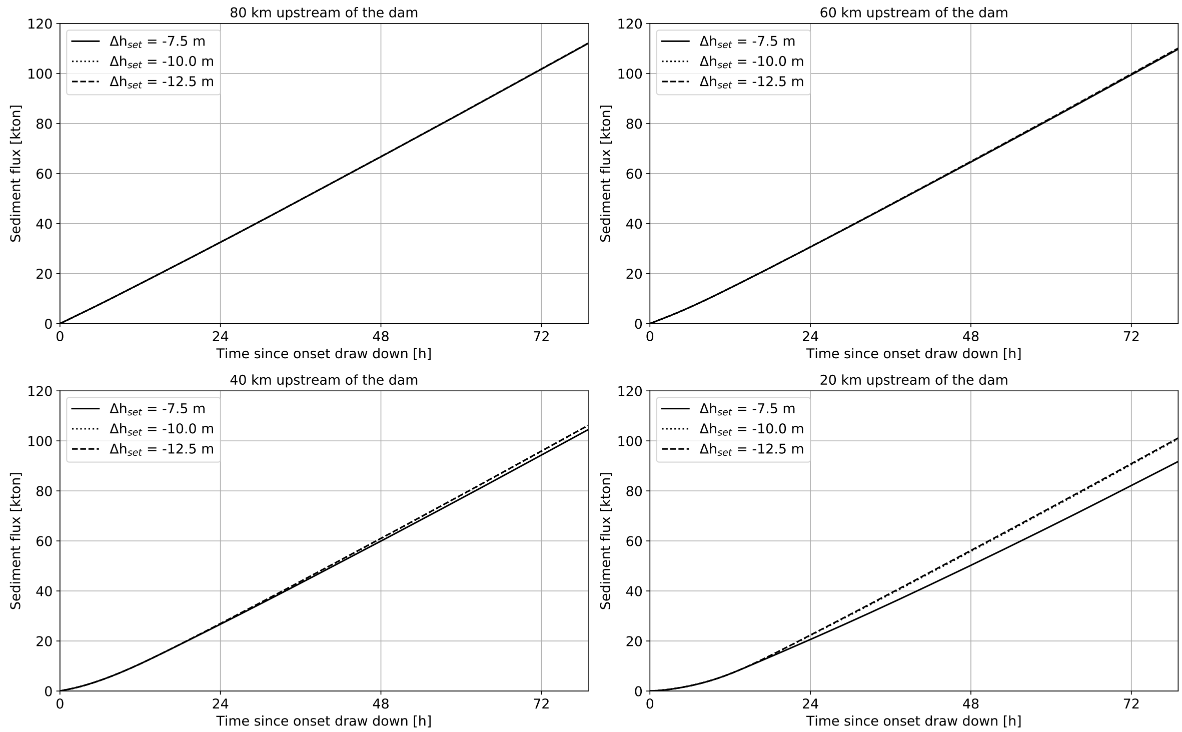

Figure C.32: Cumulative sediment flux at four cross-sections for Q = 6875 m^3/s and r = 0.6 m/h

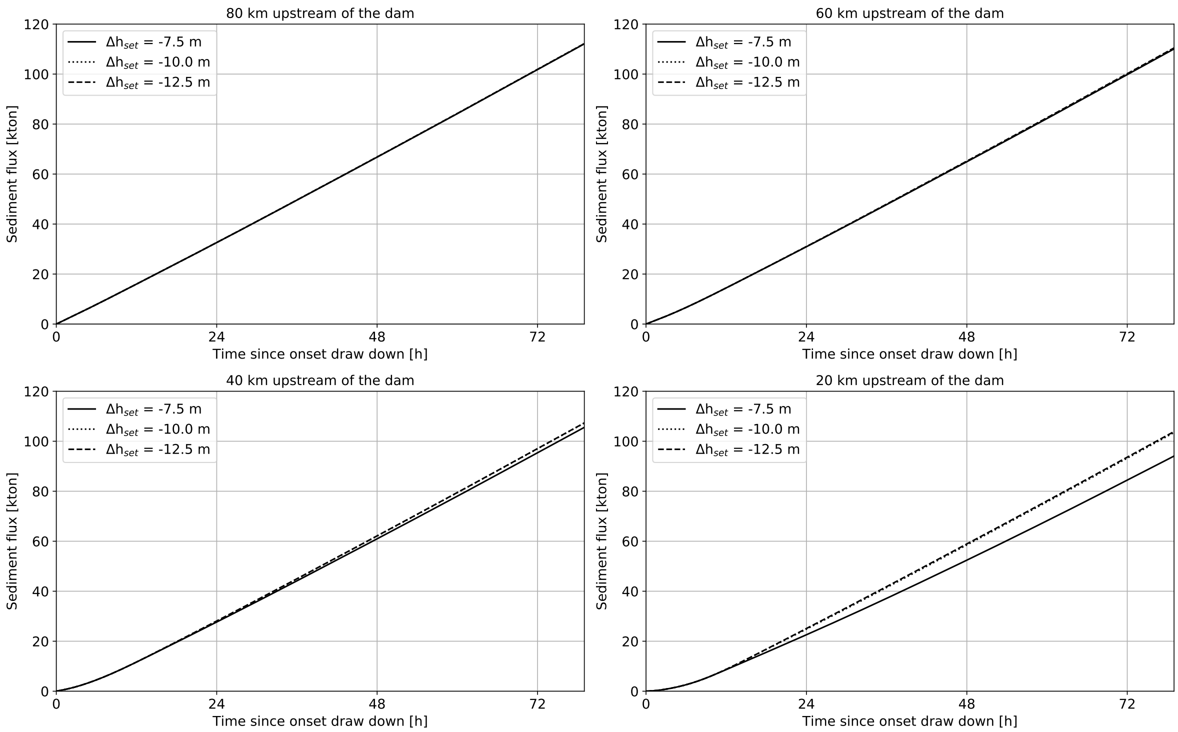

Figure C.33: Cumulative sediment flux at four cross-sections for Q = 6875 m^3/s and r = 0.8 m/h

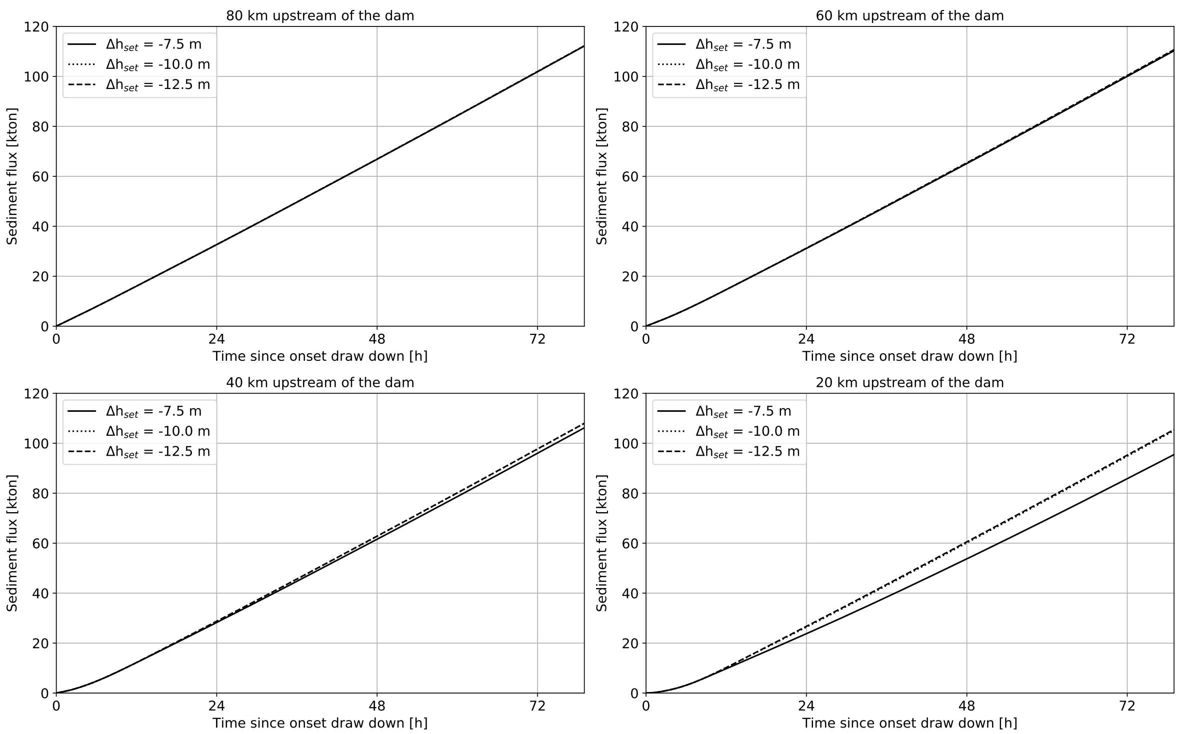

Figure C.34: Cumulative sediment flux at four cross-sections for Q = 6875 m^3/s and r = 1.0 m/h

In addition to the figures, the results of the flushing experiments are given for five cross-sections after 24 and 48 hours of flushing.

