HYDROLOGY & SEDIMENT THEME

SEA Mekong River Mainstream Hydropower Development

Theme: 1. Hydrology

Issue: 1.1 Stream Power
Issue: 1.2 Water surface level changes

Theme: 2. Sediment

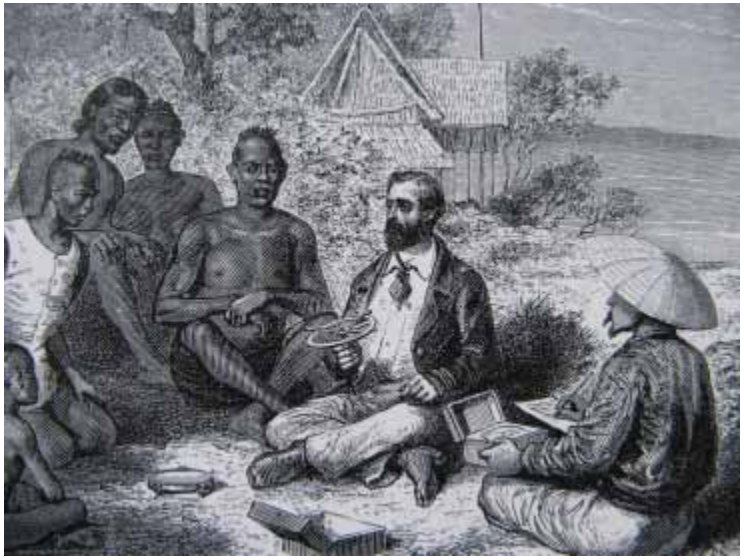
Issue: 2.1 Coarse sized sediment transport/availability
Issue: 2.2 Fine sized sediment transport/availability

STREAM POWER: concept & overview

Streampower (measured in units of MW/km or kW/m^2) is the **rate at which energy is lost in moving over the bed of the river, and lost to turbulent flow dissipation**. The power dissipation along the Mekong river in Laos is about 5 to 20 MW per km distance (depending on flow rate m^3/s and on the average channel gradient).

Streampower dissipation per unit distance

= specific weight of water x 9.8 x river discharge x water surface slope
= 1000 x 9.8 x Q x slope kwatts/km



Francis Garnier, mapping the river in southern Laos, 1866.

STREAM POWER: Energy dissipation

Water power is being rapidly dissipated as the mainstream river flows over a bed rock outcrop, upstream of Luang Prabang

Energy dissipation immediately downstream of a major irrigation intake downstream of Phnom Penh. The water surface drops about 0.5m because of power dissipation as the flow enters the canal

Photo credits: Peter Ward January 2008 Peter Ward September 2002

STREAM POWER: Energy dissipation

Power being dissipated, as water flows through a bridge opening allowing water onto the Cambodian floodplain

Streampower that is presently dissipated at the bed of the river, may be accumulated at the proposed Pak Beng damsite, and used for electrical energy production.

STREAM POWER: trends without mainstream dams

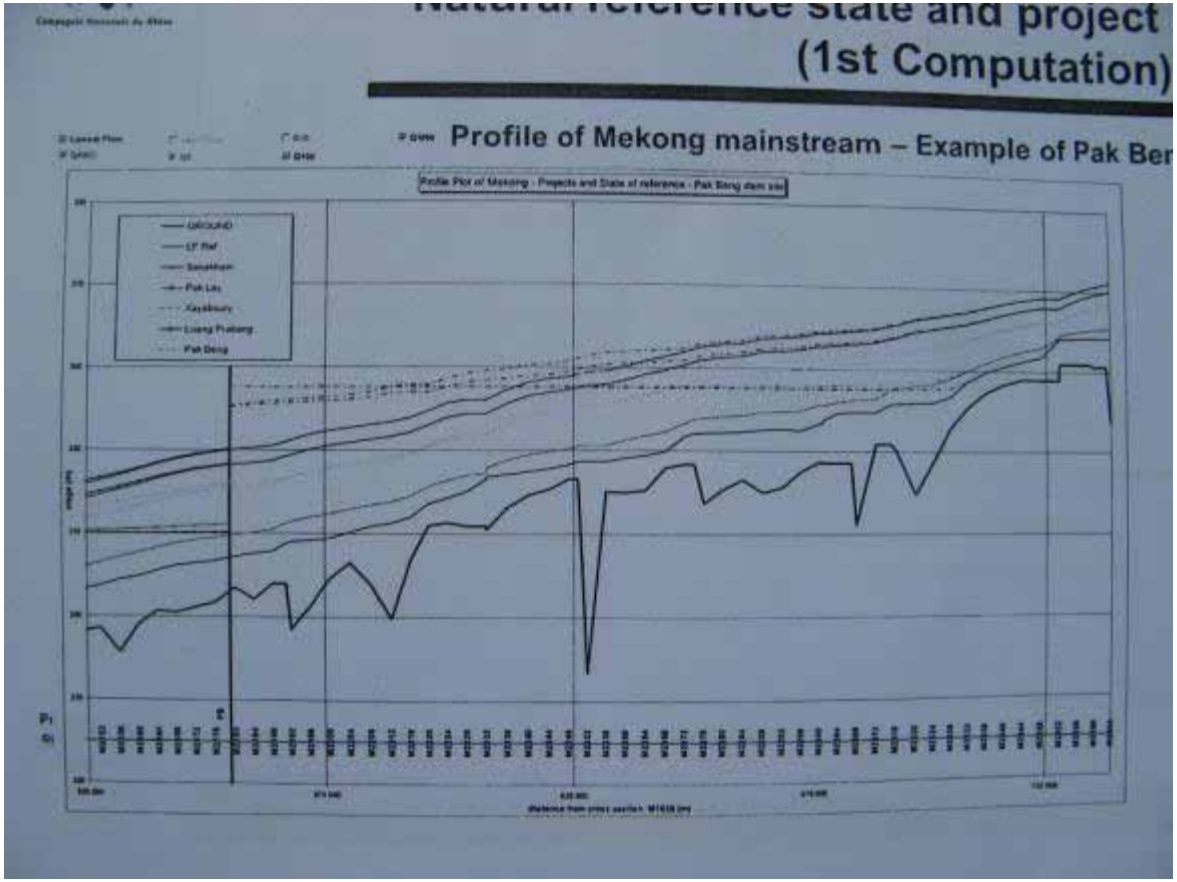
The 20 year scenario without the mainstream dams is for the **peak streampower (realised during flood events) to shift downwards** because of upstream proposed dams/reservoirs with large storage.

