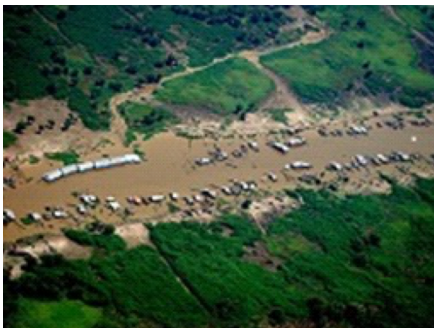
Many people depend profoundly on Mekong river aquatic resources.
Photo: Gregory Thomas, NHI.

A boy in a basin navigates through a floating village in Tonle Sap Great Lake, Cambodia, on September 13, 2009.
Photo: Sitha Som, Conservation International.



Tonle Sap River draining into the lake. Note the river settlements, on March 16, 2009.
Photo: Teo Wind, Malaysia.

A CLIMATE RESILIENT MEKONG

TECHNICAL MEMORANDUM ON OPTIONS FOR SEDIMENT PASSAGE THROUGH SAMBOR DAM

Submitted To: **Ministry of Industry, Mines, and Energy & Ministry of Water Resources and Meteorology Kingdom of Cambodia**

Submitted By: **A Climate Resilient Mekong Project**

Major Initial Funder: USAID FROM THE AMERICAN PEOPLE

Project Coordinator: NATURAL HERITAGE INSTITUTE

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1.0 INTRODUCTION

This report presents the outcome of a preliminary study of sediment management options for Sambor Dam on the mainstream Mekong River, planned by the Kingdom of Cambodia that control sediment flows into the Lower Mekong basin. Consideration of these options is important because maintaining sediment flows through these reservoirs is vital to the health of the downstream fisheries in the Tonle Sap Great Lake, the mainstream Mekong in Cambodia, and the Mekong Delta in Vietnam. Sediment passage is also important to increase the longevity of the hydropower facilities, an issue of great importance to the Kingdom of Cambodia under contracts in which Sambor Dam would be built, owned and operated by foreign investors for 25 years before it is transferred to Cambodia. At the end of the concession periods Cambodia has to be able to use the dam and its reservoir to generate hydropower for an indefinite period. This is accomplished if reservoir sedimentation is kept at bay.

The map on Figure 1 show the locations of the Sambor Dam and the Lower Se San 2 Dam, and the alternative dams proposed in this report to replace the proposed Sambor Dam and the proposed Lower Se San 2 Dam. The map also shows dams in Vietnam, which are not considered in this report.

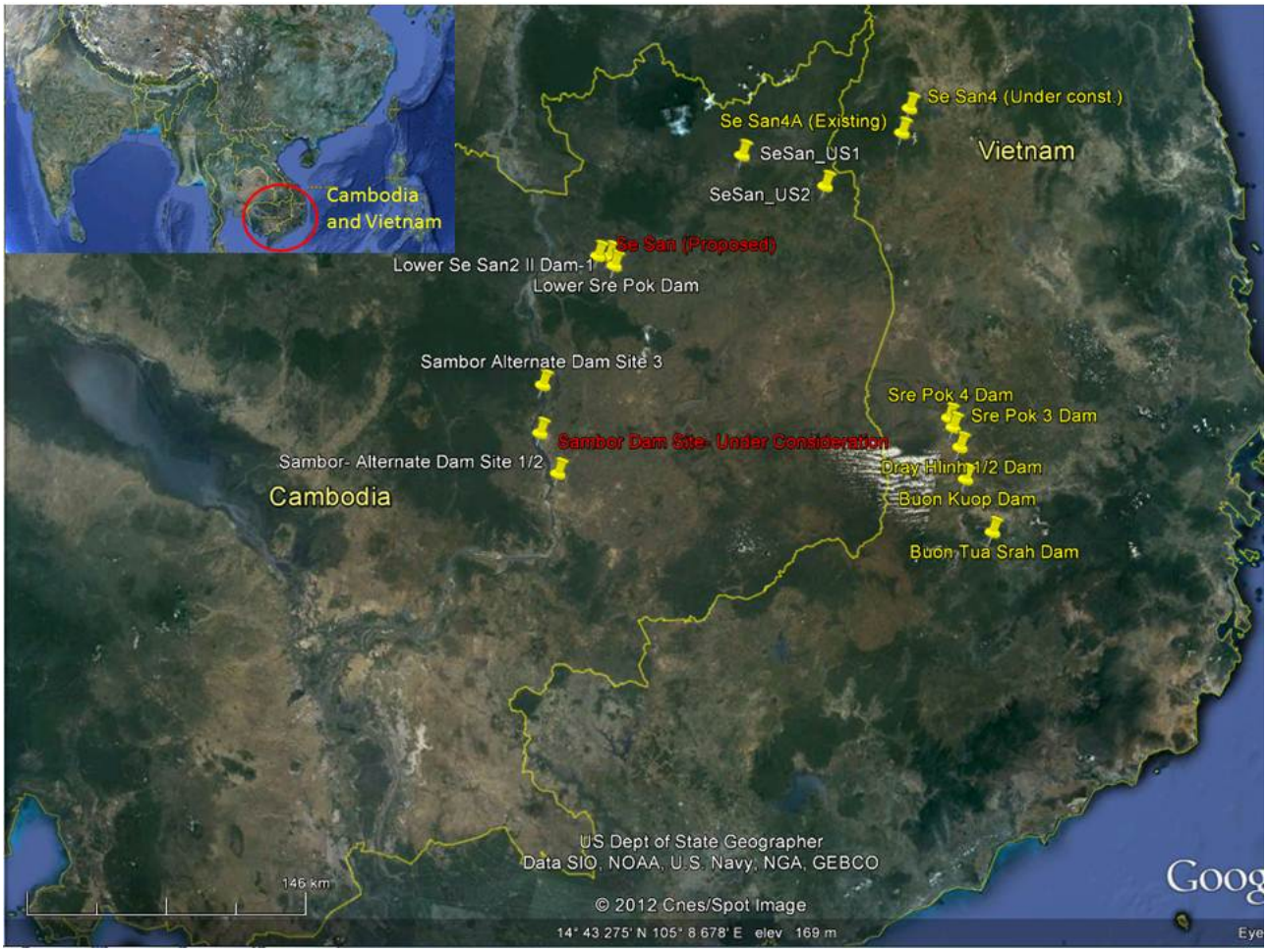

Figure 1 Location Map of Hydropower Projects on the Lower Mekong River and its Tributaries

2.0 APPROACH

2.1 Introduction

The study entailed evaluating the potential to pass sediment through Sambor and Lower Se San 2 Dams and their reservoirs by making use of established reservoir sedimentation management techniques. This was done by first considering the potential to pass sediment through the currently proposed dams. If it was found that the sediment passage ability of the currently proposed dams can be improved, alternative designs were conceived and analyzed. The designs with the greatest potential to pass sediment to the downstream river were identified. These studies were executed at pre-feasibility level and will require further refinement during the feasibility and design stages of the projects.

2.2 Data

Flow and sediment data and the information on reservoir type and size were obtained from various sources (such as ICEM, 2009; Meynell, 2011; and http://www.3sbasin.org/iucn/). Additionally, topographic information were obtained from Google Earth and from the University of Florida, Digital Collections (http://ufdc.ufl.edu/UF00075733/00001/thumbs) (Accessed on 11/07/2012) and site-specific topography were developed at 5-m contour intervals.

2.3 Sediment Management Alternatives

At least eleven different techniques exist to manage sediment in reservoirs (see, e.g., Annandale 2011). Not all of these techniques are viable for increasing sediment passage through the dams and reservoirs assessed in this report. After consideration of the problem, it was decided that the reservoir sedimentation management techniques with the greatest potential for passing sediment through Sambor Dam and the Lower Se San 2 Dam alternatives are drawdown flushing, sluicing and bypassing.

2.3.1 Drawdown Flushing

2.3.1.1 Description

The objective of drawdown flushing is to erode and remove previously deposited sediment from a reservoir and discharge it downstream. This is accomplished by first emptying the reservoir and allowing the river flowing through the reservoir to erode and transport the previously deposited sediment. During drawdown, flushing a reservoir is brought to the original river-like condition by releasing reservoir flows through bottom outlets or large radial gates if a dam is low enough. This is usually executed during a low-flow period, preferably just prior to the monsoon. By implementing drawdown flushing just prior to the monsoon allows the reservoir to be refilled with water once drawdown flushing is complete.

It is important for flushing flows to freely discharge through the low-level outlets or radial gates without damming; therefore the need to implement drawdown flushing during low-flow periods. Sediment is

eroded by water flowing in single or multiple channels through the sediment that previously deposited in the reservoir. The success of sediment removal by flushing depends on the reservoir size, geometry (such as width of the reservoir, the valley side slopes and longitudinal river-slope), location of the low-level outlets, the type of sediment deposited in the reservoir, and the magnitude of the flushing flows.

A distinguishing feature of drawdown flushing is that it requires emptying a reservoir and allowing the formation of river-like flow conditions over the previously deposited sediment. This requires the use of low-level or large radial gates to discharge freely the eroded sediment downstream. The creation of river-like conditions requires that drawdown flushing be implemented during low-flow periods, i.e., during the non-monsoon season. Once drawdown flushing is complete, the outlets are closed and the reservoir filled with water for continued power generation.

2.3.1.2 Assessment Criteria

White (2001) provided criteria to assess the potential for successful drawdown flushing. In general, drawdown flushing is successful in narrow, steep reservoirs where the sediment transport capacity of the water used to execute drawdown flushing is large enough to remove the amount of sediment that has deposited within a reservoir between flushing events. In order to implement drawdown flushing it is obviously also necessary to have available low-level outlets that are large enough to drain the reservoir and to freely discharge re-entrained sediment downstream.

