Mekong River Commission

Office of the Secretariat in Vientiane
184 Fa Ngoum Road, Ban Sithane Neua,
P.O. Box 6101, Vientiane, Lao PDR
Tel: (856-21) 263 263 Fax: (856-21) 263 264

mrcs@mrcmekong.org

Office of the Secretariat in Phnom Penh
576 National Road, no. 2, Chok Angre Krom,
P.O. Box 623, Phnom Penh, Cambodia
Tel: (855-23) 425 353 Fax: (855-23)425 363

www.mrcmekong.org

The ISH 0306 Study

Development of Guidelines for Hydropower Environmental Impact Mitigation and Risk Management in the Lower Mekong Mainstream and Tributaries

1st Interim Report – Final

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Volume 3 – Case Study – Objectives, Scope, Methodology and Modelling

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The Final Interim Report constitutes 3 volumes:

Volume 1: Version 1.0 – Hydropower Risks and Impact Mitigation Guidelines and Recommendations

Volume 2: Version 1.0 – Hydropower Risks and Impact Mitigation MANUAL – Key Hydropower Risks, Impacts and Vulnerabilities and General Mitigation Options for Lower Mekong

Volume 3: Case Study – Objectives, Scope, Methodology and Modelling

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Preface

This documents is the 1st Interim Report of the ISH0306 Mekong River Commission study - ***Development of Guidelines for Hydropower Environmental Impact Mitigation and Risk Management in the Lower Mekong Mainstream and Tributaries***. It builds on the work and results from inception period and the Inception Report (Volume 1 – 3) with emphasis in this 1st Interim Phase on developing; (i) Version 1.0 - Hydropower Risks and Impact Mitigation Guidelines and Recommendations (Volume 1) (ii) Hydropower Risks and Impact Mitigation MANUAL - Key Hydropower Risks, Impacts and Vulnerabilities and General Mitigation Options for Lower Mekong, as well as; (iii) Case Study – Objectives, Scope and Methodology for the 2nd Interim Phase (Volume 3). The study is supervised and coordinated by the Initiative on Sustainable Hydropower (ISH)/Mekong River Commission Secretariat (MRCS) with the following key personnel:

- Mr. Voradeth Phonekeo
- Mr. Simon Krohn and
- Mr. Piseth Chea

The project is executed by a team of experts from Multiconsult (Norway/UK) in association with Deltares (The Netherlands) plus two Key Experts on individual contracts (Australia and Austria). The following key-experts are involved:

- Mr. Leif Lillehammer (Team Leader, Multiconsult),
- Mr. Chris Grant (Hydropower Design and Operations Expert, Multiconsult),
- Mr. Jean-Pierre Bramslev (Hydropower Modeller and Economics Expert, Multiconsult),
- Mr. Ron Passchier (Hydrologist and Water Resources Modeller, Deltares),
- Dr. Kees Sloff (Hydraulic and Sediment Modelling Expert, Deltares),
- Dr. Lois Koehnken (Sediment and Water Quality Expert, Individual Consultant, Australia) and
- Dr. Stefan Schmutz (Fisheries and Aquatic Ecology Expert, BOKU - Vienna).

The team includes also the following non-key experts and support staff:

- Dr. Jørn Stave and Mr. Jens Johan Laugen (Environmental and Social Impact Assessment and Safeguards Experts, Multiconsult)
- Mr. Bjørn Stenseth (Power Economist, Multiconsult)
- Dr. Sanjay Giri (Hydraulic Expert, Deltares)
- Mrs. Carina Mielach (Aquatic Ecologist, BOKU-Vienna)
- Mr. Bernhard Zeiringer (Fish-Pass Eco-Engineer, BOKU-Vienna)
- Ms. Ragnhild Heimstad and Mr. Amrit Poudel (Terrestrial/Riparian Ecologists, Multiconsult)
- Mrs. Irene N. Koksæter (Livelihoods Expert, Multiconsult)

National Consultants also providing input to the study are as follows:

- Lao PDR: Ms. Thipsathiane Khamvongsa (Environment and Water Resources)
- Lao PDR: Mr. Lamphone Dimanivong (Hydropower and Energy)
- Cambodia: Dr. Sophal Chhun (Environment and Water Resources, Ecosystem Services)
- Cambodia: Dr. Heng Sokchay (Hydropower and Energy)
- Vietnam: Dr Nguyen Quang Trung (Environment and Water Resources)
- Vietnam: Dr. Hoang Minh Tuyen (Hydropower and Energy)

Abbreviations

BDP – Basin Development Plan

DEM – Digital Elevation Model

DSF – Decision Support Framework

HPP – Hydropower Project

ISH – Initiative on Sustainable Hydropower

LMB – Lower Mekong Basin

MOL – Minimum Operation Level

MRC – Mekong River Commission

UMB – Upper Mekong Basin

USACE – United States Army Corps of Engineers

1 Introduction

This Volume 3 of the 1st Interim Report is a stand alone document from Volume 1 and 2 as it constitutes Scoping of the Case Study (Activity/Output 5 of ISH0306) of the Mainstream Cascade to be undertaken in the 2nd Interim Phase. As such it outlines the Objectives, Scope, Methodology and Modelling of this activity.

The Case Study will focus on testing the selected mitigation options for effectiveness, sustainability and at the same time maximizing the operational flexibility of the HPP's. The mitigation guidelines studied and proposed (for both the general and detailed assessment) will emphasize on fisheries and aquatic ecology (migrations, diversity, productivity and its links to livelihood) as well as erosion, sediment and geomorphic issues and water quality. Furthermore mitigation options will also be assessed with regard to water quality, alteration of downstream flows, multiple water uses, environmental flows, biodiversity, natural resources and ecosystem services. The mitigation options will be closely linked to studies on hydropower operation and design such as operation rules and alternative layout schemes. Overview of the mainstream cascade is given in Figure 1-1.

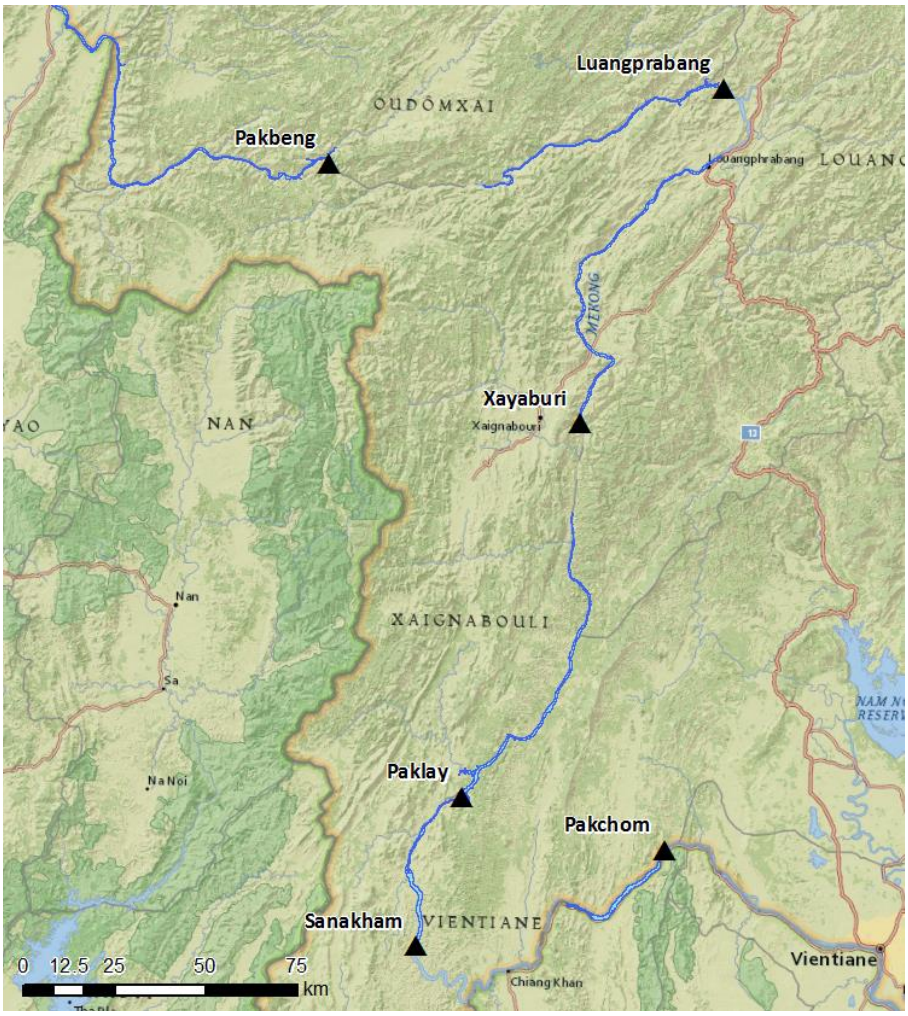


Figure 1-1. Overview of the mainstream hydropower cascade, upstream Vientiane, with its reservoirs (The reservoir areas in the map are generated in a terrain model based on NASA's SRTM data with a grid resolution of about 30 meters).

2 Case Study 2nd Interim Phase

2.1 Objectives

In order to derive the Guidelines for hydropower impact mitigation on the Mekong River and its tributaries, it is necessary to assess the effectiveness of proposed measures. For this purpose, a modelling system will be applied that is partly based on existing models, but will also make use of a number of dedicated new models.

In this Report, a description is given of the application of models for the derivation of the Guidelines. For this purpose, first a short description is given of the salient features of the Mekong River as far as this is important for the modelling application. Subsequently the dominant processes in the river system are described that will need to be modelled. Next, the modelling system itself is described, making a distinction between the overall model of the LMB and the more detailed model of the (pilot) Lao cascade.

2.2 Preliminary scenarios

A tentative list of options is given in Table 2.1 together with the objectives of the river and energy modelling to be undertaken in each case. It is envisaged that as the study proceeds further options may be introduced and a number of sub trials for each option will be undertaken to determine the most suitable parameters. The energy and revenue results will be used to assess the overall economic consequences of each option to indicate if it is likely to be feasible in practice.

Table 2.1. Preliminary Case Study Options

Option No.	Subject	Details	Objective	
			River Model	Energy Model
0	Reference Case	BDP 2040 (BDP 2030-20 Y) scenario building in the net effects of the tributary and UMB dams. Only modelled to use as a reference for 1,1 to 1,4 and 2. Seeking to understand, and separate out, the base conditions caused by these other developments to allow consideration of the incremental impact of the mainstream cascade and therefore the best mitigation of that incremental impact.	Establish baseline water quality, sediment transport and downstream morphology conditions against which mainstream cascade impacts and mitigation options can be compared. Expert assessment of fish migration and productivity baseline. Upstream fish migration assessment will be based on expert review. Model results will inform assessment of the scenarios.	N/A
1,1	5 Project Cascade (Scenario 1 in Council Study)	Add Pak Beng, Luang Prabang, Xayaburi, Pak Lay and Sanakham assuming fish passage design similar to Xayaburi. No draw down and sediment management strategy at the 5 new schemes. Operate cascade 100% base load at full supply level, 24 hours per day, 7 days per week.	Establish water quality, sediment transport and downstream morphology conditions to be compared with Baseline Scenario 0. Determine long term implications of sediment retention in cascade schemes until equilibrium is achieved. Model results will inform expert assessment of impact on fish migration and productivity.	Establish energy and revenue from the 5 cascade schemes.
1,2	5 Project Cascade + Sediment Draw Down	As Option 1.1 but with sediment management by reservoir draw down during frequent (2 year) floods at all 5 projects following the Xayaburi strategy. Sub trials will be conducted to determine the consequences of a range of partial draw down strategies. (Flood draw down at Xayaburi and associated sediment flushing will still be required to limit high backwater levels at Luang Prabang.)	Establish effectiveness of sediment flushing in the cascade during low return period floods compared with Option 1.1. Model results will inform expert assessment of impact on fish migration and productivity.	Establish energy and revenue from the 5 cascade schemes. Determine energy difference against Option 1.1