The peak streampower is the main factor influencing the transport of coarse sediment, and erosion/deposition processes along the river channel.

Increased peak flows associated with *climate change* will partially or fully offset this projected reduction in peak streampower.

STREAM POWER: with mainstream dams

With mainstream dams: Proposed reservoirs will cause a major and irreversible shift in the way stream power is dissipated in the river.



e.g. Pak Beng proposed dam. Note the flat water surface on the reservoir at low flows, and the much reduced gradient (factor of 2.5 times reduction) at very high flows.

Streampower dissipation per km is reduced accordingly.

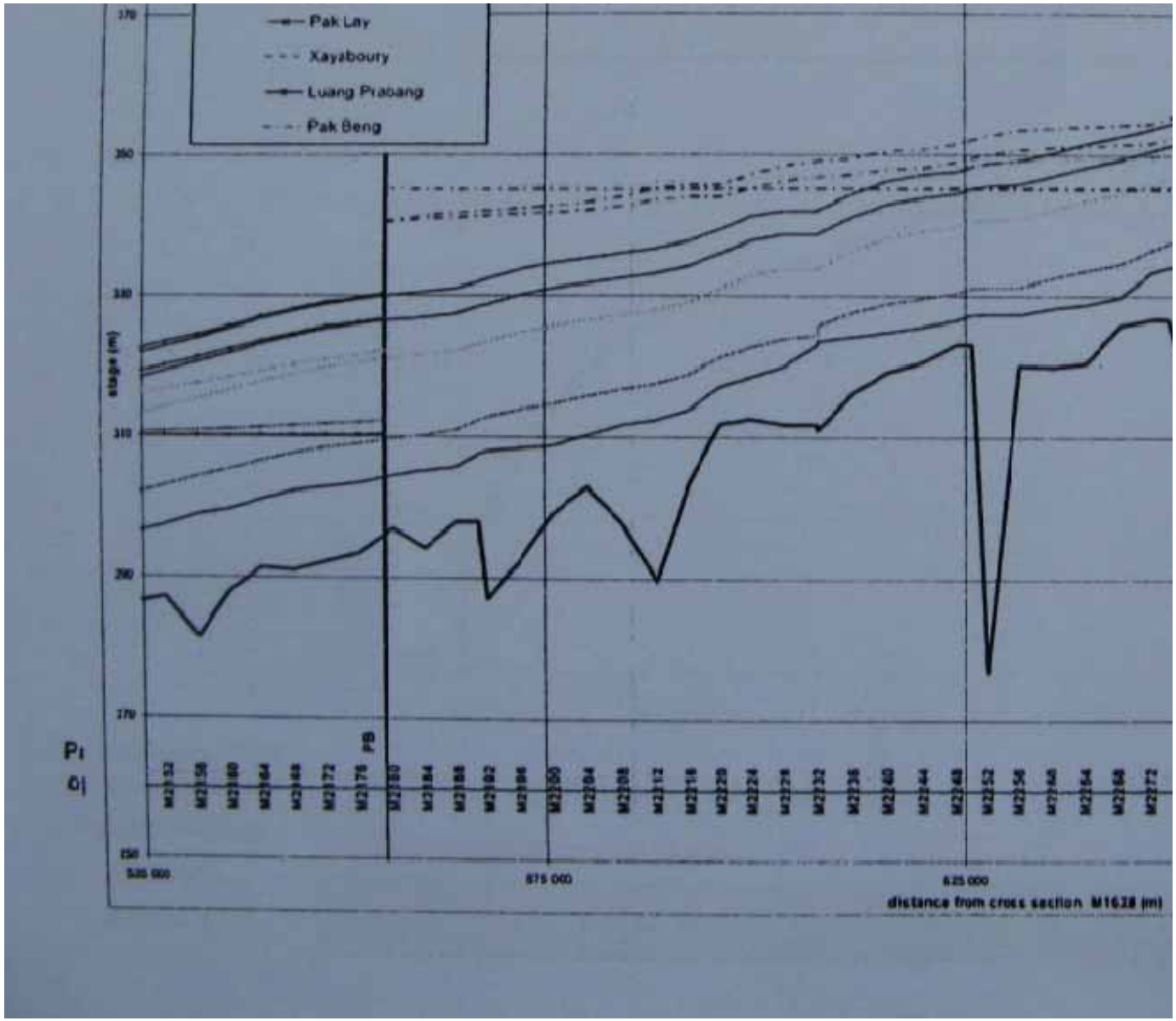
CNR Optimisation Study of the Mekong Mainstream ROR Hydropower 2009

STREAM POWER: with mainstream dams

Pak Beng proposed reservoir:

The original elevation Was 345 m for reservoir, about 15 m above record flood stage

Base on the optimization study this was revised by Lao Dept. of Electricity to 340 masl to avoid flooding in KengPhaDai
=> Reservoir is ~5-10m above highest flood recorded to date (about 80 years)



STREAM POWER: with mainstream dams

The length of river affected if all proposed reservoirs are developed is about 66 % of the total 1,760 km river distance from the Sambor damsite to the upper end of Pak Beng reservoir.