To assist dam designers in decision-making, White (2001) devised six parameters that may be used to determine the potential success of drawdown flushing. The proposed parameters were validated by using data from 14 dams where drawdown flushing has been implemented in the past. Drawdown flushing was deemed successful at six of those dams and unsuccessful at the remaining eight. This recorded experience provides a good basis for predicting potential drawdown flushing success at other projects. The six criteria are conceptually presented in what follows. More detail may be found in White (2001).

2.3.1.2.1 Sediment Balance Ratios (SBR and SBR_d)

The sediment balance ratio (SBR) quantifies the ability to re-entrain and transport previously deposited sediment during drawdown flushing. The SBR is the ratio between the amount of sediment that may be removed by the water flowing through the reservoir during drawdown flushing and the amount of sediment that has deposited in the reservoir between drawdown flushing events. Conceptually, the SBR is defined as follows:

$$SBR = \frac{Sediment\ volume\ that\ may\ be\ removed\ during\ flushing}{Sediment\ volume\ deposited\ between\ flushing\ events}$$

Due to the fact that the sediment transport capacity of the water used during drawdown flushing is determined by the amount by which the water surface in the reservoir is drawn down, White (2001) also proposed to use an additional criterion, which is the SBR if the reservoir is drawn down to the maximum extent possible. He named that parameter SBR_d.

The SBR represents the sediment balance ratio if the water level at the dam is drawn down to the elevation of the low-level outlet. Such an outlet may not be located right at the bottom of the dam, due to design constraints. The SBR_d parameter provides an indication of the potential to successfully flush the sediment from the reservoir should one be able to draw down the water surface to the lowest level possible, i.e., to the level of the riverbed at the dam. For flushing to be successful both SBR and SBR_d must be greater than one, i.e., the potential to flush sediment out of the reservoir must be greater than the amount of sediment that deposited in it during the period between flushing events. SBR_d will always be greater than SBR, making it, in essence, a superfluous parameter.

1.1.1.1.1 Drawdown Ratio (DDR)

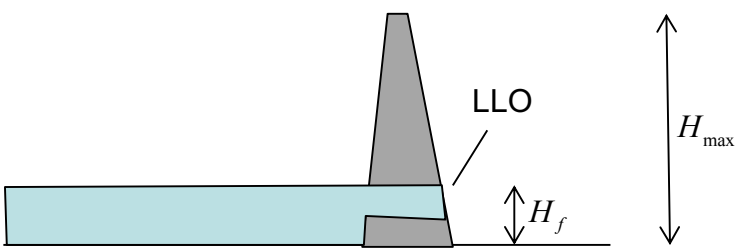

Figure 2 Variables defining the DDR

Another parameter devised by White (2001) is known as the drawdown ratio (DDR). This parameter quantifies how far the water surface elevation can be drawn down using a low-level outlet (LLO) or a radial gate. The parameter is defined as:

$$DDR = 1 - \frac{H_f}{H_{max}}$$

The meaning of the variables H_f and H_{max} are shown in **Error! Reference source not found.**.

By making use of the fourteen projects where drawdown flushing has been implemented, White (2001) found that if DDR > 0.7, then flushing may be successfully implemented (see further on).

2.3.1.2.2 Flushing Width Ratio (FWR) and Top Width Ratio (TWR)

The two ratios known as the flushing width ratio (FWR) and the top width ratio (TWR) provide some idea of the ability to remove substantial amounts of deposited sediment from a reservoir by means of drawdown flushing. **Error! Reference source not found.** represents an average cross section of a

reservoir valley. Suppose that sediment has filled the entire valley and that an attempt to remove sediment through drawdown flushing is made. When using drawdown flushing a channel is eroded into the deposited sediment. The dimensions of that channel are defined by W_f and W_{ftop}, i.e., the bottom width and the top width of the channel that is eroded into the deposited sediment during the flushing event. The dimensions of the original reservoir valley are defined by W_{bot} and W_{top}, i.e., the bottom and top widths of the reservoir valley.

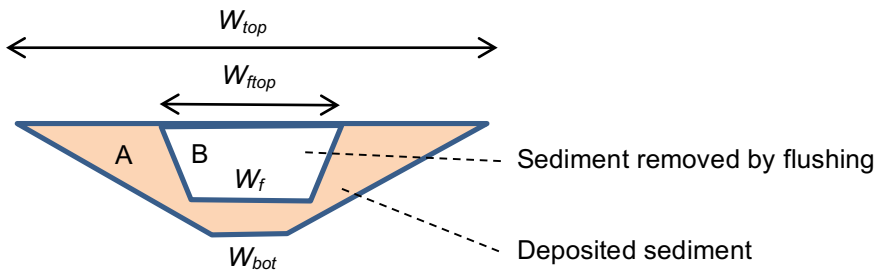

Figure 3 Cross Section of Reservoir Valley and Variables Used to Quantify FWR and TWR

The FWR is defined as:

$$FWR = \frac{W_f}{W_{bot}}$$

And the TWR is defined as:

$$TWR = \frac{W_{ftop}}{W_{top}}$$

From **Error! Reference source not found.** it can be seen that if drawdown flushing results in both the top and bottom widths of the eroded channel exceeding the top and bottom widths of the reservoir valley, then all the sediment would have been removed. Therefore, in the ideal case drawdown flushing would be successful if both the FWR and TWR parameters are greater than one. In cases where they are slightly less than one, it may mean that only part of the sediment may be removed. It means that some but not all of the reservoir storage space may be preserved in the long term.

2.3.1.2.3 Long-Term Capacity Ratio (LTCR)

From a practical point of view, it may not be possible to remove all deposited sediment from reservoirs by making use of drawdown flushing, as indicated in the previous section. Therefore, what one wishes to know is how much of the original reservoir volume can be preserved in the long term if drawdown flushing is regularly implemented. The long-term capacity ratio (LTCR) provides a measure of how much of the reservoir volume might be preserved in the long term when regularly implementing drawdown flushing. It is defined as the ratio between the cross sectional area of the channel eroded into the deposited

sediment (the area B in **Error! Reference source not found.**) and the total cross sectional area of the reservoir valley prior to sedimentation (the sum of area A and area B in **Error! Reference source not found.**), that is:

$$LTCR = \frac{Area\ B}{Area\ A\ + Area\ B}$$

2.3.1.2.4 Validation of Criteria

The criteria defined in the previous sections are used in the RESCON model (Palmieri et al. 2003) to assess the potential success to use drawdown flushing to remove deposited sediment from reservoirs. That model, i.e., the RESCON model, has been used to assess the dams and reservoirs investigated in this study. The criteria used in the RESCON model are shown in **Error! Reference source not found.**.

Table 1 Drawdown Flushing Criteria Used in the RESCON Model

Parameter Name	Criterion
SBR	> 1
LTCR	> 0.35
DDR	> 0.7
FWR	> 1
TWR	~ 1
SBR_d	> 1

The viability of these criteria to predict the potential success of implementing drawdown flushing to remove adequate amounts of deposited sediment from reservoirs were reviewed by White (2001). He used information obtained from fourteen projects to perform the assessment. Drawdown flushing was deemed successful at six of those projects, and unsuccessful at the other eight.

Error! Reference source not found. and **Error! Reference source not found.** compare the calculated values of SBR, FWR, LTCR and TWR to the criteria set in **Error! Reference source not found.**. The comparison of the DDR values is shown in **Error! Reference source not found.**. It is observed that the criteria are substantially satisfied. These criteria were therefore used to assess the potential for drawdown flushing at the dams and reservoirs reviewed during this study.

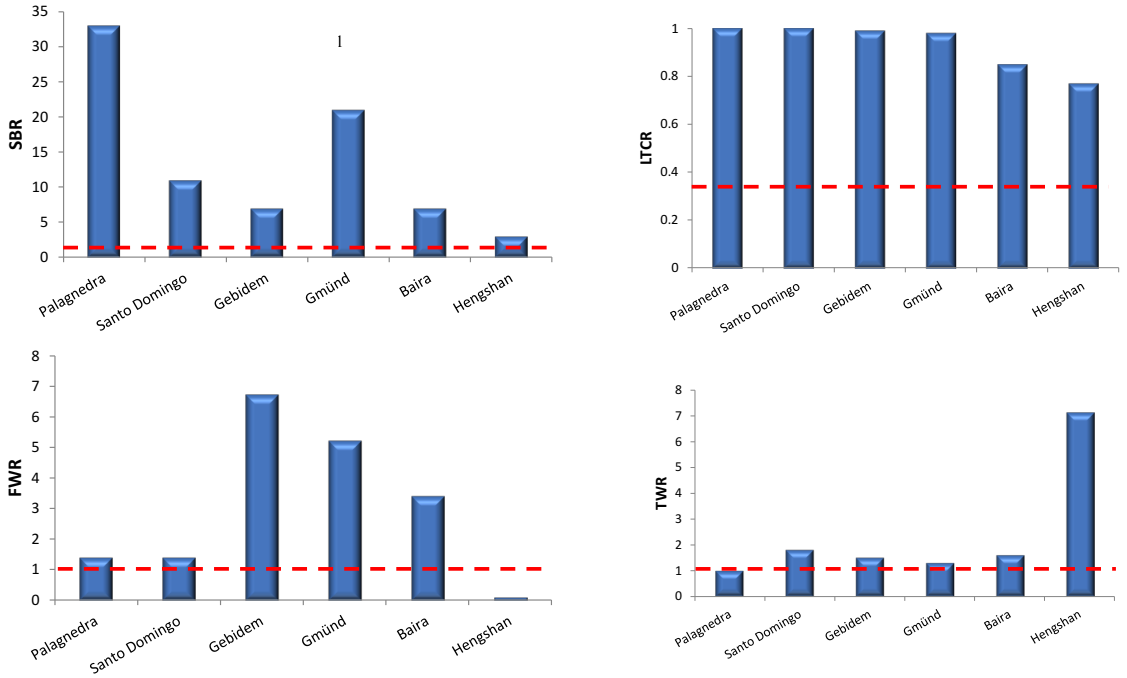

Figure 4 Comparison of Flushing Criteria Parameter Values at Reservoirs that have been Successfully Flushed (White 2001)