Option No.	Subject	Details	Objective	
			River Model	Energy Model
1,3	5 Project Cascade + Hydro Peaking (Joint Operation in Council Study - Scenario 2)	As Option 1.2 but incorporating hydro peaking to transfer limited flow to high tariff times of day and days of the week when river flow drops below installed capacity. Conduct sub trials to determine acceptable amplitudes and ramp rates in head ponds and in the tail water levels and discharges downstream of Sanakham.	Determine impact of hydro peaking on head pond levels, tail water levels and wave propagation to inform judgements on acceptable hydro peaking amplitudes and ramp rates, particularly with reference to hydro safety, navigation, fish stranding and geomorphology.	Establish energy and revenue from the 5 cascade schemes. Determine energy and revenue difference against Options 1.1 & 1.2
1,4	5 Project Cascade + Shut Down	As Option 1.1 but with reservoir draw down to natural river conditions + total station shut down for duration of peak upstream fish migration period (May?) and again later in the wet season for peak downstream fish migration period. Reservoir draw down and re-fill achieved gradually using turbined flows and maintain draw down using spillway gates.	Establish effectiveness of improved fish migration and productivity using model results to inform expert assessment. Assess effectiveness of sediment flushing arising as a consequence of draw down and shut down strategy.	Establish energy and revenue from the 5 cascade schemes. Determine energy and revenue difference against Options 1.1 & 1.2
2	3 Project Cascade + Sediment Draw Down	Cascade comprising Pak Beng, Luang Prabang and Xayaburi. Operate as Option 1.2	Establish water quality, sediment transport and downstream morphology conditions to be compared with Option 1.2. Model results will inform expert assessment of impact on fish migration and productivity.	Determine energy and revenue difference against Option 1.2

Option No.	Subject	Details	Objective	
			River Model	Energy Model
Scenarios for High Level Assessment (no detailed modeling but economics versus environmental benefit assessment)				
3	Lower dams	Sub divide one or more of Pak Beng, Luang Prabang and Pak Lay.into two half height schemes, equip with low speed bulb turbines and operate as Option 1.2	Establish effectiveness of lower dams and smaller impoundments with respect to sediment flushing, water quality and fish passage compared with Option 1.2	Determine energy and revenue difference against Option 1.2
4	Revised locations (fish)	Investigate revised locations of one or more of Pak Beng, Luang Prabang, Pak Lay and Sanakham with respect to major tributaries to improve fish connectivity. Operate as Option 1.2	Model results to inform expert assessment of effectiveness of relocated dams with respect to fish connectivity and migration compared with Option 1.2	Determine energy and revenue difference against Option 1.2
5	Revised locations (sediment)	Investigate revised locations of one or more of Pak Beng, Luang Prabang, Pak Lay and Sanakham with respect to major tributaries to reduce sediment retention. Operate as Option 1.2	Investigate sediment retention and transport compared with Option 1.2	Determine energy and revenue difference against Option 1.2

3 Testing mitigation options

3.1 Description of Mekong system

3.1.1 Geographical subdivision

In order to select the correct models for hydropower risk and environmental impact mitigation in the Mekong, the geographical layout or the position of the model in the basin, is an important criterion.

The LMB can be divided into the following stretches for the purpose of the modelling:

1. Chiang Saen – Vientiane
2. Vientiane – Phnom Penh
3. Tonle Sap system
4. Phnom Penh – start Mekong Delta
5. Mekong Delta

The first stretch is chosen to represent the reach with and without the dam cascade (and main-stream reservoirs), as well as the transition from a bed-rock dominated channel to a fully alluvial sand-bed channel. This stretch forms the subject of the case study of the Lao cascade.

The next stretch from Vientiane to Phnom Penh represents the main river and the tributaries that are now modelled using the DSF modelling suite. The boundary at Phnom Penh is chosen as this is the location of the start of the point of inflow towards the Tonle Sap system.

A special case is the Tonle Sap lake system with the bi-direction flow system connected to the Mekong River at Phnom Penh.

The fourth stretch is the last part of the Mekong River, with tributaries up till the point of noticeable impact of the tides on the flow. Evidently this is not a well-defined location, but for the purpose of the present study, it is sufficient to use a point below which the impact of the mitigation measures on the salt intrusion might become noticeable.

The fifth stretch represents the Mekong Delta, which is a very complicated system with tidal influence. Here, particular attention needs to be given to salt water intrusion that has a direct impact on irrigation water availability and fishery.

Considering the application of models in the case study of IHS0306, the geographical layout can be roughly lumped into three parts, as shown in Figure 3.1.

1. Upper Mekong Basin, upstream from Chang Saen
2. Lao cascade reach, including the Pakbeng, Luangprabang, Xayaburi. Paklay, Sanakham and Pakchom dams and their reservoirs.
3. Lower Mekong Basin.

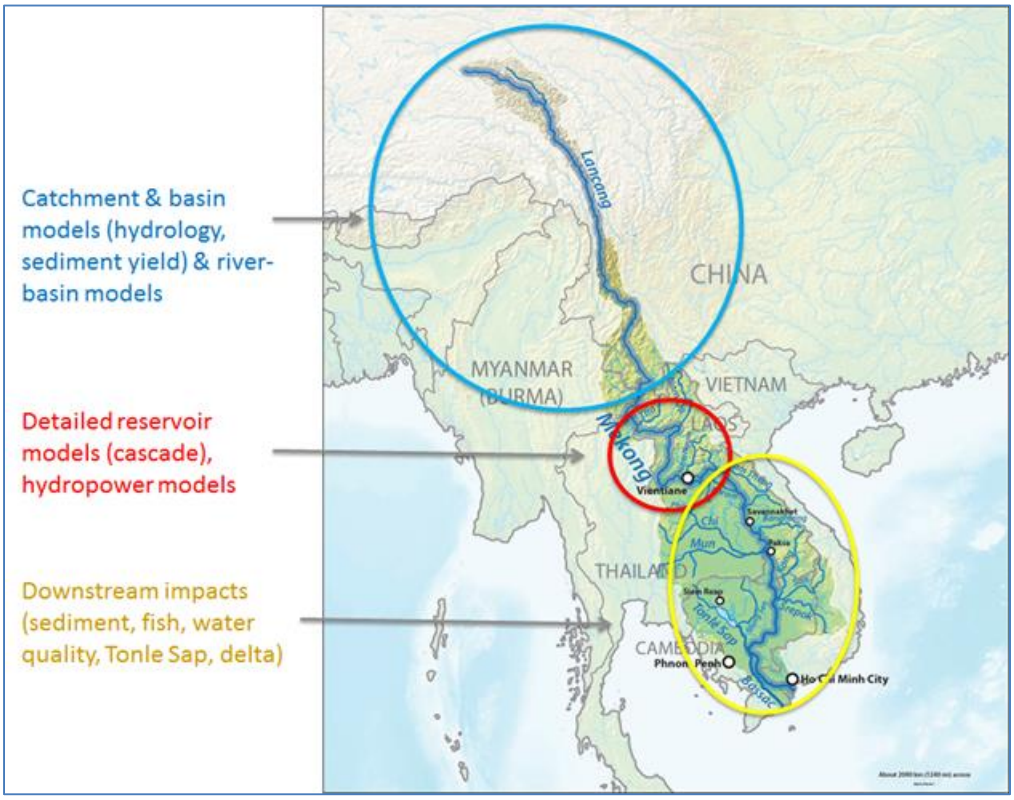


Figure 3.1 Geographical layout of the modelling domain, applied to the upper Lao Cascade.

In order to assess the impacts of dams and measures, simulations are required of the entire LMB. Depending on the location of the considered dam cascade, certain parts of the domain can be replaced/added with additional hydropower-modelling and reservoir models. For the case study in ISH0306, impacts will be assessed at and downstream of the Lao Cascade. Nevertheless, for many impacts it is the full LMB, starting from Chiang Saen, which needs to be included in the modelling.

3.1.2 Dominant processes to be modelled

The following processes will need to be modelled:

1. Rainfall-runoff in the tributaries
2. Sediment input from the various tributaries
3. Flow routing through the main channels
4. Sediment routing with the flow routing
5. Tonle Sap system, including sediment and water quality issues
6. Salt-water intrusion in the Mekong delta

An overview of the various processes along the main river is shown in Figure 3.2. The various dominant processes are further discussed in the next paragraphs.

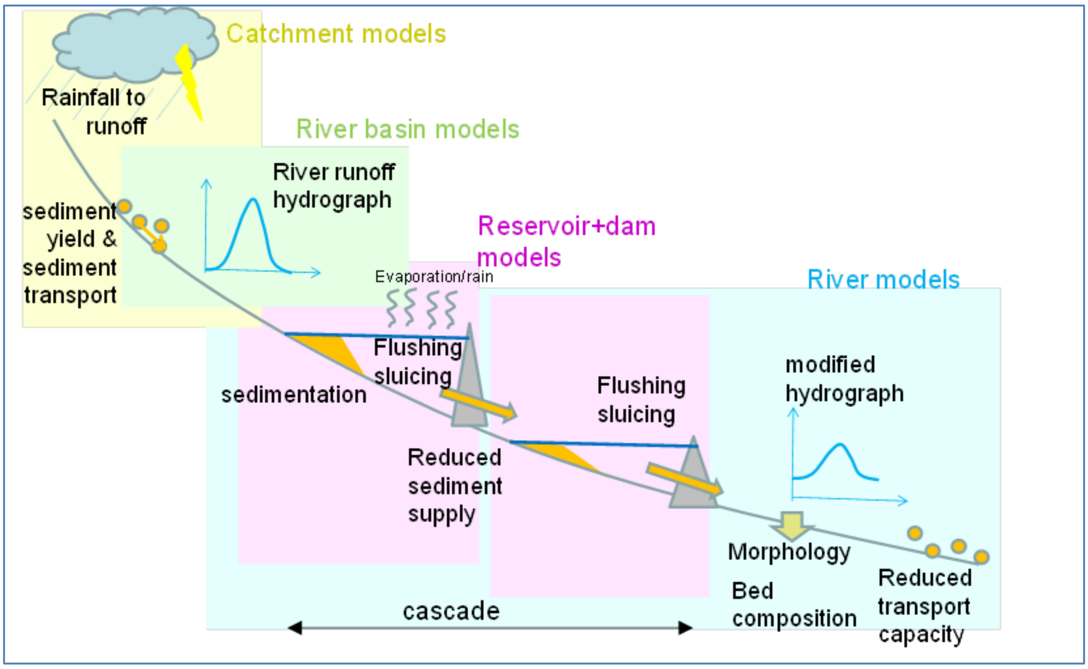


Figure 3.2 **Dominant processes along the Mekong River.**

3.2 Modelling approaches for specific processes and functions

3.2.1 Rainfall-runoff in the tributaries and the UMB (Chinese dams)

The boundary conditions of the cascade models are formed by the inflow from the UMB (Lancang) and the various tributaries up till Vientiane. For the former, use will be made of the discharge and sediment concentrations as provided by the modelling of the UMB by the DSF suite of models. This is specifically necessary to simulate the future scenarios, as the measured records up till present only just start to show the impacts of the Lancang cascade. The existing databases for DSF scenarios (Council study and BMP) contain results for hydrology with the lower six dams in the cascade, as well for the full fourteen dams in the cascade. The impact of the upper 8 additional dams is considered relatively small compared to the lower Lancang cascade, as the latter contains significant larger storage reservoirs.

Also for the tributary flows the simulated discharge series have to be retrieved from the DSF model, depending on the chosen future state of development of tributary dams.

The following future scenarios are considered relevant for the relevant inflows to the cascade in this case study.

Table 3-1. Future scenarios covered by the DSF model runs in Council Study and BDP2.

Type	Comment	Expected availability
Council Study 2008 with 2040 (or BDP 2030-20Y) tributary development and UMB	This condition is needed for the base condition. It contains both flow and sediment input from UMB and tributaries.	December 2015
Council Study development scenario 2040 (tributaries 2040, main-stream dams and UMB)	This is the preferred scenario for setting-up the cascade. However, the required conditions from the DSF will not be available in time for this project.	Prognosis: 2016
BDP 2 scenario 2030-20Y	These simulations were completed in 2011, but only for hydrodynamics. The results do not include the model updates of the DSF after 2011.	Directly available (may involve re-running the models)

In the DSF modelling work the time-series of discharges and water levels is based on hydrological conditions for the period 1985-2007. However, the modelling work for the BDP 2 scenarios was completed in 2011, and is only based on conditions for the period 1985-2000.

3.2.2 Sediment input from the various tributaries

Sediment input to the cascade is determined by the amount of catchment erosion, by instream sediment processes in the tributaries and reservoirs, and by sediment supply from the UMB. The DSF models are presently being prepared to calculate the sediment discharge in the Mekong basin (using SWAT and EWater sources). However, the relevant components and the calibration are probably not completed in time for usage in the ISH0306 case study (situation end 2015).

Alternatively, the potential sediment inflow from the tributaries and rivers can be estimated from a combination of results of sediment-balance/budget studies for the main-river, catchment size and erosion potential, and sediment trap-efficiency of planned tributary dams. These data can partially be obtained from existing EIA's for planned and constructed tributary dams, updated with recent sediment data if possible.

Results will be used for a selection of modelling scenarios as defined by the BDP and similar to those used in the Council study, as presented in Table 3-1.