Stream power will be released at the turbines, in the tailraces, and (during wet season spillage) at the dam spillways. Water power releases localized and concentrated: no resemblance to the present and future trend of the Mekong river flow.

Implications as follows:
1. Major changes to sediment transport of most sizes (see Theme Sediment Transport)
2. Major changes in transport of organic and woody debris
3. Significant and irreversible changes in fisheries migration and passage
4. Risk factors for anthropogenic uses of the river, such as possible detriments to navigation and detriments to fishing opportunities.

WATER SURFACE LEVEL CHANGES

	
Irrigation intake upstream of Luang Prabang. The maximum height of the structure is set to be higher than the highest floods, and the bottom of the tower is set on bedrock, at a location that does not accumulate sand.	Government water level gauge at Kratie. The slope gauge is set at an angle, built in to the side of the concrete steps. Seasonal water level fluctuations for the Mekong mainstream are 15 to 20 m at this location.

Photo credit: Peter Ward 2008 Peter Ward 2003

WATER SURFACE LEVEL CHANGES: without LMB mainstream hydropower

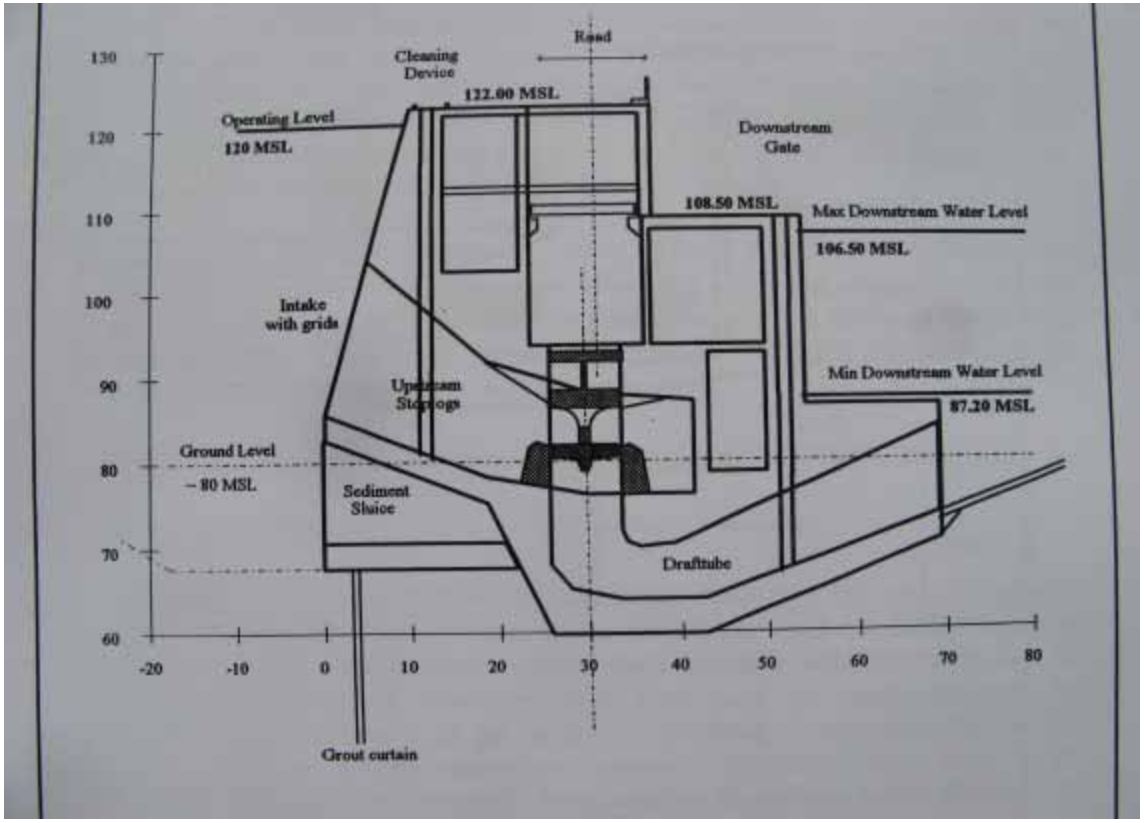
1. Rate of change of water surface level is important. In the natural river system, typical values are approximately 0.2 to 0.5 m/day.

2. *Extremities of water levels* are important, and drive the aquatic ecology system. The present trend (with 20 year scenario) is for a reduction in the hydrograph maxima, and an increase in the hydrograph minima, associated with water storage in large capacity reservoirs.

For large off-channel storage systems (e.g. Tonle Sap system), the seasonal fluctuations in level will be smaller than baseline under the 20 year scenario, driven largely by the increase in low flows/water levels that are predicted.