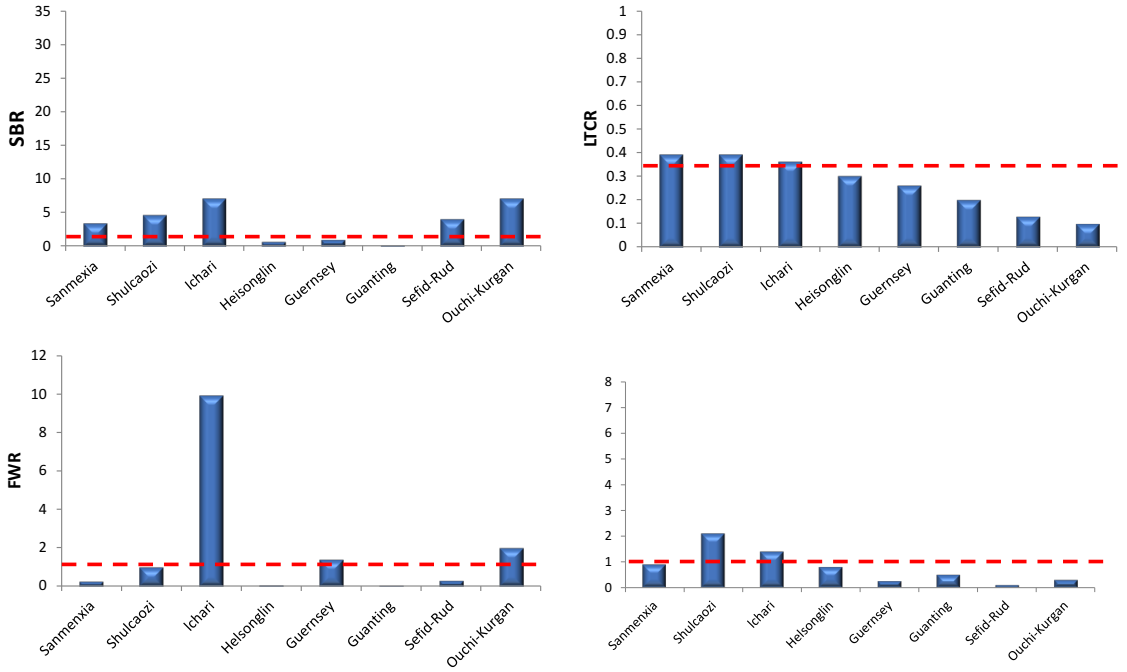

Figure 5 Comparison of Flushing Criteria Parameter Values at Reservoirs that have not been Successfully Flushed (White 2001)

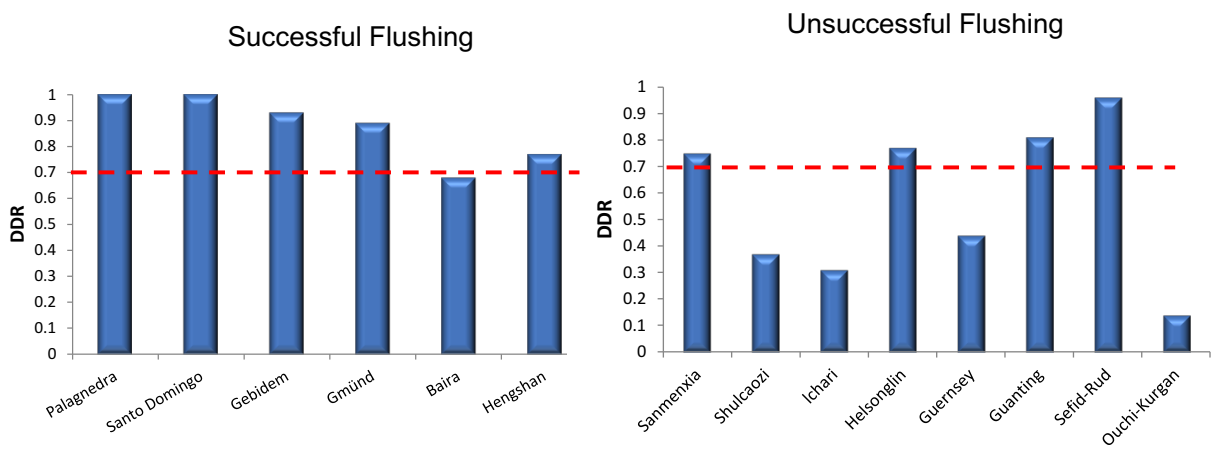

Figure 6 Comparison DDR Parameter Values and Criteria for Reservoirs that are Known to have and have not been Successfully Flushed (White, 2001)

2.3.2 Sluicing

2.3.2.1 Description

Sluicing is a sediment management technique implemented during floods, i.e., during the monsoon. The objective of sluicing is to minimize the amount of sediment that will deposit in a reservoir. This is done by creating flow conditions in a reservoir that are characterized by high sediment carrying capacity. In the ideal case, which is seldom accomplished, the sediment transport capacity in the reservoir will be equal to the sediment transport capacity of the river carrying sediment into the reservoir. Should it be possible to accomplish this goal the amount of sediment carried into a reservoir from upstream (S_1) will equal the amount of sediment discharged downstream (S_2), with no net amount of sediment depositing in the reservoir (**Error! Reference source not found.**).

The sediment transport capacity in the reservoir is maintained at a high level by drawing down the water surface elevation at the dam as much as possible while floodwaters flow through the reservoir. By doing so, the energy slope of the water flowing through the reservoir is increased, thereby maximizing the sediment transport capacity of those flows. The water surface elevation at the dam is drawn down by using low- and / or mid-level gates at the dam. It is obviously not possible to draw down the flows in a reservoir to the same extent required by drawdown flushing. The reason for this is that sluicing is implemented during high flows (the monsoon) during which time the rate of flow into the reservoir is normally larger than the free-flow discharge capability of low-level outlets.

Sluicing is best implemented in narrow reservoirs, located in relatively steep rivers where monsoon flow volumes are large relative to the reservoir volume. Successful flushing also requires provision of enough large mid- and low-level outlets in the dam that will allow the water surface elevation at the dam to be drawn down significantly during flood flows characteristic of the monsoon. Dams that are designed with the ability to significantly draw down the water surface elevation at the dam during the monsoon have a

much greater potential to successfully transport large amounts of sediment through the reservoir without deposition; thus fulfilling the purpose of sluicing.

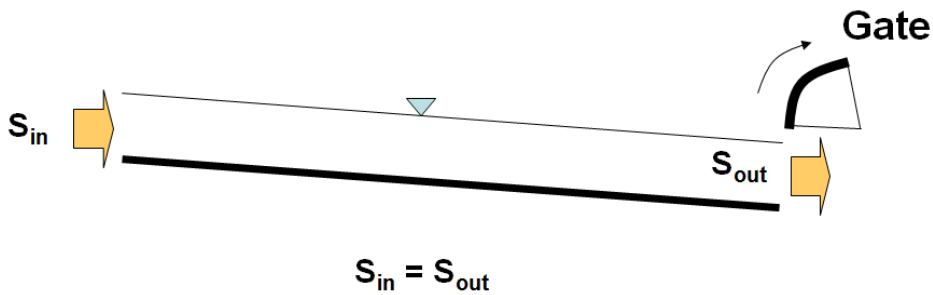

Figure 7 Concept of Sediment Pass-through by Making Use of Sluicing

2.3.2.2 Assessment Criteria

The engineering profession has not developed simple criteria for assessing the potential success of sluicing at pre-feasibility level investigations. The potential for implementing sluicing has therefore not been assessed during this study. It is left for more detailed assessment during the feasibility and design phases of the projects.

2.3.3 Bypassing

2.3.3.1 Description

Two principal bypass techniques exist, the one technique uses by pass tunnels and the other uses river modification or existing river channels. In the case of the projects under consideration it was found that the use of bypass tunnels is not desirable.

2.3.3.1.1 Bypass Tunnels

A bypass tunnel conveys the water and sediment carried by floods around a reservoir for release downstream of the dam. A schematic illustrating the configuration of a bypass tunnel is shown in **Error! Reference source not found.**. A diversion weir is constructed on the upstream end of the reservoir, which divert floods with high sediment loads into a tunnel for discharge downstream of the dam.

During average flow conditions, the water is allowed to flow over the diversion weir into the reservoir, instead of into the tunnel. Average river flows contain low sediment loads, resulting in low volumes of deposited sediment within the reservoir. By following this operational procedure, it is possible to store water in the reservoir during low flow conditions and route sediment around the reservoir during high flow conditions, when the sediment loads are high.

Five known bypass tunnel schemes exist in Switzerland and four in Japan, with others planned. These schemes are suited to mountainous regions with relatively high river slopes (1% to 4% slopes) and relatively small reservoirs. Typical tunnel lengths range from about 250m to 4,000m.

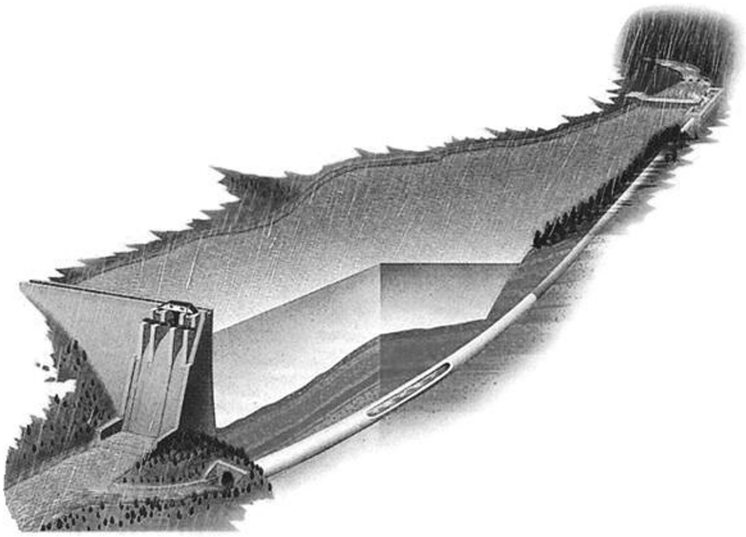

Figure 8 Sketch illustrating the bypass tunnel concept

The earliest example of the successful implementation of a bypass tunnel is located at Nunobiki Dam in Japan. Soon after the dam was built in 1900, it was realized that sedimentation would rapidly reduce its reservoir volume. The dam owners decided to construct a bypass tunnel, which was completed in 1908. If not for this tunnel, the reservoir would have been filled with sediment by 1926. Instead, by using the tunnel to bypass sediment during floods a constant reservoir storage volume has been maintained since 1908. The bypass tunnel and reservoir is still in use at this time; it has been gainfully used for more than 100 years to effectively manage reservoir sedimentation.

