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Effects of Mining and Hydropower on Metals in Surface Waters

Case: Nam Ngum

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Nam Ngum, a river in Lao PDR, is experiencing rapid development of hydropower and mining. Hydropower dams may influence the water quality via sediment trapping and hydrology changes. They also create barriers for migration of aquatic animals. Mining, on the other hand, has potential severely impair water quality in their surroundings.

Nam Ngum River Basin is located north of Vientiane. The watershed contains tropical and sub-tropical areas of distinct dry and wet seasons. The watershed is divided in mountainous Upper Nam Ngum (The area upstream from the dam Nam Ngum 1) and relatively flat Lower Nam Ngum in Vientiane Plains. Mining operations are largely located in the upper part of the watershed, with only a few mines located in the lower part.

Mining operations usually impact surrounding water bodies. Acid Mine Drainage brings water of low pH and high metal content into streams. Runoff from the mining sites has high concentration of suspended solids. Because of the affiliation of metals to adhere to solid particles (instead of being in a soluble form) in the water column, sediment transport becomes a major factor in the distribution of mine related pollution of waters. Polluted sediments get transported into reservoirs where they may leach out into solution in anoxic, low pH conditions.

Where water quality data is available (mostly in the Lower Nam Ngum), no sign of mining related pollution could be traced. The major mining sites are far upstream and beyond several reservoirs that trap contaminants. In the Nam Ngum, mining pollution seems to be therefore concentrated in the area where water quality data is not currently available.

A water quality sampling programme is suggested which addresses the gaps of sampling network in the Nam Ngum. A set of 7 new networks, 10 existing ones and cooperation with mining and hydropower companies would create a monitoring network for efficient management of the water resource for all stakeholders. With recent developments in water quality monitoring and industrial development, Nam Ngum may have the potential to become a benchmark watershed of water resource management in south-east Asia.

Keywords	Mining, hydropower, reservoir, metal pollution, phosphorus

List of Abbreviations

NNRB	Nam Ngum River Basin
IWRM	Integrated Water Resource Management
ANC	Acid Neutralisation Capacity
SS	Suspended Solids
AMD	Acid Mine Drainage
Lao PDR	Lao People's Democratic Republic
NN1-5(R)	Dams and related reservoirs along Nam Ngum
NL1-2(R)	Dams and related reservoirs along Nam Lik
MRC	Mekong River Commission
WQI	Water Quality Index
TSS	Total Suspended Solids
DPO4	Dissolved Phosphate (PO_4^{3-})
PTOT	Total Phosphorus
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
NREI	Natural Resources and Environment Institute
EMSP	Environmental Management Support Program
PBM	Phu Bia Mining
TDS	Total Dissolved Solids
UNN	Upper Nam Ngum
LNN	Lower Nam Ngum
NSD	Nam Song Diversion Dam
ISC	Index of Stream Condition
QHDXH	Qin Huang Dao Xin He Ferrous Mine
PK	Phu Kham gold-copper mine
BH	Ban Houayxay gold-silver mine
FP	First Pacific Mining Ltd.

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1 Introduction

Water, especially fresh water, is one of the key resources in societies everywhere. Its quality and availability determine the potential human uses of that water resource, but it is also a key element in any ecosystem. The Nam Ngum River Basin (NNRB) is a watershed that is experiencing rapid development from a near-pristine state towards an efficiently utilized water resource. Six hydropower dams already operate in the basin with nine more in the construction or planning stages. Five of the six existing dams started operation since 2000. Damming a river potentially changes the hydrological regime downstream, reduces peak flows as well as increases minimum flow and reduces nutrient levels.

NNRB is also experiencing fast development in the mining sector due to its rich unexploited mineral resources. Mining effluents can cause serious damage to aquatic ecosystems and render the water unfit for human or industrial use for long periods of time. The population in large parts of the watershed use the surface water and wells for their water consumption. Impairment of the water villages and households use may have catastrophic effects on the livelihoods of these people.

The aim of this project is to study the current water quality in the basin and to evaluate the effects of mining and dams to the water quality. An Integrated Water Resources Management (IWRM) model developed by Environmental Impact Assessment Finland Ltd is used in assessing the condition in the river. Finally, a water quality monitoring network is suggested to fill in the gaps of water quality data currently available. The project is funded by Challenge Program on Food and Water Opportunity Funds (Ref. no: 537-04-03-MUL-HT-M170).

2 Theoretical background

2.1 Reservoir Water Quality

Reservoirs are water bodies that are formed or modified by human activity for a specific purpose, such as drinking water, industrial or cooling water supply, power generation, irrigation or river regulation and flood control. (Thornton, Steel, & Rast, 1996)

Definitions of terms related to reservoirs used in this thesis are as follows:

- Dam – A physical structure on the course of the river built to create a reservoir.
- Reservoir – A water body created by a dam for a specific need and subsequently managed to provide water for human activities.
- Off-river reservoir – A reservoir that is not built along the course of a river, but that is fed through canals or pipes.
- Impoundment – A reservoir that is created by damming a river with consequent inundation of land area upstream.
- Cascade – A series of river impoundments.

Reservoirs exhibit variation of form and water quality in a much larger scale than is considered limnologically normal. This means that evaluation of reservoirs without significant qualification could lead to misleading statements. Reservoirs do, however, share attributes with natural lakes and rivers. All reservoirs are subject to water quality standards dictated by the intended use of water and by ecosystem health. (Thornton, Steel, & Rast, 1996)

Impoundments usually have a maximum depth that is considerably greater than the average; as a result much of their volume is originating from shallow areas. They have a tendency towards sinuous form and substantial shallows and deep gulleys. This leads to high horizontal and lateral heterogeneity in their physiochemical and biological water quality. (Thornton, Steel, & Rast, 1996) Figure 1 illustrates the different zones and their characteristics an impoundment created by a dam usually has.

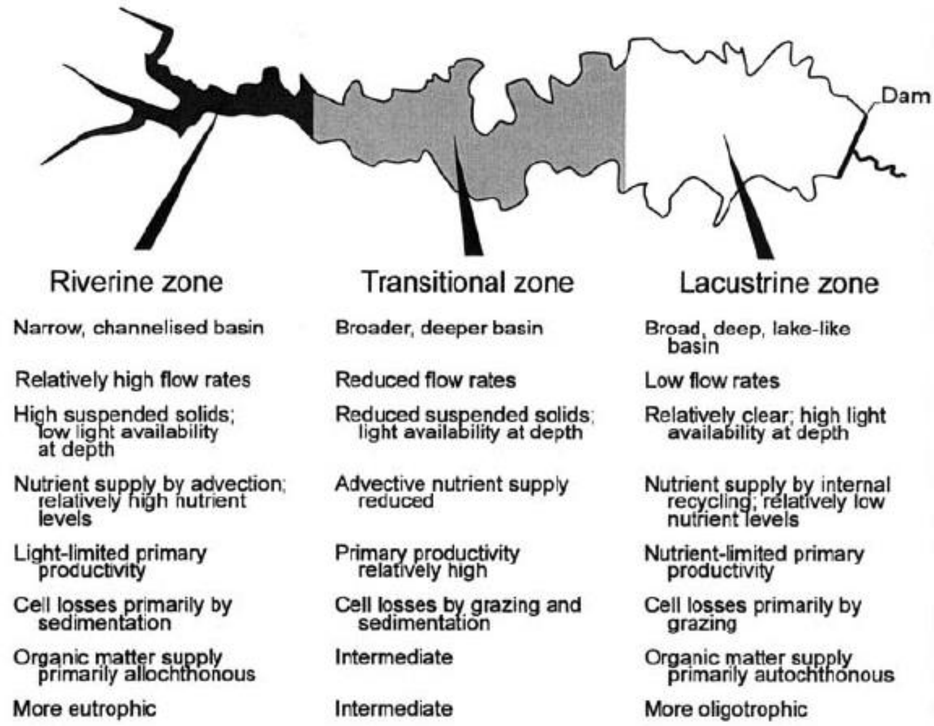


Figure 1.Complex river impoundment zonation and the characteristics of different zones. (Thornton, Steel, & Rast, 1996)

Many of the hydrological, chemical and biological characteristics of reservoirs are similar to those of natural lakes. However, the operation of the dam that confines the reservoir may significantly alter the responses when compared to natural lakes. Reservoirs created by river impoundments experience three stages; a tropic surge (the release of nutrients from flooded vegetation and other biological matter), a transition stage and finally stabilization. (Thornton, Steel, & Rast, 1996)

2.1.1 Physiochemical characteristics

Reservoirs can exhibit greater variability in their annual cycles than natural lakes due to their form and changes in operation of dams and water usage. Fluctuating water levels can affect thermal patterns at different times of the year. For example, sometimes a reservoir can be deep enough to exhibit thermal stratification, while at lower supply levels, mix repeatedly due to shallow depth. (Thornton, Steel, & Rast, 1996)

Stratification of reservoirs also affect water quality downstream from the outlet, depending on the vertical position of the outlet (Figure 2).

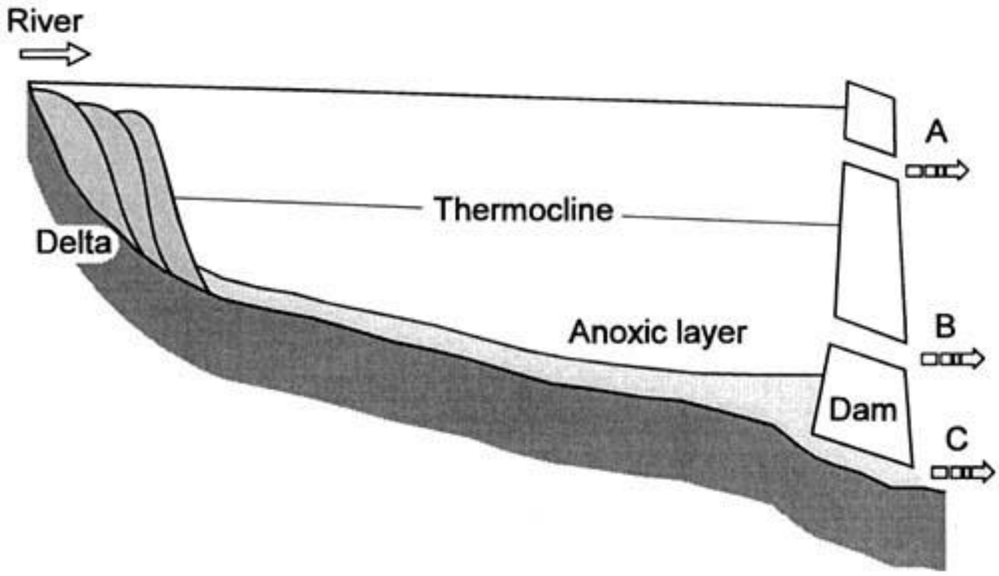


Figure 2. Water quality of the reservoir and sample withdrawal point can sometimes be dependent from the withdrawal point (A,B,C). A: Oxygenated epilimnetic water; B: Anoxic hypolimnetic water; C: Anoxic, sediment rich water. (Thornton, Steel, & Rast, 1996)

In reservoirs subjected to stratification, the oxygen gradient caused by a thermocline can cause anoxic conditions to form. Anoxic conditions in rich sediments found in most reservoirs dissolves large amounts of iron and manganese (and other metals) back into the water column and causes the formation of hydrogen sulphide. This effect is more common in tropical reservoirs than in ones located in temperate areas because of higher ambient temperature exciting higher decomposition rates. (Thornton, Steel, & Rast, 1996) As biological material decays, it consumes approximately 1.5 to 1.8 grams of O_2 per gram of mineralised organic matter (dry weight). (Thomas, Meybeck, & Beim, 1996)

In addition to mobilizing trace elements from the sediments, anoxic conditions also release phosphorus from the sediments. The release of phosphorus from sediments is closely associated with synchronous release of iron. Reduction of Fe^{3+} to soluble Fe^{2+} also mobilizes P. If phosphorus is not utilized by primary producers before, P released to the hypolimnion will generally stay there until the water is reoxygenated by overturn. P will then adsorb into insoluble iron species and particulates in the water column and return into the bottom sediments. (Thomas, Meybeck, & Beim, 1996)

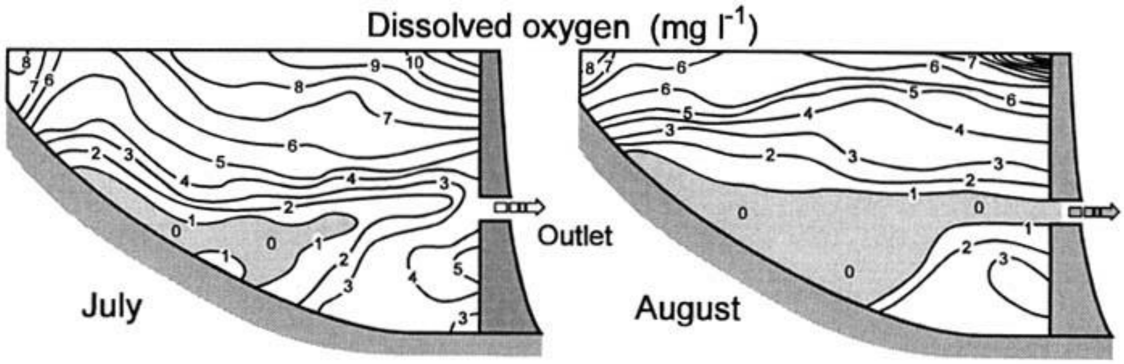


Figure 3. Metalimnic anoxia caused by mid-depth water withdrawal from reservoirs. (Thornton, Steel, & Rast, 1996)

Anoxic conditions can also appear in the metalimnion if water is withdrawn from mid-depth, as shown in Figure 3.

2.1.2 Biological characteristics

Biological characteristics of reservoirs and lakes is highly dependent of the availability of nutrients and the subsequent primary production. Nutrients are derived from external transport (allotrophy) and/or internal recycling (autotrophy) by decay of organic material or dissolution from sediments. (Thomas, Meybeck, & Beim, 1996)

Figure 4 below shows the causes and effects of eutrophication. Eutrophication may manifest itself either by macrophyte growth in shallow lakes (a particular problem in the tropics) or more commonly, phytoplankton growth. The nature and extent of the nutrient utilization depends on many factors which define the amount of biomass production at the primary producer level (see the causes in Figure 4). The effects of eutrophication can be highly detrimental and severely limit the possible uses of the water. (Thomas, Meybeck, & Beim, 1996)

Reservoirs may be classified by their trophic state in a similar manner as lakes, however, reservoirs may exhibit spatial variation in their state. Reservoir may be eutrophic around their river inlets, and at the same time show oligotrophic characteristic in deeper parts close to the dam site. (Thomas, Meybeck & Beim, 1996)

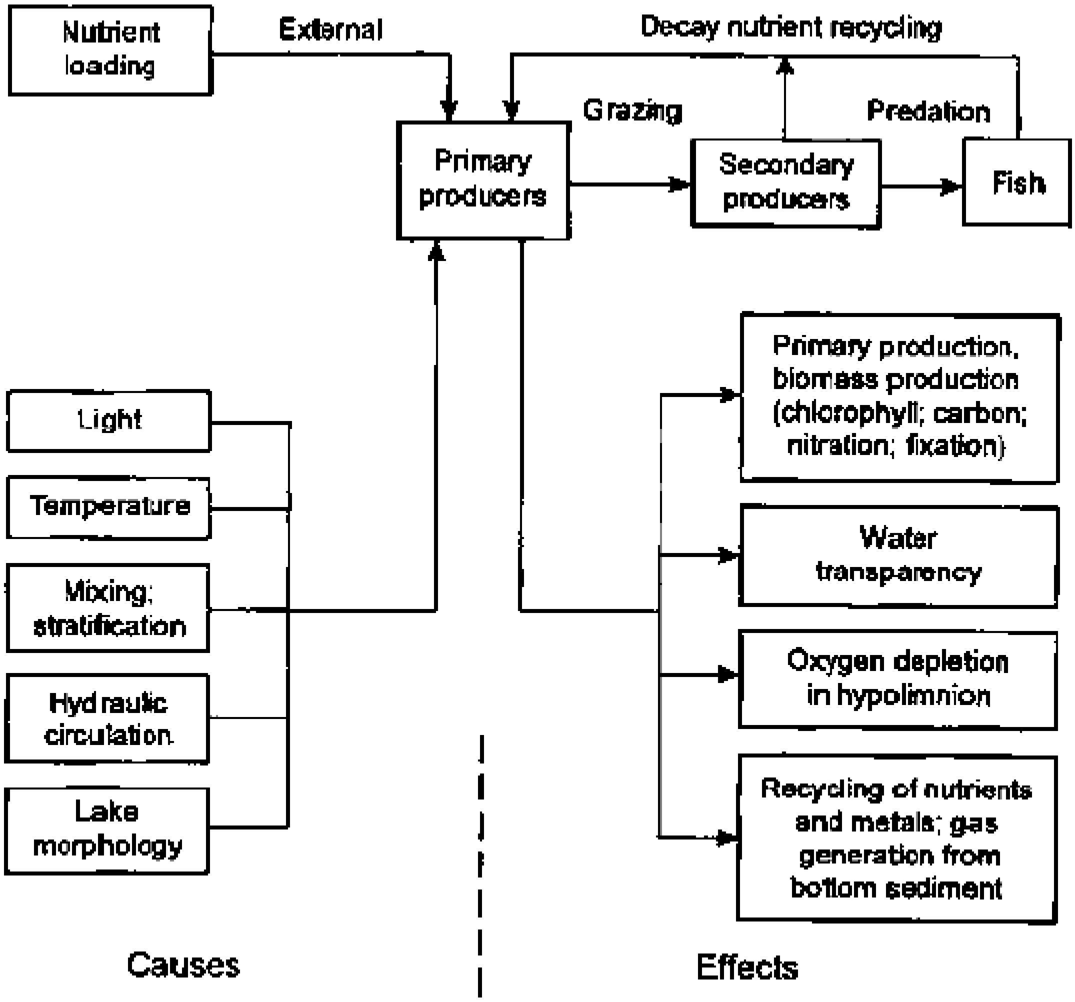


Figure 4. Simplified diagram of the causes and effects of eutrophication. (Thomas, Meybeck, & Beim, 1996)

Trophic state is normally determined with the combination of total phosphorus, chlorophyll concentration and Secchi depth. Limits of these variables are shown in Table 1.