WATER SURFACE LEVEL CHANGES: with LMB mainstream hydropower

For the 20 year scenario **with proposed mainstream dams**, bear in mind the very large nature of the hydraulic equipment. *The size of the turbines is very much larger than units of the same power capacity for medium/high heads.*



Flow with all turbines operating is typically about 4000 m3/s, and minimum flow is typically about 1000 m3/s. *Sudden opening of spillway gates will produce flows, of up to 30,000 to 50,000 m3/s*

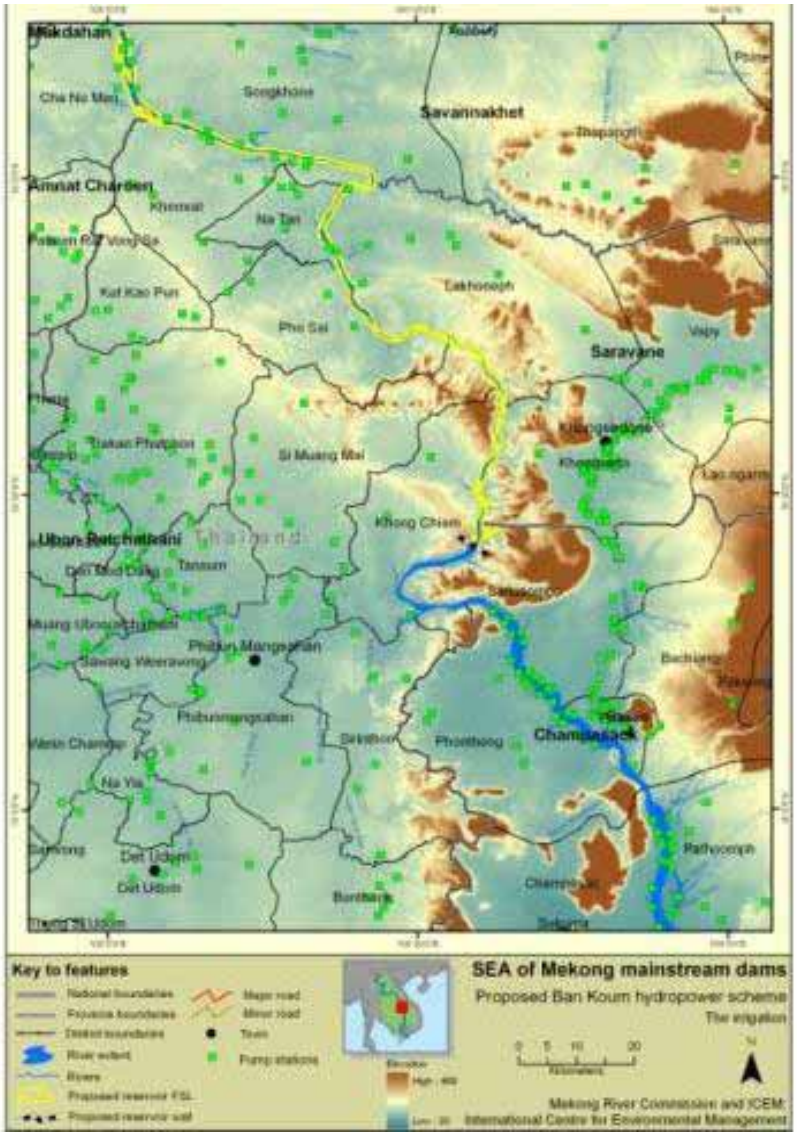
Capable of producing huge fluctuations in river flow downstream

WATER SURFACE LEVEL CHANGES: with LMB mainstream hydropower

The main additional effects from the proposed mainstream dams on water surface levels can include:

1. Flooding at elevations grater than recorded in history (typically within 10 km or more of the proposed dam sites)
2. Rapid and extreme water surface fluctuations associated if operated for **hourly peaking** to meet short term electricity demand
3. Large and unforeseen flows possible, in event of mechanical breakdowns at the dams, and/or urgent need to lower reservoir surface levels at short notice
4. Loss of cultivable land on the river bank, subject to seasonal inundation and drying
5. Damage to infrastructure at the river bank, e.g irrigation intakes, boat docks

WATER SURFACE LEVEL CHANGES: impacts on irrigation



700 existing and proposed pump stations, About half (309) will be affected by the mainstream reservoirs

Inside reservoirs

- Will have lower potential pumping heads (lower cost)
- Need to be removed to higher locations to remain operable
- And potentially need to be resized for lower pumping head in order to take advantage of reduced cost

Downstream of reservoirs

- new flow regime imposed by the mainstream projects will induce migration of the river thalweg and would require pump relocation
- Potential for daily fluctuation in the order of meters

Complexity of pump operations could increase depending on power generation strategy

Ban Koum: *16 pumping projects are located in the reservoir, and 26 within 100km downstream which service a total of 9,825ha of irrigated area*

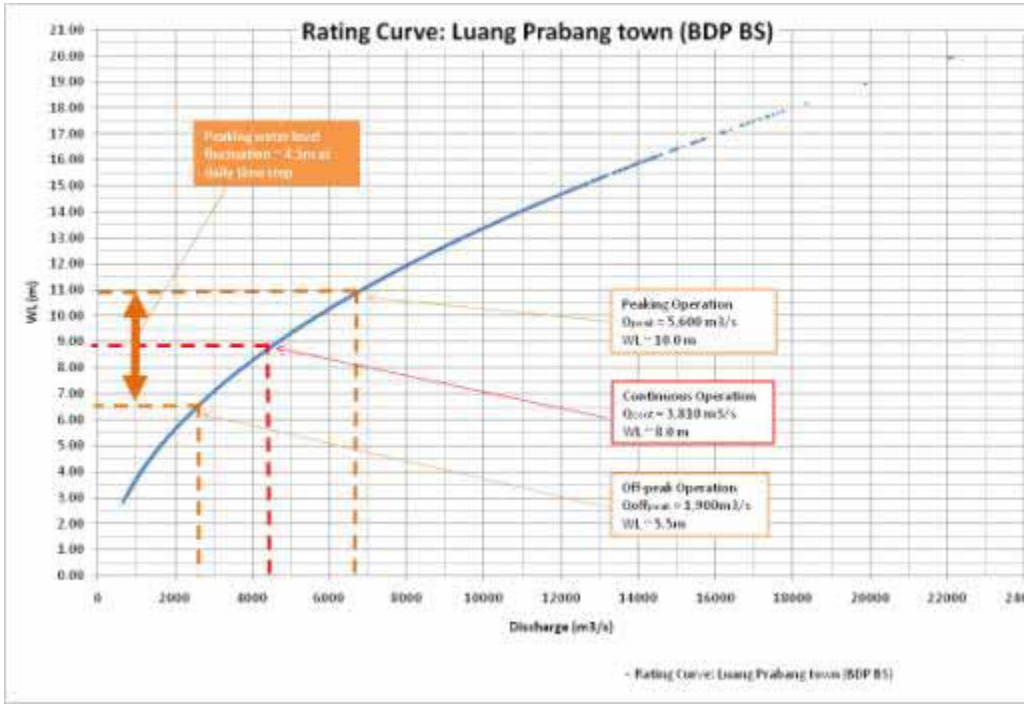
WATER SURFACE LEVEL CHANGES: impacts on rapid changes in downstream water levels