Q = 2750 m^3/s										
$\Delta h_{set} = -12.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	16.0	14.2	11.5	8.9	6.1	23.3	21.5	18.8	16.1	11.8
0.6	16.0	14.5	12.7	11.1	8.5	23.4	21.9	20.0	18.3	14.4
0.8	16.0	14.7	13.2	12.3	10.1	23.4	22.0	20.6	19.5	16.0
1.0	16.0	14.8	13.6	13.1	11.2	23.4	22.1	20.9	20.2	17.1

Q = 2750 m^3/s										
$\Delta h_{set} = -10.0 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	16.0	14.1	11.2	6.1	1.4	23.3	21.4	18.3	10.4	2.1
0.6	16.0	14.5	12.4	8.1	2.3	23.4	21.8	19.6	12.9	3.2
0.8	16.0	14.7	13.0	8.9	2.8	23.4	22.0	20.1	13.7	3.8
1.0	16.0	14.8	13.3	9.4	3.3	23.4	22.1	20.5	14.3	4.3

Q = 2750 m^3/s										
$\Delta h_{set} = -7.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	16.0	14.1	10.2	2.7	0.5	23.3	21.3	16.4	4.2	0.7
0.6	16.0	14.4	11.1	3.1	0.8	23.4	21.6	17.2	4.6	0.9
0.8	16.0	14.5	11.5	3.4	1.0	23.4	21.8	17.7	4.9	1.1
1.0	16.0	14.8	13.3	3.7	1.1	23.4	21.9	18.1	5.1	1.3

Q = 4125 m^3/s										
$\Delta h_{set} = -12.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	31.9	29.4	24.9	20.1	16.0	46.7	44.4	39.5	34.5	28.9
0.6	32.0	29.9	26.6	23.7	20.6	46.4	44.6	41.3	38.9	33.4
0.8	32.1	30.2	27.5	25.5	23.1	46.8	44.9	42	39.9	36.0
1.0	32.1	30.3	28.0	26.6	24.8	46.8	45.0	42.6	41.0	37.6

Q = 4125 m^3/s										
$\Delta h_{set} = -10.0 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	31.9	29.4	24.8	18.8	10.5	39.3	44.1	39.3	32.2	19.3
0.6	32.0	29.9	26.5	22.0	13.4	41.0	44.6	41.0	35.5	22.6
0.8	32.1	30.2	27.3	23.6	15.2	41.9	44.9	41.9	37.3	24.6
1.0	32.1	30.3	27.8	24.7	16.5	42.3	50.0	42.3	38.3	26.0

Q = 4125 m^3/s										
$\Delta h_{set} = -7.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	31.9	29.2	23.5	11.7	12.5	46.6	43.7	36.8	18.7	4.8
0.6	32.0	29.7	24.8	13.0	14.3	46.7	44.2	38.2	20.1	5.3
0.8	32.0	29.9	25.5	13.7	15.4	46.7	44.4	38.9	20.8	5.8
1.0	32.1	30.1	25.9	12.2	16.2	46.7	44.6	39.3	21.3	6.1

Figure C.35: Sediment flux at five cross-sections for flushing events for Q = 2750 m^3/s and Q = 4125 m^3/s after 24 and 48 hours of flushing.

Q = 5500 m^3/s										
$\Delta h_{set} = -12.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	52.3	49.3	43.3	39.1	30.6	76.3	73.3	67.2	59.8	56.3
0.6	52.4	49.9	45.4	40.8	37.2	76.4	73.4	69.3	64.5	59.5
0.8	52.4	50.2	46.4	43.2	40.7	76.5	74.2	70.3	66.8	63.0
1.0	52.5	50.4	47.0	44.6	42.9	76.5	74.4	70.9	68.2	65.2

Q = 5500 m^3/s										
$\Delta h_{set} = -10.0 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	52.3	49.3	43.2	35.5	27.6	76.3	73.4	67.1	59.0	49.3
0.6	52.4	49.9	45.3	40.0	33.5	76.4	73.9	69.2	63.6	55.5
0.8	52.4	50.2	46.3	42.3	36.8	76.5	74.2	70.2	65.9	58.8
1.0	52.5	50.4	46.9	43.7	38.9	76.5	74.4	70.8	67.3	61.0

Q = 5500 m^3/s										
$\Delta h_{set} = -7.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	52.2	49.1	42.0	28.4	12.5	76.2	72.9	64.9	46.1	21.9
0.6	52.3	49.6	43.8	31.2	14.3	76.3	73.4	66.7	49.1	22.4
0.8	52.4	49.9	44.6	32.7	15.4	76.4	73.7	67.9	50.6	23.6
1.0	52.4	50.1	45.2	33.6	16.2	76.4	73.9	68.1	51.5	24.4

Q = 6875 m^3/s										
$\Delta h_{set} = -12.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	76.6	73.3	66.4	57.2	50.6	111.7	108.4	101.5	92.0	84.8
0.6	76.8	74.1	68.7	62.7	59.0	111.9	109.2	103.8	97.5	93.2
0.8	76.9	74.4	69.9	65.4	63.4	112.0	109.5	104.9	100.2	97.6
1.0	76.9	74.6	70.5	67.0	66.1	112.1	109.7	105.6	101.9	100.3

Q = 6875 m^3/s										
$\Delta h_{set} = -10.0 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	76.6	73.3	66.4	56.9	49.4	111.7	108.4	101.4	91.7	83.7
0.6	76.8	74.0	68.7	62.3	57.5	111.9	109.1	103.7	97.2	91.7
0.8	76.9	74.4	69.9	65.0	61.7	112.0	109.5	104.8	99.9	96.0
1.0	76.9	74.6	70.5	66.6	64.4	112.0	109.7	105.5	101.5	98.6

Q = 6875 m^3/s										
$\Delta h_{set} = -7.5 \quad m$	Distance from dam (after 24 hours)					Distance from dam (after 48 hours)				
rate [m/h]	80 km	60 km	40 km	20 km	dam	80 km	60 km	40 km	20 km	dam
0.4	75.6	73.1	65.5	51.8	33.8	111.7	108.1	100.0	83.8	58.4
0.6	76.7	73.8	67.6	56.2	38.6	111.8	108.8	102.1	88.4	63.5
0.8	76.8	74.1	68.6	58.4	40.9	111.9	109.1	103.2	90.7	66.4
1.0	76.8	74.3	69.2	60.0	42.6	112.0	109.3	103.8	92.1	68.2

Figure C.36: Sediment flux at five cross-sections for flushing events for Q = 5500 m^3/s and Q = 6875 m^3/s after 24 and 48 hours of flushing.

D
Operational scenarios

The electricity and sediment flux of all runs are presented in this appendix. Only the results with limited sediment spread in the same run are plotted. The results of the random sampling method are presented first. Secondly, the results of the pre-determined strategies are presented.

D.1. Results of random sampling method

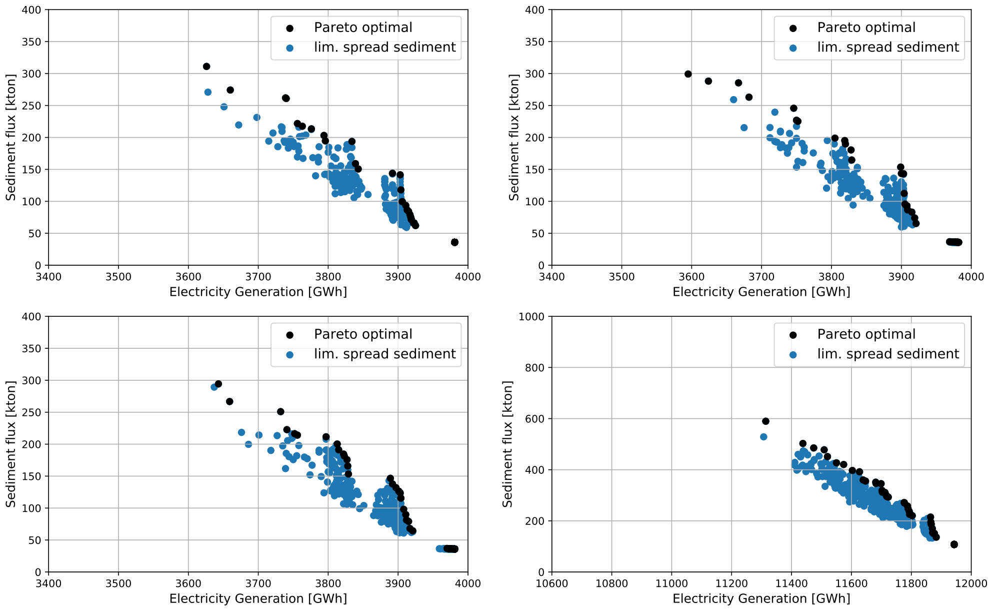

Figure D.1: Electricity generation versus sediment flux, with on average one flushing event in the wet season, threshold discharge at 5000 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

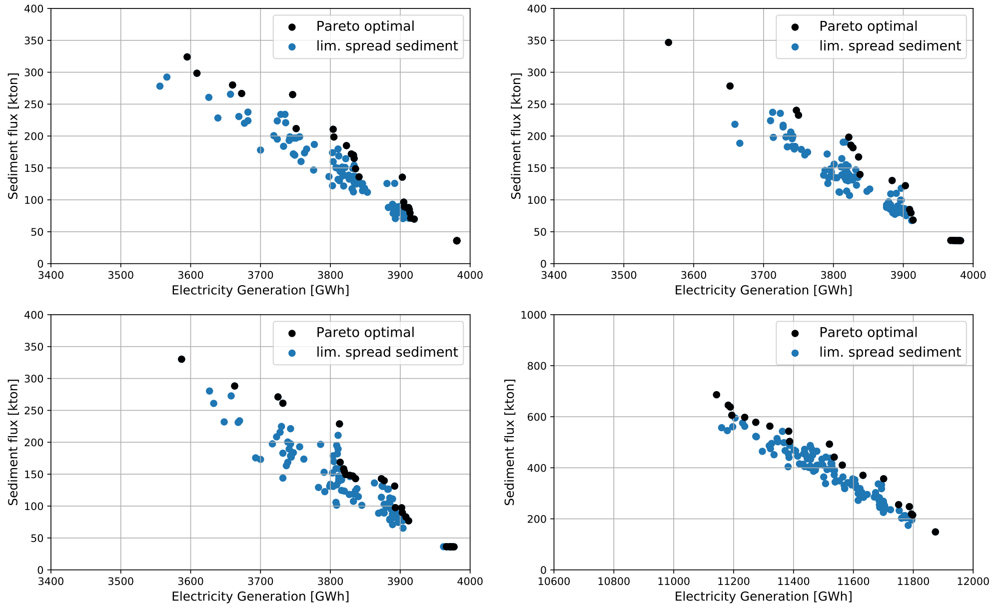

Figure D.2: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 5000 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