2.3.3.1.2 River Modification

An interesting bypass scheme that has been designed for Nagle Dam in South Africa is shown in **Error! Reference source not found.**. That dam and its reservoir are located in a river with high sediment loads and have been successfully operated since 1950. The dam is located at the downstream end of a large river meander and its reservoir is located in the meander bend, upstream of the dam.

At the upstream end of the meander a flood weir was installed, which is opened during average flow conditions but closed during floods. During average flow conditions the water flows through the open flood

weir into the reservoir. These waters contain low sediment loads and the amount of sediment deposited in the reservoir during such conditions is small.

When floods containing high sediment loads occur, the flood weir is raised and the gate of the diversion channel opened. The water containing high sediment loads then flows through the diversion channel and is released downstream of the dam. In this manner the high sediment loads are not conveyed into the reservoir during flood conditions and do not deposit within it.

It is very important to note that the diversion channel at Nagle Dam is located on top of a strong rock formation. In the absence of such a favorable geologic condition, diversion of large floods will likely be unfavorable. It is known that short-circuiting of river meanders often result in significant river degradation. The rock on which the diversion is located prevents such erosion in the case of Nagle Dam.

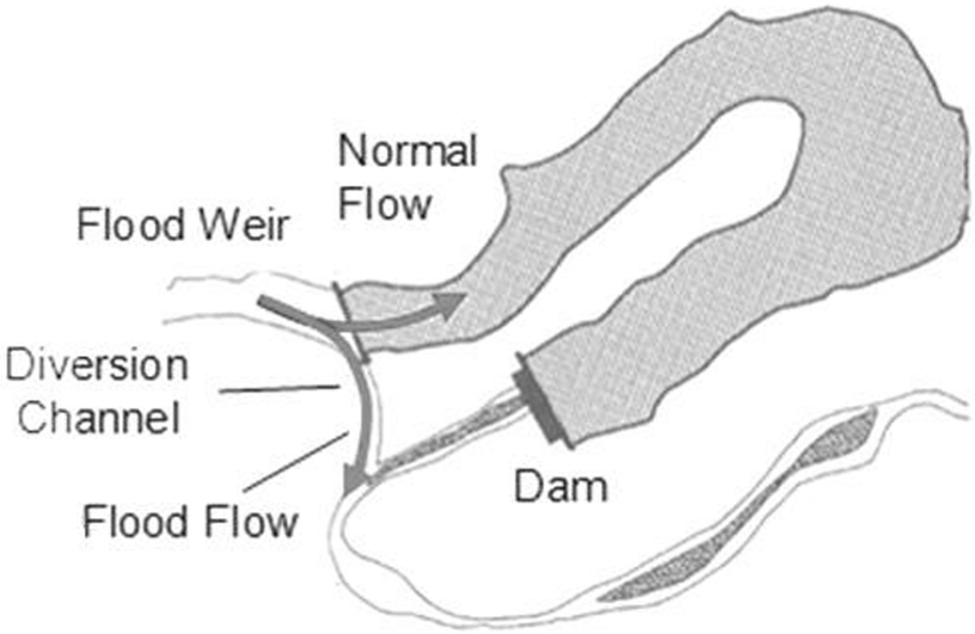

Figure 9 Bypass scheme at Nagle Dam, South Africa through river modification

2.3.3.2 Assessment Criteria

The desired configurations for this reservoir sedimentation method is determined by conceiving the right layout and using the sediment concentration in the flows during the flood season to estimate how much sediment may be bypassed. This is done by multiplying the diverted amount of water with its sediment concentration.

2.4 Essential Design Elements

Implementation of drawdown flushing, sluicing, and density current venting requires incorporation of low- and mid-level outlets in dams. Without the availability of such outlets, it is not possible to implement any of the three reservoir sedimentation management techniques considered in this study. It may also be necessary to install a lining in the low-level outlets to resist the effects of abrasion.

2.4.1 Outlets

Dam design elements required to facilitate successful implementation of drawdown flushing, sluicing, and density current venting include low- and mid-level outlets (**Error! Reference source not found.**). The outlets are used differently in each case.

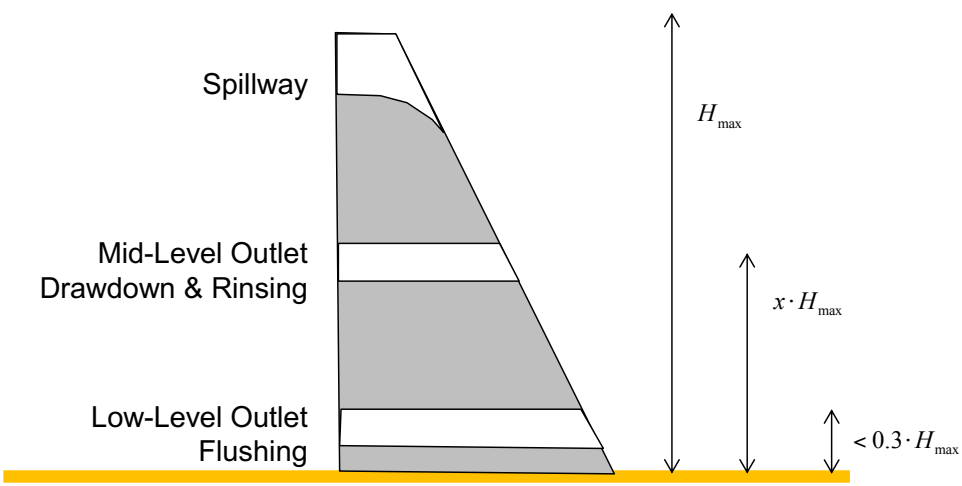

Figure 10 Essential Dam Design Elements Required to Facilitate Drawdown Flushing, Sluicing, and Density Current Venting

2.4.1.1 Drawdown Flushing

To implement drawdown flushing, executed during the non-monsoon season, it is necessary to first empty the reservoir. This is accomplished by opening both the mid- and low-level outlets. Using both outlets allows rapid emptying of the reservoir. Once the reservoir is empty, the low-level outlets are used to discharge the water containing re-entrained sediment to the downstream river. After drawdown flushing has been completed, the low-level outlets are closed to refill the reservoir. When the water level reaches the mid-level outlets, they are opened to allow discharge of clean water to the downstream river. Release

of this clean water is necessary to rinse the fine sediments that may have deposited along the riverbanks and on the riverbed of the downstream river reach. Rinsing the fine sediment with clean water enhances environmental conditions and appearance. After rinsing is complete, the mid-level outlets are also closed to continue filling the reservoir.

In some cases large radial gates that may replace much of the dam can be used to facilitated drawdown flushing, as proposed in this report (**Error! Reference source not found.**). Should these gates stretch completely across the river, essentially replacing the dam structure, opening them completely essentially represents "removal of the dam" during low flows, thereby establishing natural flow conditions.

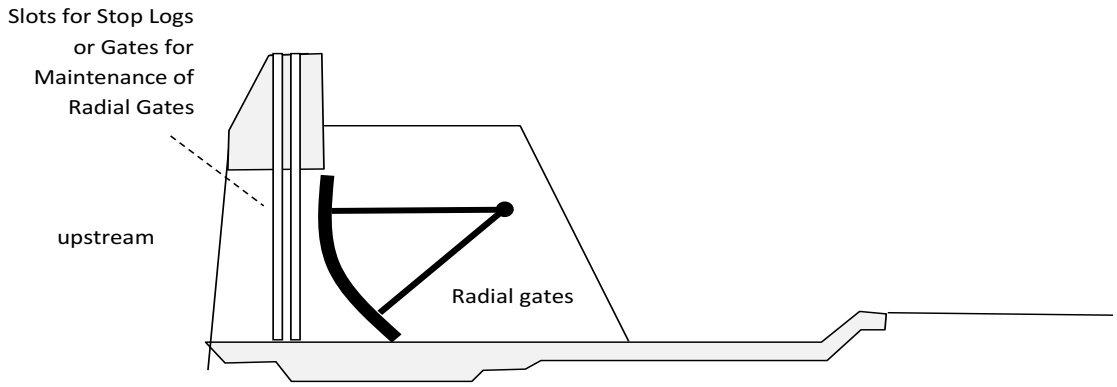

Figure 11 Radial Gates may also effectively be used to facilitate drawdown flushing

2.4.1.2 Sluicing

Sluicing is executed during flood (monsoon) conditions, which means that it will not be possible to empty the reservoir. The objective during sluicing, i.e., to maximize the sediment transport capacity of the water flowing through the reservoir, is accomplished by opening both mid- and low-level outlets. By modulating the openings of the low- and mid-level gates it is also possible to regulate the sediment concentration in the water released downstream of the dam. Once sluicing is complete, the low-level outlets are closed and the mid-level outlets may be used to rinse fine sediments that may have deposited along the downstream river reach, if necessary. Upon completion of the rinsing process, the mid-level outlets are also closed and the reservoir refilled with water.

2.4.1.3 Lining

It may be necessary to line the low-level outlets to prevent damage by abrasion. This may be accomplished by using high-strength concrete, steel or other abrasion resistant materials like basalt tiles.