Table 1. Parameters defining the trophic state of a lake and their limits.

CHARACTERISTIC OF THE TROPHIC CLASSIFICATION OF LAKES			
Parameters	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus (mg/m3) Avg	8	26.7	84.4
Range	3.0 – 17.7	10.9 – 95.6	16 – 386
Chlorophyll a (mg/m3) Avg	1.7	4.7	14.3
Range	0.3 – 4.5	3 – 11	3 – 78
Secchi Disk Depth (m) Avg	9.9	4.2	2.45
Range	5.4 – 28.3	1.5 – 8.1	0.8 – 7.0

As with physiochemical characteristics, reservoirs can also affect biological characteristics in a way that is not normal to natural lakes. Extreme fluctuations of water level cause problems to rooting aquatic macrophytes and fish spawning areas. (Thornton, Steel, & Rast, 1996)

2.1.3 Residence time

The concept of residence time is important. It may be expressed theoretically as the reservoir volume divided by the rate of outflow. Residence time in reservoirs is generally shorter than in natural lakes. Theoretical residence times do not actually occur in nature. Depending on the morphology, thermal structure and water circulation, lakes and reservoirs (impoundments) contain different water masses. Warm epilimnion water flows over the water under the thermocline and has much shorter residence time. Deep waters with poor mixing have much longer residence times. (Thomas, Meybeck, & Beim, 1996)

Residence time is important because it can be used to estimate self-purification rates and recovery speed after contamination with a pollutant. Simplified, residence time will tell how long it takes for a water body to replace polluted water with clean water. However, this does not take into account aforementioned differences with water masses within the reservoir or the chemical nature of the pollutant.

2.1.4 Contaminants

Contaminants in fresh water systems can be found in solution in water, in sediments and in biota. Although some elements considered as pollutants are naturally present in surface water (i.e. toxic metals), they usually do not pose a threat to human health. Anthropogenic activity (mining, industries) may have increased the erosion of naturally occurring elements and/or changed their chemical form. This can lead to levels of contaminants that become a hazard for aquatic ecosystems and to human health. Synthetic organic compounds do not occur naturally and are always manufactured. (Thomas, Meybeck, & Beim, 1996)

Concentration in a reservoir water or sediment is a result of contaminant load (mass/time) distributed over the lake, which is termed the loading (mass/volume or area/time). Inputs of contaminants to the reservoir have a direct impact on the inlet and the dispersion over the water mass is controlled by diffusion and water mass movement.

Stratification (and retention time) play a key role in spatial distribution of contaminants in a reservoir. In the case of a stratified reservoir, soluble contaminants in warm incoming water mix well and rapidly in the epilimnion. Depending on the water temperature, the incoming water can also interstratify or move into the hypolimnion. The elimination of contaminants in the hypolimnion is much slower than in the epilimnion. The retention time and rate of elimination of contaminants is also dependant on the water withdrawal point at the dam site (see Figure 2 and Figure 5). (Thomas, Meybeck, & Beim, 1996)

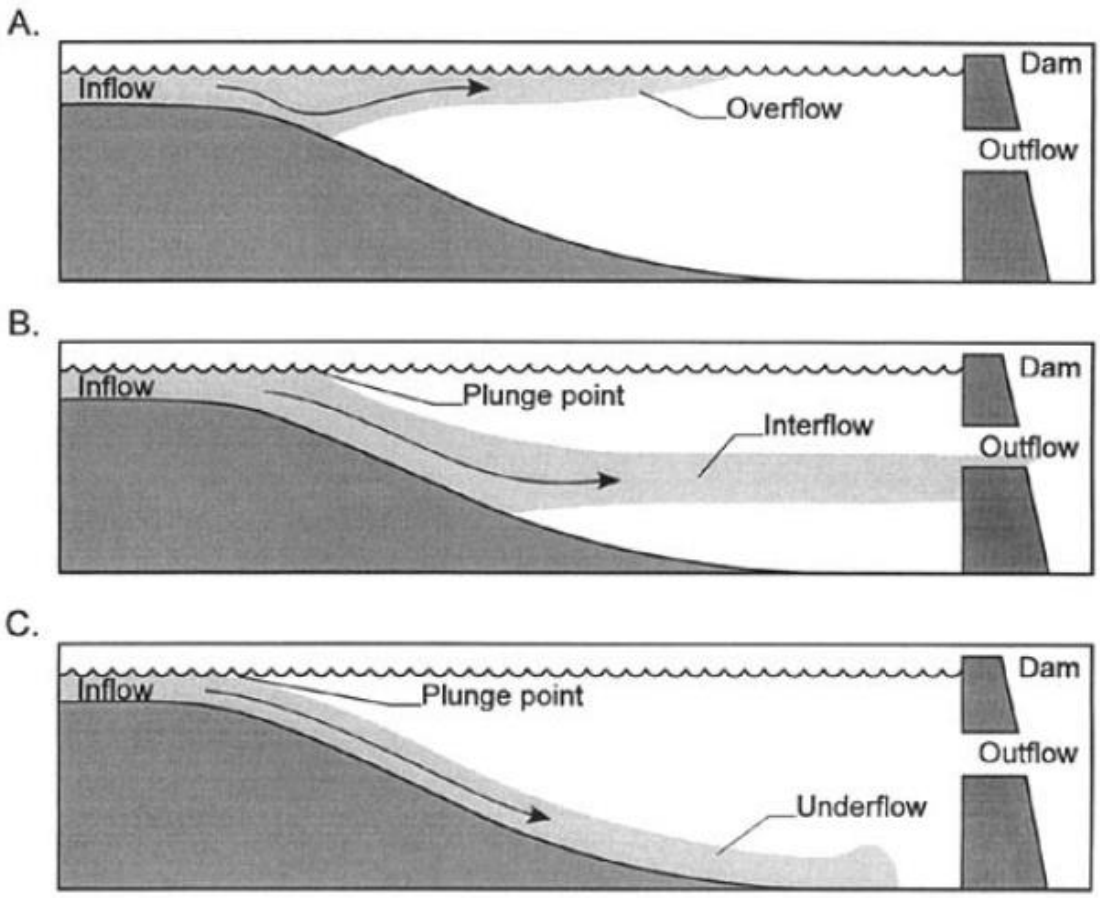


Figure 5. Density flows of incoming water into reservoirs. A. Warm overflow. B. Interflow. C. Underflow. (Thornton, Steel, & Rast, 1996)

The fate of contaminants of low solubility (toxic metals and many organic pollutants) or which are fat soluble is predominantly dictated by adsorption into suspended particles. Their elimination follows the process of sedimentation. (Thomas, Meybeck, & Beim, 1996)

2.1.5 Acidification

Acidification of lakes and reservoirs is generally the result of acid rain by pollutants SO_2 and NO_x. Lakes can be classified in three categories according to acidity; bicarbonate lakes, transition lakes and acid lakes. In the first mentioned, bicarbonate prevents acidification. Transition lakes exhibit large fluctuations of pH resulting in fish kills. Acid lakes have a stable low pH and no fish. (Mason, 1996)

The most vulnerable water bodies are ones which have soft water. Soft water has low amount of buffering capacity due to low concentrations of dissolved salts. Lake sensitivity to acidification can be expressed in terms of Acid Neutralising Capacity (ANC):

$$ANC = \sum[Ca]+[Mg]+[Na]+[K]-\sum[SO_4]+[NO_3]+[Cl]$$

ANC classifications for Eastern Canadian lakes is shown in Table 2.

Table 2. Lake sensitivity of acidification in terms of Acid Neutralising Capacity. (Thomas, Meybeck, & Beim, 1996)

ANC (µeq l-1)	**Sensitivity**
≤0	Acidified
0-40	Very sensitive
40-200	Sensitive
>200	Insensitive

Acidification changes water chemistry and the composition and abundance of fauna and flora. The process is complex and does not solely depend on pH, but concentration of metals, hardness, alkalinity and dissolved organic matter play a role. In addition to changes in water chemistry, species richness is affected by the resultant physiological stress and changes in food availability and predator community. Acid lakes tend to have one fourth to one eight phytoplankton of species richness than neutral oligotrophic lakes. The shift in phytoplankton is often toward inedible species. (Mason, 1996)

2.2 Sediments

Sediments in rivers are a result of weathering of natural rock and biological activity in a water body (e.g. algae). Suspended particulate matter is the fraction of solid particles in the water that is left after filtration through 0.45 µm filter. Smaller particles than this is considered as the dissolved fraction. (Meybeck & Thomas, 1996)

The elemental composition of sediments is generally close to the composition of the weathered rock in the watershed in systems where mechanical erosion dominates. In cases where chemical alteration exceeds mechanical erosion, soluble elements (such as Ca^{2+}, Mg^{2+} Na^{+}, K^{+} and dissolved SiO_2) are in their dissolved phase, while less soluble elements (Al, Fe, Ti, Mn) remain in particulate matter and eventually get enriched in the sediments. (Meybeck & Thomas, 1996)

Current velocity, particle size and water content of minerals are involved in erosion, transportation and deposition of sediments. These factors are described as Hjulström curves (Figure 6), which describe threshold velocities for erosion. Two transport systems can be described; transport in suspension and traction at the bottom. (Meybeck & Thomas, 1996)

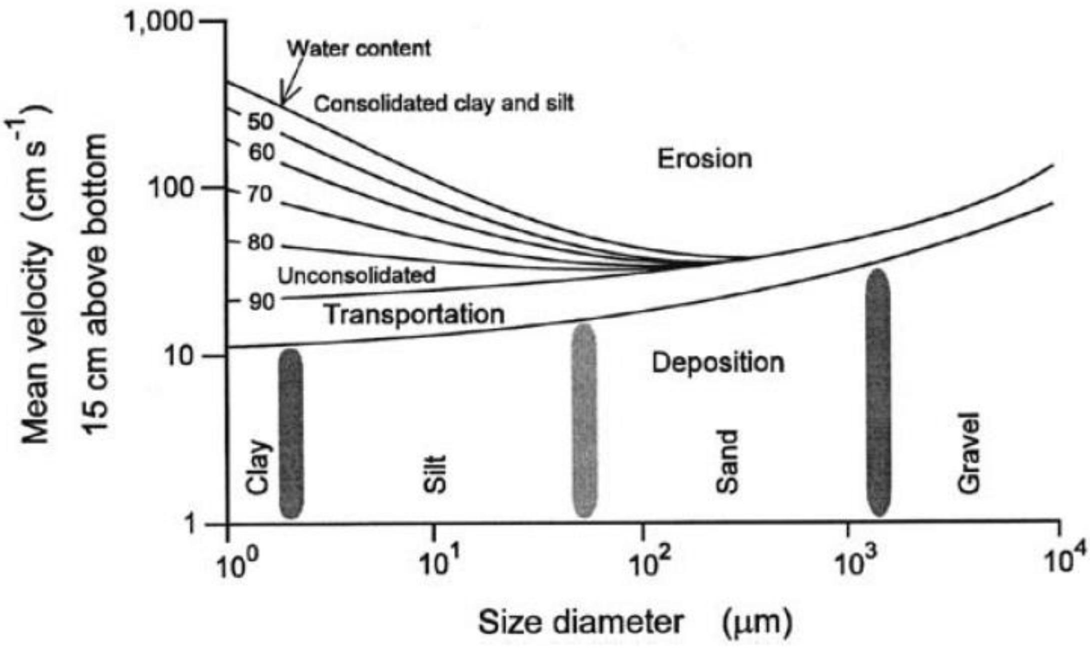


Figure 6. Hjulström curves defining erosion, transport and deposition of sediments according to grain size and water content. (Meybeck & Thomas, 1996)

Sediments enter lakes and reservoirs from river input, erosion of shoreline and lake bed, airborne inputs and autochthonous sediment production (organic matter e.g. algae). In reservoirs river input and shoreline erosion are the dominant factors. Due to decreasing water velocity, coarse SS are deposited in the river mouth while finer SS is transported further. (Meybeck & Thomas, 1996)

Specific surface area is the most important factor considering pollutant adsorption capacity of sediments. It is inversely proportional to the grain size; 10 m^2 g^{-1} for clay to 0.01 m^2 g^{-1} for sand. Finer particles are generally richer in trace elements. In cases of water pollution, the additional inputs of pollutants are generally found adsorbed onto particles or bound to organic material. (Meybeck & Thomas, 1996)

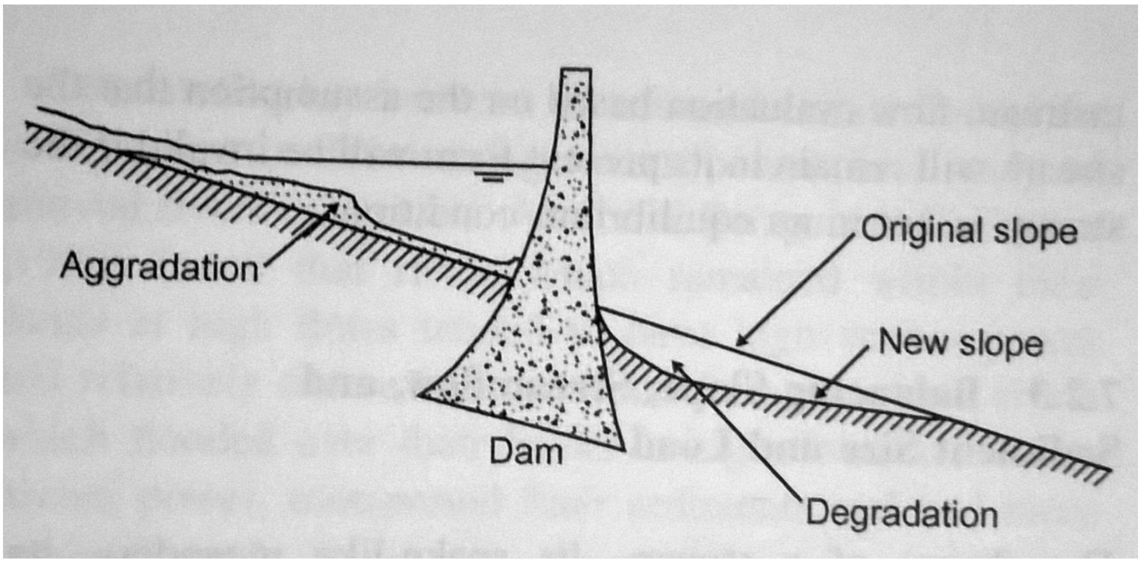


Figure 7. Aggradation and degradation of sediments resulting from dams. (Gordon, McMahon. Gippel, Finlayson & Nathan, 2004)

The deposition of sediments in reservoirs and erosion immediately downstream is shown in Figure 7. When dams are constructed in sequence forming a cascade, they reduce the amount of suspended load on the stream and may yield water quality improvement such as decreased turbidity, increased photic zone and primary production. Contaminants may also be trapped by the reservoir. (Thornton, Steel & Rast, 1996)

2.3 Metals in Fresh Water

In water systems, metals can be found in three phases; bottom sediment, suspended sediment and soluble phase (see Figure 8). In most fresh water systems biota is also an important partition. The most important factor regarding the partitioning is pH. All the major pathways of metal partitioning are heavily dependent in pH. (Elder, 1988)

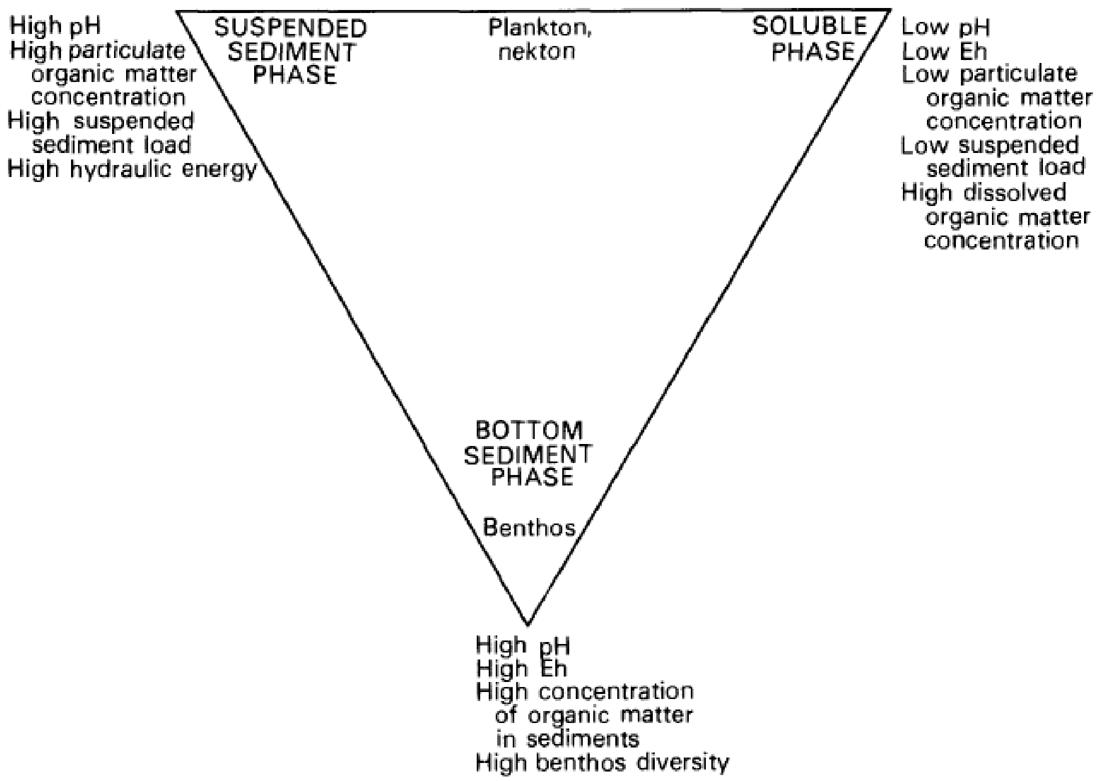


Figure 8. The partitioning of metals in aquatic systems. Factors which favour a phase is given for each phase, and biological components (plankton, nekton and benthos) are marked according to the phase they are most closely associated. (Elder, 1988)

Metals in suspended and bottom phase can be associated either with inorganic particles, organic particles or biota. Main mechanism involved is adsorption, which is reversible and results in an equilibrium between adsorbed and desorbed forms of the metal. Absorption and assimilation also play a role with biota. (Elder, 1988)

Dissolved metals exist either associated to ligands or as a hydrated form $M(H_2O)_x^{n+}$, where M is the metal and n is the ionic charge. Acidic waters carry relatively large amounts of metals in dissolved phase. (Elder, 1988)

2.3.1 Metal Solubility

In addition to pH, solubility of metals is highly dependent on the oxidation state. In anoxic conditions metals such as Fe^{2+} and Mn^{2+} are highly soluble and tend to be released into the solution. Metal phosphates (e.g. Al-phosphate, Fe-phosphate, and Ca-phosphate) are more soluble under low pH. Lead forms insoluble sulphides under low pH and redox conditions.