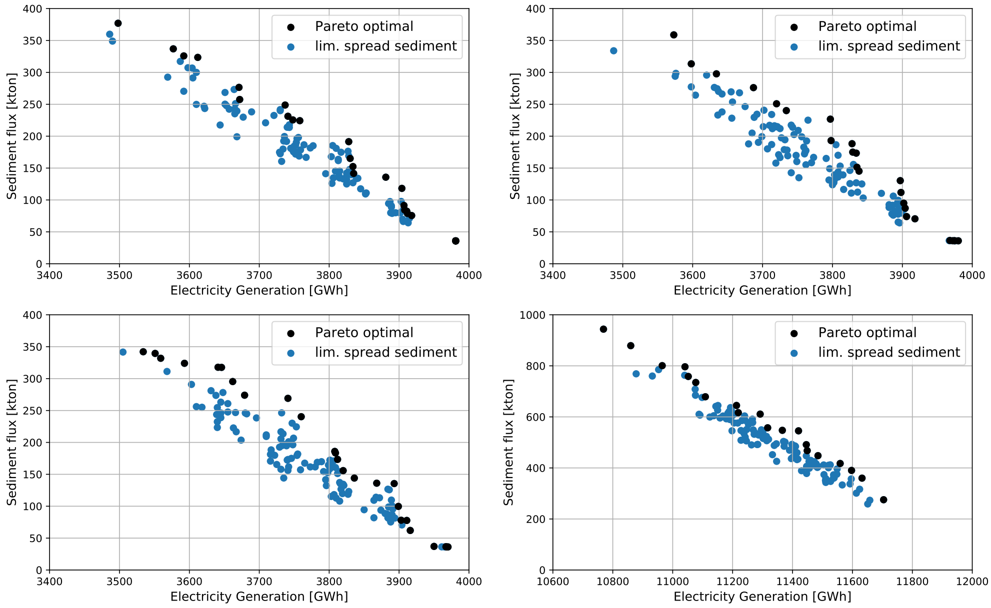

Figure D.3: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 5000 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

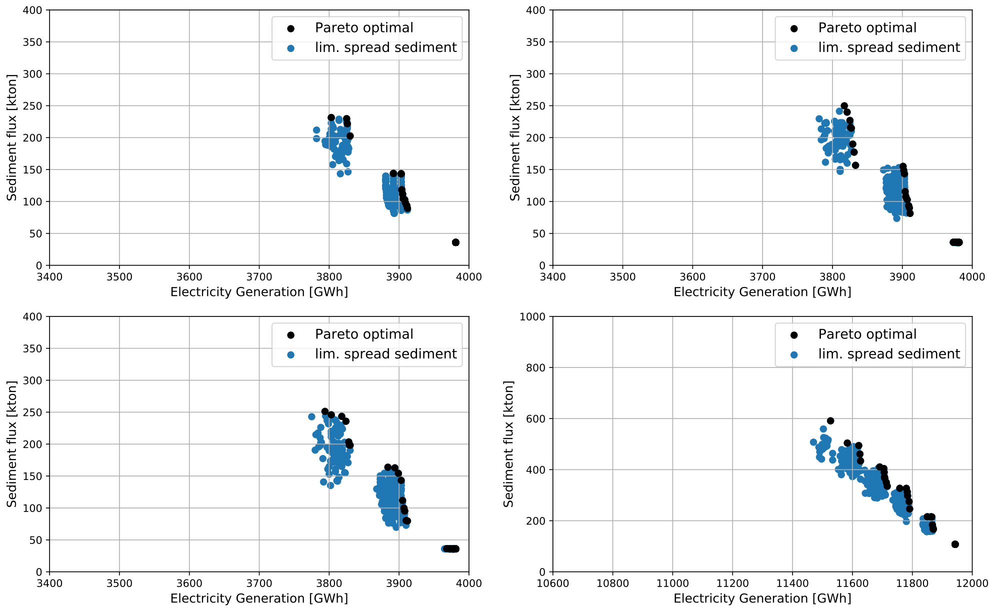

Figure D.4: Electricity generation versus sediment flux, with on average one flushing event in the wet season, threshold discharge at 6500 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

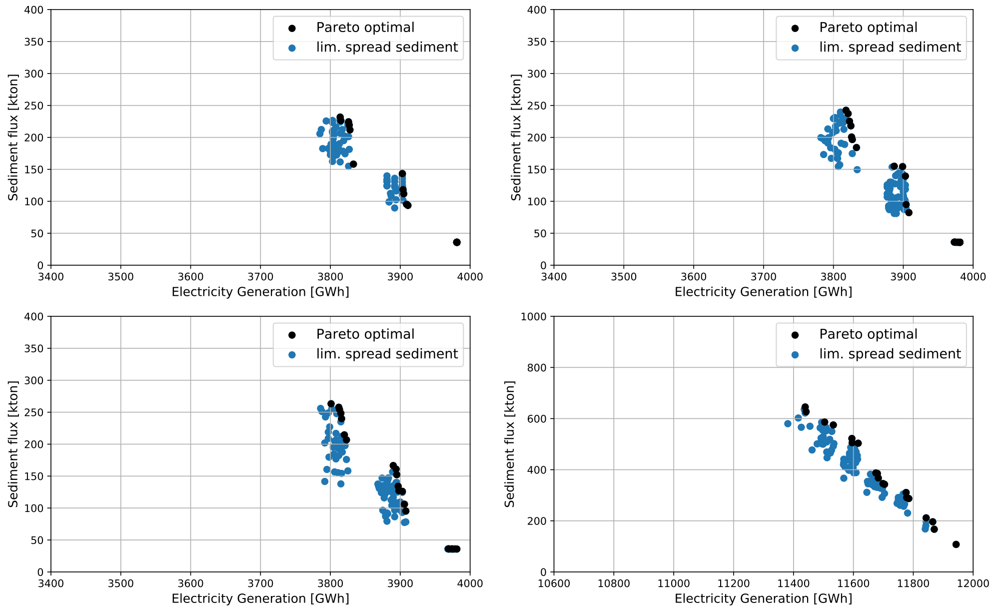

Figure D.5: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 6500 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

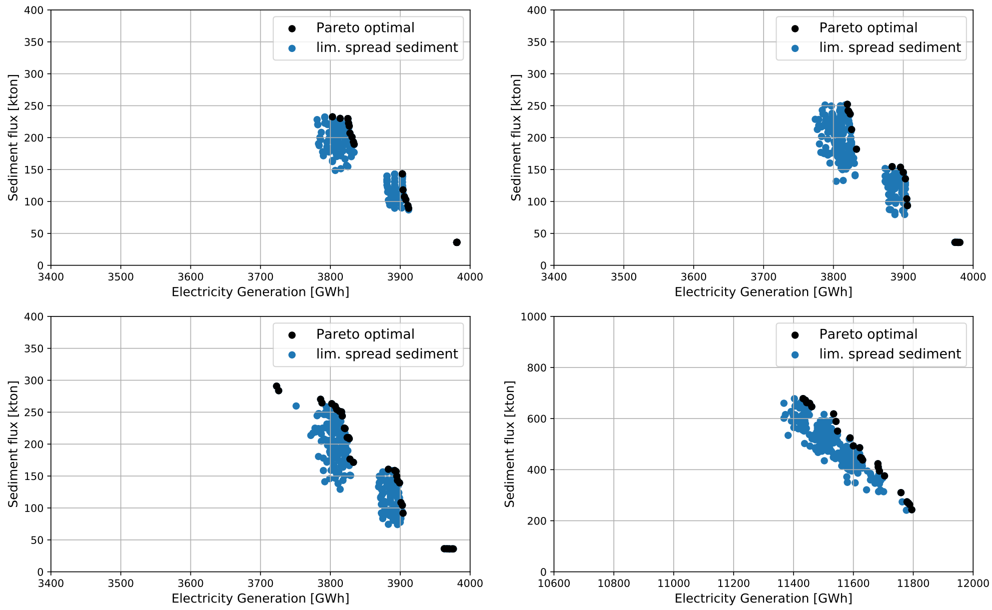

Figure D.6: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 6500 m^3/s and using all draw down rates (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