3.2.3 Reservoir cascade modelling

In fact the most important part of the modelling for the Case Study is the reservoir simulations of the cascade. In the cascade the reservoirs are assumed to be connected in the sense that the tailwater of each reservoir is connected to the dam of the upper reservoir (with no or hardly any free-flowing river sections). The new detailed models for the cascade therefore need cover the full cascade reach without gaps that have to be filled in by the DSF. Two types of models are needed for the cascade:

- Hydropower model for hydropower optimisation and joint operation;
- 3D model for detailed flow and sediment movement in the reservoirs.

For hydropower modelling HECResSim will be used, which is a public-domain software package in the HEC modelling suite. It is not fully resolving the flows in reservoirs and channels, but is a water-balance approach specifically designed for river systems with multiple hydropower reservoirs. The model will make use of the input series that are produced as part of the scenario simulations of the DSF and the results will be used as input to the Delft3D model. Due to the simplified approach for channel flow, the approach is showing limitations with respect to simulating the tail-water variations of individual reservoirs (see Chapter 4.2).

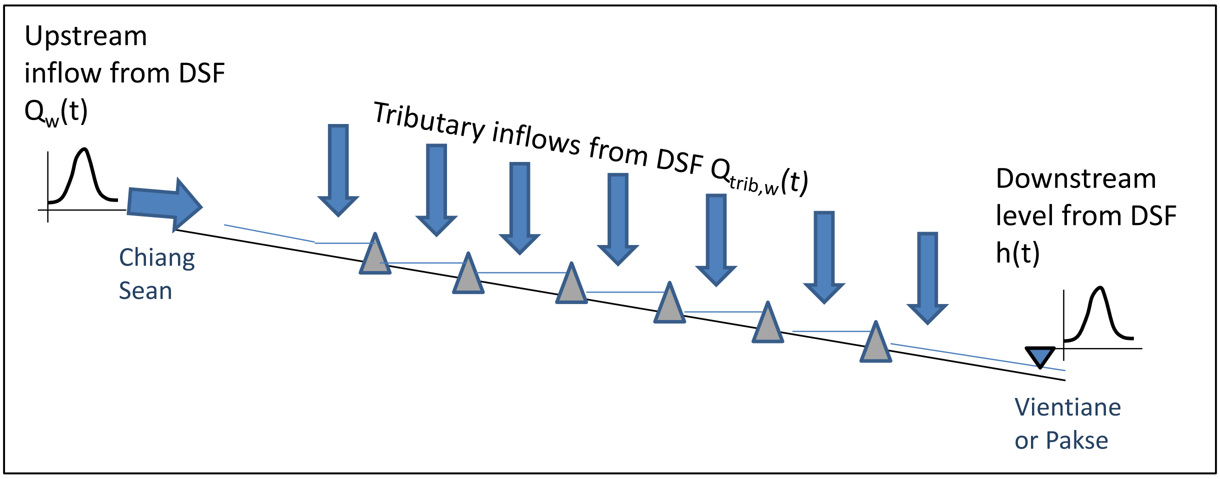


Figure 3.3 **Schematic presentation of the cascade and the required data inputs from the DSF for the hydropower modelling.**

Figure 3.3 shows how the flow-discharge series for each time step t at Chiang Sean (Qw(t)) and at tributary mouths (Qtrib,w(t)) are obtained from the DSF model calculations for chosen development scenarios, e.g. BDP2 or CS 2040. The figure also shows that at the downstream end, a water level time series from the DSF model runs is prescribed as well. The choice of the location of the downstream boundary will determine at which location the DSF has to generate the data.

For detailed modelling of the flow and sediment processes in the reservoirs, use will be made of the open-source Delft3D software package. This modelling system allows for a 3-dimensional hydrodynamic simulation of the flow processes in the reservoirs including the erosion, sediment transport and deposition processes. It is also fully dynamic, which means that unsteady flow processes on small time scales (minutes) can be resolved, with bed-level and bed composition update at each computational time step.

For each of the reservoirs in the cascade, a separate model will be built and the results of the upstream reservoir will form the input for the next downstream reservoir. In this way the flow conditions and impacts are routed through the cascade. Figure 3.4 shows one single model within the series of connected Delft3D models in the cascade, and how data from DSF and hydropower modelling is used as input to the Delf3D model. Note that for this model also sediment loads have to be prescribed as function of time at the upstream boundary and from tributaries. The inflow of water and sediment at the upper boundary follows directly from the output of dam spills and power releases from the upstream Delft3D model. For the first (upstream) Delft3D model, for Pak Beng, the inflow from Chiang Sean coming from the DSF has to be used.

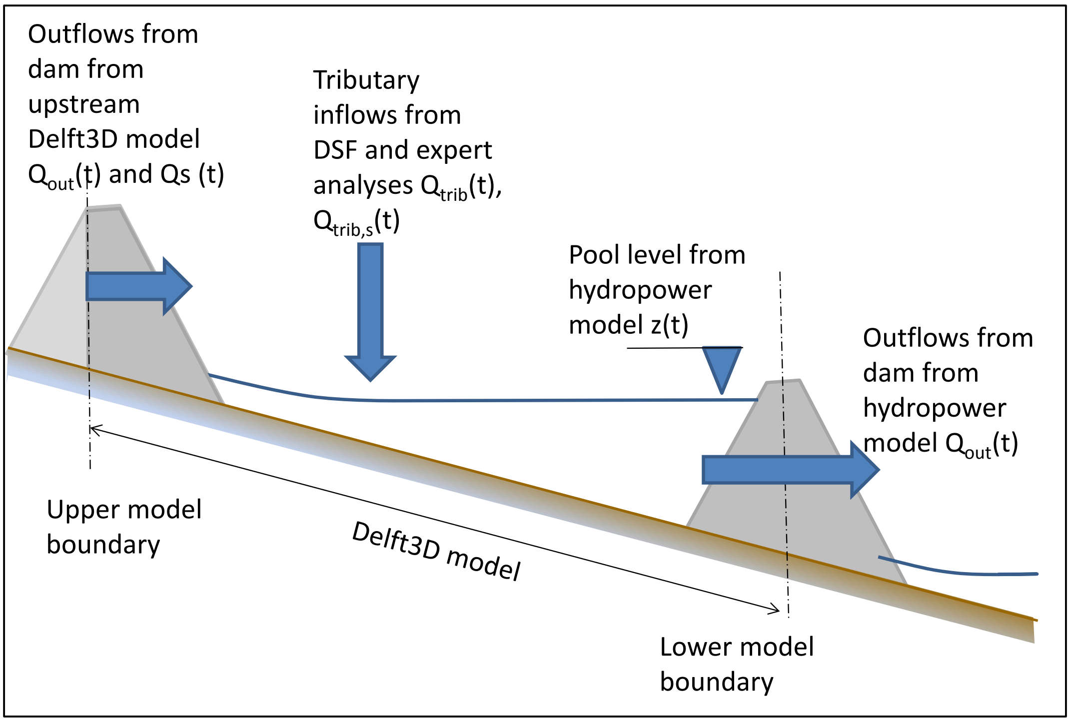


Figure 3.4 Schematic presentation of a Delft3D model for one reservoir, with indication of data input from the DSF and hydropower modelling.

Delft3D simulations will also be carried out for temperature modelling. For this cascade, the temperature is a key parameter to assess water quality issues. The temperature model in Delft3D simulates the possible temperature (and salinity) stratification (if any), and the relevant lake mixing processes. Analyses of these results will be used to make a general assessment of the water-quality risks and mitigation effects. For the temperature modelling it is necessary to make assumptions on the temperature of the inflows from upstream and from tributaries.

The various mitigation options that will need to be studied to assess their efficiency for incorporation in the Guidelines will be represented in the 3D model according to their particular characteristics. Operational measures can be simulated mostly by prescription of operation levels of the reservoir pool, and the outflows at different outlets at the dam. The results of the simulation of the most downstream reservoir will form the input for the subsequent simulation of the downstream processes along the mainstream up till the Mekong Delta.

3.2.4 Flow routing through the main channels downstream

Modifications in flow conditions in the reach downstream of the cascade can be assessed using the one-dimensional river models. Most of these impacts, such as changes in hydrograph of hydropeaking, will travel down as damped long waves, for which these 1D models are well suited. The input of flow conditions at the lower dam (Pakchom or Sanakham dams) is directly coming from the lower Delft3D model as time series of water discharges and sediment loads. Tributary inflows are taken from the DSF models (similar to the hydropower and reservoir modelling).

Downstream from the lower dam of the cascade, the ISIS one-dimensional modelling module of the DSF can simulate the relevant unsteady-flow processes with very small time scales (ranging from days to hours). The model is therefore suitable to simulate even the effects of variations caused by hour to hour operation, such as with power peaking. The model includes both main-channel and flood-plain flow, but does not fully resolve the details of the flow variations in the cross-section. Details of higher resolution (e.g flow in side channels, or inundation depths per cell in flood plains) require the more detailed 2D/3D models in DSF, or can be based on postprocessing and expert opinions of the 1D model results. The choice for this approach depends on the availability of relevant 3D models and their support for the considered reach. The focus of the modelling will be on the reach downstream of the cascade, down untill Pakse. This limitation is imposed due to the difficulties that still exist to model the flows through the section of the four-thousand islands, using the 1D modelling approach in the DSF.

For this purpose, the resulting series from the cascade simulation will be used as input for the DSF modelling. However, in case the DSF system and the support from the MRC modelling team is not available at the time the results need to be prepared, there is an option to use a simplified version of the existing ISIS hydrodynamic flow model. In order to be able to use the free version of the model, avoiding licensing issues, the original number of cross-sections, somewhere in the order of 500, will be cut down to the maximum allowed number of 250 cross-sections. In some cases, river stretches will need to be cut up into more parts to keep the total number of cross-sections within this limit. The simplification is considered still sufficiently accurate to allow for the study of the hydrodynamic impact of the various measures represented by sub-scenarios in the cascade study, particularly for comparison between the impacts of the measures (i.e. comparing in a relative manner instead of by absolute values).

3.2.5 Sediment routing (with the flow routing)

In line with routing flows through the lower reach, it is best to use the ISIS modelling system to also route the sediments. For this purpose the time series of discharges from the lower dam, as well as sediment loads from this dam (Delft3D model), have to be used. Also it is possibly necessary to use the simplified ISIS version. However, this requires additional testing to prevent errors or problems with the free demonstration version.

3.2.6 Tonle Sap system, including sediment and water quality issues

For the simulation of the expected impact of various mitigation measures in the cascade, it is important to assess the changes that may occur in the flow system of Tonle Sap. This is a complicated system, especially if the sediment and water quality issues need to be addressed as well. A quick assessment with an approximate or analytical approach, following changes in Mekong flows and loads at Phnom Penh, is considered unreliable due to this complexity. For the water balance of the lake, it would be possible to use a simple approach based on volumes, but for sediment and water quality this is not the case. Still, it is necessary to make a first judgement on the basis of these conditions at Phnom Penh, in order to propose a limited number of situations / scenarios for further more detailed analysis.

Within the DSF, the 3D WUP-FIN model for Tonle Sap is considered best suited for simulating detailed flow, sediment and water quality for the river and lake. Expected impacts of mitigation measures on the conditions may have been sufficiently damped to consider them of secondary order compared to regular flow changes. It is therefore assumed that in this assessment it is possible to use existing WUP-FIN results (from the Council Study scenarios) to estimate the impacts on Tonle Sap (by expert-judgement and interpolation of results of various runs).

3.2.7 Salt-water intrusion in the Mekong delta

The impact of mitigation measures in the Lao cascade on the Mekong delta are likely to be small given the large distance between the two sites and the major amount of water that enters the river from intermediate tributaries. However, an impact may be expected particularly during the dry season on the flows and in general on the sediment influx. The complexity of the Mekong delta does not allow for an in-depth analysis of the system, but an indication of the expected changes due to the changes in the flows particularly during the dry season can be made, e.g. on the salt-water intrusion that has implications for the irrigated agriculture and fisheries in the delta. For this purpose, use can be made of an analytical method that was developed and successfully applied for the Mekong delta by Savenije from Delft University of Technology and Nguyen from UNESCO-IHE (Nguyen and Savenije, 2006). This method will be used in the present study as well.

4 Details on hydropower and reservoir modelling

4.1 Introduction and overall setup

To quantitatively design and evaluate the potential mitigation measures of the Lao Cascade, a suite of special models will be applied. It is important that these models are part of the MRC, and therefore should be freely available for MRC after completion of the present study. It is also important that any new models are well connected (both results and exchange of information) to the existing modelling framework of MRC, i.e. the DSF system.

Figure 4.1 shows the components of the presently available MRC Decision Support Framework (DSF), together with new additional components to be used for the cascade modelling. The eWater component is in fact part of DSF as it is a replacement of the obsolete IQQM module.