Figure 9 shows an example of the relation of various metals to organic particles in low pH conditions. (Meybeck & Thomas, 1996)

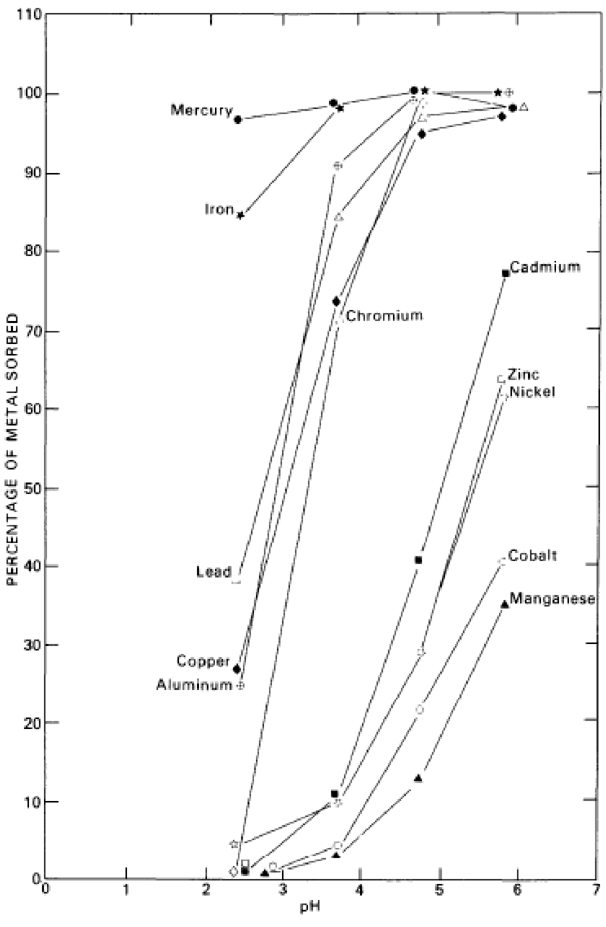


Figure 9. Adsorption of different metals on humic acids as a function of pH. Initial concentration of each metal is 0,0005 M. (Elder, 1988)

Redox potential, Eh, characterises the tendency of chemical species to exchange electrons. The measurement and interpretation of the redox potential is often difficult because of the many factors affecting it. In water, oxygen, iron, sulphur and some organic compounds are the most important in determining the Eh of the system. Eh in natural waters varies between -500 mV and +700 mV. (Chapman & Kimstach, 1996)

The combined effect of Eh and pH is shown in Figure 10. The coloured area in the figure indicate solid phase. The diagram is affected by temperature, pressure and the presence of organic carbon.

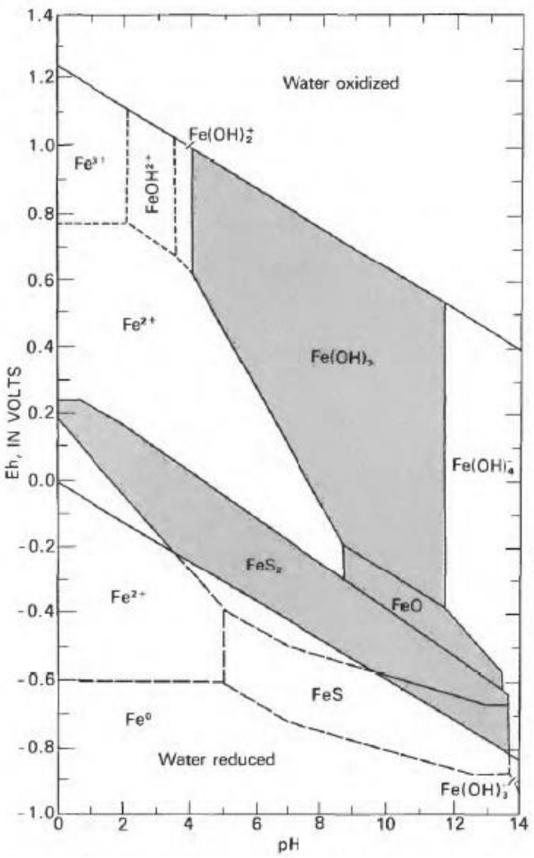


Figure 10. Stability diagram of iron between solid and dissolved forms as a function of pH and Eh at 25° C and 1 atmosphere. (Elder, 1988)

The true solubility of metals in natural waters is a product of several environmental factors and may be very different from laboratory experiments. (Elder, 1988)

2.3.2 The Effect of Hydrology on Metal Partitioning

The movement of water has a large influence on the partitioning of metals via transportation of sediments and mixing characteristics in lakes and reservoirs. The proportion of metals in the suspended phase increases with the energy of flow. Discharge can have negative or positive impacts on dissolved metal concentrations depending on the nature of the pollution source. (Elder, 1988)

In general, contaminant concentrations (including metals) decrease to a point with increasing discharge. As discharge increases further, contaminant concentration starts to increase. This effect is due to domination of different processes in different flow regimes. At low discharge, desorption dominates the movement of contaminants between sediments and water. Desorption stays fairly constant when increasing flow enhances dilution. At high discharges, resuspension (or erosion) of sediments brings contaminants into the water column increasing their concentration. Dissolved forms of metals dominate during low flow, while suspended phase dominates during high flow. Dissolved phase is more bioavailable, which makes low flow regimes more harmful to aquatic organisms. (Elder, 1988; Mason, 1996)

In stratified lakes and reservoirs Fe and Mn form a cycle due to differences in solubility and mobility between oxidation states. Near the hypolimnion, iron exists as insoluble ferrous iron. This is a pathway of removal of iron from the hypolimnion, but at the same time the dissolution of iron from sediments increases the iron concentration near the hypolimnion. Fe and Mn are important in the transport of other metals in reservoir water due to their tendency to form compounds. The cycle is presented in Figure 11. (Elder, 1988)

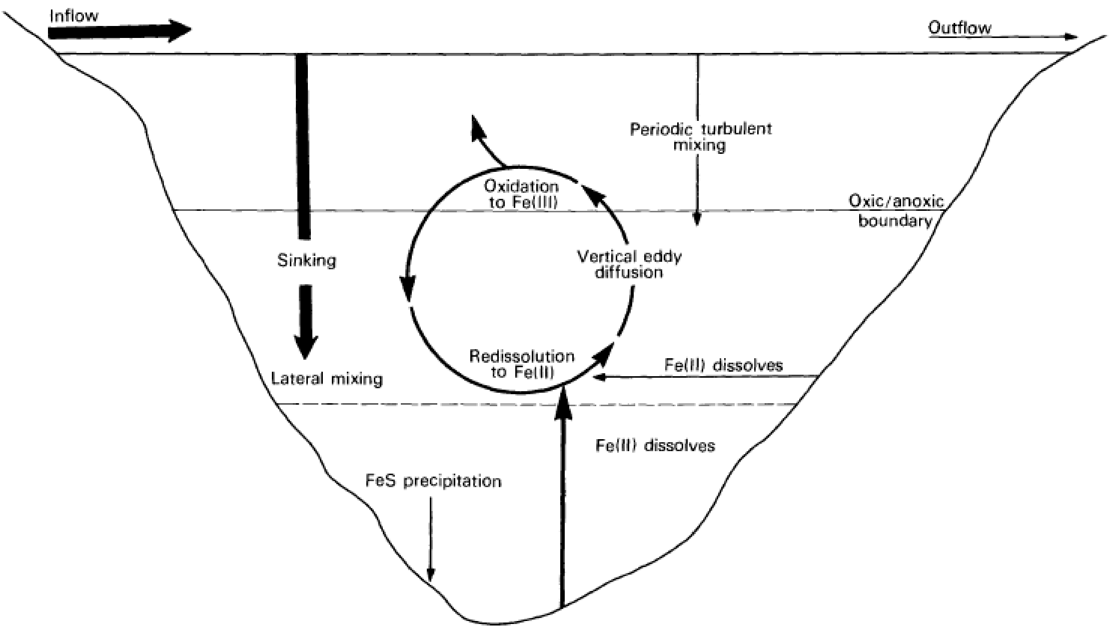


Figure 11. The iron cycle in a stratified lake. Arrow thickness indicates the importance of processes in the diagram. (Elder, 1988)

2.3.3 Acid Mine Drainage

Acid Mine Drainage (AMD) is waste water from mining sites that is extremely rich in metals. AMD usually also contains large amounts of sulphate (from pyrite and other sulphide ores), which produces low pH in the drainage. Sites where a specific metal is mined tend to release high amounts of other metals in their drainage.

AMD formation is primarily a function of the mineralogy of the rock material and the availability of water and oxygen. Because the mineralogy of each mining site is different, the prediction of AMD potential is difficult, costly and lacks reliability. (U.S. EPA, 1994a)

Mining waste that has potential to generate AMD include mined material such as spent ore from heap leach operations, tailings, and waste rock units, including overburden material. Difference of waste rock piles and tailings impoundments as a source of AMD is shown Table 3.

Table 3. Differences in AMD generation of waste rock piles and tailings impoundments. (U.S. EPA, 1994a)

Acid Generation Factors Affecting	**Waste Rock Piles**	**Tailings Impoundment**
Sulphide Source	Variable in concentration and location. Conditions may vary from sulphide rich to basic over short distances.	Conditions uniform, often with very high sulphide content.
Particle Size	Average rock size typically greater than 20 cm (but highly variable).	Tailings may be 100% less than 0.2mm.
pH Variation	Highly variable conditions over short distances.	Fairly uniform conditions with a few major horizontal zones.
Initiation Of Rapid Oxidation	Usually starts immediately after first rock is placed (in "trigger" spots).	Usually starts after tailings placement ceases at end of mine life.
Oxygen Entry	Rapid along preferential flow paths. Seasonal variations in flow path "flushes" out stored products resulting in concentration peaks.	Seepage slow and uniform. Reduced flow path variation and stored product "flushing."
ARD Releases	Large infiltration resulting in large seepage from toe and to groundwater. Rapid release following generation, sometimes with both neutralized and acid ARD seeps.	Large early top surface ARD runoff. Lower infiltration. Gradual transition in seeps from process water to neutralized ARD to low pH ARD.

AMD is generated by oxidation of sulphide metal minerals. They are usually present in the host rock from which most metals are mined. The generation requires both oxygen and water. Chemical reactions for pyrite (FeS_2) are as follows (U.S. EPA, 1994a):

1. $2FeS_2(s) + 2H_2O + 7O_2 \rightarrow 4H^+ + 4SO_4^{2-} + 2Fe^{2+}$
2. $4Fe^{2+} + O_2 + 4H^+ \rightarrow 4Fe^{3+} + 2H_2O$
3. $2FeS_2(s) + 14Fe^{3+} + 8H_2O \rightarrow 2SO_4^{2-} + 16H^+$
4. $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+$

Finally $Fe(OH)_3$(s) precipitates and can be identified by the amorphous yellow, orange or red deposit in the stream bottom.

Wet and dry cycles of the mining heaps are important as the oxidation products are likely to accumulate during dry periods. Frequent wetting (precipitation) results in a more uniform volume and concentration of AMD generated. A high wetting event (e.g. a storm or heavy rain) will flush out the contaminants to the environment. This is typically observed in areas of dry and wet seasons. (U.S. EPA, 1994a)

3 Description of Study Area

The Nam Ngum watershed is located in central Lao PDR and is one of the main tributaries of the Mekong River. Classified as the fourth largest Mekong sub-basin in Lao PDR, its total length is 354 km and its catchment area is 16 841 km^2 (Komany, undated). The river discharges an annual 21 billion m^3 into the Mekong, contributing up to 14 % of its flow (Clausen, 2011). The most important tributaries discharging into the Nam Ngum are Nam Lik and Nam Song from a total of 15 tributaries (WREA, 2008).

3.1 Climate, Geography and Population

NNRB contains sub-tropical and tropical areas and is affected by a seasonal monsoon. The rainy season lasts from May till October. The dry season can be divided in cold dry (November to February) and hot dry (March and April). The rainy season brings in 84 to 94% of the annual precipitation. The annual mean precipitation varies from 3500 mm to 1400mm and the annual basin average is approximately 2000 mm. (Idom, 2013)

The southern area of the watershed is a part of the Vientiane plains, while the northern part is mountainous. The elevation varies from the 160 m in the lowlands to the maximum of 2270 m in the northeast. Figure 12 shows a map of elevation in the NNRB.

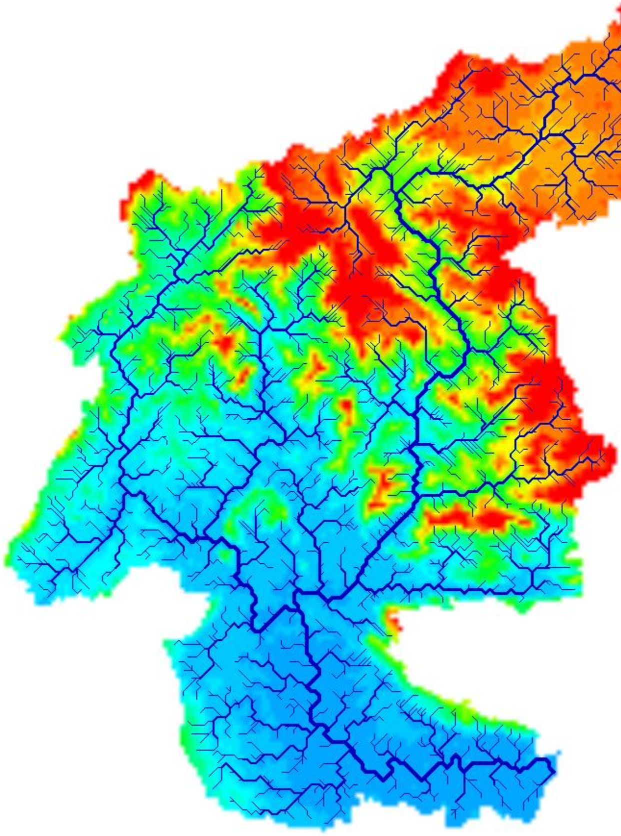


Figure 12. Map of elevation in the NNRB.

The basin is characterized by steep slopes. There are two flat areas; Vientiane Pains in the south and the Plain of Jars in the northwest of the basin. Only 16 % of the basin has slopes lower than 5 degrees. Majority of the basin has slopes steeper than this and at the extreme, the slope reaches 56 degrees. The steep topography creates a narrow river network. Most of the hydropower dams planned in the basin take advantage of the height of the cliffs. (Idom, 2013)

Soil in the river basin is dominantly acrisols and lithosols, as shown in Table 4. Acrisols are characterized by low fertility and toxic amounts of alumina. (Idom, 2013)

Table 4. Soil type classifications and their abundance in Nam Ngum River Basin. Data acquired from the model.