Rapid fluctuations of river flows and levels will arise, because the time needed to open and close turbines is small, order of 10 minutes or less.

Water surface fluctuations of **4 to 5 m** are possible at Luang Prabang, associated with changing the turbine flow rate from minimum to maximum if not controlled by operating rules. Opening and closing turbines may arise from a variety of planned and unplanned circumstances, and breakdowns of plant and electrical transmission systems.

Example: *The time elapse for a rapid fluctuation from opening the turbines at the proposed Luang Prabang damsite, will be about 1 to 1 ½ hours to the city of Luang Prabang, very little warning time for bank-side residents to prepare for inundation.*

Guidelines for ramping rates will have to be developed and enforced as indicated in the MRC Preliminary Design Guidance.



WATER SURFACE LEVEL CHANGES: impacts on rapid changes in downstream water levels

Rapid fluctuations of river flows and levels will arise, because the time needed to open and close turbines is small, order of 10 minutes or less.

Re-regulation dams downstream of the proposed projects are not feasible for removing daily flow fluctuations, because of the very large flows/volumes involved for storage and release.

Cities such as Luang Prabang are almost certainly vulnerable to rapid flow changes from upstream dams.

The delta part of the river in Vietnam may not be subject to fluctuations from hourly peaking at the proposed Sambor site (if operated for peaking), because of the large transit time for flow changes to be transmitted to the delta. For this reason, salinity changes in the delta associated with hourly peaking may not arise.

WATER SURFACE LEVEL CHANGES: implications of failure and human error

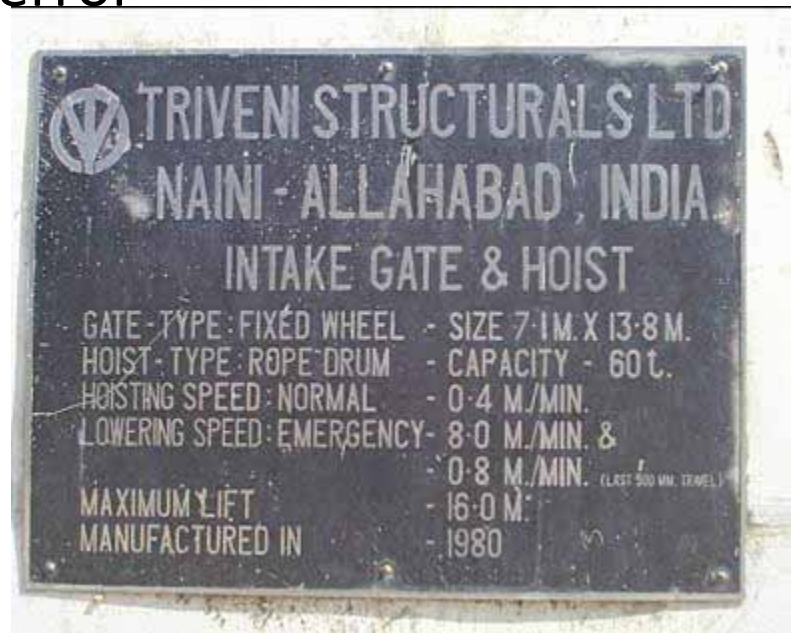
Further unprecedented fluctuations in flow/level may arise from break-downs, malfunctioning or operator error in controlling the spillway gates.

With a failure of the primary and back-up facilities to raise the spillway gates during the onset of the flood season, there is a significant risk of dam overtopping, and serious damage to the dam and the mechanical/electrical equipment. In the worst case the dam abutments may be eroded.

The best case scenario is that catastrophic releases of this type will not occur.

A concerted effort will be needed for the establishment /enforcement and execution of a program of comprehensive dam safety management reviews and monitoring as indicated in the MRC Preliminary Design Guidance.

WATER SURFACE LEVEL CHANGES: implications of failure and human error



Work needed in future:
comprehensive dam safety review,
photos from Srinigarind dam, Thailand

Photo credit *Peter Ward*

WATER SURFACE LEVEL CHANGES: implications of failure and human error

Proposals for Sambor dam are for 30 to 40 spillway gates of dimensions 18 m x 20 m each, with extremely large total release capacity, greater than any historically recorded flood.