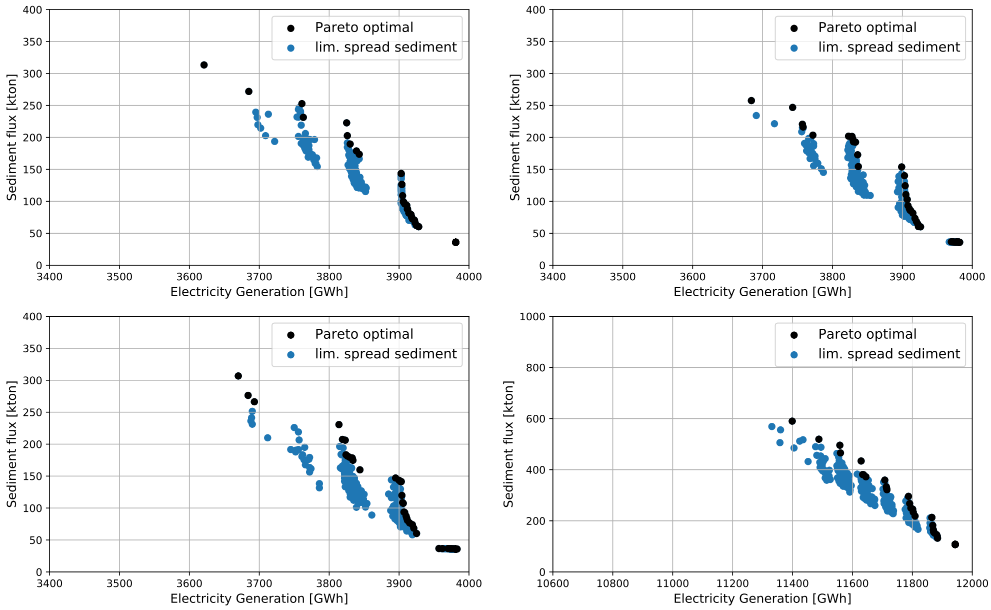

Figure D.7: Electricity generation versus sediment flux, with on average one flushing event in the wet season, threshold discharge at 5000 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

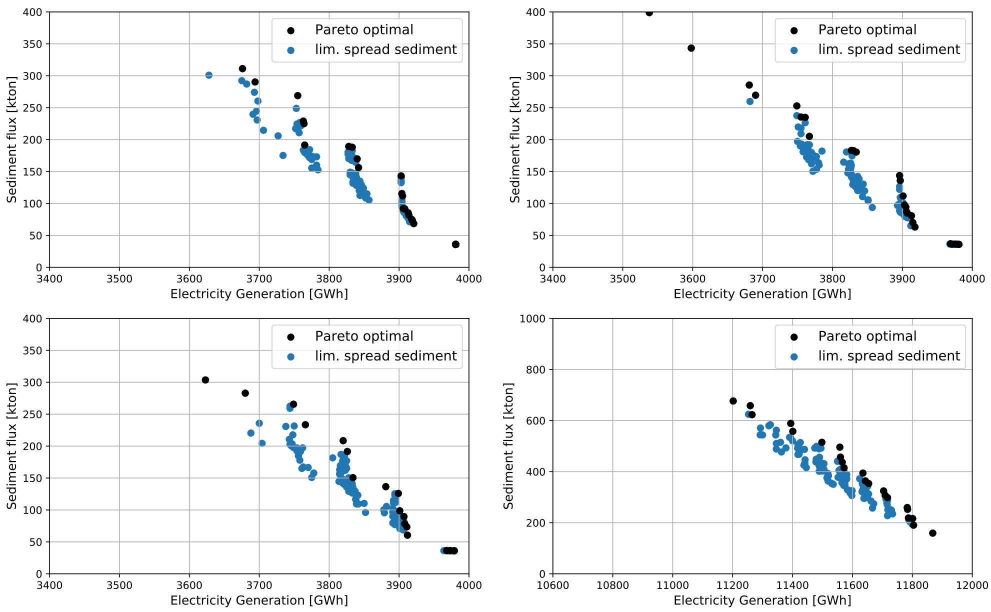

Figure D.8: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 5000 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

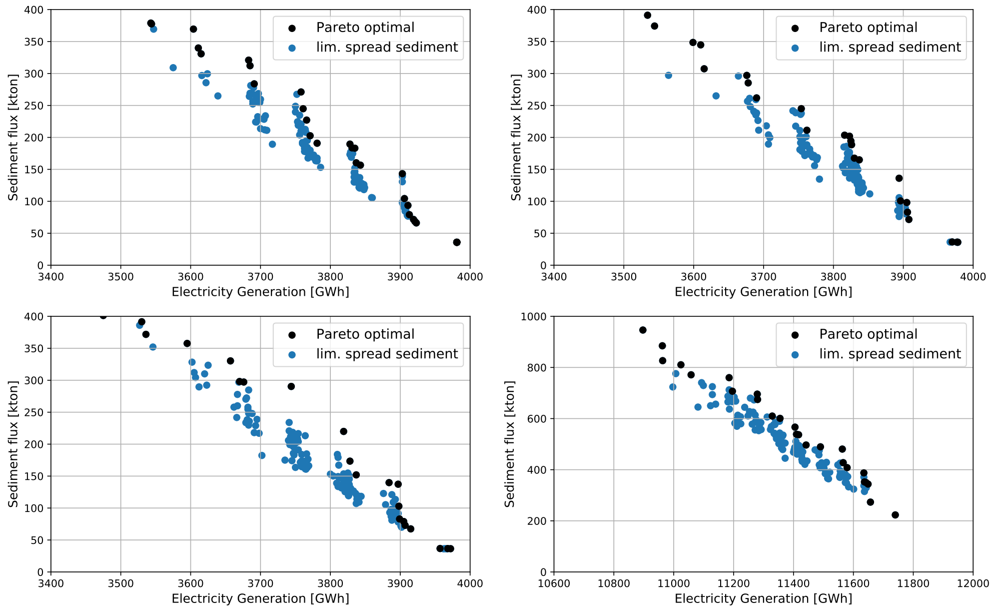

Figure D.9: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 5000 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

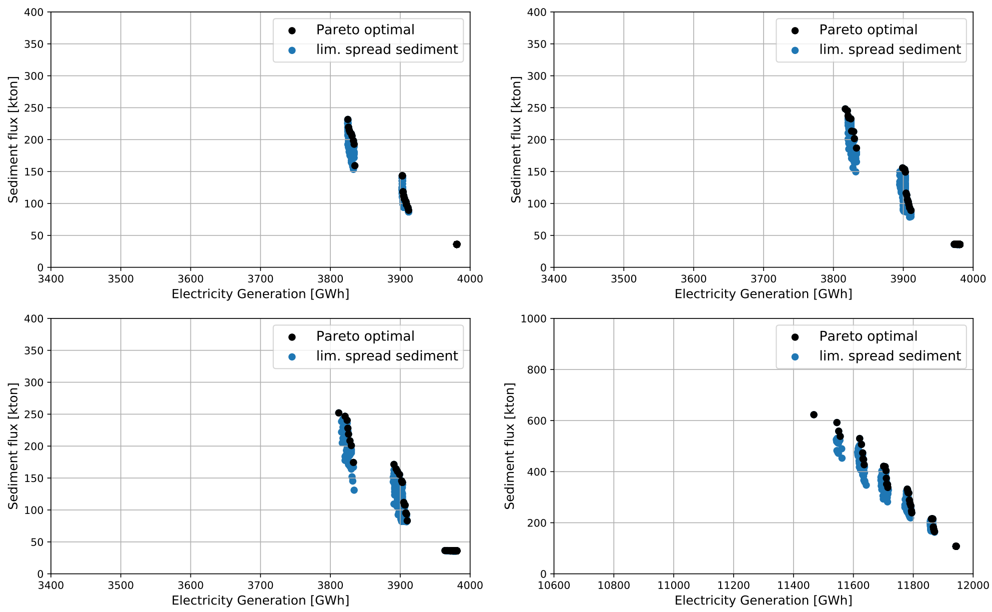

Figure D.10: Electricity generation versus sediment flux, with on average one flushing event in the wet season, threshold discharge at 6500 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

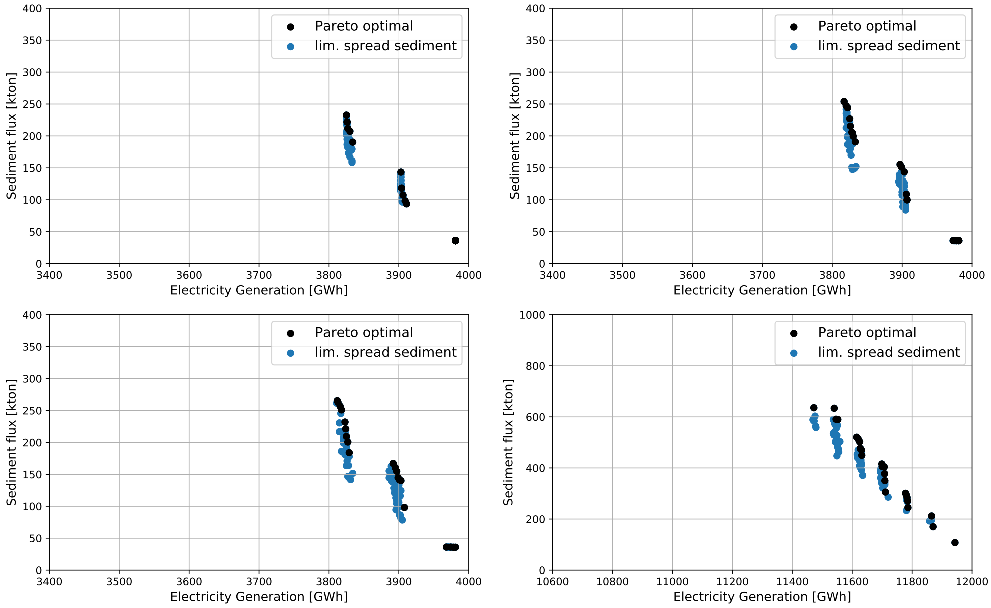

Figure D.11: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 6500 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