Soil type	**% of area**
Water	3
Acrisols	82.1
Histosols	0.43
Argic	0.25
Ferrasols	0.41
Alluvial	0.16
Lithosols	13.6
Cracking	0
Calcisol	0
Residential area	0.01
Rock	0

Population in the basin is concentrated in the Vientiane Plains area, as can be seen in Figure 13 below. Population centers also exist in the Plain of Jars area in the northeast and in Vangvieng area in central NNRB.

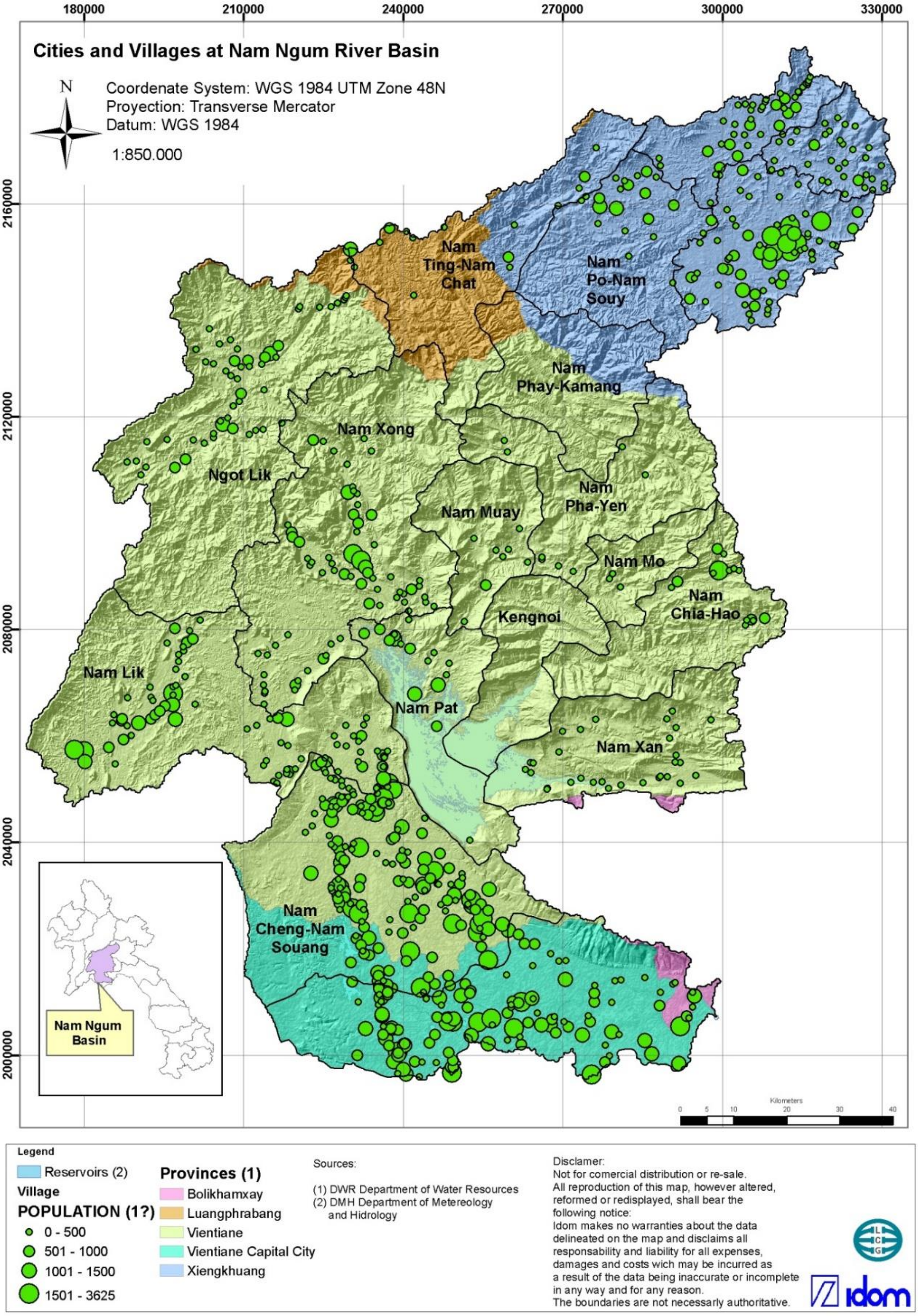


Figure 13. Cities and villages in the NNRB. (Idom, 2013)

3.2 Hydropower

There are currently six hydropower dams in operation in the NNRB. The first hydropower station, Nam Ngum 1 (NN1), started commercial operation in 1971. Nam Lik 1-2 (NL1-2, 2010), Nam Ngum 2 (NN2, 2012) and Nam Ngum 5 (NN5, 2012) are located in the watershed itself. Nam Leuk and Nam Mang 3 hydropower stations (operation started in 2000 and 2004, respectively) are not located in the actual watershed area, but they are used to transfer water from other watersheds into NNRB. Overall installed capacity of the river basin is 1090 MW. (Idom, 2013)

The development of hydropower within the basin is accelerating with four hydropower stations are planned to start operation before 2018. Nam Ngum 3 is the most notable of these, and it is planned to be completed in 2018. In addition to these, five other projects are planned. (Idom, 2013) A diagram of the hydropower situation in the basin is shown in Figure 14.

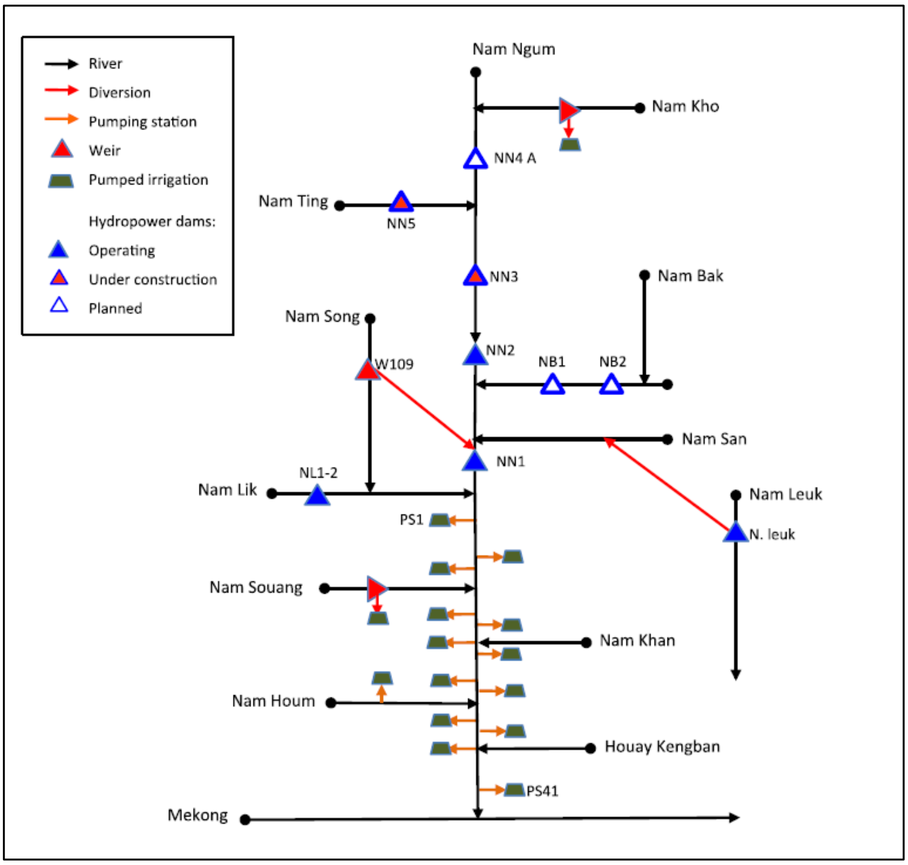


Figure 14. Node-link hydrological diagram of the NNRB. (Idom, 2013)

3.3 Mining

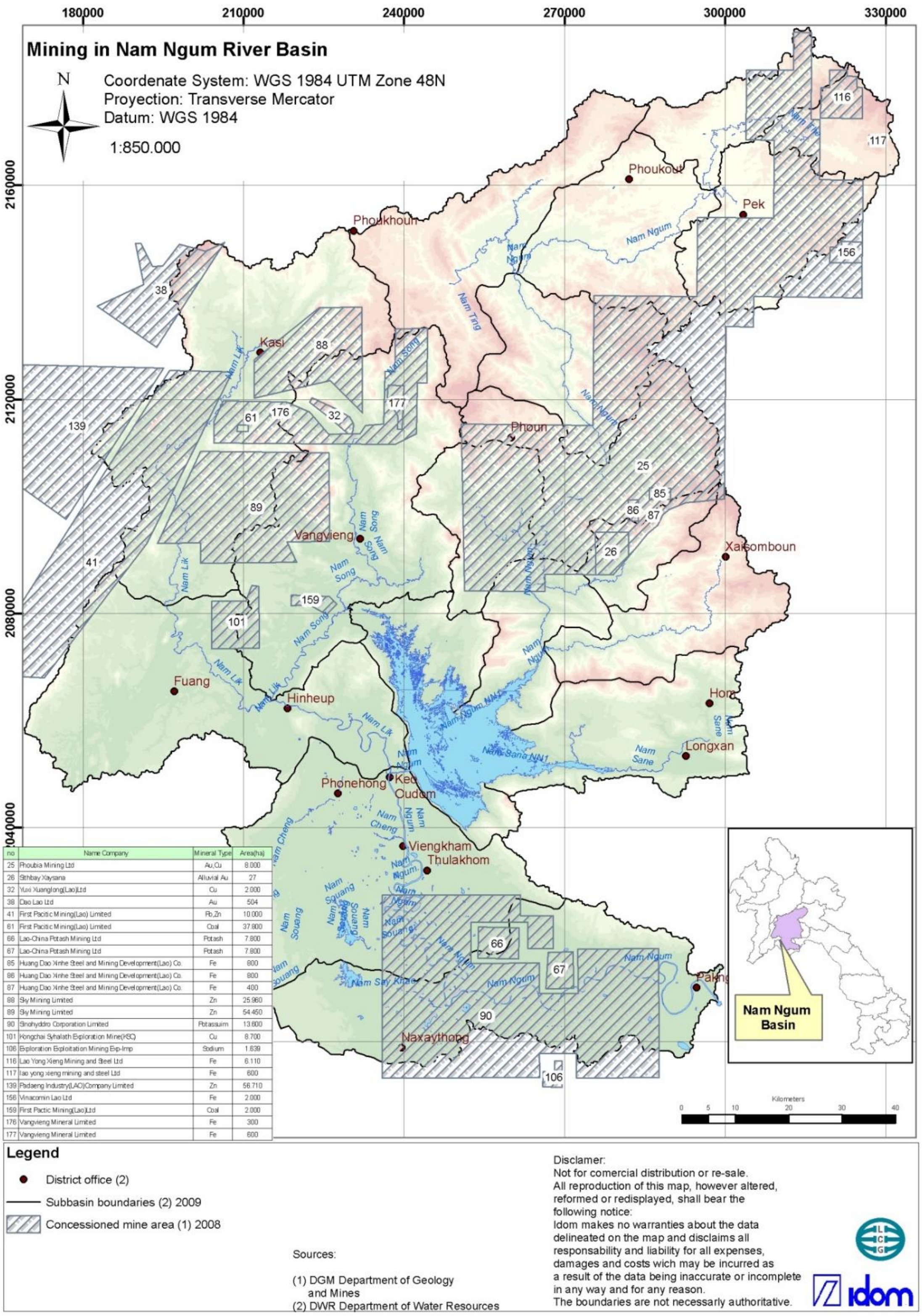
Mining sector is considered as a key sector of development by the government of Lao PDR and its products account for about 50 % of the country's exports and 10 % of state revenues. (Idom, 2013)

NNRB has significant potential for gold, silver, copper, lead-zinc, tin, potash (Vientiane Plain area) and coal. Although majority of the mining projects are in prospecting or exploration phase, some major mines are already in operation. A summary of these is shown in Table 5. (Idom, 2013)

Table 5. Main mining operations in the NNRB in 2013. Modified from: (Idom, 2013)

Name Company	Mineral type	District	Area (Ha)	Concession period (years)
Phou Bia Mining Limited	Copper-gold -silver	Saysomboune	5.000,00	20
Qin Huang Dai Xin He	Ferrous	Saysomboune	15,00	20
Vangvieng Minerals	Ferrous	Kasy-Mat	220,08	10
Tangnay Ming Limited	Copper	Kasy	1,00	10
Bukane Limited	Lead-Zinc	Vangvieng	1,25	10
Lao First Pacific Limited	Coal			17
Cement Lao Limited	Coal	Vangvieng	53,5	20
Cement Lao Limited (II)	limestone	Vangvieng	0,73	30
Sino Hydro Mining Limited	Potassium	Xaythany/Pakngum	39,38	30
Lao-Chinese Potassium Mining	Potassium	Xaythany/Pakngum	78,00	30
Lao-Yong Zieng Ferrous Limited	Ferrous	Perk	26,55	7

Potassium, potash and sodium mining is concentrated to the southern part of NNRB (the Vientiane plains). The western NNRB has copper, zinc and ferrous mines and smaller operations of coal and gold mining. The eastern part of the basin consists of major ferrous, aluminium and gold and copper mines. A map of concessioned mining in the NNRB is shown in Figure 15.



no	Name Company	Mineral Type	Area(ha)
25	Phoubia Mining Ltd	Au,Cu	8.000
26	Sithbay Xaysana	Alluvial Au	27
32	Yuxi Xuanglong(Lao)Ltd	Cu	2.000
38	Dao Lao Ltd	Au	504
41	First Pacitic Mining(Lao) Limited	Pb,Zn	10.000
61	First Pacitic Mining(Lao) Limited	Coal	37.800
66	Lao-China Potash Mining Ltd	Potash	7.800
67	Lao-China Potash Mining Ltd	Potash	7.800
85	Huang Dao Xinhe Steel and Mining Development(Lao) Co.	Fe	800
86	Huang Dao Xinhe Steel and Mining Development(Lao) Co.	Fe	800
87	Huang Dao Xinhe Steel and Mining Development(Lao) Co.	Fe	400
88	Sky Mining Limited	Zn	25.960
89	Sky Mining Limited	Zn	54.450
90	Sinohyddro Corporation Limited	Potassuim	13.600
101	Kongchai Syhalath Exploration Mine(KSC)	Cu	8.700
106	Exploration Exploitation Mining Exp-Imp	Sodium	1.639
116	Lao Yong Xieng Mining and Steel Ltd	Fe	6.110
117	lao yong xieng mining and steel Ltd	Fe	600
139	Padaeng Industry(LAO)Company Limited	Zn	56.710
156	Vinacomin Lao Ltd	Fe	2.000
159	First Pactic Mining(Lao)Ltd	Coal	2.000
176	Vangvieng Mineral Limited	Fe	300
177	Vangvieng Mineral Limited	Fe	600

Figure 15. Concessioned areas in the NNRB. (Idom, 2013)

The operating mines have created some environmental issues. Stakeholders in these areas have reported problems with water quality downstream from the mines. The reported problems include fish kills, chemical pollution, river bank erosion and waste water plants that do not function well enough. (Idom, 2013)

4 Water Quality in NNRB

The water quality in Nam Ngum River has been found to be generally in good condition and without a large anthropogenic impact (low population density, small amount of industry) (Komany, undated). However, several stressors are present in the NNRB and there is a danger of water quality deterioration in the future. The stressors include for example agriculture, fisheries, population pressure and economic development (MRC, 2007). Most importantly, mining activities and hydropower development are growing economic fields and could have serious impact on the water quality. Urban areas in Lao PDR generally lack a satisfactory level of wastewater treatment. (Komany, undated)

Agriculture is a growing stressor. While the farmers do not use extensive amounts of agrochemicals yet, their use is expected to increase significantly in the future. This is likely to cause increased nutrient runoff from the fields (Komany, undated). The building of dams and reservoirs also allows for more irrigation which is likely to increase agricultural activity. Slash-and-burn techniques are still used in the northern regions of NNRB. Increased population have decreased fallow periods, which are essential for nutrient replenishment in the soil. This causes soil degradation, erosion and sedimentation in the rivers (Komany, undated; WREA, 2008).

Mekong River Commission (2008) has evaluated the Water Quality Index (WQI) for Nam Ngum at the Ban Hai measuring station. It found that the quality of water that discharges into Mekong is generally of high quality (see Figure 16), although impacted by anthropogenic actions.