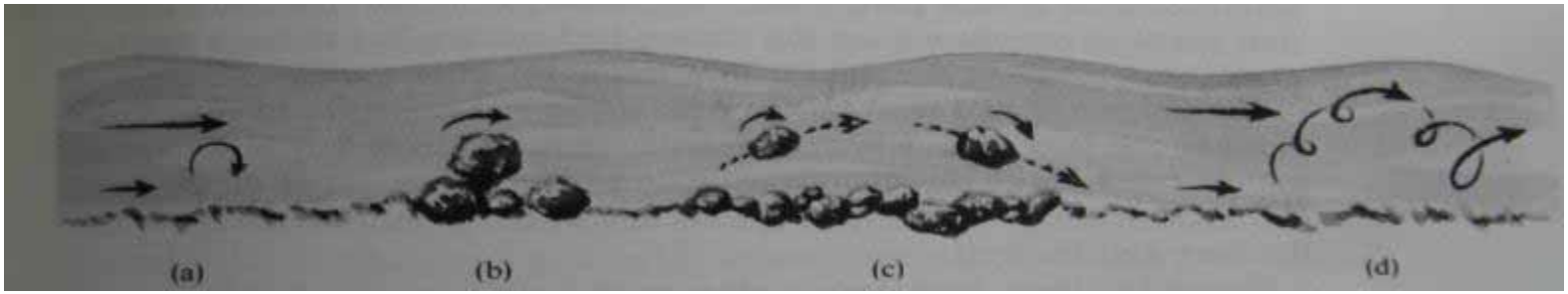
Serious and significant management implications for the safe operation of these gates, and of the sluicing gates.

Major and urgent need for internationally agreed guidelines to be in place, to avoid catastrophic, and unforecast flood releases.

Should such major and important management decisions be in the hands of a private power producer?

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: concept

Coarse sized sediment e.g. coarse sand, gravel and larger sizes, conveyed in the Mekong River mainstream as bed load, and moves downstream annually by distances of a few tens of meters to a few kilometers. Prior to the closure of Manwan dam (1992), there were no anthropogenic obstacles to the transport of bed load in the mainstream.



Action of water on particles near the stream bed, rolling and saltating grains from Dunne and Leopold 1978. Streampower is fed from the moving water to the bed, and supplies energy to move coarse particles.

Dunne T., and L.B. Leopold 1978. Sediment production and transport. Chapter 17 of *Water in Environmental Planning*. W.H. Freeman and Company. 818 pp.

Settling Velocity and Particle Size

Class name	Diameter, mm	Approx settling velocity, mm/s	
Very coarse sand	1 to 2	150	
Coarse sand	0.5 to 1	80	
Medium sand	0.25 to 0.5	38	
Fine sand	0.125 to 0.25	18	
Very fine sand	0.062 to 0.125	8	From Stokes Equ
Coarse silt	0.031 to 0.062	1.9	From Stokes Equ
Medium silt	0.016 to 0.031	0.5	From Stokes Equ
Fine silt	0.008 to 0.016	0.13	From Stokes Equ
Very fine silt	0.004 to 0.008	0.032	From Stokes Equ
Coarse clay	0.002 to 0.004	0.008	From Stokes Equ
Medium clay	0.001 to 0.002	0.002	From Stokes Equ

COARSE SIZED SEDIMENT : mechanisms of transport

Whether sediment moves slowly as bed load, or is thrown into suspension and moves quickly downstream, may be roughly determined from the water velocity.

A useful rough guideline for determining if sediment will move as bed load is:

Find the settling velocity of the sediment and compute the Rouse number P as follows:

Rouse number $P = v_s / (0.40\, u_*)$

where the shear velocity $u_* =$ *approximately u/20 and*

v_s *is the settling velocity of the sediment*

$2.5 > P < 7.5$ implies movement of the sediment as bed-load.

COARSE SIZED SEDIMENT : mechanisms of transport

Coarse sized sediment transport example:

For conditions **where the mean velocity is 2 m/s**

$2.5 < P < 7.5$ implies $100 \text{ mm/s} < v_s < 300 \text{ mm/s}$

Meaning very coarse sand/ fine gravel move as bed-load

In reaches where the velocity is lowered (e.g. from a downstream bed rock sill) the sand deposits, and over a period of time raises the river bed and changes the velocity conditions, until a new equilibrium is produced.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: Zone 2

Zone 2: Higher gradient, higher velocity reaches. Many bedrock sills, river surface at high flows smoothes its way over these, moving very coarse sand bedload and creating pockets of *very coarse sand, mixed with finer material.*

Pak Beng: Very coarse and coarse sized sand, transported downstream as bed load in peak flow events.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: Zone 3

Zone 3: River impacted by bedrock at Khammarat, near the far south end of the zone, causing a lower gradient (S approx 0.5 x 10^{-4}), lower velocity situation for the majority of the Zone 3 river distance. Sediment in this zone moving as bed load is *coarse sand size, with some medium sized sand.*

Situation persists for a very long distance (about 550 km) from upstream of Vientiane to Khammarat.

We arrived at KengKanien, the last great rapids before Khammarat. The phenomenon of the great whirlpools presented itself in the most remarkable way. Amidst the plumes of foam and waves whirlpools several meters wide and deep are formed, and after 2 to 3 minutes disappear, only to form again soon. From KengKanien to Khammarat the bed of the river is shrewn with thousands of rocks of all shapes and sizes. The men were continually in the water and hardly ever stopped pushing, lifting or carrying the barge. Upstream the rocks slowly thinned out and the current greatly slowed down, until the Mekong, again a superb river, ran full to the edges in its vast bed.