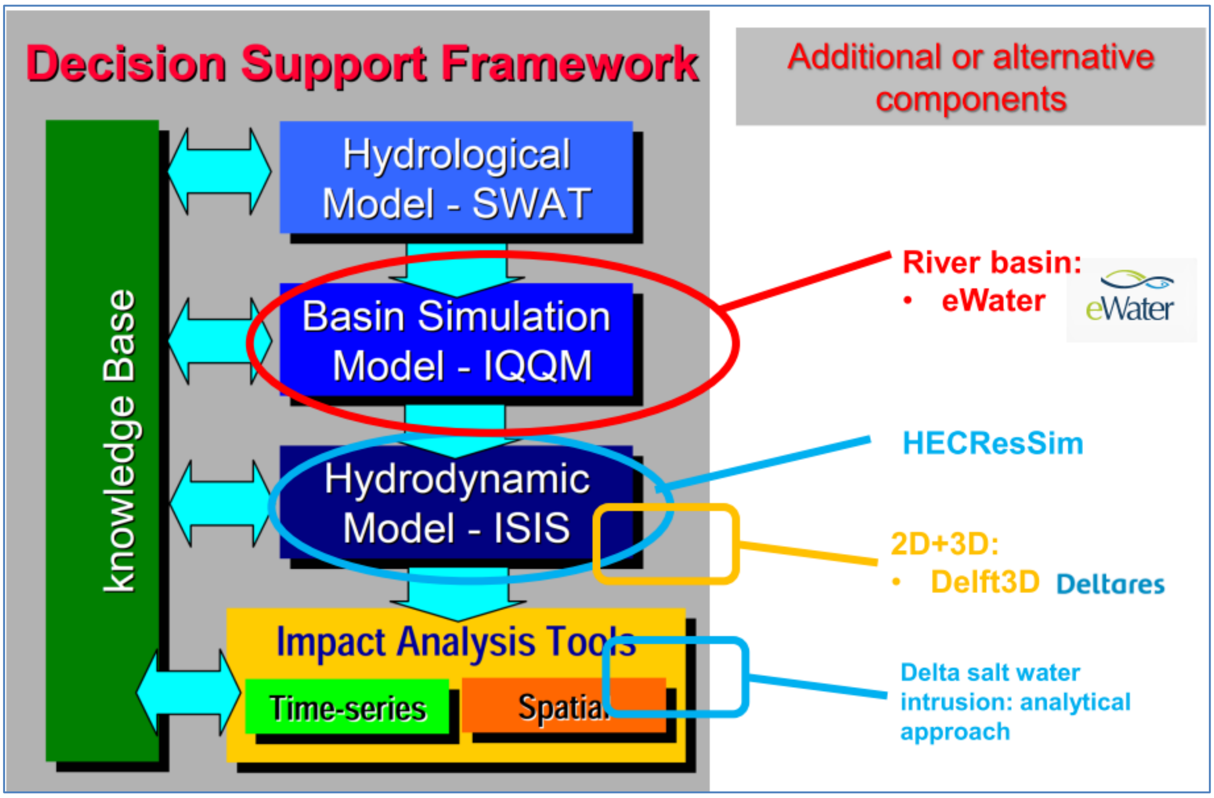


Figure 4.1. Overview of modelling systems.

In order to assess the impact of potential mitigation measures, simulations are required of the entire LMB. Although the impact will be assessed downstream from the Lao Cascade, i.e. roughly downstream from Vientiane, it is the full LMB starting from Chiang Saen that needs to be included in the modelling.

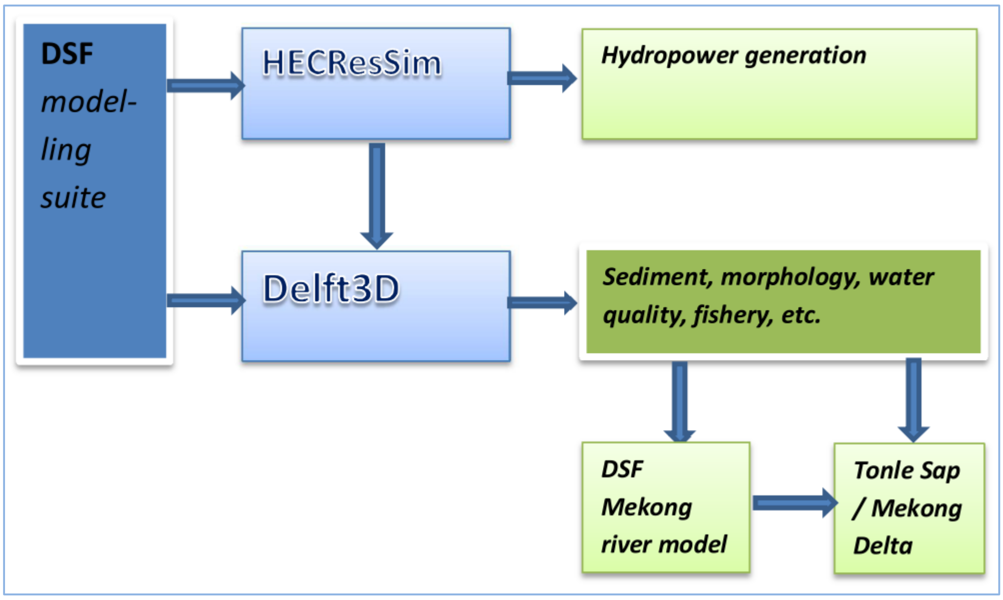


Figure 4.2 Layout of modelling framework.

In Figure 4.2 an overview is given of the various steps of the modelling activities. The input towards the cascade modelling will be based on existing (DSF) modelling efforts, whose results feed into both the HEC-ResSim hydropower model and the Delft3D hydrodynamic model. The latter will also make use of the results of the hydropower model. The results of the Delft3D modelling will form the basis for the assessment of the impact of the various possible measures in the Lao cascade on sediment, morphology, water quality, fishery, etc. The assessment in the LMB downstream from the Lao cascade starts off from the results of the Delft3D modelling of the lowest reservoir. It will preferably be based (again) on the DSF modelling system for the main river, with the addition of special tools / techniques for the Tonle Sap and Mekong Delta.

In Figure 4.3 the geographical extension of the various modelling efforts is roughtly indicated.

In the following paragraphs, the two main modelling systems will be discussed that will be used for the simulation of the Lao cascade. First the hydropower model, that produces part of the boundary conditions for the hydrodynamic (3D) model, which is discussed in the second part of this Chapter.

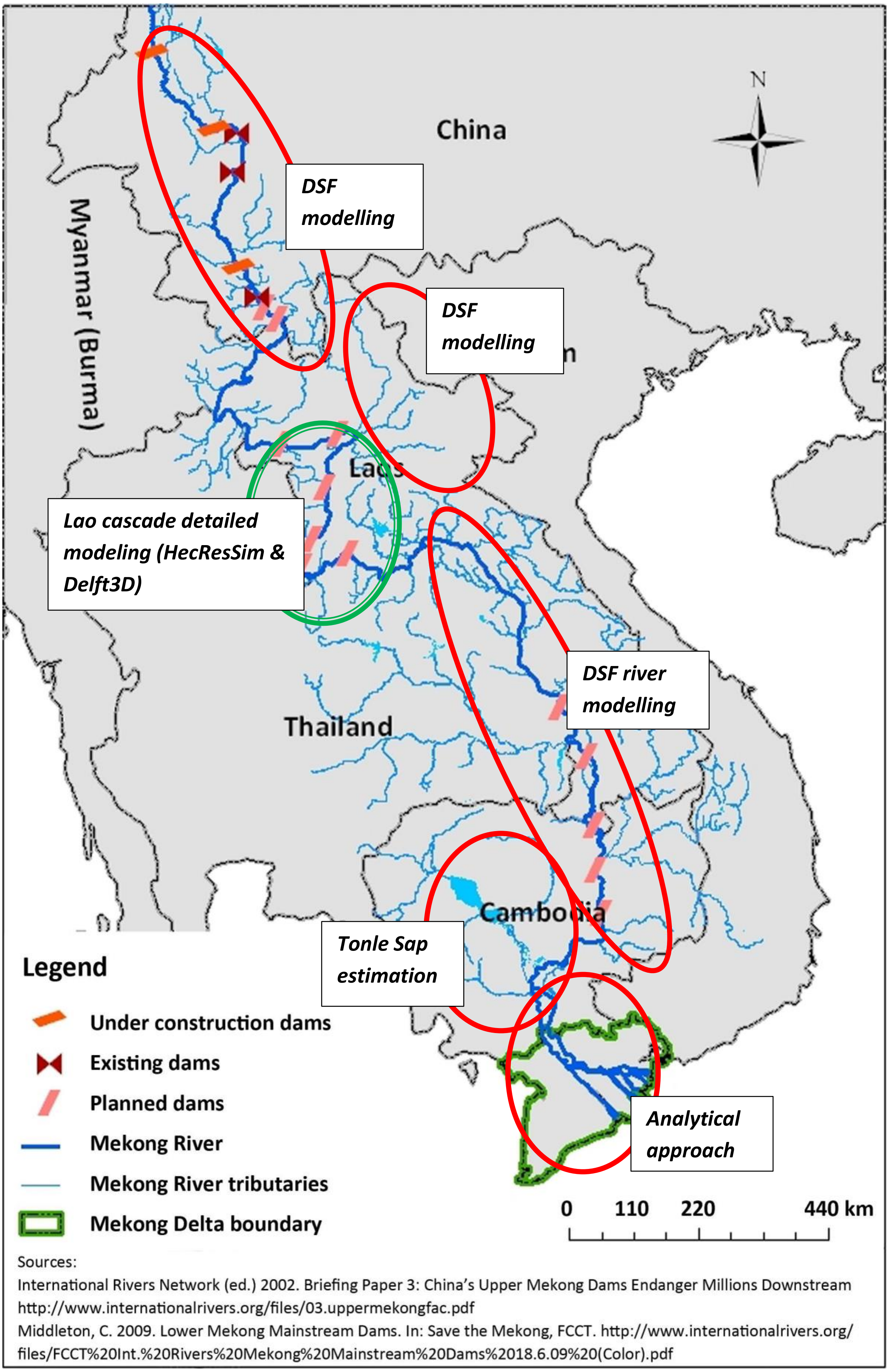


Figure 4.3 **Geographical location of the modelling efforts.**

4.2 Hydropower model for the Lao Cascade

4.2.1 Modelling system

The main purpose of the hydropower modelling is to establish a relationship between different scenarios for hydropower and water resources management on one side and financial implications on the other, in most cases meaning loss of generation income as a consequence of mitigation measures or other imposed modifications/limitations to the exploitation of the hydropower potential, as part of the proposed Guidelines. Figure 4.4 illustrates the Methodological Framework for Hydropower modelling. Comparison of modelled scenarios will put a "price tag" on various mitigating options.