2.5 Sediment Management in Dam Cascades

When passing sediment through cascades of dams, as in the case under consideration along the Xe Kong River, it is usually preferred to concurrently release sediments from all dams in the cascade. This may be performed by first opening outlets at the upstream dams, followed by sequential opening of outlets at the downstream dams. Detailed specification of how this should be accomplished is project specific. The procedure is determined by more detailed study and refined through experience gained during implementation.

3.0 SAMBOR DAM ON MEKONG RIVER, CAMBODIA

Sambor Dam has not been constructed, and is in the pre-feasibility stage. Therefore, we were able to focus our efforts not only on sediment management techniques, but also on optimization of the dam location for proactive sediment management. The current proposed dam location is just downstream of a wide, braided section of the river. This is an unfavorable location, because sediment is difficult to remove from a wide reservoir. Therefore, three proposed alternative dam locations, presented in the report, indicate much greater potential to pass sediment. The preliminary estimates indicate that it may be possible to retain about 50% or greater of the original reservoir storage volumes, while accepting reductions in installed power ranging between about 23% and 48%. Additionally, the alternative locations will decrease the proposed inundation area of the reservoir.

3.1 Existing Design Location

The Sambor Dam is the furthest downstream among all existing and proposed dams in the Lower Mekong Basin (LMB) and is located near Sambor village in Cambodia. The proposed dam is 56 m high and 18 km long with a rated head of 23 m. It creates a reservoir of 620 km^2 surface area, which amounts to 465 Mm^3 of active storage and 5,206 Mm^3 of total storage. The proposed installed capacity is 2,600 MW with 11,740 GWh of annual energy production. **Error! Reference source not found.** shows the approximate location and cross section of the proposed Sambor dam.

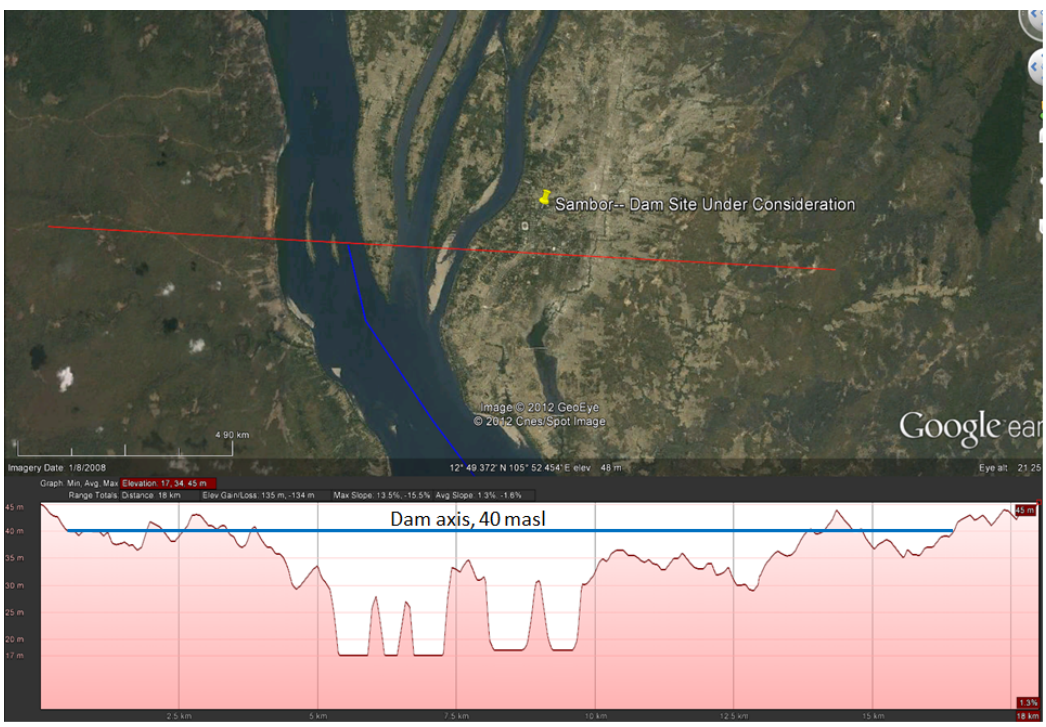

Figure 12 Location of Proposed Sambor Dam Site and Cross Section

3.1.1 Sediment Management Assessment

The RESCON model was used to evaluate the sediment management feasibility, using the following data (Meynell, 2011 and NHI Database):

Table 2 Reservoir Information of Proposed Sambor Dam

Item	Units	Value
Total reservoir volume	mill m^3	5,206
Bottom width of the dam	m	5,000[a]
Top level of the reservoir	masl	40.0
Minimum bed level	masl	17.1
Available head	m	22.9[b]
Reservoir length	m	35,700
Mean inflow	m^3/s	13,800
Mean annual sediment inflow	tons/year	81,000,000

3.1.2 Results

Table 2 presents Long-term capacity ratio (LTCR) and Sediment balance ratio (SBR) values, determined using the RESCON model, for various flushing flow magnitudes at the proposed Sambor Dam.

Table 3 Proposed Sambor Dam- Drawdown Flushing Feasibility

Flushing Flow	LTCR		SBR	
	Result	Criterion	Result	Criterion
Average flow (13,800 m^3/s)	0.13	>0.35	1.78	>1.0
1.5 times average flow	0.16		3.01	
2 times average flow	0.19		4.37	

LTCR and SBR are two indicators to determine drawdown flushing feasibility. LTCR, which is the ratio of the eroded valley area to the total valley area just upstream of the dam is a proxy for estimating the percentage of the original reservoir volume available in the long-term, when the sedimentation in a reservoir reaches equilibrium. RESCON documentation recommends a minimum value of LTCR as 0.35 for flushing to be feasible. SBR is the ratio of the sediment transport capacity of the flushing flow and the total amount of sediment discharging into the reservoir between drawdown flushing events. The recommended minimum value of SBR is 1.0.

[a] Top width of reservoir is 18,000 km.
[b] The rated head range from 16.5m to 33m in the data sources available to National Heritage Institute.

The results in Table 2 indicate that although the sediment transport capacity of the average flow is high enough to transport the annual amount of sediment through the reservoir, it is not geomorphologically possible to remove the deposited sediment. The reason for this is that the expanse of the deposited sediment upstream of the dam will be much wider than the width of a channel that can be eroded into the deposited sediment. The LTCR, which represents the relative amount of deposited sediment that can be removed over the long term (as a decimal), is very low (0.13 to 0.19). This indicates that only about 13% to 19% of the original reservoir volume can be maintained in the long-term and that drawdown flushing is not a viable approach to evacuate the majority of the deposited sediment.

3.2 Sambor Alternative-1 Dam Site

An alternative site for Sambor Dam was identified by making use of Google Earth. **Error! Reference source not found.** shows the location of the alternate site, which is approximately 25 km downstream of the proposed site. **Error! Reference source not found.** shows a close-up of the site and its cross section.

Figure 13 Relative Locations of Proposed and Alternative-1 Dam Sites at Sam

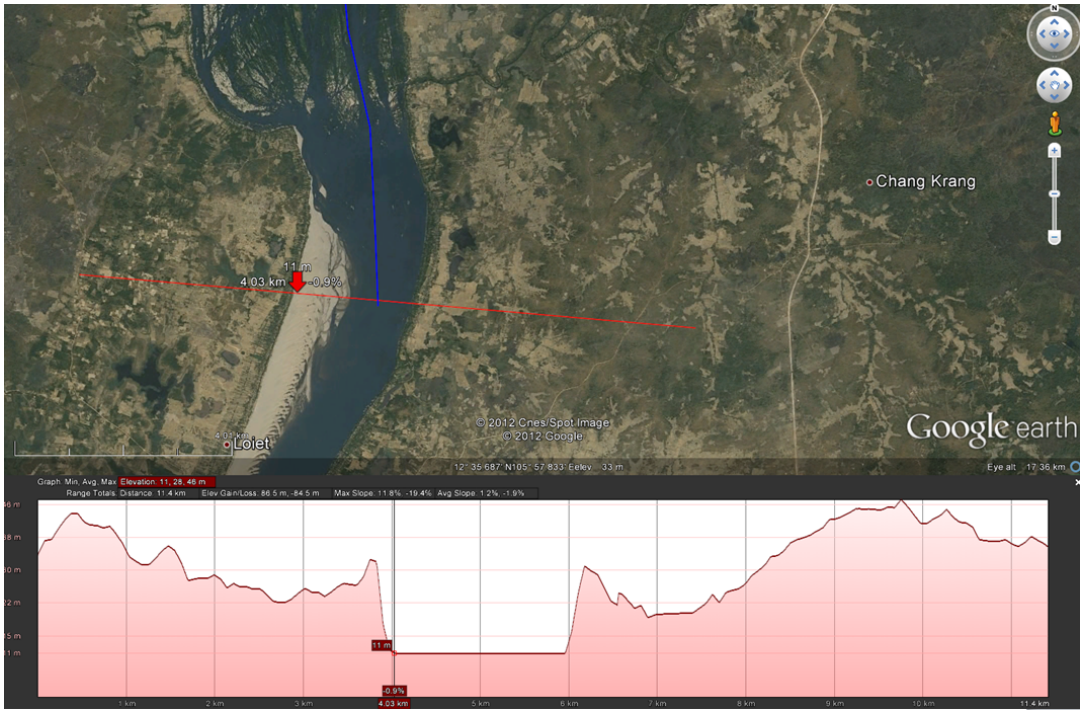

Figure 14 Location of Alternative-1 Sambor Dam Site and Cross Section

With the dam axis at 30 masl and minimum bed elevation of 12 masl, the available gross head for this alternative is 18 m and the dam length is 6.3 km. A schematic design of the dam cross section is presented on **Error! Reference source not found.**. Alternative-1 will have an installed capacity of about 2,000 MW with 9,229 GWh of annual energy production. The energy calculation is based on the same design flow (17,640 m^3/s) and number of operation hours (i.e., 4,515 hours per year) as the base case (i.e., the proposed project).