Quote from Francis Garnier "Travels in Cambodia and Part of Laos": The Mekong Expedition Report (1866-1868) Volume 1, p 202. White Lotus Press 1996.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: without LMB mainstream hydropower

Reduction in the transport of coarse sized (and other sized sediment) in the river downstream of the China border, from blockage of transport caused by Manwan, Jinghong and Mansong dams.

Further reduction from completion of an additional two dams in China downstream of Jinghong.

For the downstream river, reductions in the transport of medium sized sediment is felt first, as this is rapidly depleted from storage on the bed and banks of the river. The sedimentary nature of the river bed coarsens in response.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

- Expected localisation in stream power dissipation for the majority of the 1760 km distance from Pakbeng backwater to Sambor, there will be much reduced water power available to suspend particles and keep them moving.

- The result of this will be enhanced sedimentation, with the formation of deltaic type deposits at the head of each of the reservoirs

- Middle and lower parts of each reservoir will sediment during flood events, associated with reduced velocities/gradients

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

- Highly likely risks that coarse sized sediment, e.g. medium sand, coarse sand, and gravel will accumulate in parts of the river where it has never accumulated in the past, for example in the *headwater reaches* of the ten proposed reservoirs.

- Other submerged areas of the proposed reservoirs, not subject to scour associated with opening of the spillway gates, will also accumulate sediment.

- Amount of accumulation will depend on the sequencing of the construction of the proposed cascade, and on the contribution from immediately upstream tributaries.

Note that upstream scour/sediment removal associated with opening gates is localised. It will not be possible to remove sediment from much of the reservoir bottom.

The main effect of the operation of the sediment gates and spillway gates will be to assist in keeping clear *the area immediately upstream* of the turbine intakes.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Velocity that will apply to flood flow (e.g mean annual flood) through a typical reservoir (with the spillway gates open) about *one-half* of the velocity for the same discharge in the absence of the reservoir.

Luang Prabang site example, mean velocity during a 2 year return period flood event with the dam in place will be approximately 1 to 1.2 m/s, compared with approximately 2 to 2.5 m/s for the 20 year scenario without the mainstream dams.

Implications:

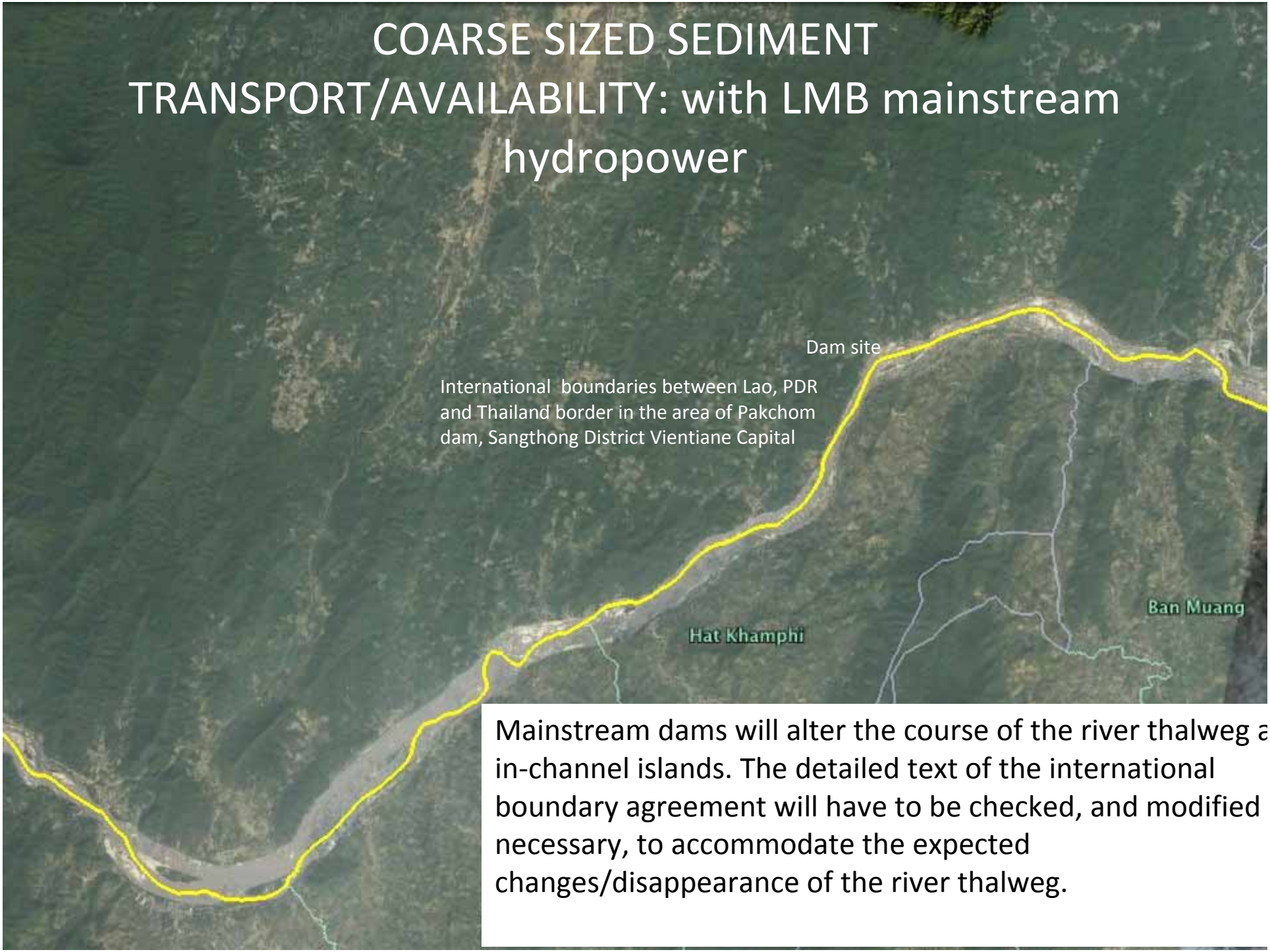
1.Medium sand sizes which move totally in suspension w/o the project will move partly as bed load and partly in suspension. Will get stuck/delayed at the reservoirs.