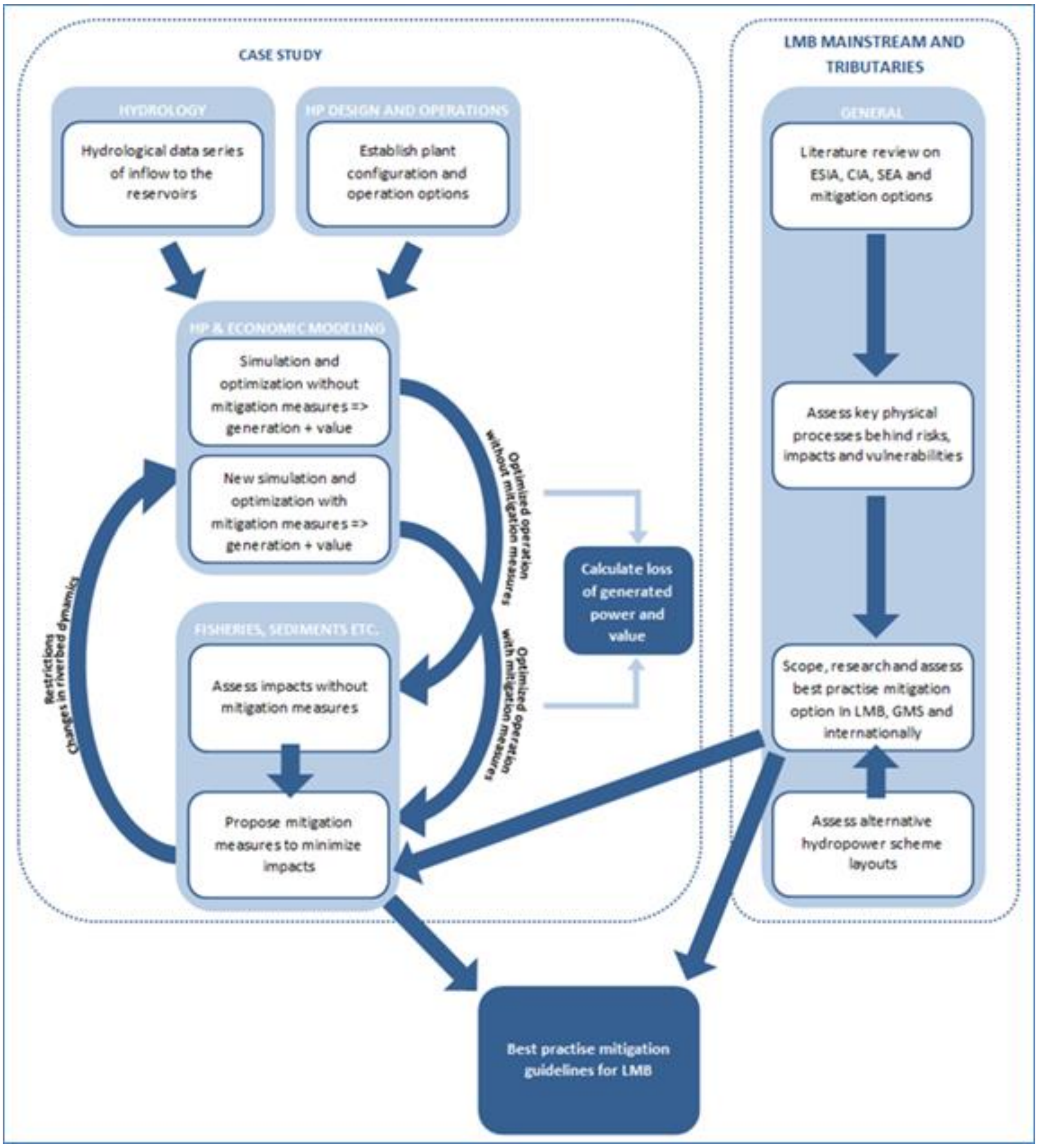


Figure 4.4 **Methodological Framework for Hydropower modelling.**

The three most important elements in the computation of income from energy generation at any time are 1) the energy tariff at the given time of the day and week; 2) the discharge through the turbines at the given moment, and 3) the hydraulic head at the given moment. The two latter elements define the power of the energy production at that time.

It is the intention to carry out the modelling with the software “HEC-ResSim”, as requested by the Client. This is a freeware, developed by US Army Corps of Engineers (USACE). The software is a lumped, conceptual model, which means the simulated processes do not take into account any distribution over a spatial extent. The software calculates the variation of reservoir levels in a water balance calculation. The tailwater has to be provided by the user.

In a moderately steep river in natural condition, a rating curve (tailwater curve) can be established by physical discharge measurements on place, as well as through modelling. When there is reservoir downstream however, one cannot produce a tailwater curve neither through measurements nor through simple calculations. This requires classical 1-dimensional model simulations of the river in order to take into account the backwater effect from the downstream reservoir, which may vary in a complicated pattern. This is not possible with HEC-ResSim alone. It should be noted that the tailwater is in most cases not simply identical with the downstream reservoir level – or at least not at all times. The tailwater is however strongly influenced by the downstream reservoir level.

In the Inception Report it was suggested to utilise a 1D hydraulic model for the hydraulic part of the hydropower modelling and consequently a 1D hydraulic model was established, utilising river bed cross sections acquired from the DSF ISIS model. Since then the wish for open source software was expressed and consequently the approach was modified to carry out the modelling with HEC-ResSim. Hence Mike11 will be used to provide the data that would otherwise be too uncertain / incorrect. The tailwater curve is an example of a theme where HEC-ResSim has to be assisted with the Mike11 hydraulic model.

It should be noted that in the real world, as well as in the hydrodynamic model results, the tailwater curve is not a curve in the traditional sense (meaning a 1-1 relationship), but rather a cloud; for each discharge value there is not one but an entire range of tailwater levels, namely depending on the downstream water level at any time. One limitation in HEC-ResSim is that one can only enter a 1-1 relationship. This means that one must decide for one relationship to input, and thereby discard a large amount of occurring cases, which constitute the “cloud”. This inevitably introduces an error and is equivalent to assuming that the downstream reservoir never changes its level (or does not influence the upstream tailwater). This error must be taken into account when evaluating the HEC-ResSim results (the generated energy). A sensitivity analysis will be carried out for such an evaluation.

Another element in which HEC-ResSim may require input from a hydraulic model regards the transport time from one dam to the next. In order to examine options for Joint Cascade Operation, this lag time will play a certain role, possibly a major role, since preliminary simulations indicate that the transport time through the entire Cascade will be in the order of magnitude of 8 hours, or half of the Peaking Period. It will be attempted to use results from the Mike11 to “calibrate” the HEC-ResSim model.

4.2.2 Interconnection with other modelling

One basic input to the HP model is runoff from upstream, i.e. inflow from China, as well as tributary inflows along the Cascade reach. These inflows will need to be provided by the DSF modelling team in order to reflect the future basin development. As was discussed already in Chapter 3.2.1, the actual future situation that will be used in this study will depend on the timely availability of the modelling results of DSF.

The final output from the HP modelling is, as mentioned, generated income from power generation. Furthermore, intermediate outputs for pure hydraulic parameters will constitute the boundary conditions for the Delft3D hydraulic sediment models that are discussed in the next Chapter. In the HP modelling, one integrated model encompasses the entire cascade, whereas this would be impractical for the Delft3D modelling, which instead will establish separate models for each reach between two dams (plus the most upstream reservoir). Consequently, each Delft3D model reach requires a set of boundary conditions: an inflow (time series) at the upstream boundary and a water level (time series) at the downstream boundary. The upstream boundary flow and sediment flux will come directly from the same Delft3D modelling of the reservoir directly upstream and these results will be compared with those from the HP modelling in order to ensure that these are sufficiently similar.

There may be a larger number of model runs under HP modelling than under Delft3D sediment modelling. Under a given scenario, a number of HP model runs may be carried out to optimise the operation under that scenario, and only the final, optimised result, will be “coupled” with the Delft3D sediment model. On the other hand, it may also happen that the Delft3D sediment models show that the HP-modelled HP operation did not achieve its goal (i.e. with respect to flushing), so that there may also be a trial-and-error approach in the two co-operating modelling systems.

4.3 Detailed reservoir modelling for the Lao Cascade

For the simulations of the reservoirs, the open-source modelling system Delft3D is applied. This software is supported and maintained by Deltares, and its source code is freely available from the Deltares website.

We can distinguish three phases in reservoir operation that characterise specific sediment processes and sediment management in the reservoirs. The three phases are:

1. Reservoir filling phase: during filling (by flood waters) sedimentation processes are dominant;
2. Operation at MOL (minimum operation level), or sluicing phase, in which incoming (high loads of) sediments are sluiced through the reservoir without deposition through reduced depth and increased velocities. Erosion and sedimentation fluxes at the bed are more or less in balance.
3. Flushing with full water-level draw down, in which the reservoir level is fully lowered (e.g. to sluice level) and erosion processes are dominant during the lowering process.

Delft3D software

Delft3D is a world leading 3D modelling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. The FLOW module is the heart of Delft3D and is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation programme which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid or spherical coordinates. In 3D simulations, the vertical grid is defined following the so-called sigma coordinate approach or Z-layer approach. The MOR module computes sediment transport (both suspended and bed total load) and morphological changes for an arbitrary number of cohesive and non-cohesive fractions. Both currents and waves act as driving forces and a wide variety of transport formulae have been incorporated. For the suspended load this module connects to the 2D or 3D advection-diffusion solver of the FLOW module; density effects may be taken into account. An essential feature of the MOR module is the dynamic feedback with the FLOW and WAVE modules, which allow the flows and waves to adjust themselves to the local bathymetry and allows for simulations on any time scale from days (storm impact) to centuries (system dynamics). It can keep track of the bed composition to build up a stratigraphic record. The MOR module may be extended to include extensive features to simulate dredging and dumping scenarios.

Models will be set-up to simulate the erosion and sedimentation processes during all these three phases. This means that the models have to include the dynamics of flow (unsteady flow, time-dependent emptying and filling, low-flow and high-flow conditions). In principle the reservoir models are meant to support the development of an adequate sediment management strategy for the reservoir cascades, considering the three phases of sediment processes and management.

More specifically the reservoir models are used to calculate:

- detailed hydrodynamics: transverse and longitudinal variation in water depth, flow velocity, bed shear stress; horizontal and vertical circulation, and mixing processes;
- suspended-load and wash-load concentration: advection-diffusion process; fall velocity versus turbulent mixing; sand-mud mixtures;
- bed-load transport of sediment mixtures (gravel-sand mixtures);
- bed composition changes of the active layer of the bed; under-layer book-keeping system;
- sedimentation and erosion of the bed;
- non-erodible layers, such as bed rock sections;

Scenarios with different operational mitigation strategies require a full dynamic (unsteady) approach, covering periods of at least one year with the relevant discharge and reservoir-level variations (the full hydrograph).

More details of the approach, and the 2D and 3D modelling characteristics, are presented in the Annex of this report.

4.4 Modelling of operational mitigation measures

Flushing and sluicing operations are measures that have to be simulated fully dynamic with reduced reservoir levels and high inflows. When dealing with this kind of operations, it is necessary to consider the following three phase of operation:

Filling

- Discharge is blocked. Flow velocities drop
- Significant sedimentation

Water level at Minimum Operating Level: sluicing

- During flood: maintain high velocity
- Balance erosion and sedimentation

Water level draw down: flushing

- Flow velocities increase in lower reach
- Channel erosion

Figure 4.5 shows which processes determine the sediment balance of the reservoir, and which have to be modelled. Flushing and sluicing can be used to influence the components “transport” and “entrainment/deposition” in this figure (higher velocities cause increased transport etc.).

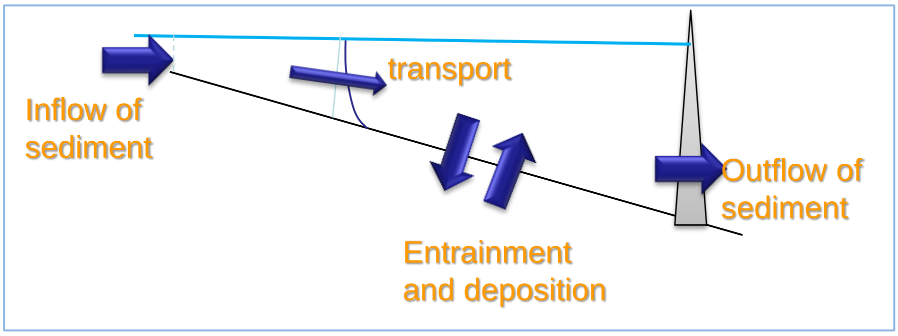
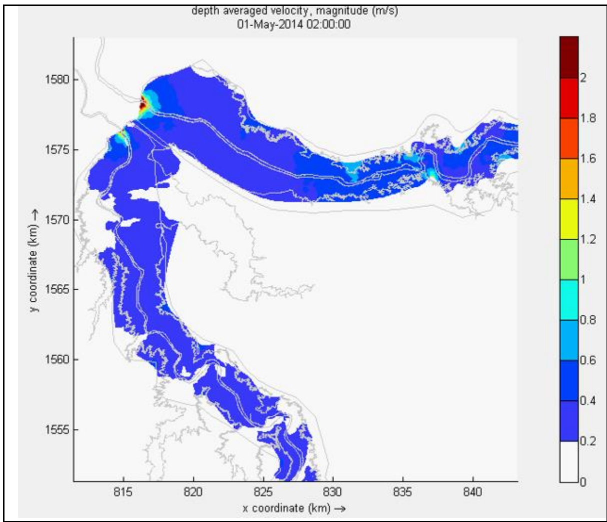


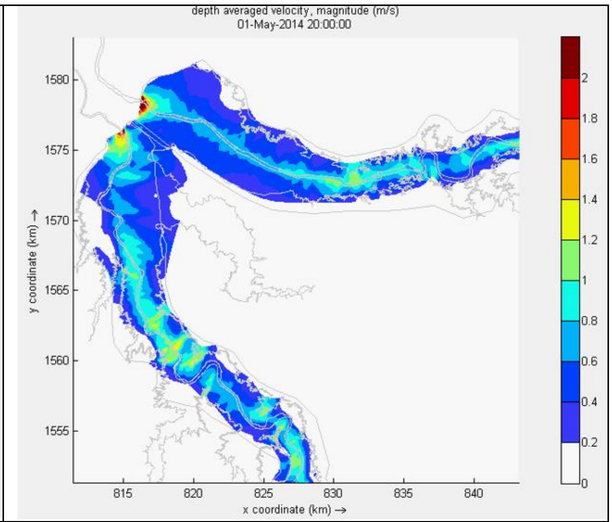
Figure 4.5 Relevant processes for modelling sediment management operation measures.