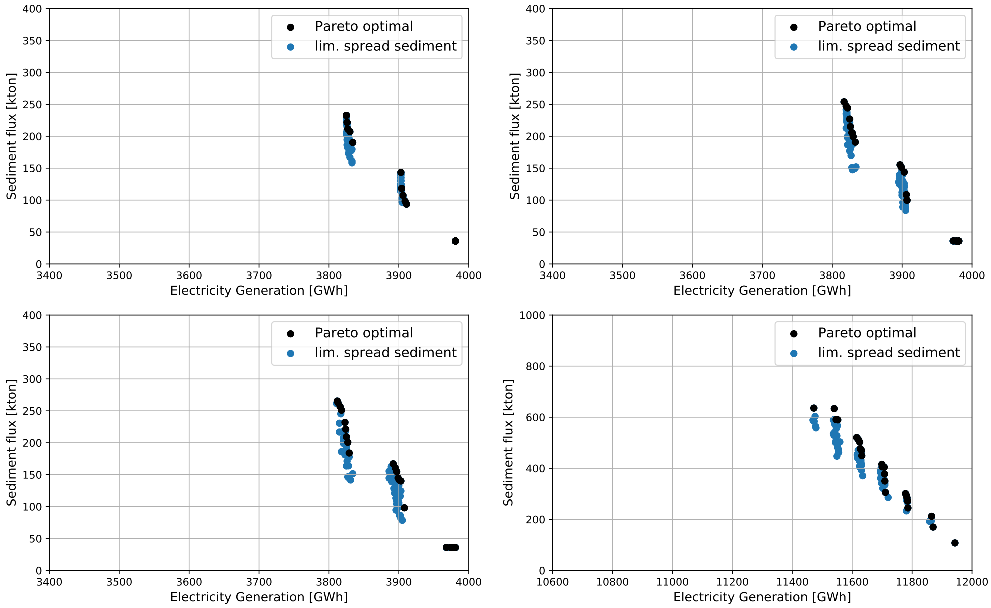

Figure D.12: Electricity generation versus sediment flux, with on average two flushing events in the wet season, threshold discharge at 6500 m^3/s and only using draw down rates of 0.8 m/h and 1.0 m/h (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

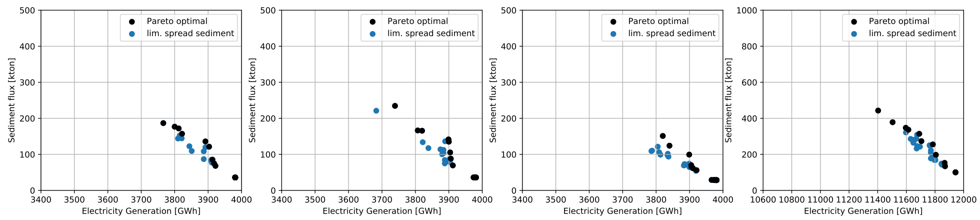

Figure D.13: Electricity generation versus sediment flux, with on average one flushing event in the wet season, threshold discharge at 5000 m^3/s and using all draw down rates with reduced sediment permeability at dam 3 (panel 1 to 3 - dam 1 to 3, panel 4 - sum cascade)

D.2. Results pre-determined scenarios method

The results of the simulations using pre-determine scenarios are presented here. Section D.2.1 presents the results of the pre-determined scenarios flushing the cascade from the upstream dam into downstream direction. Section D.2.2 presents the results of the pre-determined scenarios flushing the cascade from the downstream dam into upstream direction. For each pre-determined two Pareto optimal fronts are presented. The first Pareto optimal front

D.2.1. Results flushing cascade in downstream direction

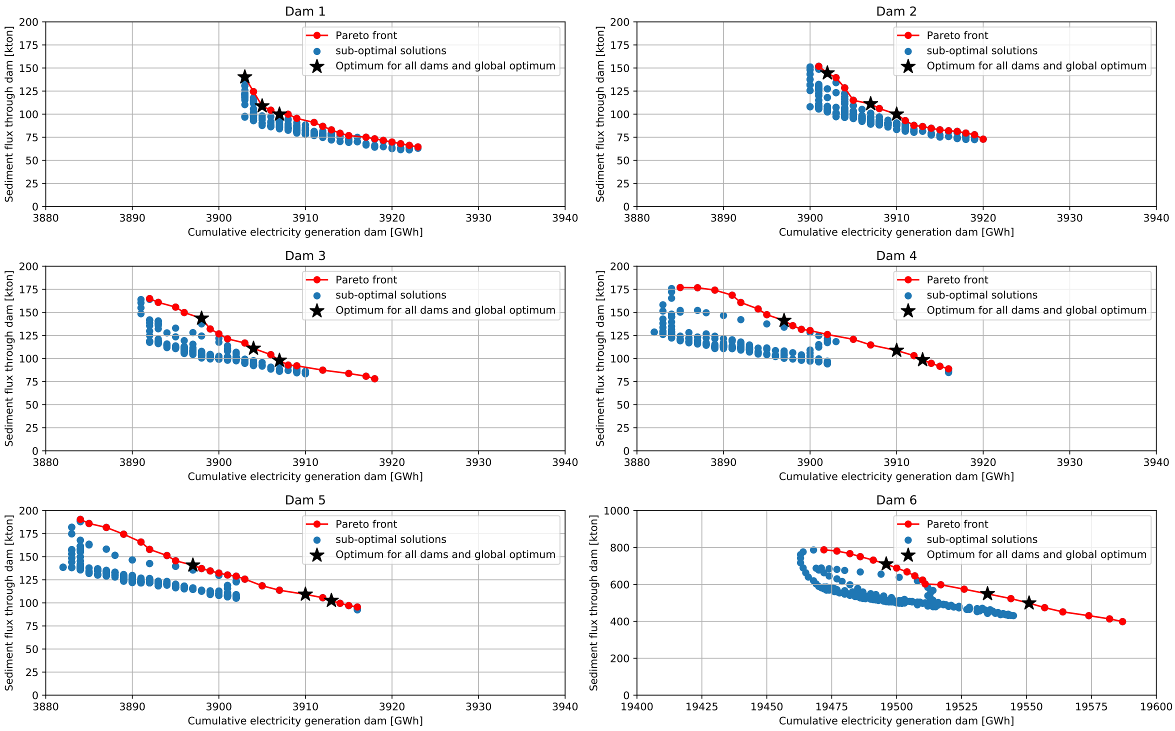

Figure D.14: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where all dams flush simultaneously.

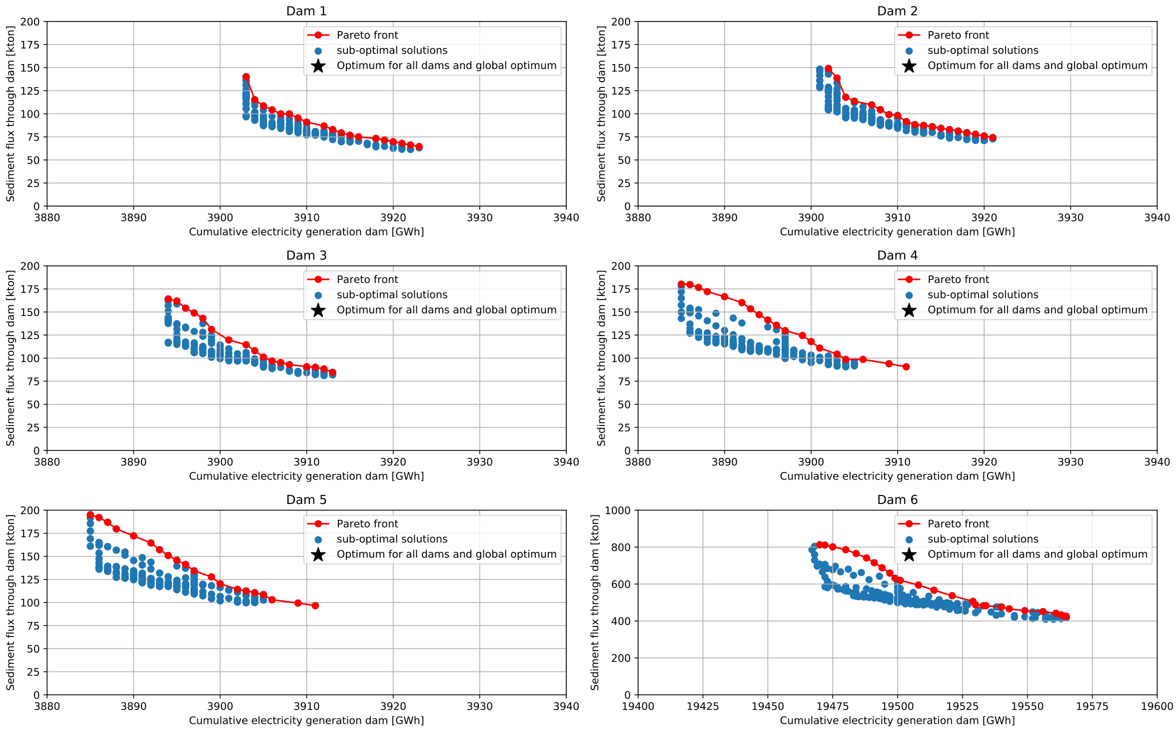

Figure D.15: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 6 hours between the onset of draw down operations.