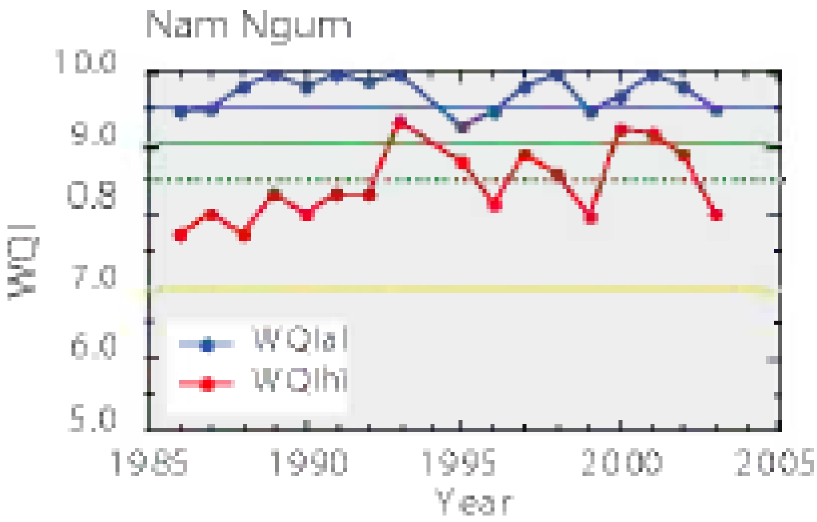


Figure 16. Water quality trend at the Nam Ngum tributary station of Mekong. Horizontal lines represent threshold of water quality. Blue for High Quality, green for Good Quality and yellow for Moderate Quality (WQIal). For WQIhi the thresholds are blue for Not Impacted, dotted green for Slightly Impacted and yellow for Impacted. (MRC, 2008)

High seasonality in weather conditions in the area have dramatic effect on the water quality in different months. Dry season is characterized with extremely low river discharge whereas wet season flow can be extremely high. Generally in the lower Mekong area, it has been found that in the wet season, precipitation, mean water level and discharge increase TSS, NO^{3-}, DPO4, TOTP and COD of the rivers. High water quantity also lowers DO, pH, conductivity, Ca, Mg, Na, K, alkalinity, Cl, SO_4^{2-} and Si in the river system. (Prathumratana, Sthiannopkao, & Kim, 2008)

4.1.1 Current Data and Monitoring Network

The data concerning water quality in the NNRB is fragmentary and not always reliable. Data is currently not collected to a single database and is held by several stakeholders including environmental departments of the government of Laos and mining, hydropower, industrial and tree plantation companies. (Idom, 2013)

Latest water quality monitoring was made by the Natural Resources and Environment Institute (NREI) with the support of Environmental Management Support Program (EMSP). Two small water quality surveys were conducted in 2011-2012 and 2012-2013. The most recent monitoring network is presented in Figure 17.

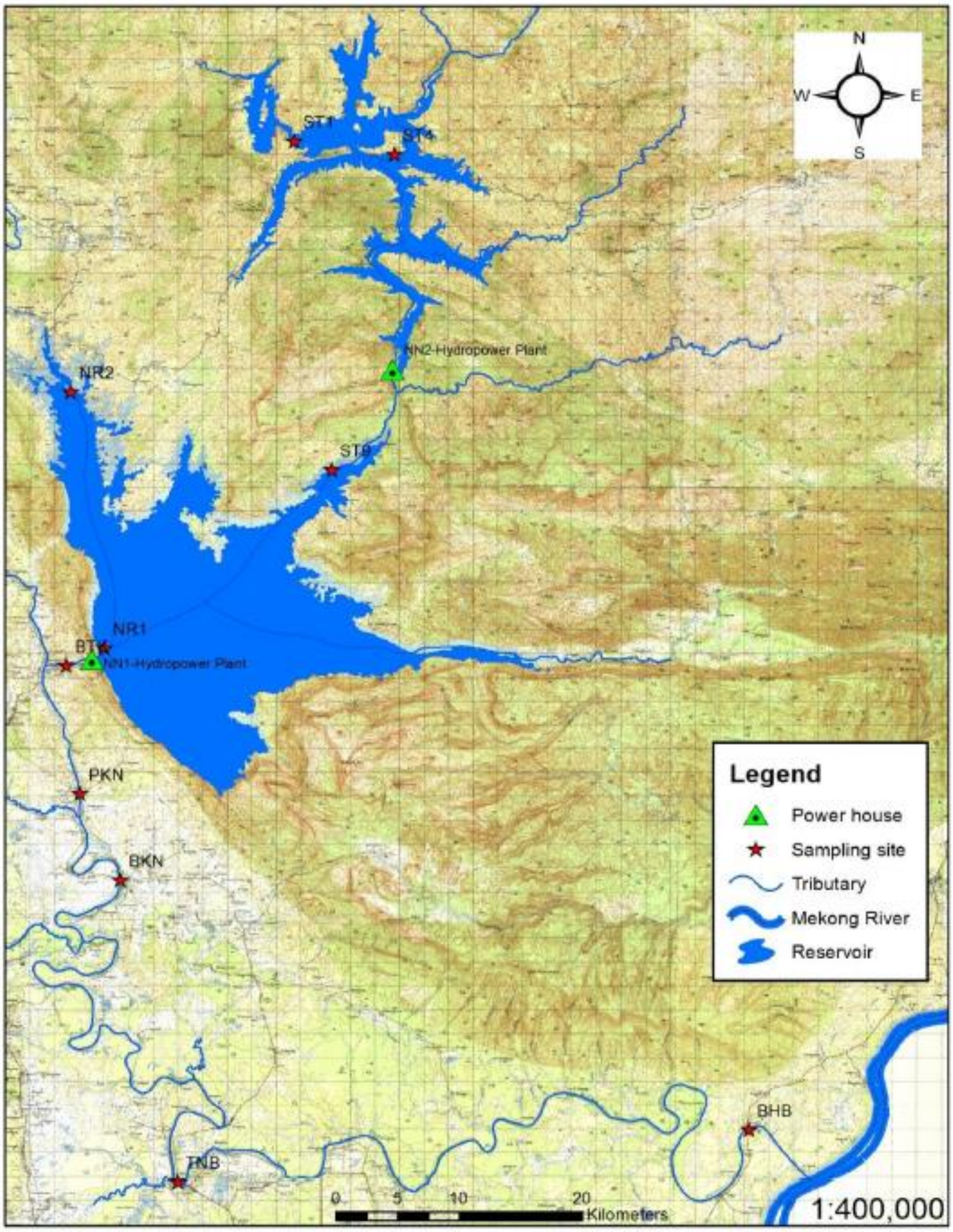


Figure 17. Monitoring stations of NREI study of the status and trend of Lower NNRB water quality monitoring programme. (NREI, 2014)

The sampling sites and their coordinates are listed in Table 6 below.

Table 6. Water quality monitoring network used by NREI in their 2013 campaign.

No	Sampling Site	ID	UTM	Coordinates
1	NN1-Reservoir (site1)	NR1	E 0419680 N 2051273	102°33'3346" E 18°31'1569" N
2	NN1-Reservoir (site2)	NR2	E 2073188 N 0239388	102°31'42.20" E 18°44'02.00" N
3	NN1-Reservoir (site3)	ST9	E 2092945 N 0266038	102°46'31.10" E 18°54'55.70" N
4	NN2-Reservoir (site1)	ST1	E 2094282 N 0257545	102°41'52.40" E 18°55'35.60" N
5	NN2-Reservoir (site2)	ST4	E 2093147 N 0265656	102°46'30.00" E 18°55'02.10" N
6	Ban Tin Keo	BTK	E 0239031 N 2050174	102°31'40.80" E 18°31'33.70" N
7	Pakkanjung	PKN	E 0240072 N 2039409	102°32'23.74" E 18°25'43.39" N
8	BanKeun	BKN	E 0243429 N 2032122	102°34'18.75" E 18°21'47.57" N
9	Tha Ngone Bridge	TNB	E 0248068 N 2006759	102°37'06.95" E 18°08'03.95" N
10	Ban Hai Bridge	BHB	E 0294414 N 2011136	103°03'22.58" E 18°10'47.00" N

In addition to the stations mentioned, the Mekong River Commission operates three water quality sampling locations (NN1, Thalath and Tha Ngon). Data from 1985 to 2000 of the MRC stations was available for use in this thesis. Water quality is also being monitored by hydropower stations and major mining companies.

4.1.2 Nam Ngum 2 Reservoir Water Quality

The station names related to NN2 (ST1, ST4 and ST9) are integrated to the code system of NN2-Hydropower Station's Water Quality Monitoring Programme.

ST1 is located on the east side of the reservoir, near Ban Houayxai. An Au-Ag mine operated by Phu Bia Mining (PBM) is located to the south-east of the station and drains further into the reservoir. The station is on a good location for a reference station. (NREI, 2014) ST4 is located on a deep central sub-basin of the reservoir. ST9 is located in NN1 reservoir, 20 km downstream from the NN2R outlet.

The reservoir water quality is highly dependent on the seasonality in weather. The reservoir water is only mixed in the low water dry period and exhibits stratification from April-May.

NN2R is located in an area of low population density; therefore nutrient input to the reservoir are mainly natural runoff. Trophic state classifications are strongly based on chlorophyll content of the water, but data of chlorophyll is not available in the NNRB. Dissolved P concentration in 2013 is low (below 0.01 mg l^{-1}) in dry and wet season in the NN2. However, TOTP concentration exceeds by far the limit for eutrophic water (>0.020 mg l^{-1}) in all stations (see Figure 18). In addition, Secchi depth at all stations exceeded the limit for eutrophic water. NN2 reservoir may therefore be classified as a eutrophic water body.

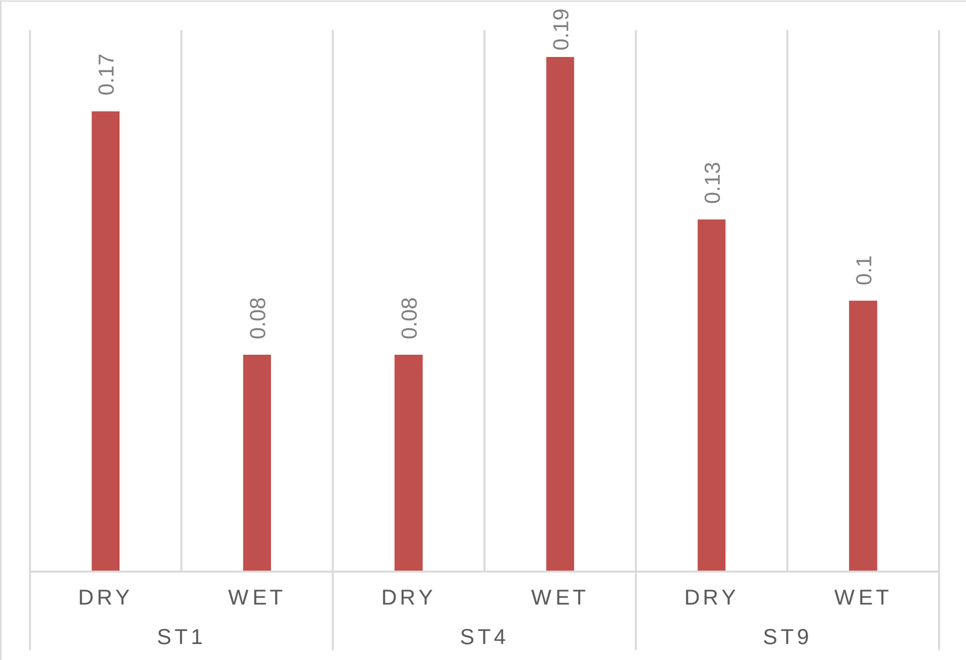


Figure 18. Total P content (in mg l^{-1}) in NN2 sampling points (ST1 and ST4) and downstream (ST9) in dry and wet season 2013. Data by NREI (2014).

Conductivity in the reservoir is generally in the order of 100 µS/cm; however, values as high as 1200-1400 µS/cm are found in waters coming from Phu Kham gold mine. This indicates that metal and TDS content is high in the mine waters. In addition, sulphate concentration from the PBM gold mine were 350-480 mg l^{-1} in 21-27 Oct 2013 while at the same time, the sulphate concentration in Nam Mo, which receives the mine water and drains into the NN2, had a sulphate concentration of 1-3 mg l^{-1}. (NREI, 2014)

ANC capacity of the reservoir is high with values above 1000 µeq/l. ANC limit for insensitive lake system in Eastern Canada is 200 µeq/l, which means that the reservoir system is insensitive against acid attacks.

4.1.3 Nam Ngum 1 Reservoir Water Quality

NN1 has been sampled in three different locations; ST9 for the incoming water from NN2R, NR2 for incoming water from Nam Song and NR1, sampling point in the deepest part of the reservoir near the outlet. In addition, a sampling point 500 meters downstream from NN1 outlet has been set up (Code BTK).

There are three main inlets of water to the NN1R. Two of them, as mentioned above, are sampled while the third, Nam Sane, is not. Water quality between sampling points NR2 and ST9 are highly different; NR2 inlet is not regulated by a dam, while the water quality flowing to ST9 is dictated by the reservoir NN2.

The trophic state for NN1 is eutrophic with similar conditions as in NN2 (TOTP >0.11 mg l^{-1}, Secchi depth <4.0). The same applies to ANC; the reservoir is an insensitive one, although it is noteworthy to mention that station ANC in the station NR2 is double to that of ST9 (1830 µeq l^{-1} vs. 920 µeq l^{-1}). Nam Song flows into the reservoir unregulated and brings in much more minerals than Nam Ngum which is heavily regulated. (NREI, 2014)

The dissolved oxygen level in the well-mixed epilimnion is good through the year. However, according to the NREI water quality reports, the DO concentration at the depth of 30m does not reach 4 mg l^{-1} even during winter mixing. Concentration of 4 mg l^{-1} is considered the limit for aquatic life. During wet season, values as low as 0,10 mg l^{-1} were recorded. (NREI, 2012) (NREI, 2014)

In 2012, stratification was also found to lower the pH in the hypolimnion. While pH is generally in the order of 7.5-8.5 in the surface layer, a sharp decline to values of 6.5-7 is observed at the metalimnion.

Hypoxic and anoxic conditions and low pH below metalimnion leaches out metals and phosphorus from the bottom sediments. This is a possible cause of the rising conductivity of water during wet season. In 2012, the concentration at depth of 15 m (metalimnion depth) showed the highest increase in conductivity (see Figure 19). The increase can also be attributed to increased TSS concentration in the water during high erosion wet season.

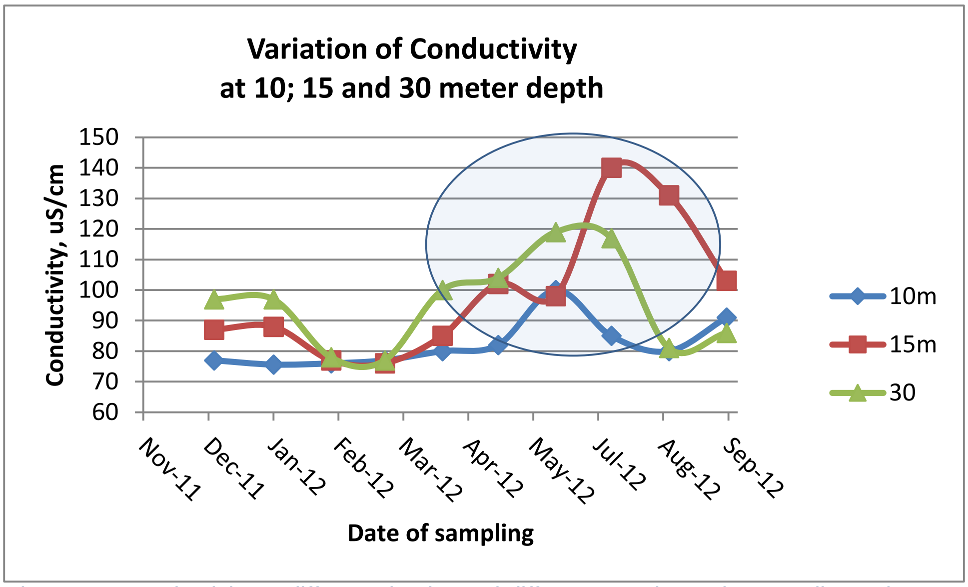


Figure 19. Conductivity at different depths and different months at the sampling point NR1 in 2012. (NREI, 2012)

The report from 2012 also notes the formation of H_2S, which was evident from the smell arising from the reservoir. This was also reported by Schouten in 1998.

4.1.4 Lower Nam Ngum Water Quality

The Lower Nam Ngum has a total of six water quality monitoring stations Five stations were used in the 2013 NREI water quality campaign. Here Nam Ngum is flowing through the most densely populated and farmed region of the whole basin.

Ban Tin Keo (BTK) is located 500 m downstream from the NN1R outlet and is therefore a representative location for the quality of water released from NN1. Pakkanjung (PKN) is located 16km downstream from BTK, after the confluence of Nam Lik and Nam Ngum. Bankeun (BKN) is 50 km further downstream in a town of the same name. Next point along the river is Tha Ngon (TNB), which is one of the stations used by MRC. Last point is Ban Hai Bridge (BHB), 20 km before the point where Nam Ngum discharges into the Mekong. In addition to the already mentioned stations, MRC operates another station called Thalath. The site is located on Nam Lik before the confluence with Nam Ngum.

The stratification and subsequent poor water quality of the hypolimnion in the NN1R affects the water quality downstream from the dam. This can be seen in the recorded DO-values just below the dam, which are considerably lower than those of Nam Lik River (Figure 20).