Flushing and sluicing can be modelled simply by lowering the water-levels imposed on the outflow boundary (i.e., the dam), to mimic the release of through gates or spillways. The corresponding outflow is automatically computed, but it can also be imposed as additional extraction near the dam. Lowering the water levels in the reservoir pool raises the flow velocity, and initiates erosion along the reservoir. During full draw down (sudden drop of water levels at the dam by using large outlet sluices) the flow velocities temporarily increase significantly in a zone that extends beyond the width of the main channel. But, after the full reservoir is drained, the velocities drop again to moderate values. An example of the evolution of flow velocities during draw down is presented in Figure 4.6. The figures show flow velocities computed with Delft3D for the Upper Atbara Reservoir in Sudan. This new dam and reservoir started impounding in 2014 and the model has been used to support definition of operation rules for sediment management (Sloff et al, 2015).

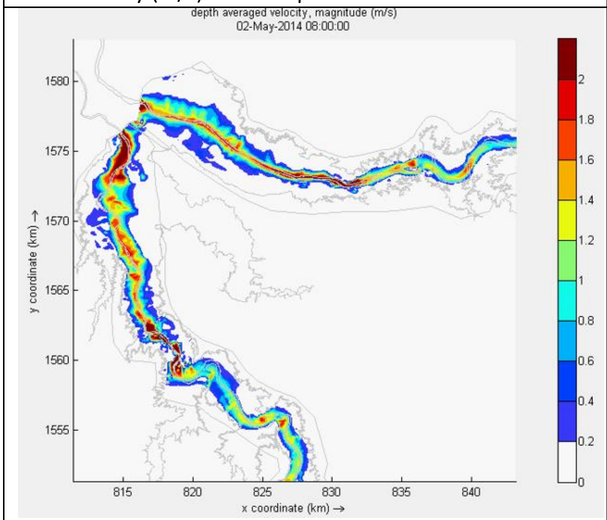
It is important that these processes are modelled with a fully unsteady approach. For instance, during draw down the highest concentration is released during the first day, i.e. during the fast drop of water levels, which is certainly related to the temporary high increase of velocities as shown above. Hence, the model needs to cover the time-dependent processes in the reservoir.



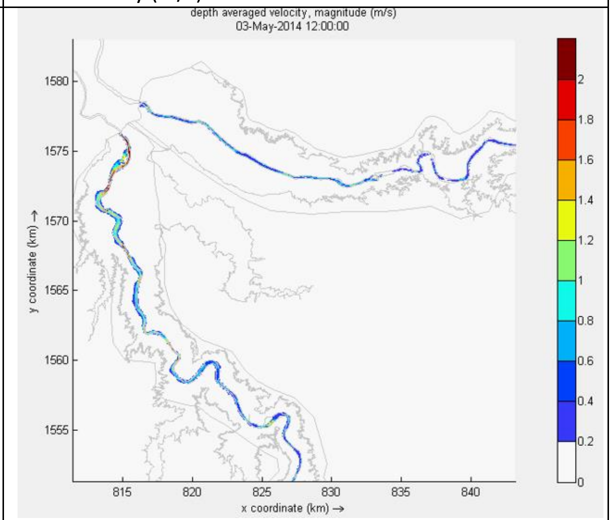
Flow velocity (m/s) normal operation level



Flow velocity (m/s) 8 hours after start draw down



Flow velocity (m/s) 32 hours after start of draw down



Flow velocity (m/s) 60 hours after start of draw down

Figure 4.6 Flow velocity during draw down flushing of Upper Atbara reservoir. Flow is from right (right bottom = Atbara River, right top = Setit River) and dam with sluices is on top left.

It should be noted that for both flushing and sluicing, the results are highly dependent on the choice of critical shear stresses for erosion and the fall velocity of the suspended sediment fractions. In the example shown above (for Upper Atbara), the models have been calibrated on the basis of measurements from an existing downstream reservoir (Kashm El-Girba reservoir). In the Mekong this is not possible.

4.5 Modelling downstream impacts

As was mentioned earlier, the impacts of mitigation measures on the downstream reach are mainly related to modified hydrograph (changed time-series of the discharges) and sediment supply. The assessment of these impacts requires knowledge on propagation of long waves, i.e. damped propagation downstream. It also requires insight in the main-channel and flood-plain hydrodynamics, and influences on inflow and outflow to Tonle-Sap. Finally it is necessary to consider sediment routing of low and high sediment concentration releases (e.g., during flushing). The impacts will be studied using simplified models, highly based on the DSF models. More specific information on the use of the 1D approach has already been discussed in this Volume 3 of the report. A number of case study options have been defined that should form the basis for the assessment of the efficiency of the various possible mitigation measures that were discussed in Volume 1 and 2 of this report.

References

Nguyen, A. D. and Savenije, H. H., 2006, Salt intrusion in multi-channel estuaries: a case study in the Mekong Delta, Vietnam, Hydrol. Earth Syst. Sci., 10, 743-754

Sloff, C.J., A.Y.A. (Amgad) Omer, K.V. (Karel) Heynert, and Y.A. (Yasir) Mohamed, 2015, Design and modeling of reservoir operation strategies for sediment management. In: J.D. Abad (Ed.), Proceedings of the 9th Symposium on river, coastal and estuarine morphodynamics, RCEM 2015 (pp. 1-3). s.l.: CREAR.

Annex Detailed modelling for the cascade

General approach of the 2D and 3D reservoir models for the cascade:

- Each reservoir is modelled separately, with the lower boundary condition defined at the dam site, and each model starting directly downstream of the previous dam. In that way the Delft3D models cover the full length of the cascade, including the possible free-flowing river sections between the subsequent reservoirs. For the most upstream reservoir the length will be based on the extent of the reservoir, and an additional upstream section of 10 to 20 km to absorb boundary effects. The decoupling of the models is allowed, since they are physically disconnected by the presence of the dams.
- Models can be run sequentially, starting upstream, where the outflow from an upstream model, is the inflow condition for the following downstream model (both water and sediment). It should be noted that in most situations the flow at the dam is not affected by the tailwater. However, during full opening of the gates, during draw-down flushing operations, the condition at the dam can be considered to be a submerged weir. For this level it is possible to use tailwater levels from the hydropower model to calculate the water levels that have to be imposed to the boundary.
- Delft3D calculates on a curvi-linear numerical grid that covers an area that is slightly larger than the inundated areas during high water level (Figure A- 1). Grid size is chosen such that the deeper channel parts are finer than the side slopes. An aspect ratio of 3 to 4 (mesh length/ mesh width) is used as guideline for setting-up the grid.

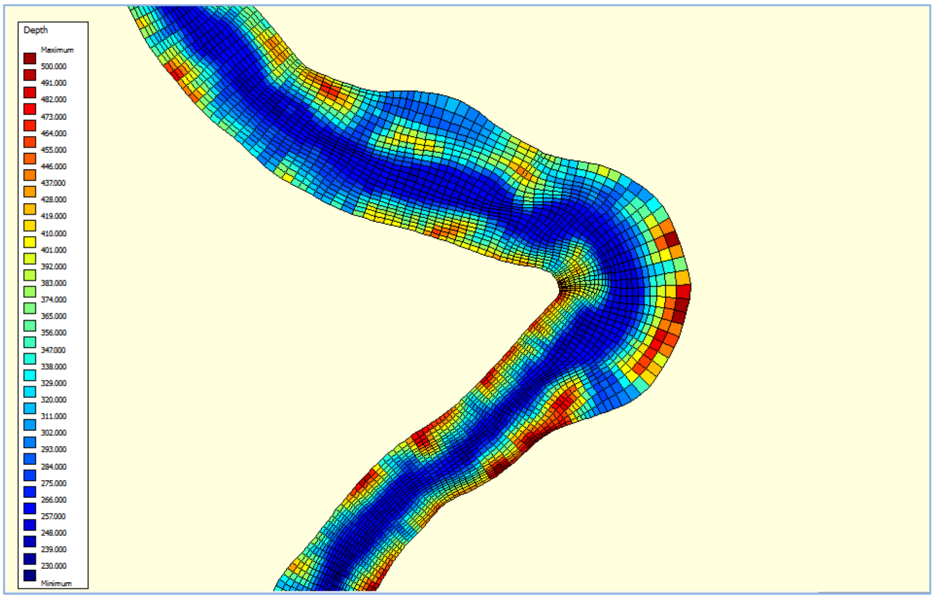


Figure A- 1 Curvilinear grid and projection of DEM on this grid.

The detailed morphology of the main channel is best reproduced when it is at least 6 cells wide. The flow is mostly constricted to this channel when water levels are lower and therefore this area is expected to show highest sediment loads and morphological changes. If less cells are available, the channel patterns in the transverse direction – including, for example, point bars and islands - are not or only approximately reproduced. In that case the model will be able to simulate the 'one-dimensional’ developments of the channel, rather than the ‘two or three-dimensional’ processes and morphological developments. For the part of the grid that covers the hills and valley, the grid resolution can be substantially lower. In the following sections the applied model domains and computation grids are presented and discussed in more detail.

- For vertical mesh (in 3D simulations) an σ-layering will be applied (i.e. a boundary fitted layers, that follow the bed topography and water surface). The advantage of this approach is that the grid follows the depth of the reservoir smoothly, and that it is very well suited for morphological simulations (versus a Z-grid approach, in which the river bed is not smoothly reproduced and requires an extra cut-cell algorithm for near-bed velocities and transport), see Figure A- 2.

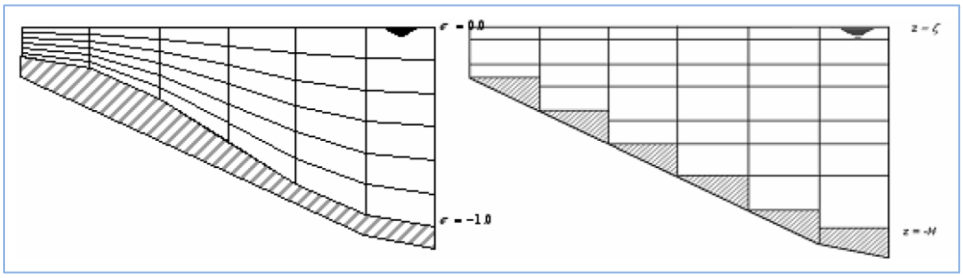


Figure A- 2 Vertical grid in 3D simulation: left σ-grid, right Z-grid.

- The hydrodynamic simulations are able to reproduce the details of flow fields around island, lateral eddy zones, and concentrated jet flows into pools (Figure A- 3).

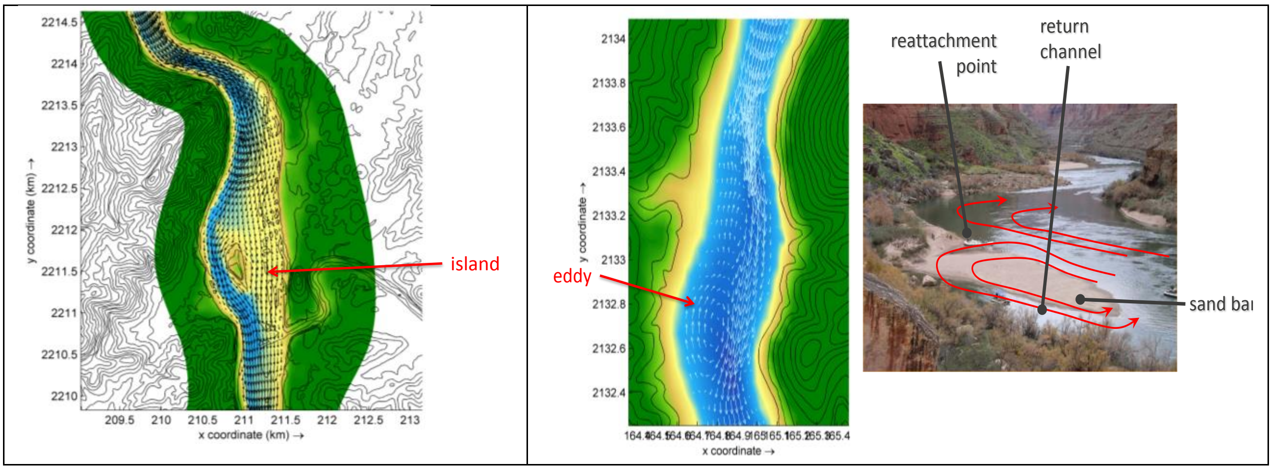


Figure A- 3 Examples of computed flow fields (depth-average velocity vectors plotted on topography) in the Mekong River (preliminary simulations using Delft3D).