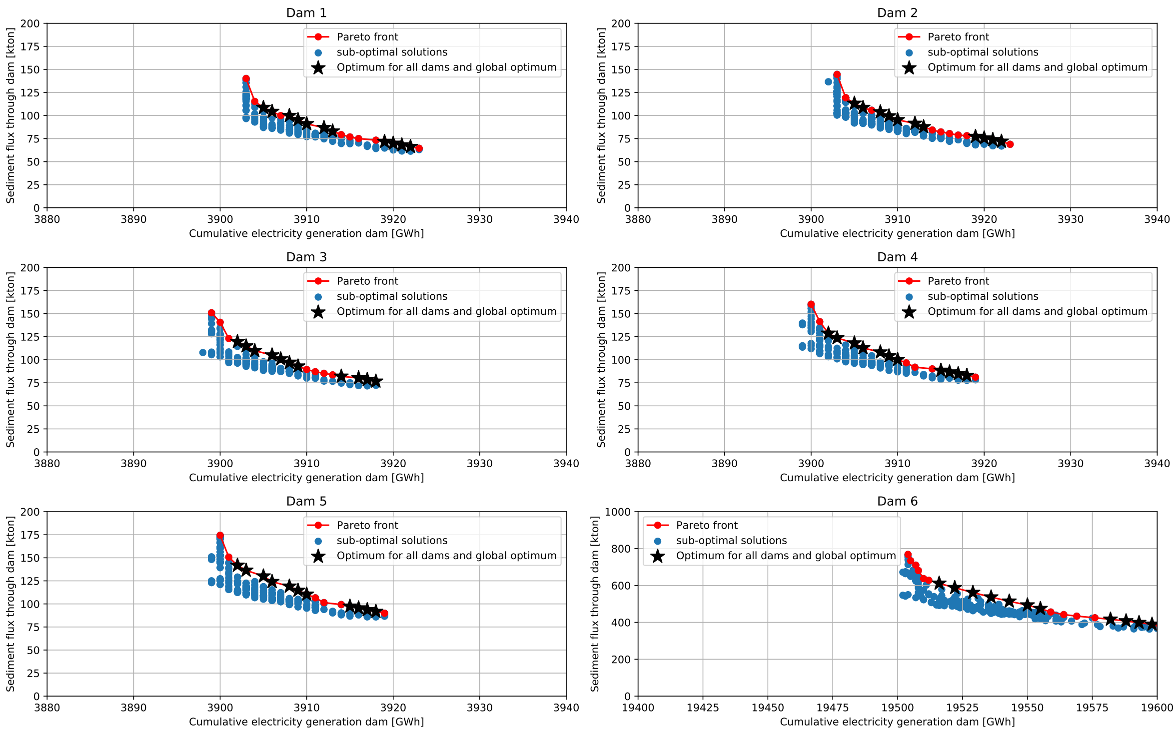

Figure D.16: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 12 hours between the onset of draw down operations.

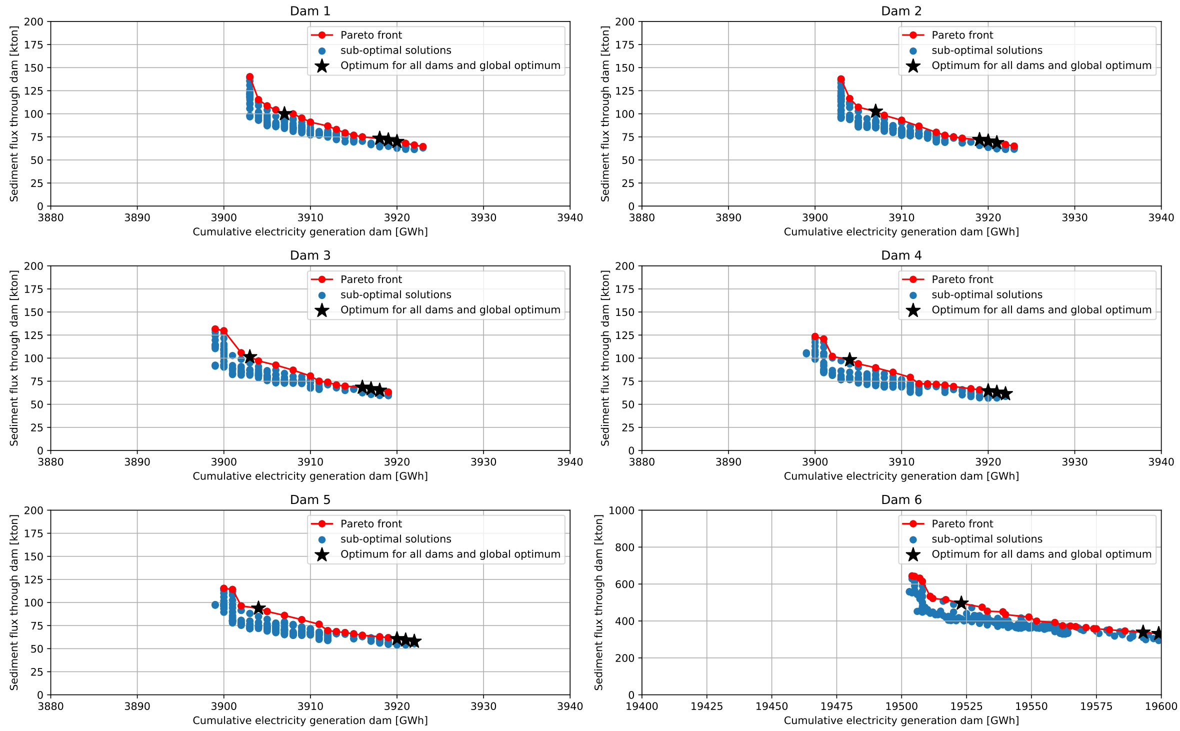

Figure D.17: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 18 hours between the onset of draw down operations.

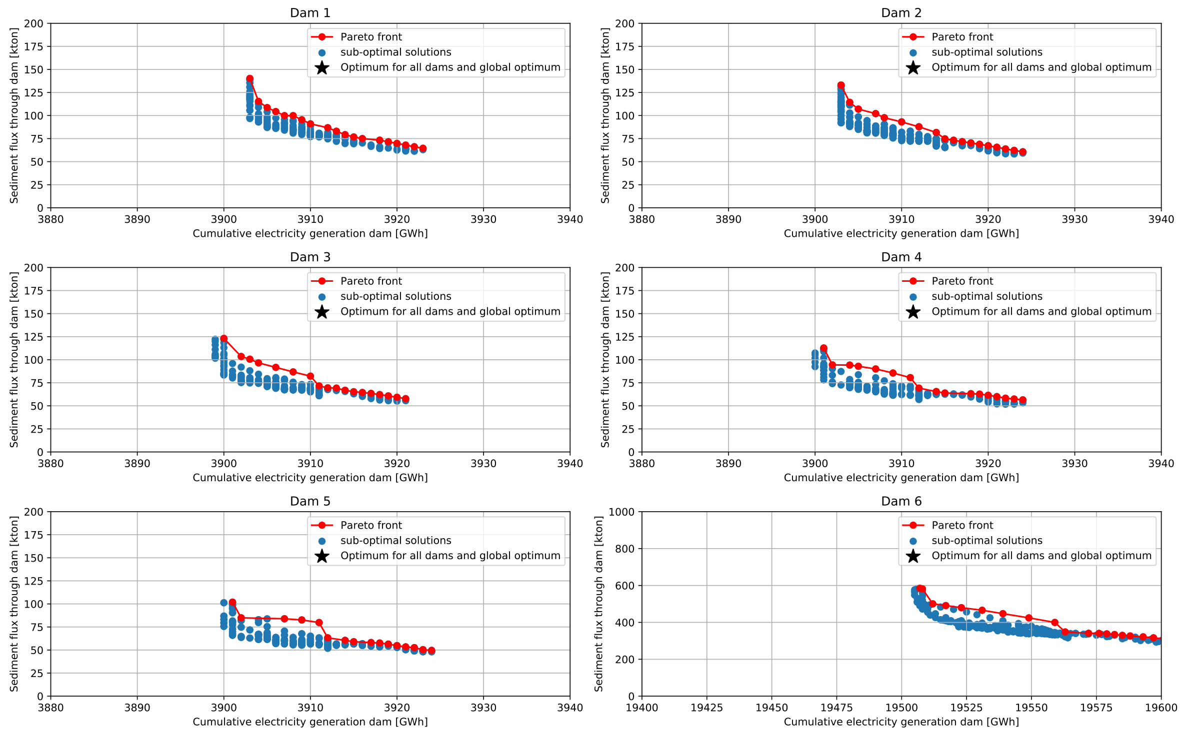

Figure D.18: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 24 hours between the onset of draw down operations.