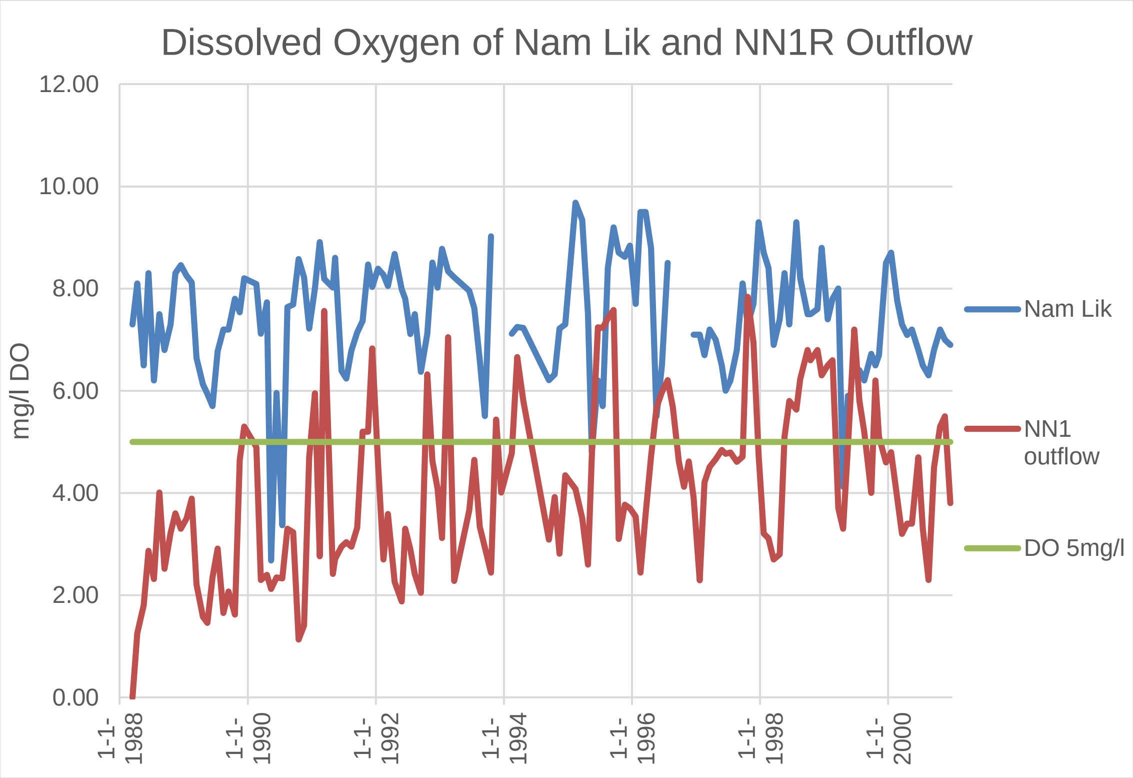


Figure 20. Dissolved oxygen content in water released from NN1R and Nam Lik (Thalath). Data by MRC.

The latest DO measurements from 2013 can be seen in Figure 21. The concentration of DO reaches a good status (>6 mg l^{-1}) only during February. DO of discharged NN1R water shows a clear trend of higher values in dry winter months than in wet summer months. This is probably due to the position of the inlet of water to the turbines of the dam. In the winter, some mixing of water occurs in the reservoir and the water intake is located in the epilimnion. During wet months, stratification and higher water level result in the water intake to be located in oxygen poor zone. The values recorded in 2013 are significantly lower than in the data by MRC at TNB.

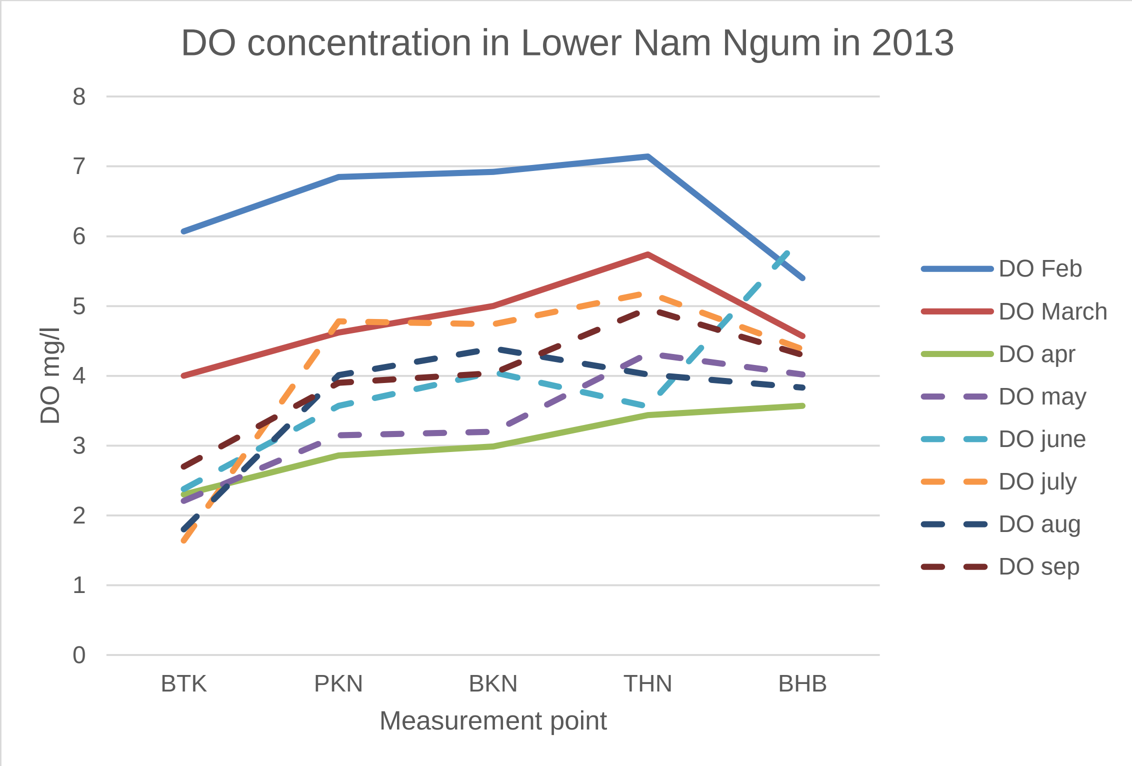


Figure 21. DO concentrations in Lower Nam Ngum in 2013. Solid lines represent dry and dotted lines wet season. Data by NREI (2014).

Conductivity in the LNN stays fairly constant. Slightly higher values were observed in the wet season than in the dry season. See Figure 22.

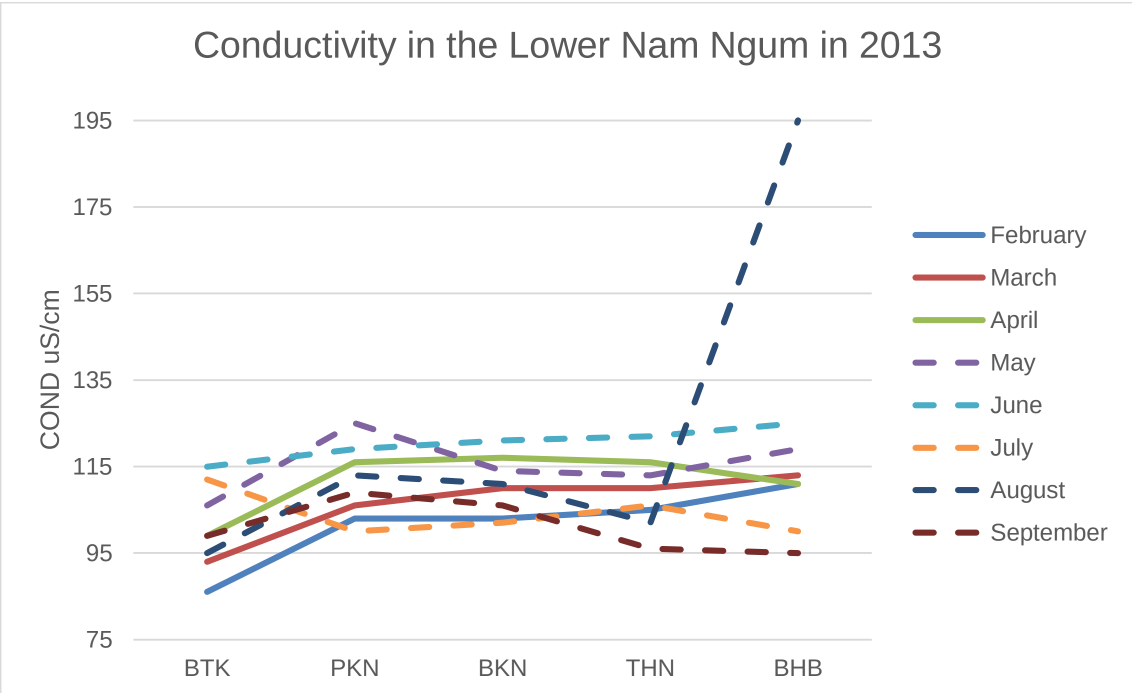


Figure 22. Conductivity in the LNN during 2013. Data by NREI (2014).

The measurement campaign of 2013 also sampled metal concentrations in the water during February and March. Cr, Cu, Mn, Ni, Pb, Fe, Zn and Cd were analysed and nearly all of the measurements (except for iron) were below detection limit of the method used. Cr and Zn were above the detection limit in March at the measurement station PKN. Figure 23 shows the concentrations detected.

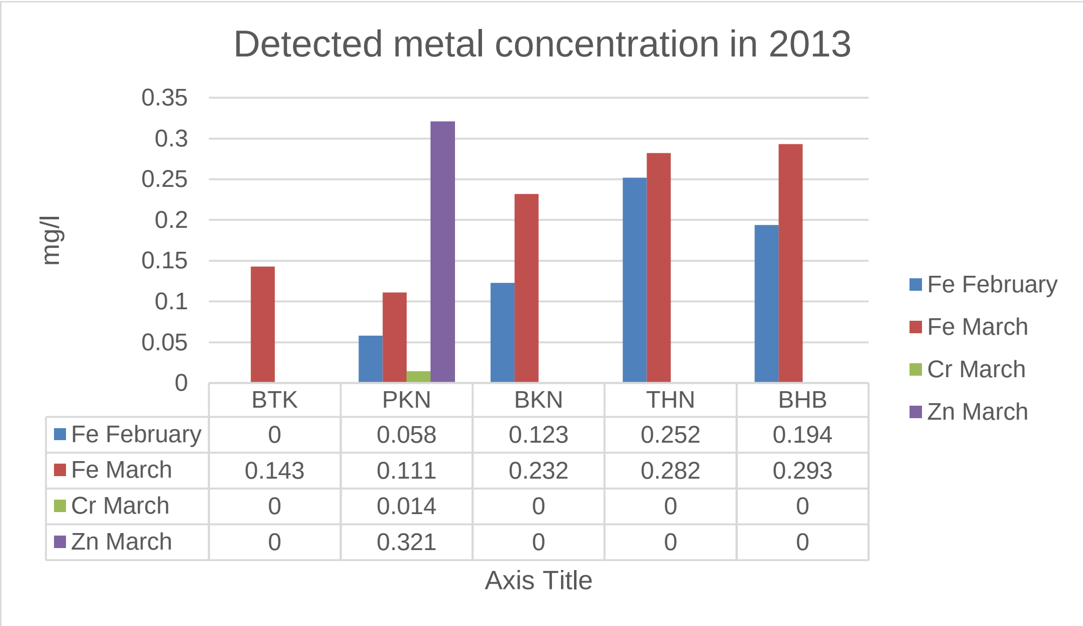


Figure 23. Detected metal concentrations in February and March 2013. The value 0 means that the concentration was below detection limit. Data by NREI (2014).

High concentration of zinc in Pakkanjung in March is noteworthy. This is probably due to a discharge from industry in the region. The rise of iron concentration between February and March could be resulting from lowered dilution capacity of water discharge. Iron concentration in the discharge from NN1 (station BTK) could be a result of leaching from sediments and subsequent release from the reservoir. Such an increase can be expected in advanced dry period. (Sracek, et al., 2012) However, the reported metal concentrations are below drinking water standards and thus the condition in the stream is good.

Nutrient content of the LNN has increased since 2000. Data from MRC at the station TNB from 1985 to 2000 show an average concentration of 0.021 mg l^{-1} for TOTP and 0.010 mg l^{-1} for DPO4 (median values of 0.015 mg l^{-1} and 0.006 mg l^{-1} respectively). The results of the recent survey on TNB can be seen in Figure 24. The average TOTP is 0.065 mg l^{-1} and DPO4 0.013 mg l^{-1}; however these averages are misleading due to the missing winter concentrations. The averages are likely to be lower due to lower P content of the dry season.

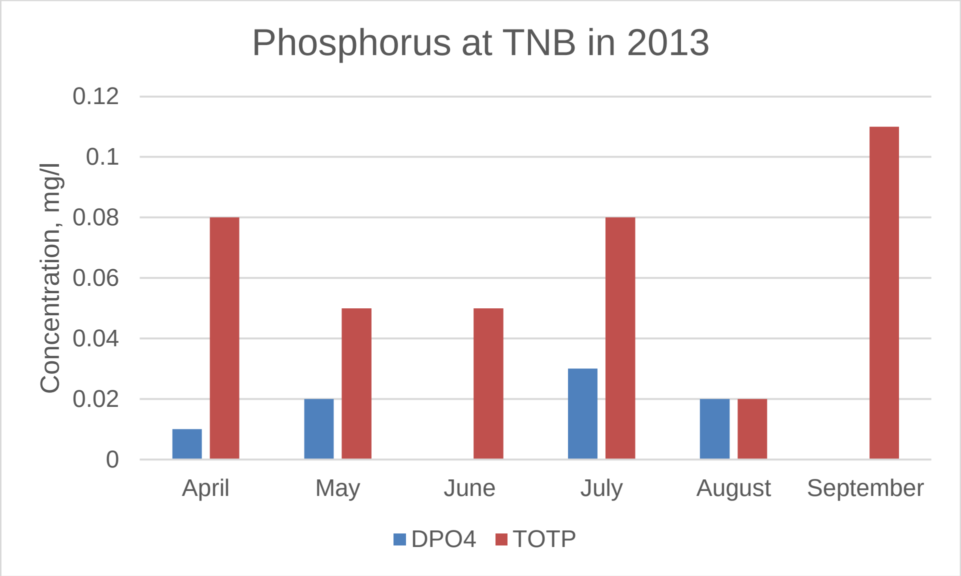


Figure 24. Phosphorus content of water at Tha Ngon Bridge measurement station in 2013. Concentration of DPO4 was below detection limit in June and September. (NREI, 2014)

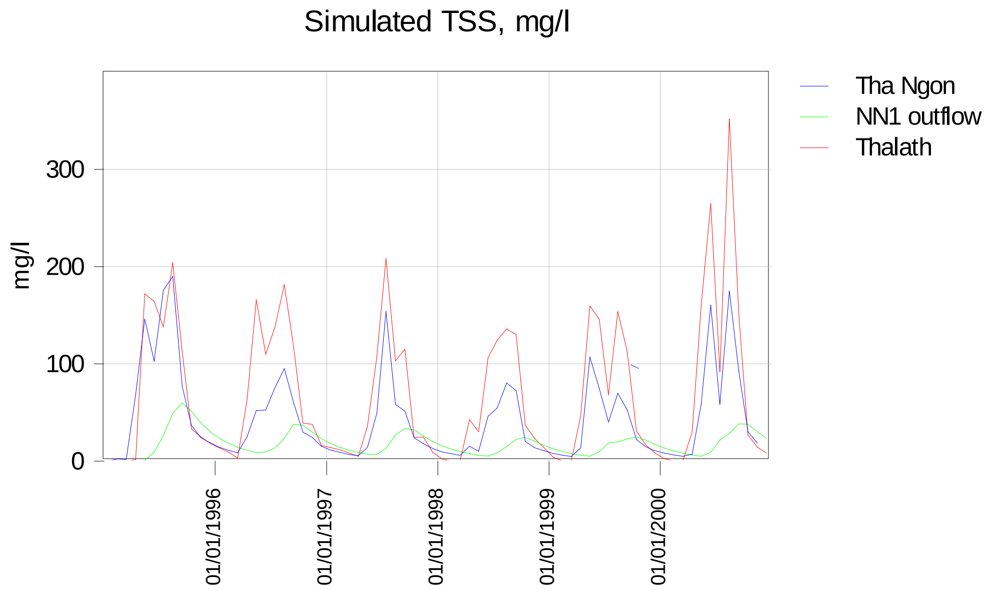
While the LNN river water is of good quality with most variables, low DO and fairly high nutrient content creates limitations for its use and for aquatic biota. The river exhibits some self-purification capacity, evidence of which can be seen in rising DO concentrations toward the outlet to Mekong. This was observed both in 2012 and 2013.

5 Results

5.1 Sediments

Sediments are important for the transport of metals and nutrients. The built and planned dams trap the sediments and the pollutants they carry into their reservoirs. Trapping can have a dramatic influence on the river downstream. In Brazil, building of Porto Primavera Dam reduced TSS content of Paraná by 96.5 %. Building of dams can have a profound effect on the hydrology of the river as well. Porto Primavera increased the erosion rate of the downstream stretch of the river by 230 % due to unnatural fluctuation of discharge and lower TSS concentration to replace eroded sediments. (Stevaux, Martins, & Meurer, 2009)

The regulation of flow in the Nam Ngum greatly affects the sediment processes in the basin. In the LNN, the concentration of suspended sediments is dictated by the SS content of largely unregulated Nam Lik and bank erosion along the river (see Figure 25). Sediments from mainstream NN are being trapped in reservoirs. A recent study by S. Dahal (2013) concluded that at any given time, more than 90 % of inflowing sediments to NN1 are trapped within the reservoir. Another study by Kummu et.al. (2010) resulted in sediment trapping efficiency of 44 %. The simulations in that study were run on data and model which included only NN1. The building of additional dams NN2, NN5 and the under-construction NN3 and NL1 reduce the available sediments in the river even further.