- The operation of the reservoir is taken directly from the hydropower modelling (HEC-ResSim): this means that inflows (time series), reservoir water levels, and outflow discharges (power outlets) are modelled equally as following from the HEC-ResSim model, see Figure A- 4. Water levels in the model can be controlled by using an open boundary at the dam site (with width equal to spillways), where water level is imposed. Additionally we can add discharge extractions located at the power outlets, for which the discharge is following from the hydropower modelling. At the upper boundary (and any tributary inflow) the time series of discharge can be imposed. Additionally we define here the concentrations of sediment per sediment fraction.

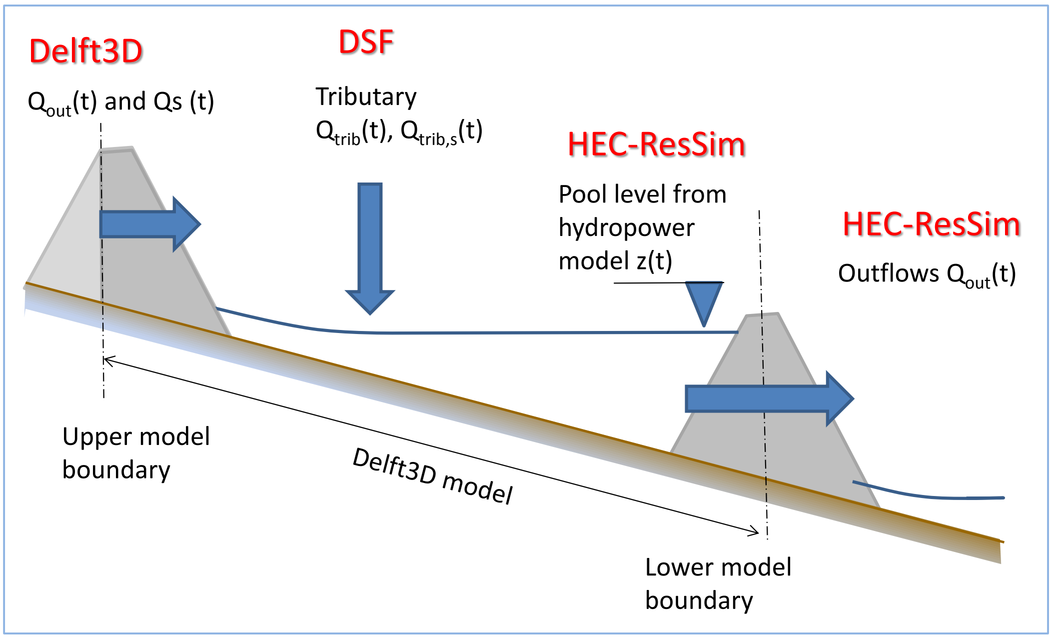


Figure A- 4 Overview and origin of boundary conditions to be imposed to each Delft3D reservoir model.

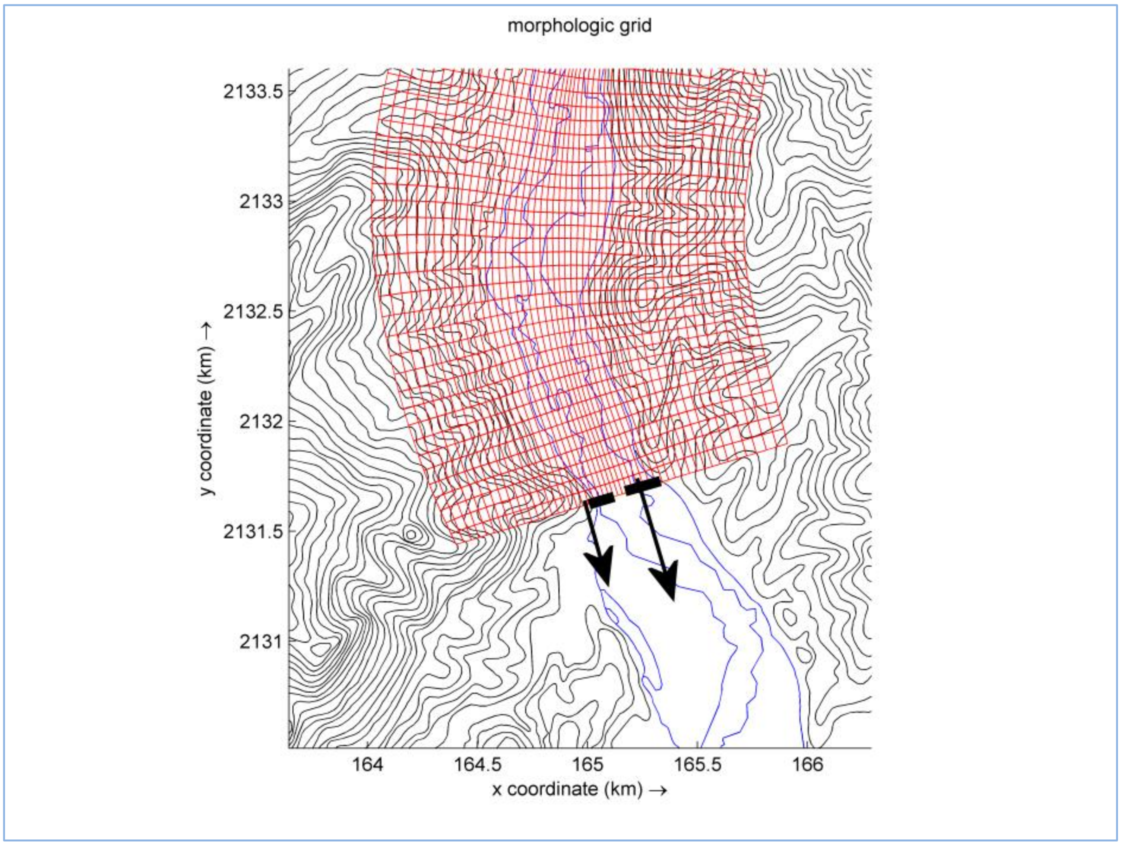


Figure A- 5 Location of outlets at the dam boundary on grid (discharge extractions=arrows; water-level boundaries=lines) (example for Xayaburi Dam).

- It is expected that for a good description of sediment, several sediment fractions, such as gravel, sand and mud (silt/clay), will be used in the model. The sediment module allows for separation of different transport modes as indicated in the following figure:

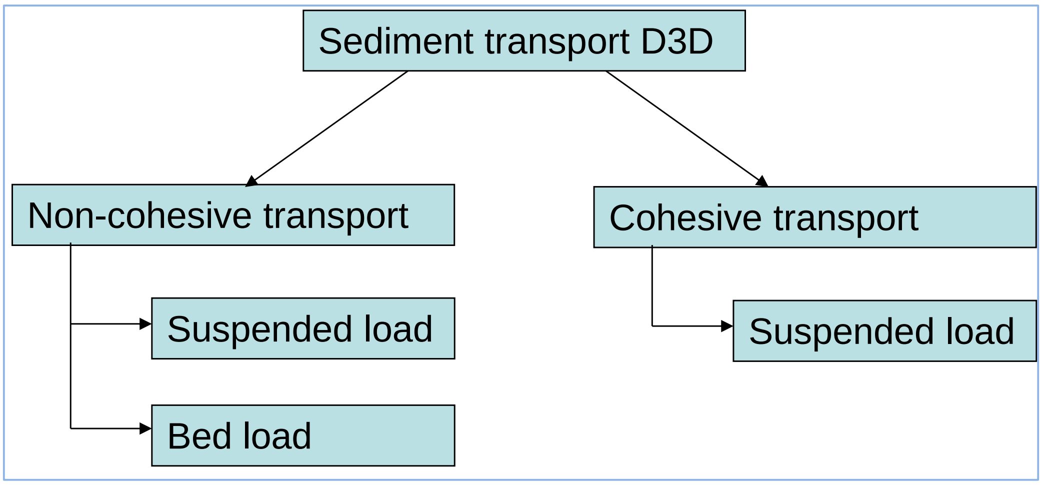


Figure A- 6 Sediment transport computation.

The *bed load* in the model is for instance computed with help of the Van Rijn formula (Van Rijn, 1984). There is a wide variation of commonly used bed-load transport models available to choose from. Slope effects (impact of gravity on movement of sediment on a slope) and helical flow (spiral flow in bends) are taken into account. Note that wash load is usually modelled using the model concept for cohesive transport, instead of that of non-cohesive transport.

For suspended sediment concentration Delft3D solves the full 3D version of the advection-diffusion model, which is as follows:

$$\frac{\partial c_i}{\partial t}+\frac{\partial u c_i}{\partial x}+\frac{\partial v c_i}{\partial y}+\frac{\partial\left(w-w_{s,i}\right)c_i}{\partial z}+$$
$$-\frac{\partial}{\partial x}\left(\varepsilon_{x,i}\frac{\partial c_i}{\partial x}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{y,i}\frac{\partial c_i}{\partial y}\right)-\frac{\partial}{\partial y}\left(\varepsilon_{z,i}\frac{\partial c_i}{\partial z}\right)=0$$

u,v,w depth-average flow velocity in x-, y- and z-direction (m/s)

c_i depth-average volumetric sediment concentration for fraction I (-)

$\varepsilon_{x,i}$, $\varepsilon_{y,i}$, $\varepsilon_{z,i}$ eddy diffusivity for x-, y- and z-direction (m^2/s)

The local flow velocities and eddy diffusivities are based on the results of the hydrodynamic computations. Computationally, the three-dimensional transport of sediment is computed in exactly the same way as the transport of any other constituent, such as salinity, heat, and constituents. There are, however, a number of important differences between sediment and other constituents, for example, the exchange of sediment between the bed and the flow, and the settling velocity of sediment under the action of gravity. These additional processes for sediment are obviously of critical importance. Other processes such as the effect that sediment has on the local mixture density, and hence on turbulence damping, can also be taken into account. In addition, if a net flux of sediment from the bed to the flow, or vice versa, occurs then the resulting change in the bathymetry should influence subsequent hydrodnamic calculations. The formulation of several of these processes (such as, settling velocity, sediment deposition and pickup) are sediment-type specific, this especially applies for sand and mud. Furthermore, the interaction of sediment fractions is important for many processes, for instance the simultaneous presence of multiple suspended sediment fractions has implications for the calculation of the local hindered settling velocity of any one sediment fraction as well as for the resulting mixture density.

The boundary condition at the bed is given by:

$$-w_{s,i}c_i - \varepsilon_{s,z,i}\frac{\partial c_i}{\partial z} = D_i - E_i \quad \text{at} \quad z = z_b$$

Where:

E_i entrainment flux at the bed for fraction *i* (m/s)

D_i deposition flux at the bed for fraction *i* (m/s)

Hence, the *transfer of sediment between the bed and the flow* is modelled using sink (D) and source (E) terms acting on the near-bottom layer.

For *cohesive sediment* fractions the fluxes between the water phase and the bed are calculated with the well-known Partheniades-Krone formulations (Partheniades, 1965):

$$Source = E_i = M_i S\left[\frac{\tau_{cw}}{\tau_{cr,e,i}} - 1\right]$$

$$Sink \quad = D_i = w_{s,i}c_{b,i}S\left[1 - \frac{\tau_{cw}}{\tau_{cr,d,i}}\right]$$

M_i user-defined erosion parameter ([kg m^{-2} s^{-1}]

S step-function, becomes 0 if quantity inside < 0

τ_{cw} mean bed-shear stress due to current and waves

$\tau_{cr,e,i}$ critical shear stress for erosion, sediment fraction *i* (N/m^2)

$\tau_{cr,d,i}$ critical shear stress for deposition, sediment fraction *i* (N/m^2)

w_s settling velocity of sediment (m/s)

$c_{b,i}$ sediment concentration of fraction *i* in bottom layer

For non-cohesive sediment, erosion and deposition is formulated slightly differently. The transfer of sediment between the bed and the flow is modelled using sink and source terms acting on the near-bottom layer that is entirely above Van Rijn's reference height *a* (usually related to height of bed forms, such as ripples and dunes). This layer is identified as the reference layer and for brevity is referred to as the kmx-layer, see Figure A- 7.