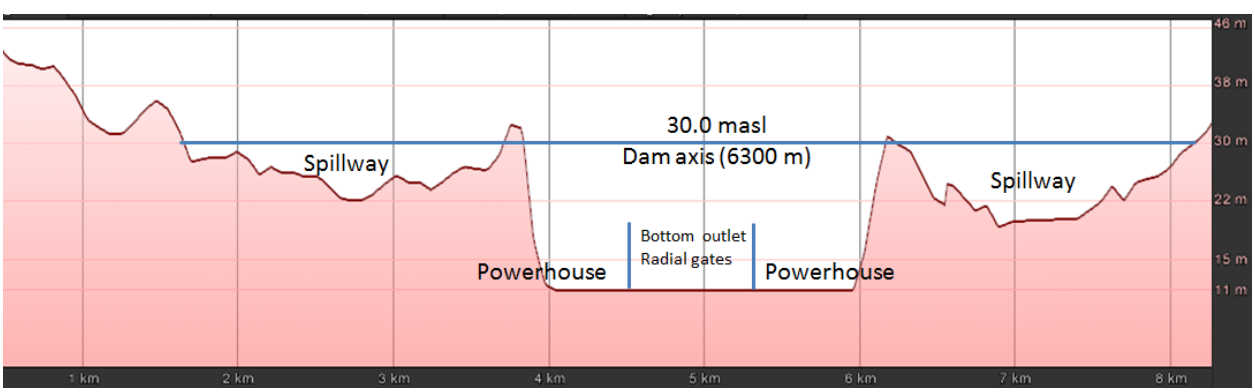

Figure 15 Cross Section of Aternative-1 Sambor Dam

3.2.1 Sediment Management Assessment

The design concept includes the provision of radial gates along the entire length of the dam, except at the powerhouse locations. **Error! Reference source not found.** illustrates a cross-sectional schematic of a possible arrangement for the radial gates. The intent is to open all these gates during drawdown flushing in the period just prior to the monsoon; essentially removing the presence of the dam. River-like flow conditions thus created remobilizes previously deposited sediment for discharge downstream. A practical height of non-pressurized radial gates, as proposed here, is likely about 12 m. Therefore, a cross-beam of about 6 m high will be required to maintain the head. A possible disadvantage of this configuration is that flushing flows may be dammed against that beam, preventing free-surface discharge at the dam (as required by drawdown flushing). Additionally, the concrete section above the top elevation of the gate will likely be required due to the limitation on the gate size of about 12 m. Such factors should be considered during the feasibility design of the project.

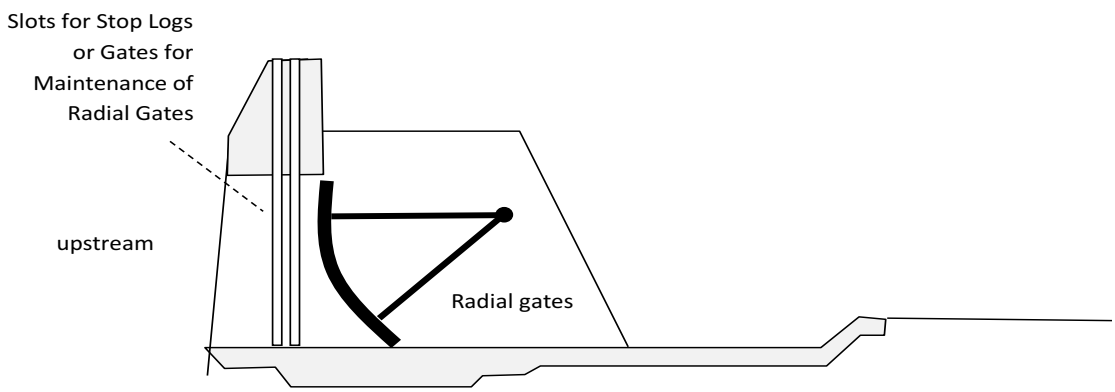

Figure 16 Radial Gate Section

Reservoir capacity is assumed by factoring by 0.52 and the length of the alternate site is changed with a factor by which net head is reduced from the base case. These estimates require confirmation when topographic data becomes available.

A RESCON analysis was performed to determine the feasibility of flushing Alternative-1 dam site. The input for this modeling are presented in Table 3 (Meynell, 2011 and NHI Database).

Table 4 Reservoir Information of Alternative-1 Sambor Dam

Item	Units	Value	Remarks
Total reservoir volume	mill m^3	2,707	Assumed 52% of the base case
Bottom width of the dam	m	2,000	
Top level of the reservoir	masl	30.0	
Minimum bed level	masl	12.0	
Available head	m	18.0	
Reservoir length	m	27,939	Using river slope from base case
Mean inflow	m^3/s	13,800	
Mean annual sediment inflow	tons/year	81,000,000	

3.2.2 Results

The RESCON results (Table 4) indicate that drawdown flushing is a feasible sediment management technique for this reservoir. The other sediment management alternatives such as dredging, HSRS, dry excavation and the inline sediment collector system are not feasible for this option due to the large reservoir size

Table 5 Sambor Alternative-1: Flushing Feasibility

Reservoir	LTCR		SBR	
	Result	Criterion	Result	Criterion
Average flow (13,800 m^3/s)	0.68	>0.35	2.7	>1.0
1.5 times average flow	0.84		4.5	
2 times average flow	0.91		6.8	

3.3 Sambor Alternative-2 Dam Site

At the same Alternative-1 dam site, Alternative-2 was evaluated, with a dam elevation at 24.0 masl. This provides a gross head of 12 m. With design discharge of 17,640 m^3/s the power plant capacity would be 1,363 MW and can produce 6,153 GWh of energy annually. The energy calculation is based on the same number of operating hours (i.e., 4,515 hours) as the base case (i.e., the proposed project).

From a hydropower generation point of view it means that Alternative-2 might be less desirable than Alternative-1. However, more detailed investigations may indicate the opposite if it is found that flow interference, as previously described, occurs when implementing drawdown flushing through the 18 m high dam (Alternative-1). In such a case Alternative-2 may be preferred if it is found that it is more effective in flushing sediment.

The cross section for Alternative-2 is shown on **Error! Reference source not found.**.

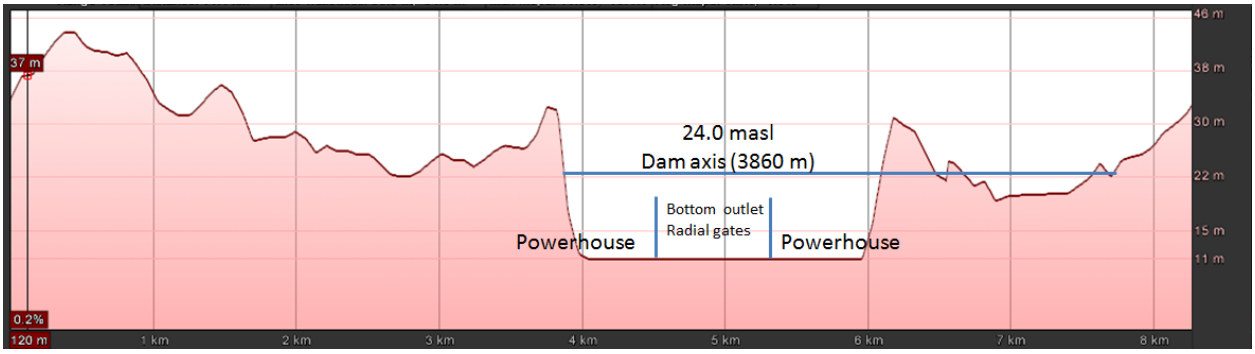

Figure 17 Cross Section of Alternative-2 Sambor Dam

3.3.1 Sediment Management Assessment

The sediment management approach when implementing drawdown flushing at Alternative-2 is similar to that for Alternative-1. The dam will almost entirely consist of 12 m high radial gates (except at the locations of the power house). The radial gate arrangement of this dam is shown on **Error! Reference source not found.**. The absence of the 6 m high beam above the radial gates is noted. The reason for this is that 12 m high gates are roughly equal to the proposed dam height. This allows for the creation of a dam consisting almost entirely of radial gates. Therefore, when such gates are opened, it may result in a completely "transparent" dam, i.e., virtually no interference between the structure and the flows during drawdown, and a greater likelihood of free-surface flow through the dam (as required by drawdown flushing). Such complete "removal" of the dam during drawdown flushing will lead to river-like flow conditions within the reservoir, which will remobilize previously deposited sediment and convey it downstream of the dam.

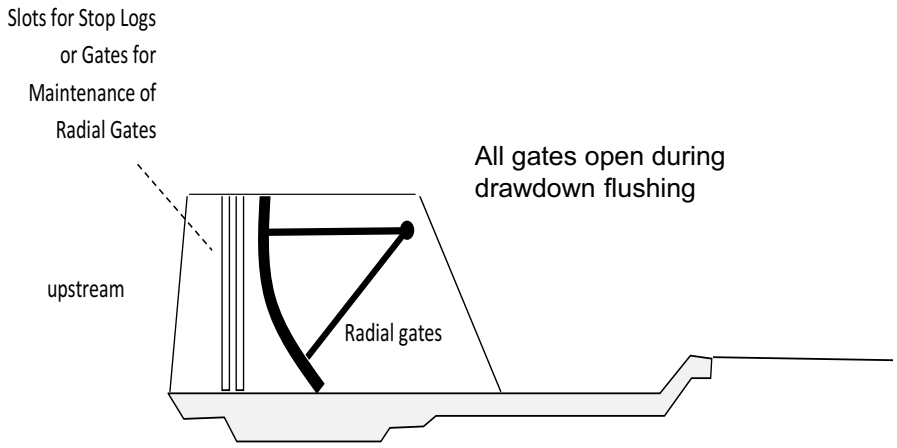

Figure 18 Schematic of Radial Gate Arrangement for Alternative-2

Table 5 contains essential reservoir data (Meynell, 2011 and NHI Database) used in the RESCON analysis.