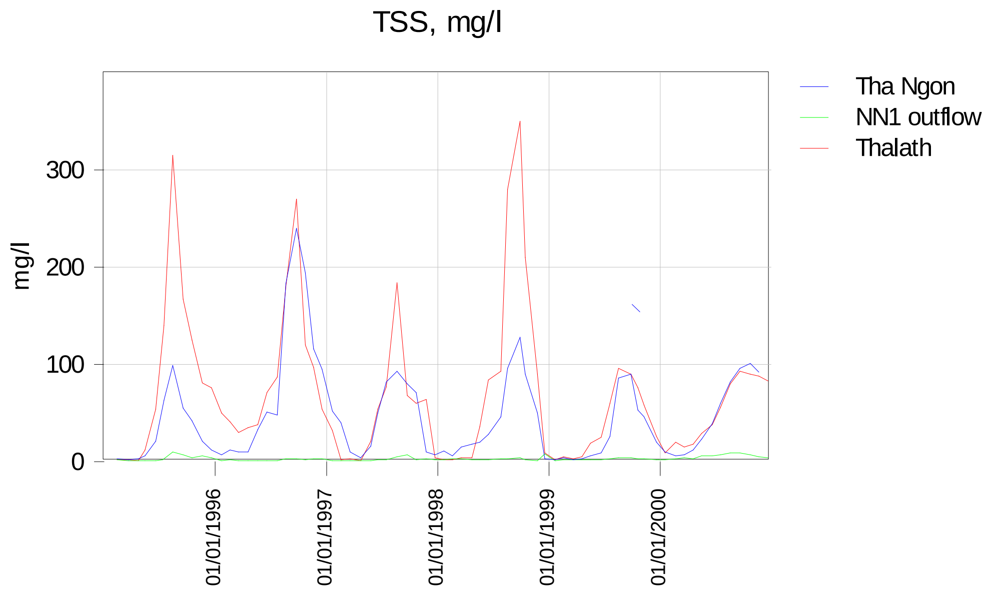


Figure 25.Simulated (up) and measured (down) TSS concentrations in the lower Nam Ngum between 1995 and 2001.

The residence times of the NNRB dams are given in Table 7. In general, all the currently operating reservoirs have high residence times; therefore it can be expected that they also have high sediment trapping efficiency. The calculation, however, does not take into account the true hydrology within the reservoirs nor their stratification.

Table 7. Residence times and average depths of the operating reservoirs at maximum and active storage level. Data from Nam Ngum River Basin Profile (WREA, 2008).

	Storage (m^3)		Surface area	Average inflow	Residence time (days)		Average depth (m)	
	Max	Active	km^2	m^3/s	Max storage	Active storage	Max storage	Active storage
NN5	3.18E+08	2.52E+08	14.6	17	216.50	171.57	21.78	17.26
NN3	1.32E+09	9.83E+08	25.6	110.8	137.89	102.68	51.56	38.40
NN2	6.77E+09	2.02E+09	87.22	193.5	405.18	120.94	77.67	23.18
NN1	7.00E+09	4.79E+09	369.4	427	189.74	129.84	18.95	12.97
NL2	1.10E+09	8.29E+08	42.2	99	128.48	96.95	26.04	19.65

In the NN1 and NN2 reservoirs, metalimnion layer (stratification) occurs at approximately 10-15 m depth. It is assumed that all of the operating reservoirs develop stratification during wet season at least close to the dam site where depth is at its maximum. Dam wall heights (Figure 26) are a good indicator of the depth of the reservoir near the outlet.

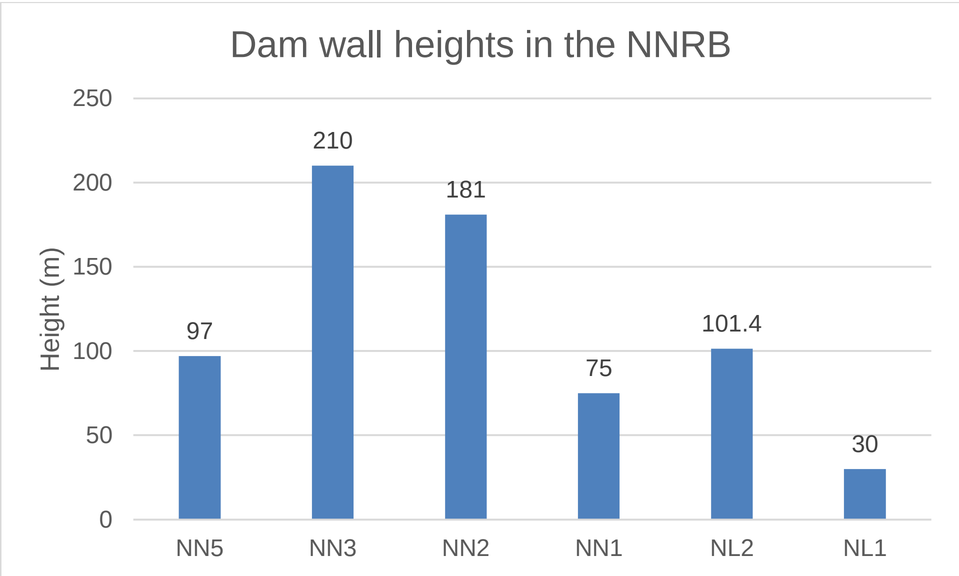


Figure 26. Dam wall heights of the operating and under construction reservoirs in the NNRB. (WREA, 2008)

The changes in river hydrology due to flow regulation have its influence on the local ecology as well. In Paraná, PP dam resulted in river substrate to change from fine-medium sand to medium-coarse sand due to erosion. (Stevaux, Martins, & Meurer, 2009) The requirements of aquatic flora and fauna to colonize a certain substrate depend on average particle size, pore space, degree of packing and surface topography. (Gordon, McMahon, Gippel, Finlayson, & Nathan, 2004) A change in substrate quality can therefore also affect species composition, richness and their colonization ability in either positive or negative way, depending on the species.

5.2 Mining

The environmental impact of mining always depends on the mining methods and the type of mineral mined. Table 8 shows a generalisation of the risk to surface water from different types of mines. In addition to the risks mentioned in the table below, increased suspended sediment load from mining operations pose a risk to the quality of water.

Table 8. Different types of mines and their risks to water quality. (Meck, Love, & Mapani, 2006)

Mine dump type	Risks to water quality
Minor metals	Arsenic, nickel, zinc, copper, acidity
Gold	Arsenic, zinc, copper, nickel, acidity
Base metals	Copper, zinc, nickel, cobalt, arsenic, acidity
Chromite and asbestos	No major risks
Platinum Group metals	Copper, nickel, cobalt, zinc, arsenic
Sulphur and arsenic	Arsenic, acidity

Soil in the NNRB is rich in aluminium. Aluminium can be toxic to aquatic animals when present in high concentrations and with low pH (Mason, 1996). The water flowing in NNRB is generally soft to moderately hard. Generally metals (lead is an exception) are more toxic in soft water than in hard one, as illustrated for zinc in Figure 27 below.

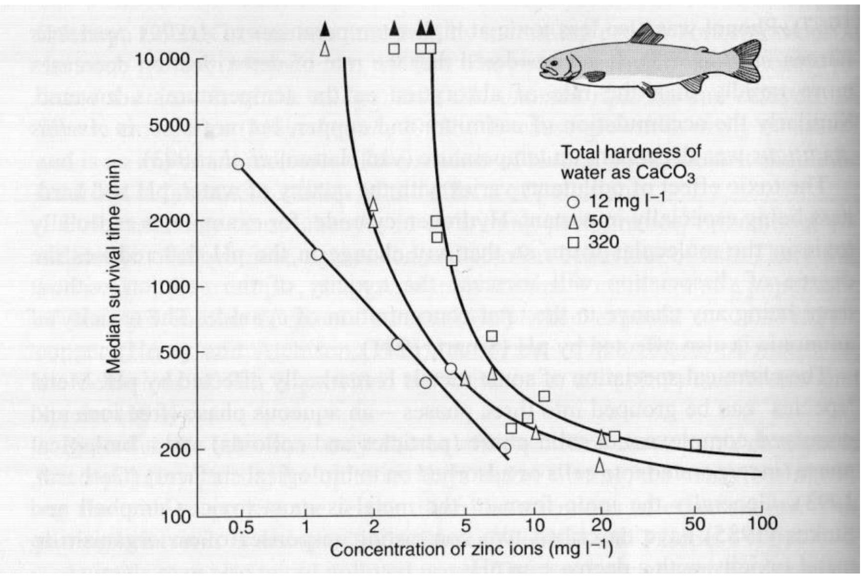


Figure 27. Median survival time of rainbow trout related to zinc concentration and water hardness. (Mason, 1996)

The highest zinc concentration of 0.321 mg l^{-1} (PKN in March 2013) in the data is not acutely harmful for fish in the soft or moderately hard waters of the Nam Ngum.

Heavy metals accumulate in sediments near mining sites, and depending on hydrology, elevated levels can be detected tens of kilometres downstream from the sites. (He, Wang, & Tang, 1997)

Mining operations where minerals containing sulphur are being processed, acid mine drainage problems can occur. This poses a great risk to the local aquatic system due to high acidity and high metal content of AMD. NNRB has a soil type which contains toxic amounts of Al and therefore rivers, lakes and reservoirs in the area receive high concentrations of Al naturally. Aluminium combined with low pH of AMD-impacted streams cause high mortality in all aquatic populations, including fish (Mason, 1996). Problems with AMD can be expected mostly in the wet season when water quantity is high and waste rock at mining sites have access to both water (via precipitation) and oxygen.

High volume of water in the wet season effectively dilutes any anthropogenic pollutants entering the water stream. In larger rivers, metals are likely to stay in particulate phase during wet season due to neutral or higher pH (high acid neutralization capacity of NNRB, Table 9) and good dissolved oxygen concentration. During dry season, water quantity and stream velocity are extremely low, and dissolved metal concentrations can be expected to rise (Sracek, et al., 2012). Unregulated streams are vulnerable against any spills from tailing dams and accidental spills from mining sites especially during dry season. These events can cause extreme deterioration of stream water quality. Small streams near mining sites are also vulnerable in the wet season due to small water quantity.

Table 9. ANC in Thalath, Tha Ngon and NN1 outflow based on historical data (1985-2000 by MRC). Values in meq/l

	Tha Ngon	Thalath	NN1 outflow
Average	0.870	1.510	0.744
Std.	0.186	0.508	0.167
Average deviation	0.148	0.438	0.128
Median	0.863	1.489	0.748
Maximum	1.308	2.434	1.304
Minimum	0.318	0.394	0.320

5.2.1 Effects on Ecology

Chronic pollution from mines typically results in communities with low species richness and high populations. In cases of chronic pollution, fish population can be expected to disappear downstream from these mining sites. In worst cases, only a very few tolerant animal species are present. Benthic communities can be wiped out by being smothered of metal precipitates at the bottom of the stream. The realized effect is a function of pH, alkalinity, hardness, dissolved organic matter and concentration of heavy metals. (Mason, 1996) Smothering of benthos by metal precipitates is the main water quality problem in streams receiving AMD in Scotland. (Younger, 2001) Figure 28 gives an example of the effect of zinc and nickel pollution (water concentration of 0.18 mg l^{-1} and 0.73 mg l^{-1} of zinc and nickel respectively, and sediment concentration of 0.83 mg l^{-1} 1.36 mg l^{-1} zinc and nickel respectively) on a small stream in Zambia. In this case, the absence of fish was probably due to absence of food sources (phytoplankton).

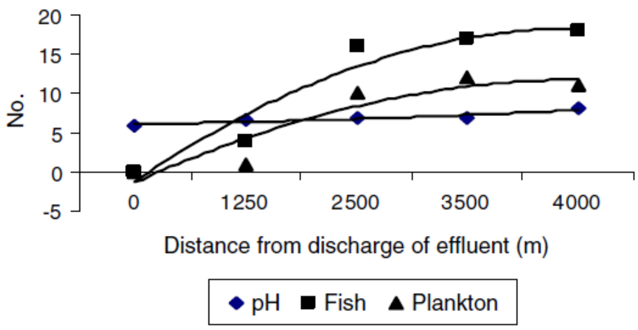


Figure 28. The impact of zinc and nickel pollution on a stream in Zambia. (Ntengwe & Maseka, 2006)

Episodic pollution can be nearly as harmful as chronic one. Streams affected by episodic pollution from mines may show only slightly higher biomass and species richness than streams receiving chronic pollution (MacCausland & McTammy, 2007).

5.2.2 Seasonality of metal pollution

The difference in water quantity and natural variation of water quality variables between dry and wet season causes also differences in (possible) pollution from mines. Only regulated rivers in the watershed (parts of Nam Ngum and Nam Lik) have considerable discharge all year round. All other tributaries exhibit extremely low flows and discharges. Due to the low stream velocity, discharge and depth in dry season, released metals and solids are likely to sediment near discharge site. These sediments are mobilized when the wet season starts, and are carried downstream. This is evident when examining the differences in TSS between dry season and wet season as shown for Thalath in Figure 29.

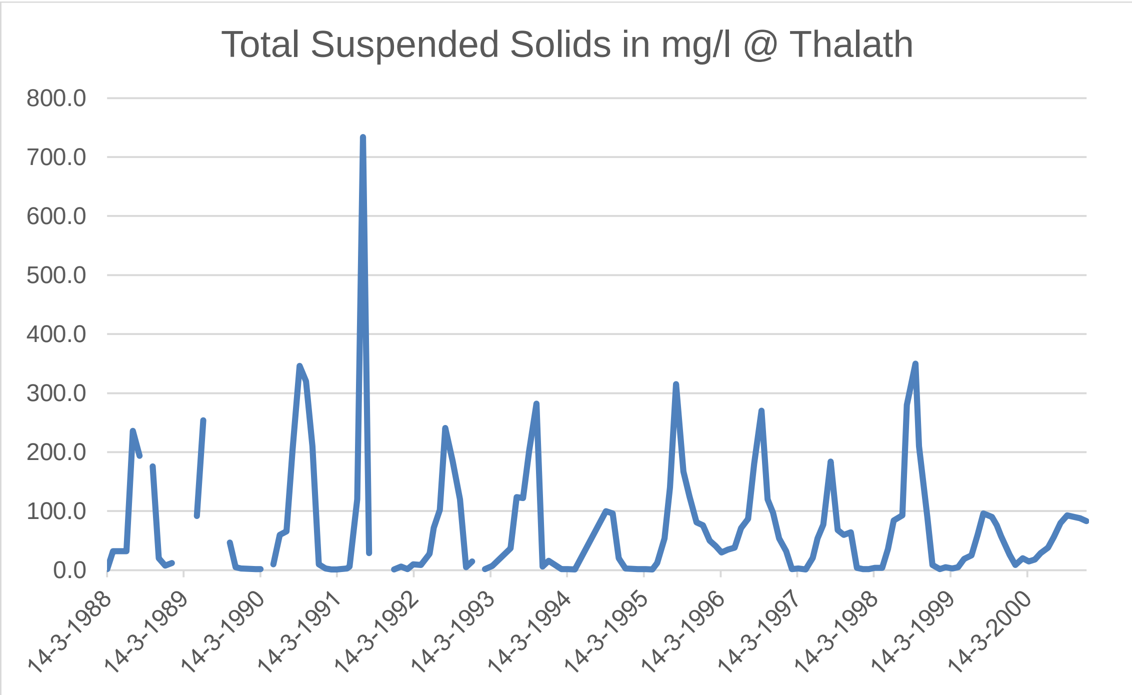


Figure 29. Measured TSS at water quality station Thalath from 1988 to 2000.

The values of environmental variables show the same pattern (although not necessarily as extreme as with TSS in Figure 29) with varying discharge over dry and wet seasons. The severity and effects of metal pollutants in the streams, lakes and reservoirs in the area is also largely dependent on the environmental conditions prevailing.

Metal contaminants in rivers can be expected to be at their highest concentrations in late dry season and early wet season. When mining, waste rock heaps are wetted after a long dry period, accumulated oxidation products are flushed out of the heaps and discharged into streams.

5.3 Upper Nam Ngum

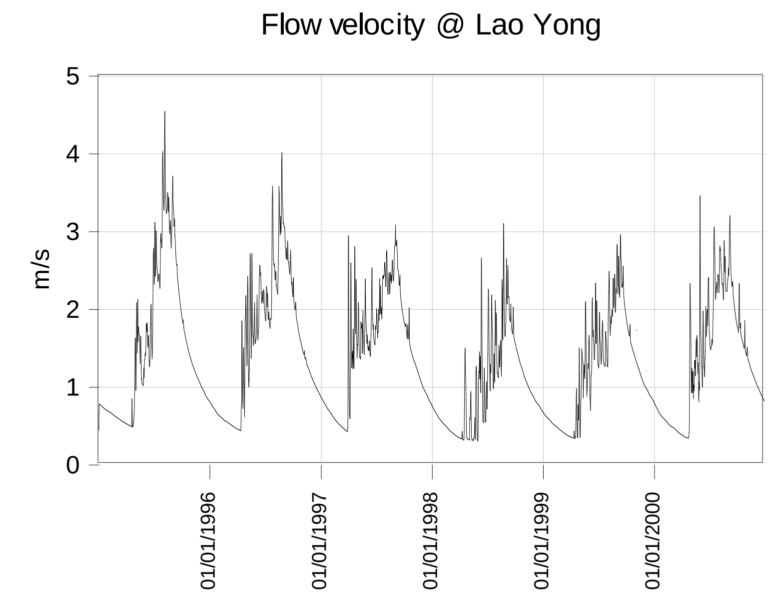
Most of the mining operations in the NNRB affect the upper part of the Nam Ngum catchment. This stretch of Nam Ngum is also the one with sediment trapping reservoirs and it is the most regulated stretch in the NNRB. Regulation of the river means that the natural extremely low dry period flows do not occur in mainstream Nam Ngum below NN5.