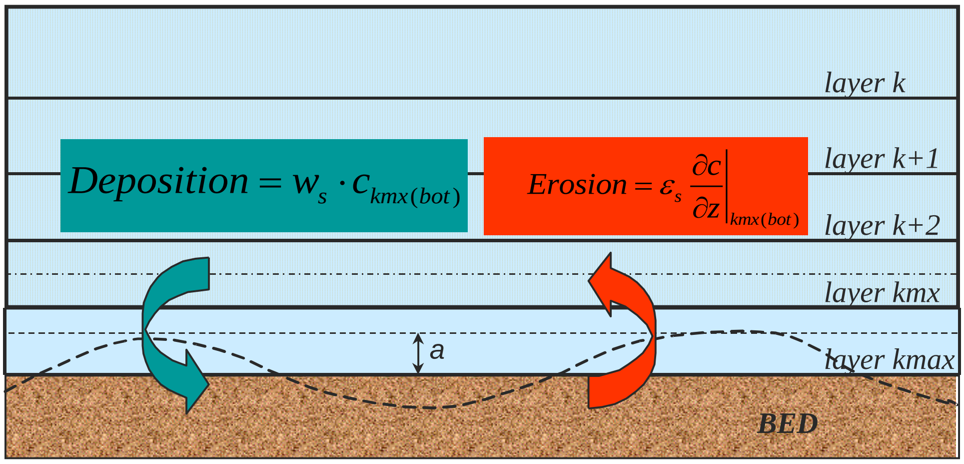


Figure A- 7 **Schematic arrangement of flux boundary condition at the bed (Delft3D, 2014).**

For the kmx-layer we assume a standard Rouse profile, to determine its concentration relative to the reference height *a*.

For non-*cohesive sediment* fractions the fluxes between the water phase and the bed are calculated with:

$$E_i \approx \alpha_{2,i}\varepsilon_{s,i}\left(\frac{c_{a,i} - c_{kmx,i)}}{\Delta z}\right)$$

$$D_i = \alpha_{1,i}c_{kmx,i}w_{s,i}$$

where

$\alpha_{2,i}$ correction factor for sediment concentration

$\varepsilon_{s,i}$ sediment diffusion coefficient evaluated at the bottom of the *kmx* cell of sediment fraction (*i*)

$c_{a,i}$ reference concentration of sediment fraction *i,* often computed using Van Rijn's sediment model.

$c_{kmx,I}$ average concentration of the kmx cell of sediment fraction *i*

Δz difference in elevation between the centre of the kmx cell and Van Rijn's reference height: $\Delta z = z_{kmx} - a$

The *settling velocity of sediment* $w_{s,0}$ is calculated in advance. For cohesive and non-cohesive sediment the fall velocity depends on the physical characteristics of the particles (e.g., particle size, relative density, flocs). Hindered settling is taken into account as well.

The classical Exner equation with entrainment and deposition fluxes E and D for suspended sediment, and gradients in x- and y-direction for bed-load transport s_b are applied to compute the *bed level changes* (bed level update):

$$\left(1-\varepsilon_p\right)\frac{\partial z_b}{\partial t}+\frac{\partial s_{bx}}{\partial x}+\frac{\partial s_{by}}{\partial x}=D-E$$

Where:

S_{bx} bed-load transport per unit of width, x-direction, sum of all fractions (m^2/s)

S_{by} bed-load transport per unit of width, y-direction, sum of all fractions (m^2/s)

ε_p bed porosity

The bedload transport is reduced if the thickness of the sediment layer becomes small. The same effect has been implemented as a reduction for the entrainment and deposition terms as well as the equilibrium concentration by a factor f_{FIXFAC} if erosion is expected to occur. This approach allows a realistic approximation of sediment and erosion processes, and sediment movement, on bed-rock sections.

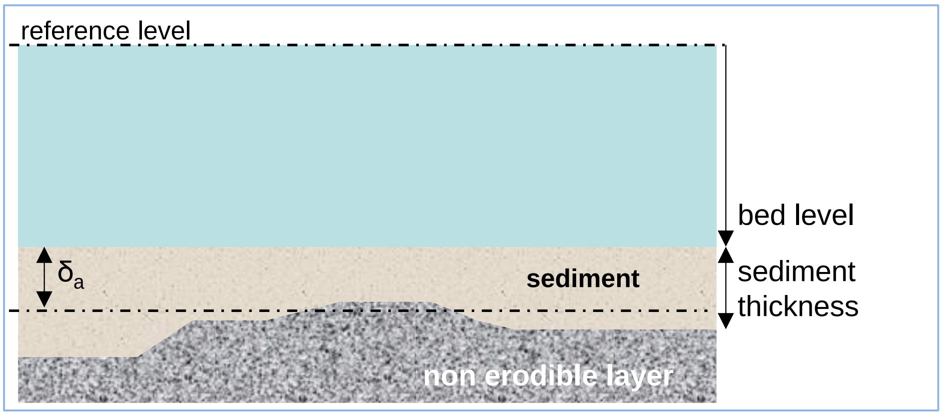


Figure A- 8 Schematic illustration of morphological changes.

A *morphological time scale factor* can be used to extend the morphological time step, and speed up the calculations:

$$\Delta t_{\text{morphology}} = f_{MOR} \cdot \Delta t_{\text{hydrodynamic}}$$

The models will be calibrated for hydrodynamics and sediment transport, such that *they match the DSF general results for the reservoir cases* (i.e., water levels, velocities and sediment transport). Note that a calibration on measured data is not possible, since the reservoirs do not exist yet.

- Bathymetric data, or initial bed profile, is derived from the DEM of MRC:
  - Selection of coordinate system:
    - Use UTM coordinates: WGS84 system, UTM zone 48N (Laos is covering 2 UTM zones: 47N and 48N)
    - Coordinate transformation using ArcGIS (Esri) and SuperTrans (Open-Earth Tools of Deltares)
    - The vertical reference for the MRC data is Ha Tien datum for the most recent DEM, but Kolkar datum for the older Chart datum that was used to level the bed.
  - Set-up of Digital Elevation Model: it is proposed to either to use the MRC soundings 1994 and 1998 for main channel, and SRTM (Space Shuttle Mission, 2000) for flood plains, or to

use the full DEM as delivered by MRC modelling team which is processed from the 1998 Hydrographic atlas and 1998 soundings for the main channel. A comparison between the contours of the 1998 atlas and the SRTM data shows good agreement for the levels outside the main channel. The soundings in the main channel are coming from the navigation program, and have to be referenced according to Ha Tien 1960 datum. It should be realised that the vertical reference of SRTM data (EGM 1996) does not fully coincide with this reference for Mean Sea Level. The difference is probably in the order of 1 to 1.5 m (in Cambodia this is 1.41 m).

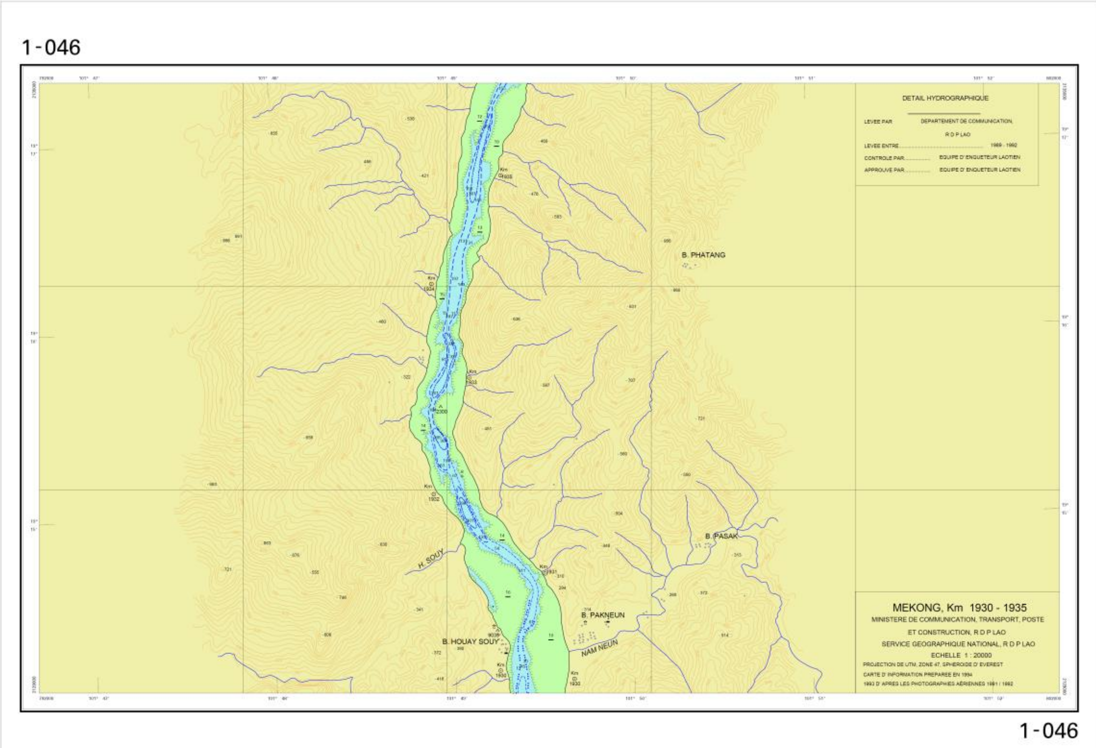


Figure A- 9 **Example of a map from MRC Hydrographic Atlas 1998, location of Xayaburi.**

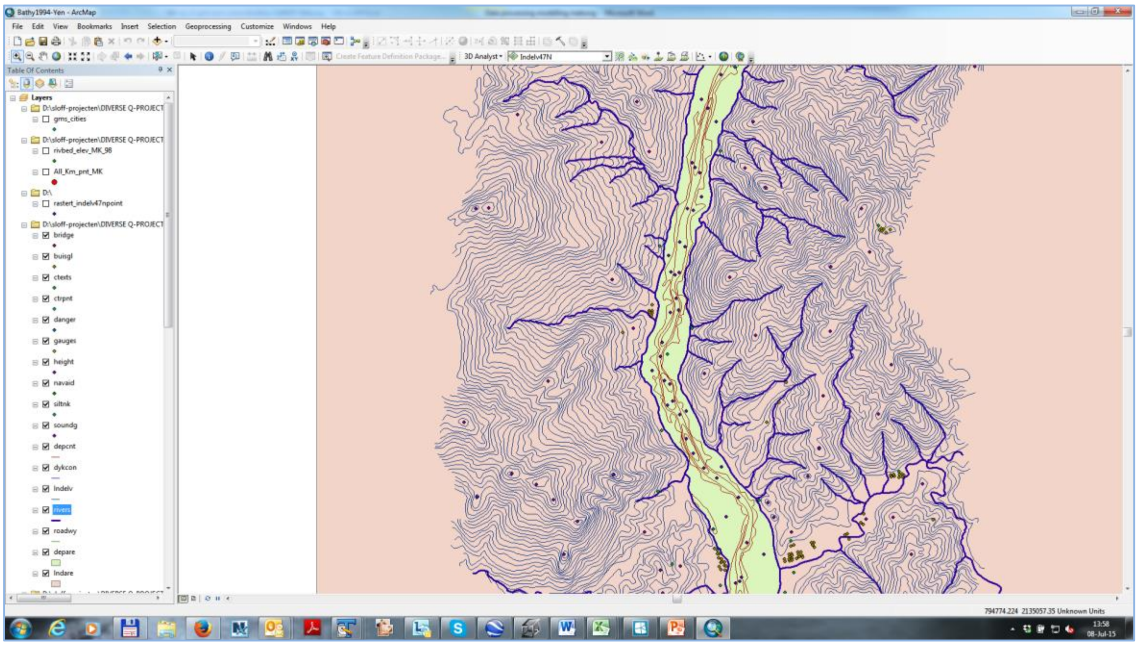


Figure A- 10 Example of the digitized version of the Hydrographic Atlas 1998 (projected in ESRI-ArcMap) for Xayaburi.

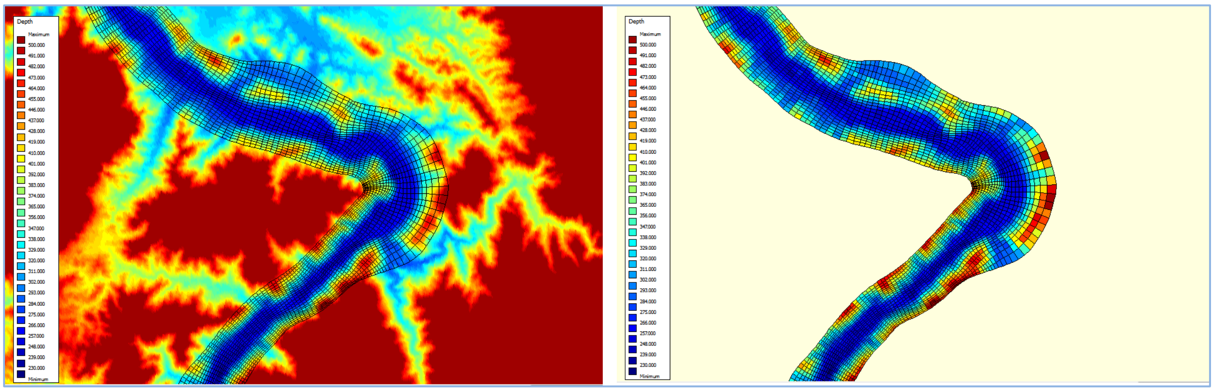


Figure A- 11 Example of projecten of DEM on the numerical grid (near Luang Prabang)