Table 6 Reservoir Information of Alternate-2 Sambor Dam

Item	Units	Value	Remarks
Total reservoir volume	mill m^3	1,041	Assumed 20% of the base case
Bottom width of the dam	m	2,000	
Top level of the reservoir	masl	24.0	
Minimum bed level	masl	12.0	
Available head	m	12.0	
Reservoir length	m	18,626	Using river slope from base case
Mean inflow	m^3/s	13,800	
Mean annual sediment inflow	tons/year	81,000,000	

3.3.2 Results

Table 6 contains the essential results of the RESCON analysis, i.e., the LTCR and SBR values. The results illustrate that drawdown flushing will likely be successful in removing deposited sediment from the reservoir. The other sediment management alternatives such as dredging, HSRS, dry excavation, and the inline sediment collector system are not feasible for this option due to the large reservoir size.

Table 7 Sambor Alternative-2: Flushing Feasibility

Flushing flow	LTCR		SBR	
	Result	Criterion	Result	Criterion
Average flow (13,800 m^3/s)	0.71	>0.35	9.64	>1.0
1.5 times average flow	0.86		16.33	
2 times average flow	0.94		24.62	

3.4 SAMBOR Alternative-3

The site for Alternative-3 is located just upstream of the proposed dam site (**Error! Reference source not found.**). The maximum water level at the reservoir is 35 masl. The dam may be constructed on the main river channel and the secondary channels on the east side of the main channel would be designed as bypass channels (**Error! Reference source not found.** and **Error! Reference source not found.**). The objective with the bypass channels is to transport the majority of the monsoon flows around the reservoir. These monsoon flows are in excess of the amounts of flow used for power generation. The dam length is approximately 3.0 km and the dam height[c] about 15 m. With a design discharge of 17,640 m^3/s the power plant capacity would be 1,703 MW, producing 7,691 GWh of energy annually. The energy

[c] Following a similar approach as for Alternate-2, most of the dam is proposed to consist of radial gates, up to 15m high, which are opened during flushing for "almost complete removal" of the dam during such operations.

calculation is based on the same number of operating hours (4,515 hours) as the base case (i.e., the proposed project). The arrangement of structures facilitating bypassing is illustrated on **Error! Reference source not found.** through **Error! Reference source not found.**.