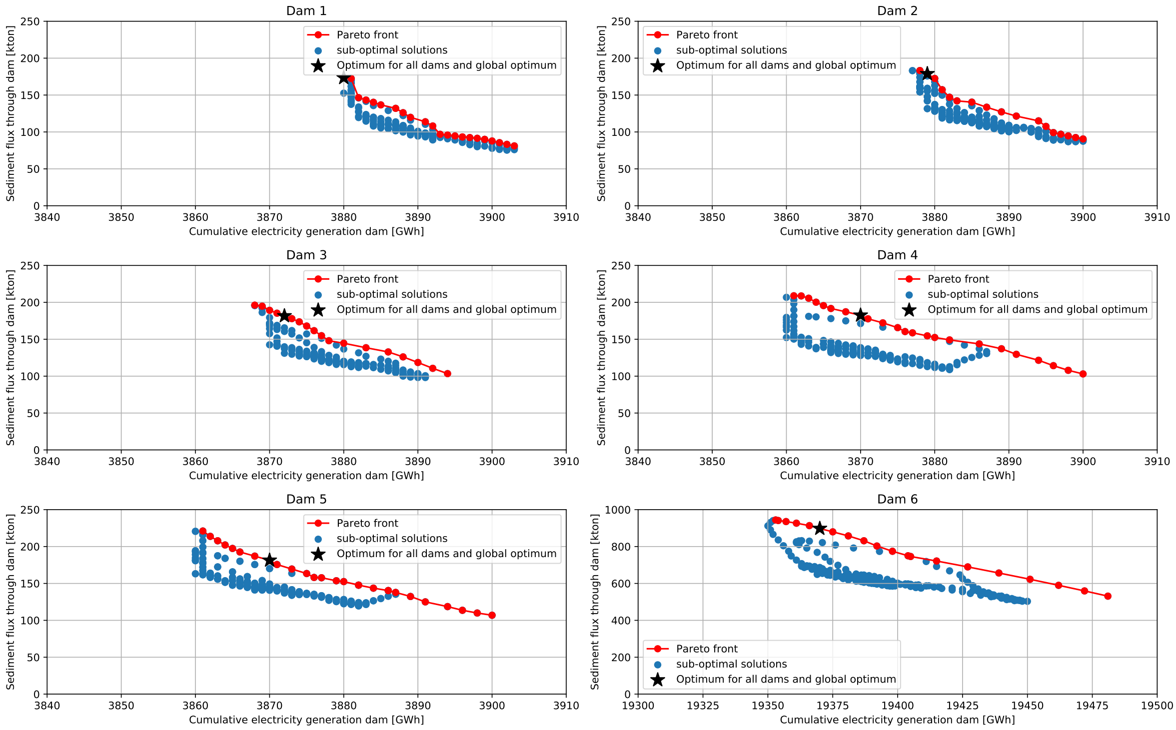

Figure D.19: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 6 hours between the onset of draw down operations. The duration at free flowing conditions is extended from 48 to 72 hours.

D.2.2. Results flushing cascade in upstream direction

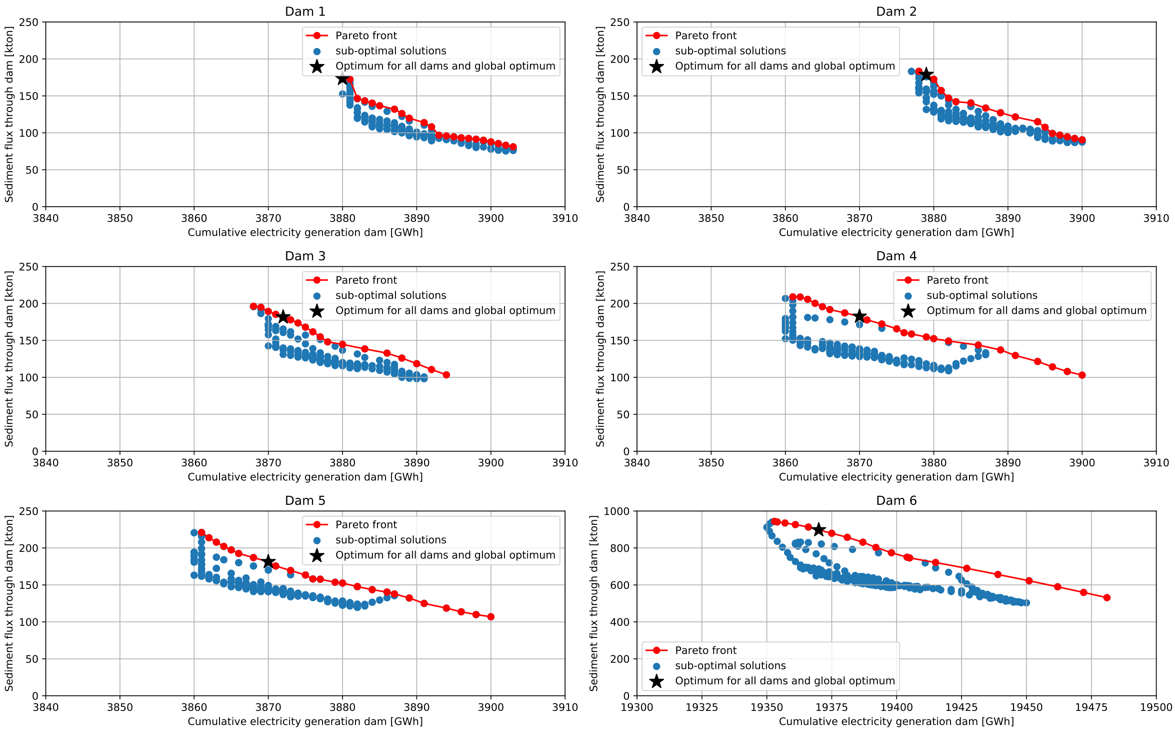

Figure D.20: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 6 hours between the onset of draw down operations.

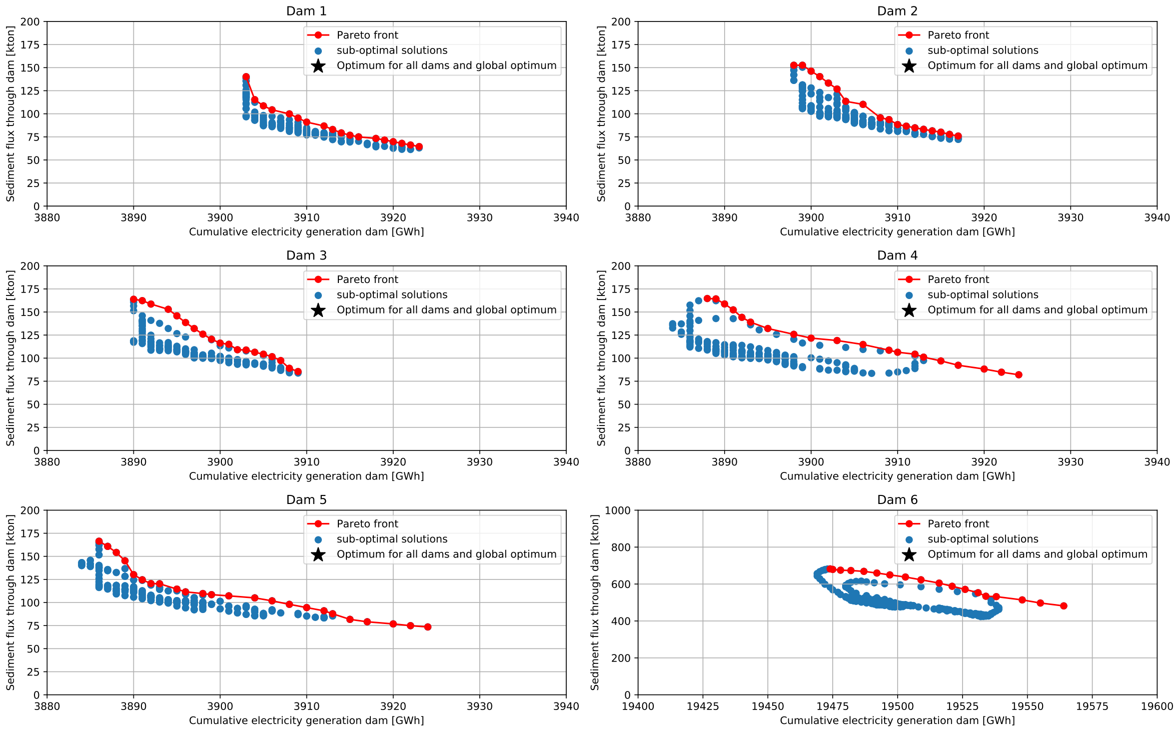

Figure D.21: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 12 hours between the onset of draw down operations.

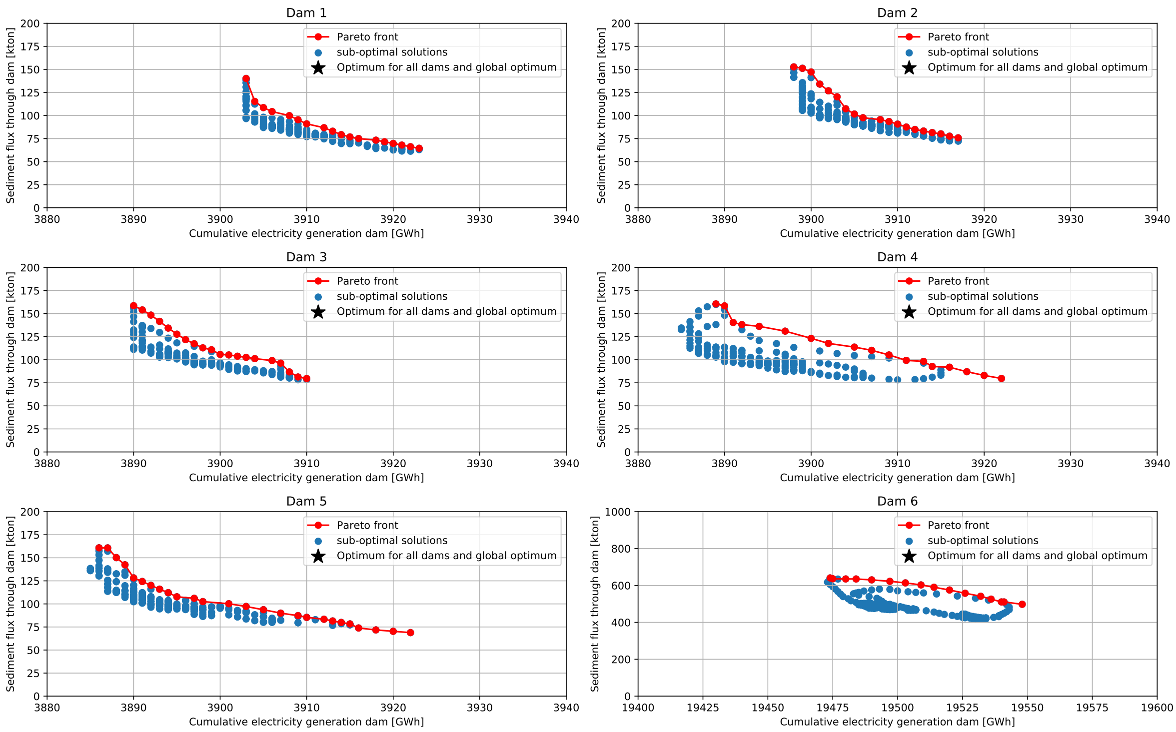

Figure D.22: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 18 hours between the onset of draw down operations.