2.Coarse sand, which moves partly in suspension and partly as bed load w/o the project, will move only as bed load. Will get stuck at the reservoirs.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

For the low gradient alluvial reach (Zone 3) from upstream of Vientiane to near Khemmarat there will be a trend towards downcutting of the river bed, with destablisation of banks.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower



Mainstream dams will alter the course of the river thalweg a in-channel islands. The detailed text of the international boundary agreement will have to be checked, and modified necessary, to accommodate the expected changes/disappearance of the river thalweg.

COARSE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Mitigation of bank erosion problems: rip-rapped embankments, but the cost per km is very high, and requires the proximity of a nearby rock quarry.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY

Fine particles moving in suspension in the Mekong mainstream (nearfield), contrasted with relative absence of fine particles in flow entering from Nam Ou (farfield), low flow season, January 2008

Flood flow season: Fine particles moving in suspension across the Cambodian floodplain during high water event, September 2002.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: context

The load of suspended (fine sized) particles has been measured at several stations on the Mekong mainstream since the 1960s. The measured load at the lowest downstream sediment station (Kratie) is about 165 million tonnes per year. Downstream of Kratie the gradient becomes small, and the the load is primarily fine sand, silt and clay sized material. Larger sizes are transported minimally.

Historic total sediment load in a similar sized river (Mississippi) was about 400 million tonnes, a century ago. Recent Mississippi values (last 20 years) have been about 36% of historic load values.

Meade, R.H., and J.A. Moody 2009. *Causes for the decline of suspended sediment discharge in the Mississippi River system, 1940 -2007*. Hydrology Processes, vol 24, pp 35-49.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY

Significant proportion of the Mekong load (165Mt/yr) is removed naturally from the river upstream of the delta, in the Tonle Sap system (4-7%), and in the Cambodian and Vietnamese floodplains (8-20%).

Maximum transport of fine particle load is in the reach downstream of the Stung Treng, to about Kampong Cham.

Suspended sediment flow at Phnom Penh, 2nd Sept 2002. Delta is towards top of photo.

Transport southwards (Mekong main channel, left), and northwards (Tonle Sap channel, right). Tonle Sap channel is carrying about 25% of sediment compared with main channel transport.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: without LMB mainstream hydropower

- The present trend is for significant reductions in the transport of fine and coarser sized material, because of the operation of reservoirs with large storage, in China, and on major LMB tributaries.

- Estimates based on trapping efficiency of the presently existing and 20 year scenario reservoirs are that 80% of the sediment load of the river will be removed.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Loss of sediment supply to the Mekong floodplains

Expected low velocities in the reservoirs for the majority of the time, implies that some of the fine sediment load will be trapped/settle to the bottom and backwater areas of the reservoirs.

e.g. *Luang Prabang reservoir with all turbines running, mean velocity in the reservoir for the final 10 km will be approximately 0.25 m/s only – insufficient to fully suspend sizes larger than coarse silt.*

Inference is: **Decreases in the concentration of suspended fine material (fine sand and silt particles) in the mainstream channel downstream of the project**

Particularly an issue during the first one to two decades following dam construction.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Decrease in natural nutrient transport to the Mekong floodplains and marine fisheries

The decrease in the fine particle component of the suspended load has vital implications for the transport of nutrients (phosphorus, nitrogen and trace amounts of important minerals) onto the floodplain, and into the Tonle Sap system. Fine particles have much more surface area per unit volume than do coarse particles, and fine particles carry the majority of the nutrients that are needed by living systems.

Natural fertilization from floodwaters that is important to about 18,000 km^2 of the Cambodian floodplain (see Fuji et al): *impacted by reductions in the concentration of suspended fine particles.*

Fujii H., H. Garsdal, P.R.B. Ward et al 2003. Hydrological roles of the Cambodian floodplain of the Mekong River. Intl Journal of River Baisn Management Vol 1, No 3 pp 1-14.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Decrease in natural nutrient transport to the Mekong floodplains and marine/estuarine fisheries

Major impact on the estuarine fishery is expected, because the majority of the fine sediment (about 80% estimated) flows to the final part of the river near the sea. Note that flocculation associated with saline water causes the fine sediment to deposit, in the area where salt water and brackish water is present.

Major reductions in sediment (projected to arise from the mainstream dams) will be felt particularly in this part of the river estuary, and offshore, with expected large impacts on fish habitat/food availability.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Decrease in natural nutrient transport to the Mekong floodplains and marine fisheries

Kootenai River, downstream of Libby Dam, Montana. Post commissioning of dam, river water became much too clear, with massive losses of suspended solids. Huge reduction of fisheries values resulted, partly associated with losses of nutrients that are now trapped behind the dam.

FINE SIZED SEDIMENT TRANSPORT/AVAILABILITY: with LMB mainstream hydropower

Decrease in natural nutrient transport to the Mekong floodplains and marine fisheries

A concerted effort, funded by the dam owner/operator, is underway to try and restore the aquatic food chain, using techniques such as nutrient addition.

SEA Mekong River
Mainstream Hydropower Development

One of the Columbia river treaty dams on the Canadian side of the Canada/US border.

Water stored in this reservoir is released during the low flow season, for beneficial use at power plants further downstream in the United States.