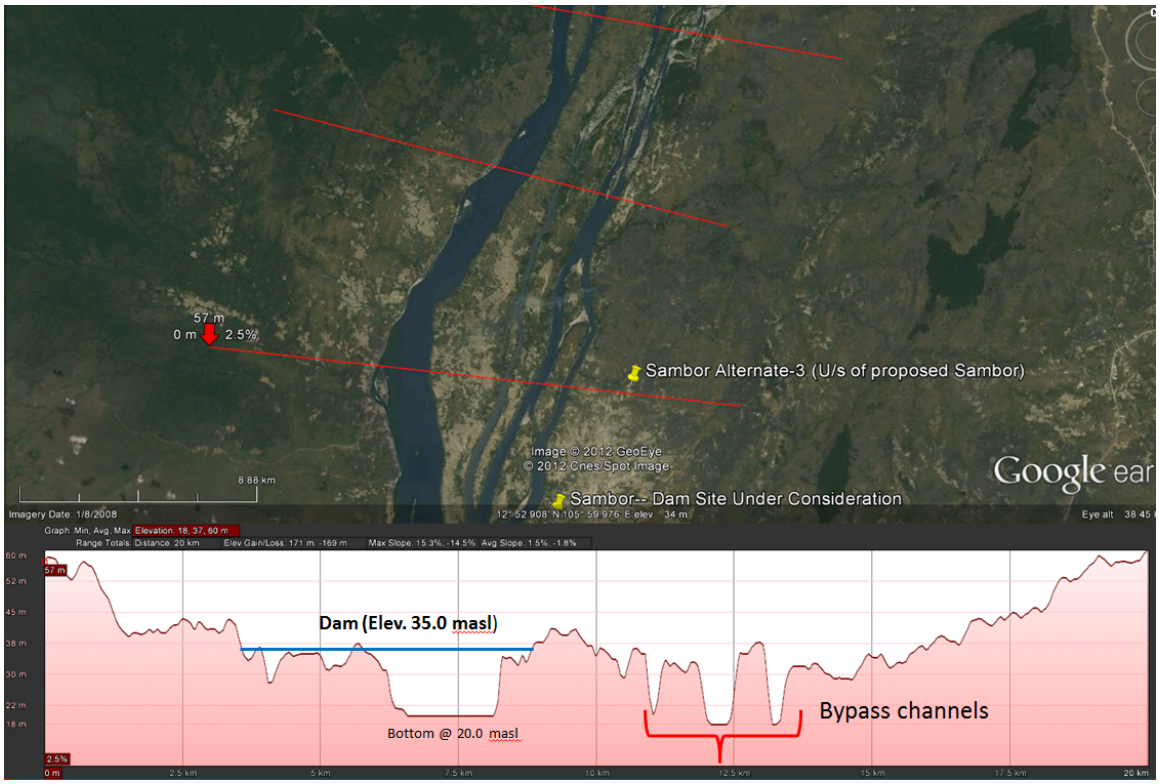

Figure 19 Sambor Dam Alternative-3: Dam Axis

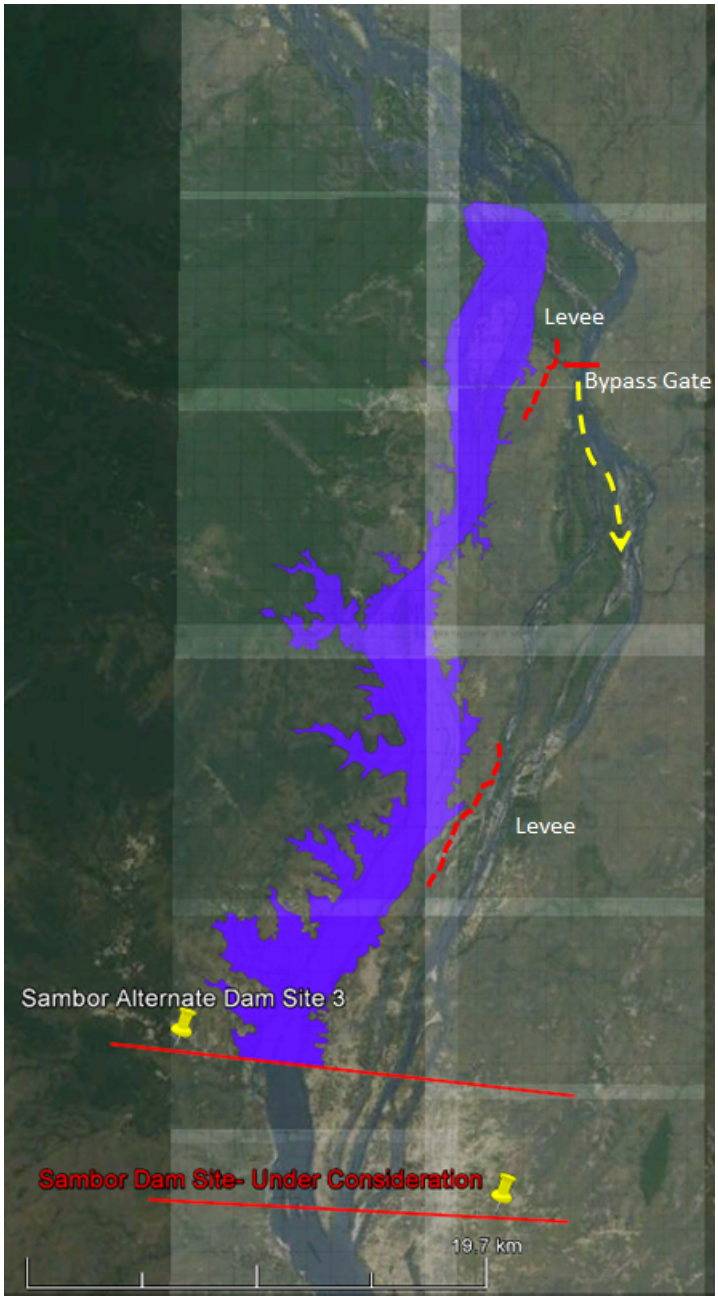

Figure 20 Sambor Dam Alternative-3: Reservoir and Bypass Channel

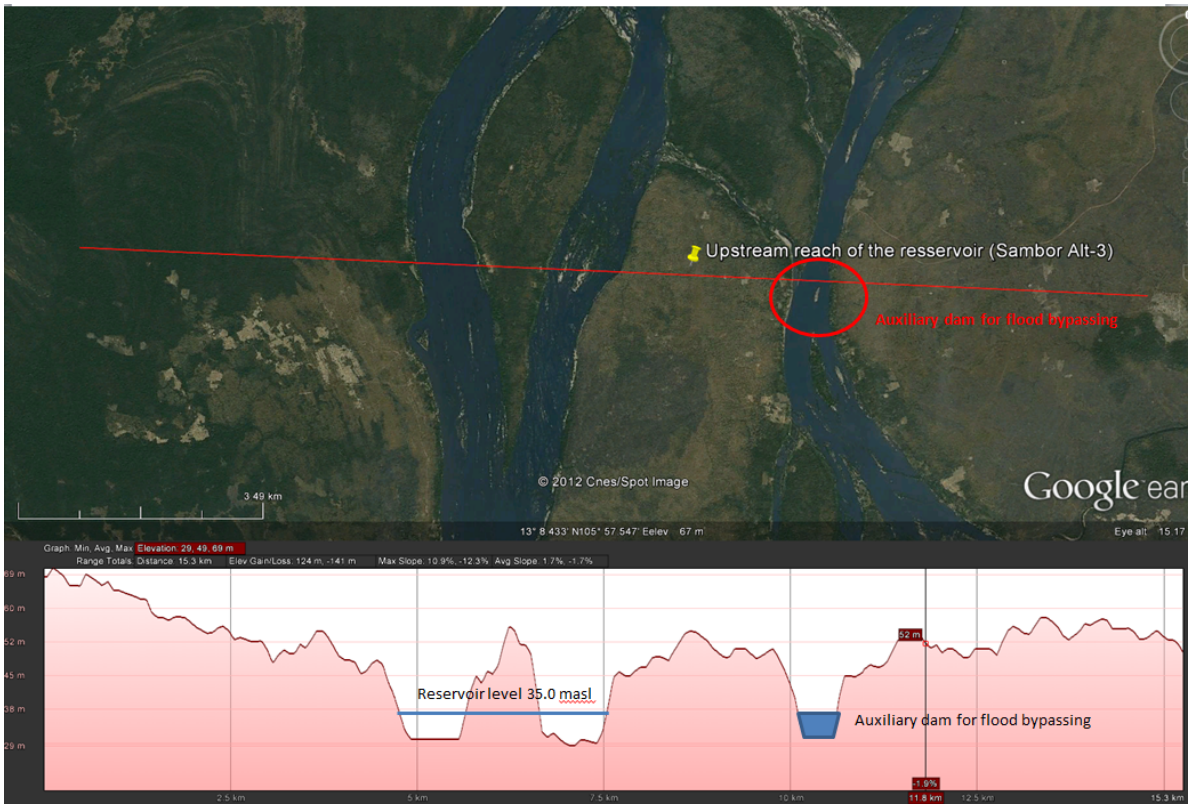

Figure 21 Sambor Dam Alternative-3: Dam at Bypass Channel

3.4.1 Sediment Management Assessment

The goal is to bypass flows which exceed twice the average flow (i.e., > 27,600 m^3/s), which corresponds to monsoonal flows. Flows exceed 27,600 m^3/s approximately 13% of the time in any year. **Error! Reference source not found.** shows an approximate hydrograph of the Mekong River at Sambor. Approximately 28% of the total sediment load will be bypassed through such an arrangement, never entering the reservoir.

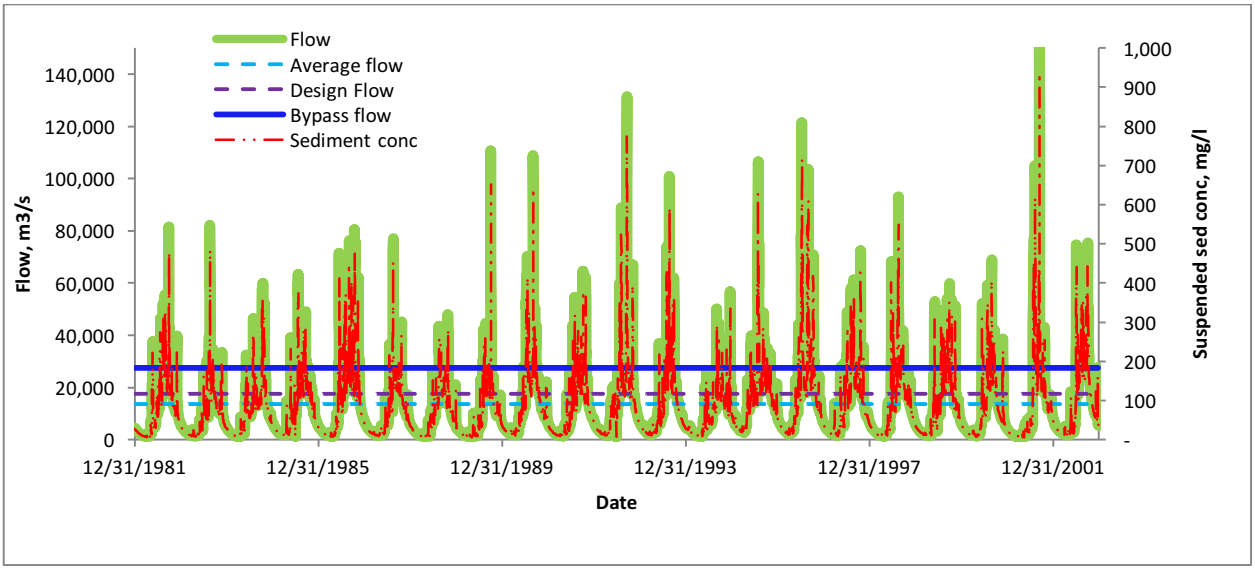

Figure 22 Flow and Sediment Graph of Mekong River at Sambor Dam

The assumed key features (Meynell, 2011 and NHI Database) of the dam are given in the table below:

Table 8 Reservoir Features of Sambor Alternative-3

Item	Units	Value
Reservoir capacity	mill m^3	2,039
Bottom width of the dam	m	1,000
Top level of the reservoir	masl	35.0
Minimum bed level	masl	20.0
Available head	m	15.0
Reservoir length	m	32,387
Mean inflow	m^3/s	13,800
Mean annual sediment inflow (after removal through bypass)	tons/year	58,398,405

3.4.2 Results

Based on the RESCON analysis the flushing feasibility for Alternative-3 is presented in Table 8.

Table 9 Sambor Alternative-3: Flushing Feasibility

Flushing flow	LTCR		SBR	
	Result	Criterion	Result	Criterion
Average flow (13,800 m^3/s)	0.88	>0.35	2.42	>1.0
1.5 times average flow	0.88		4.62	
2 times average flow	0.88		7.32	

With high LTCR and SBR, flushing is considered feasible for this option. In addition, bypassing sediment through the secondary channels, located on the left side of the main channel, improves the feasibility of passing most of the sediment for this option.

The other sediment management alternatives such as dredging, HSRS, dry excavation and the inline sediment collector system are not feasible for this option due to the large reservoir size.

3.5 Conclusions

In summary, the main features of the proposed Sambor Dam and its alternatives are given in Table 9. Table 9 illustrates that the alternative providing the greatest opportunity for passing sediment to the downstream river reaches is Alternative-3. Alternative-3 has two methods for managing the sediment. It has the ability to remove most of the sediment that may deposit in the reservoir via drawdown flushing. Additionally, about 28% of the annual sediment load will never enter the reservoir because of the bypass channel. This means that, in the long term in the case of Alternate-3, only about 12% of the reservoir storage is estimated to be lost to reservoir sedimentation. If the amount of sediment released through bypassing and drawdown flushing of the reservoir are combined it is found that about 95% of all sediment entering the project reach from upstream is passed downstream in the long term when using the mean annual discharge for drawdown flushing.

Table 10 Main Features of Proposed Sambor Dam and the Sambor Dam Alternatives

Dam	Proposed Sambor Dam	Alternative-1	Alternative-2	Alternative-3
Catchment area, km^2	643,400	643,400	643,400	643,400
Mean annual flow, m^3/s	13,800	13,800	13,800	13,800
Dam height, m	53.0	23.0	17.0	20.0
Dam length, m	18,002	6,300	3,860	2,920
Full supply level, masl	40.0	30.0	24.0	35.0
Minimum operating level, masl	39.0	29.0	23.0	34.0
Tailwater level, masl	15.0	12.0	12.0	20.0
Assumed bottom elev. of dam, masl	17.0	12.0	12.0	20.0
Total Reservoir Volume, mill m^3	5,206	2,702	1,041	2,039
Reservoir length, m	35,700	27,939	18,626	32,387
Bottom width of reservoir, m	5,000	2,000	2,000	1,000
Design head, m	22.9	18.0	12.0	15.0
Design flow (m^3/s)	17,640	17,640	17,640	17,640
Installed capacity, MW	2,600	2,000	1,363	1,703
Energy production, GWh	11,740	9,229	6,153	7,691
Date of Commissioning	--	--	--	--
Net sediment inflow, tons/yr	81,000,000	81,000,000	81,000,000	58,398,405[d]

[d] This is 72% of the total sediment load; the balance will be bypassed.

Dam	Proposed Sambor Dam	Alternative-1	Alternative-2	Alternative-3
Trap efficiency (%)	50%	45%	32%	45%[e]
Flushing discharge (m^3/s)	13,800 to 27,600	13,800 to 27,600	13,800 to 27,600	13,800 to 27,600
LTCR (criterion: >0.35)	0.13 – 0.19	0.68 – 0.91	0.71 – 0.94	0.88
SBR (criterion: > 1.0)	1.8 – 4.4	2.0 – 4.8	9.6– 24.6	2.4 –7.3

[e] This is likely an overestimate of trap efficiency because significant amounts of sediment will be bypassed during the monsoon season through the secondary channels to the left of the dam and reservoir, which was not accounted for in the trap efficiency calculation.

4.0 REFERENCES

Atkinson, E. 1996. *The Feasibility of Flushing Sediment from Reservoirs*, TDR Project R5839, Rep. OD 137. HR Wallingford.

Brune, G.M., 1953. Trap Efficiency of Reservoirs. Trans. of American Geophysical Union 34(3), 407-418.

Hotchkiss, R. H., and Xi, H. 1995. *Hydrosuction Sediment Removal System (HSRS): Principals and Field Test.* J. of Hydr. Res. Pp 479-489.

Hydropower Database (http://www.3sbasin.org/3SsDB/DB_HY/index.php?table_name=hydropower) (Assessed in September/October 201)

ICEM, 2009. MRC Sea for Hydropower on the Mekong River Mainstream, Volume I- Inception Report. International Center for Environmental Management.

Meynell, Peter-John, 2011. Mainstream Hydropower Dams in Cambodia and their Environmental Impacts (Report for IFREDI)

Morris, G.L., and Fan, J. 1998. Reservoir Sedimentation Handbook, McGraw-Hill Book Co., New York.

NHI, Natural Heritage Institute Database.

Palmeiri, A., Shah F., Annandale, G. W., and Dinar, A. 2003. Reservoir Conservation, Volume I. The RESCON Approach. World Bank.

SWECO Groner, NIVA, ENVIRO-DEV, and ENS Consult. 2006. Electricity of Vietnam, Environmental Impact Assessment on the Cambodian Side of the Sre Pok River due to Hydropower Development in Vietnam. Final Report (E-mail Version)