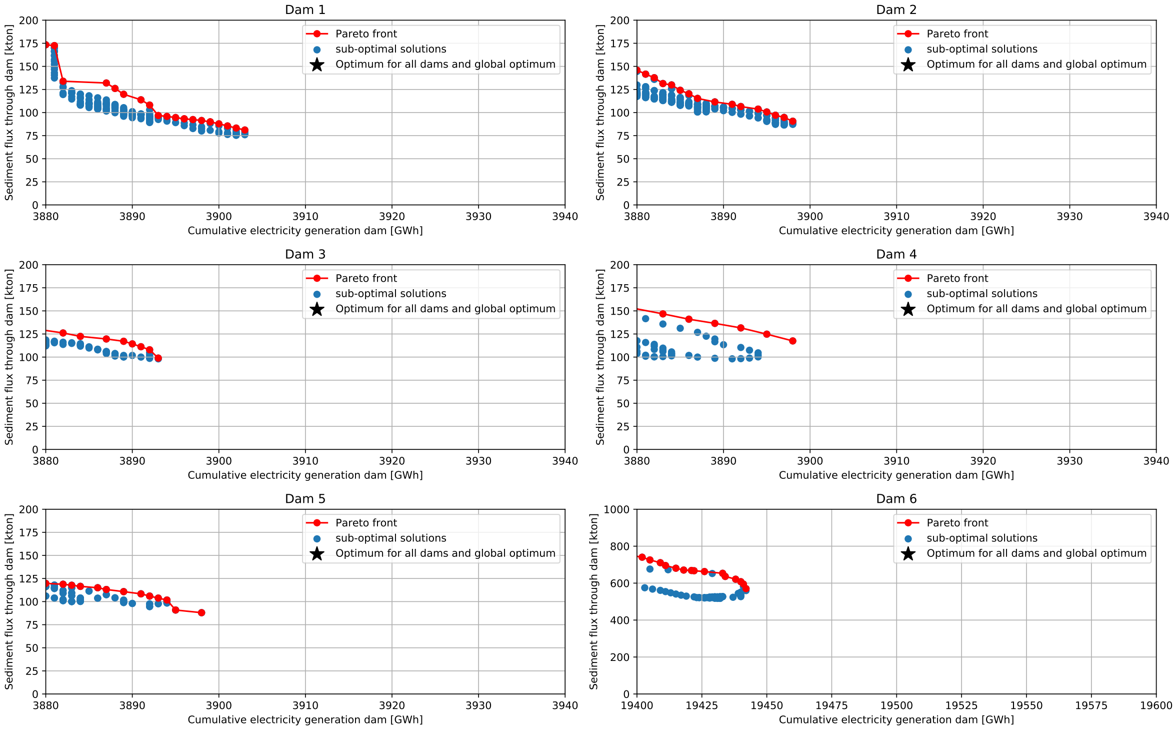

Figure D.23: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 24 hours between the onset of draw down operations.

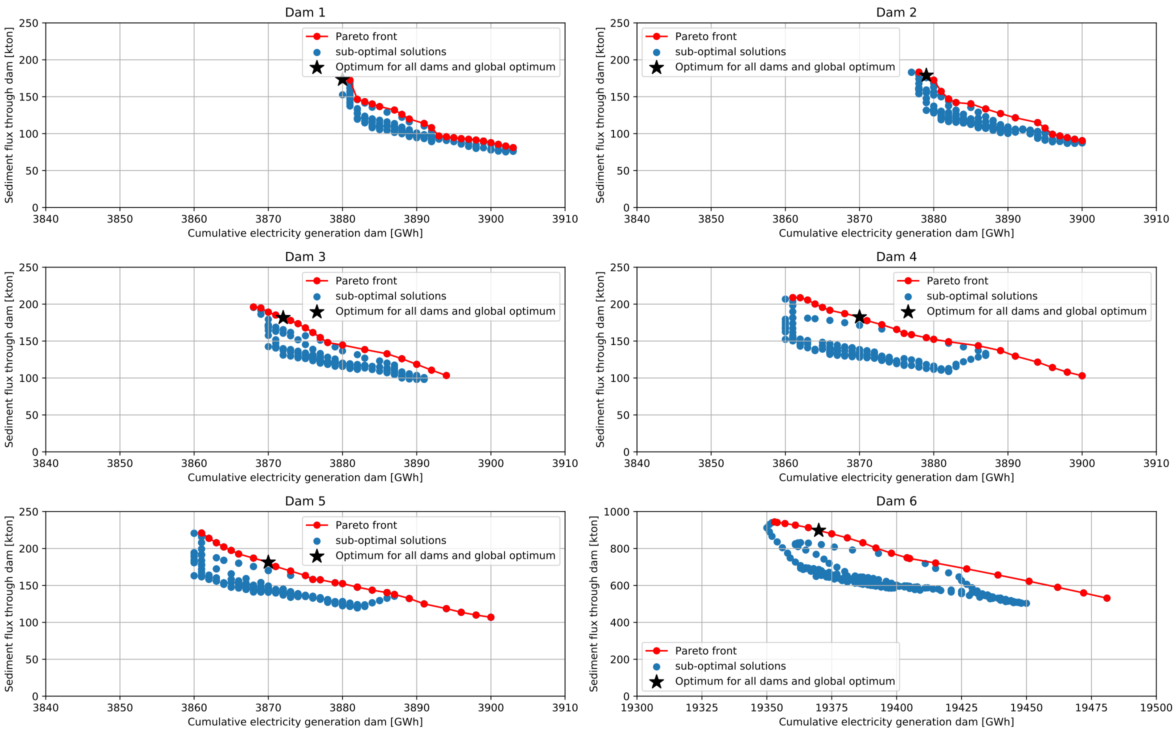

Figure D.24: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where there is a difference of 6 hours between the onset of draw down operations. The duration at free flowing conditions is extended from 48 to 72 hours.

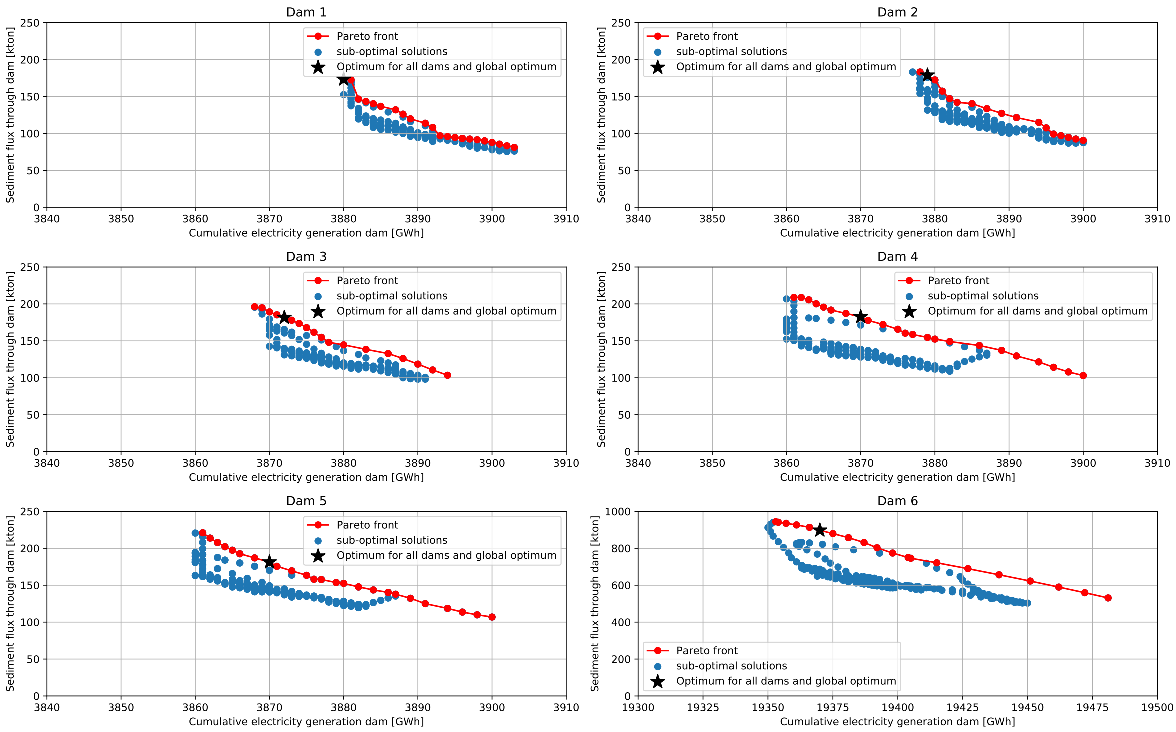

Figure D.25: Electricity generation versus sediment flux for the five dams and the total cascade for the scenario where three dams are always generating electricity. The duration at free flowing conditions is extended from 48 to 72 hours.