A few major mining sites operate in the UNN. These include Lao Yong ferrous metal mine (Peak District), Phu Bia Mining gold-silver-copper sites (Saysamboune District), a copper mining site (Hom district), and another ferrous metal site in Saysamboune District.

5.3.1 Lao Yong Ferrous Mine

Lao Yong Mining site is located in the Plain of Jars in the province of Peak. The site drains into unregulated part of the mainstream Nam Ngum via a small stream. High discharge and flow velocity (see Figure 30) of the river during wet season transports the pollutants far downstream. Pollutants can be transported as far as NN3 reservoir once it is finished in 2015. Nam Ngum flows in the Plain of Jars near largest population centres in the area. Pollutants affect the use of water in the area, including water used for irrigation.

The area where the Lao Yong site is situated (The district of Peak) receives the least amount of rain of the whole NNRB, in the order of 1400 mm/year, which also means that the quantity of water is lowest in this region. Due to low amount of water, the stream originating from the site is likely to be polluted by effluent and AMD from the site. The mine has waste water cleaning systems, but it is reported not to function properly, especially in the wet season. Concentrations of heavy metal are therefore likely to be high within the stream and in Nam Ngum downstream from the site. Stakeholders have reported fish kills downstream from the mining site (Idom, 2013).



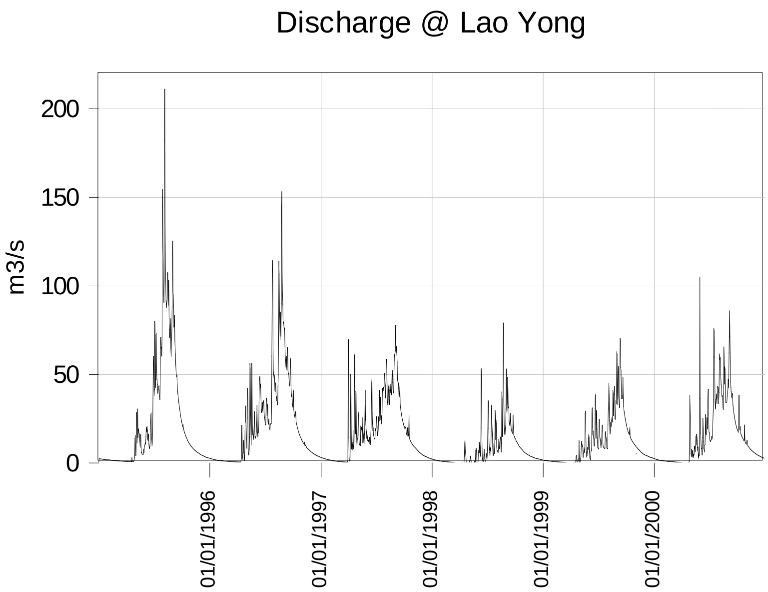


Figure 30. Simulated flow velocity and discharge of mainstream Nam Ngum at Lao-Yong ferrous mining site.

Table 10 shows analysed concentrations from AMD, discharge and surface waters near ferrous mines in the United States. It is noteworthy to see the low pH and extremely high sulphate concentrations in the AMD from ferrous metal mines.

Table 10. Examples of metal concentrations and pH of surface waters in or near ferrous mining sites.

Sample location	Average concentration in mg/l								
	Cu	Ni	Mn	Pb	Cd	Sulfate	Fe	pH	Source
AMD	0.62	17.6						4.5-8.5	1
AMD			121	0.05	0.02	5130	1.13	4.1	1
Discharge	1.7	40							1
Near site	0.45-1.17	14.5-15.4					0.1-0.6	5.0-6.1	1
Mine water	0.009-0.0034		<0.1	<0.01	<2.0	5.0-10.2	2.19-2.63	5.4-6.5	2
Upstream	Trace		0.092				7.53	6.8-7.8	3
at site	<0.022	<0.025	0.25				22	5.7-6.8	3
1,5km downstream	<0.02	<0.025	0.21				16.2	5.2-6.2	3
2km downstream	<0.01	<0.008	0.16				13.94	5.5-6.2	3

1 (U.S. EPA, 1994d)
2 (Tiwary;Singh;& Tewary, undated)
3 (Ghose & Sen, 1999)

As mentioned earlier, the streams are most vulnerable during dry season due to small discharge. Mining sites operate all year round. Assuming that the ANC capacity at Thalath (based on historical data between 1985-2000, no flow regulation) is representative for unregulated river in NNRB, Nam Ngum can neutralize 1.15 meq/l acids in advanced dry season. Simulated flow of Nam Ngum at Lao Yong site can be as low as 0.3 m^3/s. The wet season flow of Nam Ngum on the other hand is high, effectively diluting pollutants entering the mainstream. Some of the metal pollution may find its way to reservoirs downstream.

Once operation starts in 2018, NN3 reservoir will exhibit similar stratification and subsequent oxygen depletion in the hypolimnion as described for NN1 and NN2 in chapter 4. Anoxia lowers pH in hypolimnetic water which increases metal leaching from the sediments. In case the water intake of the NN3 dam is below thermocline, dissolved metals are released downstream. The effect lasts as long as the metals stay in solution. Since concentrations in released water will probably not be very high and the good ANC capacity of the river, metals precipitate quickly out of solution and will follow the movement of the sediments they adhere to. Because of regulation, the stream velocity will remain high (simulated minimum value 3 m s^{-1}), and metals are likely to stay in particulate form while they stay in riverine environment.

5.3.2 Qin Huang Dao Xin He Ferrous Mine

Qin Huang Dao Xin He (QHDXH) has a ferrous mining site operating Saysamboune. The site is located to the east from NN2 reservoir though the exact location of the site could not be found for this thesis. Most likely the site lies 30-40 km upstream Nam Mo from the reservoir.

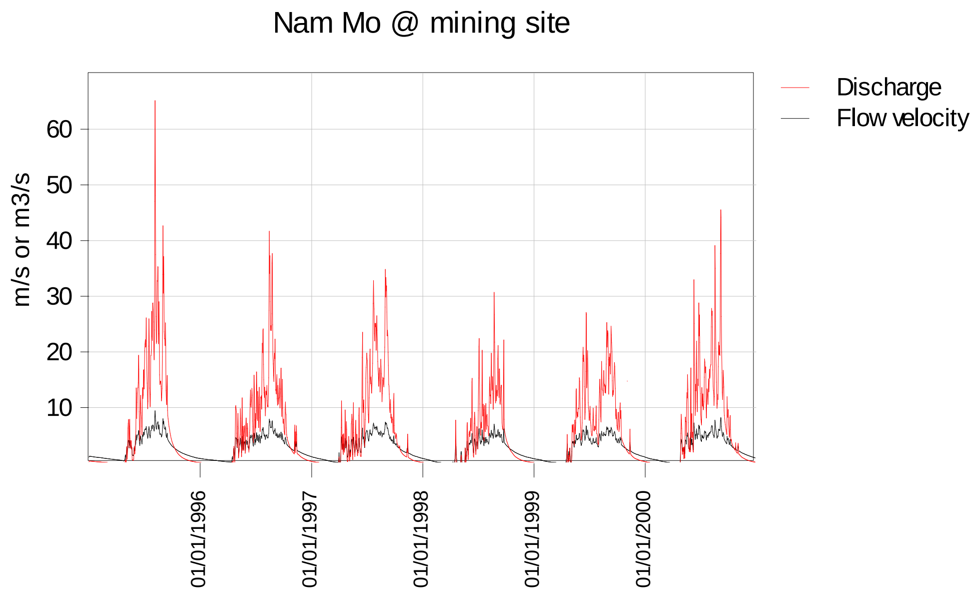


Figure 31. Simulated discharge and flow velocity of the river Nam Mo near the approximate location of the QHDXH ferrous mining site.

Nam Mo, the tributary of Nam Ngum flowing in the site area is unregulated; therefore it exhibits the same characteristics as Nam Ngum near the Lao Yong site. According to simulation, the flow velocity of Nam Mo reaches nearly zero in advanced dry season and reaches a maximum of 8 m s^{-1} during wet season. Dry season discharge can also reach near zero while the summer maximum discharge can rise up to 60 $m^3 s^{-1}$ (see Figure 31 above).

The effluents and AMD from the site is likely to pollute the area around the site in the same way as described above for Lao Yong. Polluted sediments from the site are highly likely to reach NN2 reservoir, however, Phu Bia Mining gold-copper site is a more important source of pollutants to the NN2 reservoir.

5.3.3 Phu Bia Mining Sites

Phu Bia Mining (PBM) operates two mining sites in the vicinity of NN2. In addition to the operating Phu Kham (PK, gold-copper) and Ban Houayxay (BH, gold-silver) mines, PBM has three prospective sites around NN2R. Gold producing mines are located in the vicinity of the reservoir itself. The locations of the sites are shown in Figure 32.

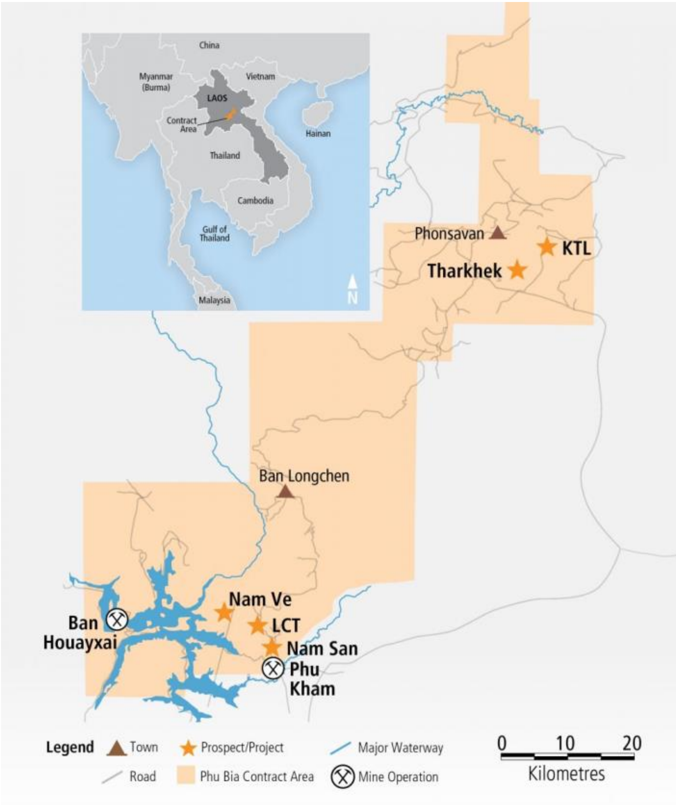


Figure 32. Locations of Phu Bia mines and exploration gold mining locations. (PanAust, 2013)

Discharge from PK enter Nam Mo approximately 5 km before entering NN2 reservoir. According to simulation, Nam Mo has an average winter (dry season) flow of 2.5 m^3 s^{-1} and an average summer (wet season) flow of 40.7 m^3 s^{-1} at the mining site. Maximum flow can exceed 200 m^3 s^{-1}. The stream flow velocity at the site varies between a minimum of 0.3 m s^{-1} to the maximum of 13 m s^{-1}. The variability of stream velocity and discharge can be seen in Figure 33. The flow velocity and discharge are considerably higher here than at QHDXH ferrous mining site further upstream.

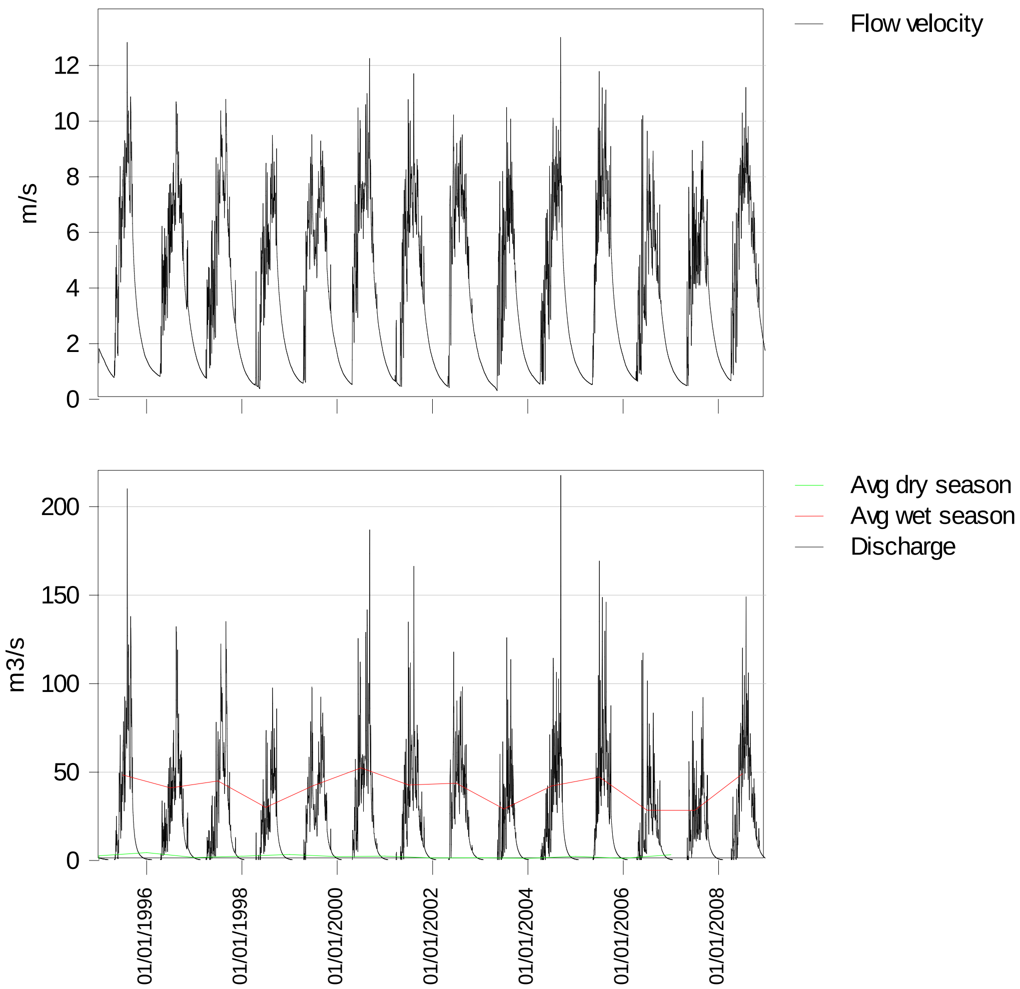


Figure 33. Simulated flow velocity and discharge of Nam Mo River at Phu Kham mining site.

Prior to operation, PBM estimated that the greatest potential risk to the environment from operation is AMD. The site is predicted to produce 150 million tons of waste rock during its lifetime (until 2021), of which 60 % is estimated as having potential for AMD formation. With an average sulphur content of 3 %, the maximum potential amount of sulphuric acid produced in the site is 91.8 kg H_2SO_4 per ton of waste rock. (Phu Bia Mining, 2013)

The mining waste that is potentially AMD forming are treated according to their risk potential. The most risky material is placed permanently under water with a protective alkalinity of more than 30 mg l^{-1} and no dissolved oxygen. Medium risk waste is isolated from oxygen by burial and compaction of covering material. The safety measures have led to effluent water quality that is of fairly good quality. (Phu Bia Mining, 2013) However, it has been reported by local stakeholders that the PK and BH gold mines produce water quality problems (water chemistry, suspended solids load) to nearby streams. (Idom,

2013) In addition, NREI (2014) reports of high conductivity (an indicator of metal pollution and/or excess mineral content) of the water originating from the Phu Kham mining site.

Waste water from the PK and BH gold mining sites also affect the water quality of NN2 reservoir. BH is situated at the banks of northern part of the reservoir and PK, via smaller streams and Nam Mo, affects the southern part. Since NN2R is made up of small sub-basins, the discharge water from NN2 is probably not excessively polluted by mine pollution. Theoretical residence time of the NN2 is 120-410 days (see Table 7, page 39) which indicates a high sediment trapping efficiency. The long residence time also hints for retention of metal pollutants in the reservoir. Since the reservoir is made of smaller sub-basins, the areas of highest metal pollution are likely to be found in sub-basins that receive polluted water and sediments.

Table 11. Examples of water quality and sediment variables related to gold mines.

Sample media	Sample location	Average concentration									pH	Source
		Cu	Ni	Zn	Pb	Cd	Co	Cr	Hg	Fe		
Water mg/l	Leachate	2.48	3.12	0.76	0.84	0.07	2.08	2.83			2-8	1
	Surface water	3.39	2.37	3.7	1.02	0.12	1.95	2.48			Neutral	1
	Surface water								1.85			2
	Sedim. pond	2.4-7.68							0.01		10.2-11.4	3
	Discharge	0.026-0.183									8.4-8.9	3
	At site	9.23	1.02	0.74	0.003	0.005	1.19					4
	Near site	1.64		1.01	0.07	0.03		0.01	0.06			5
Sediment mg/kg	Sediment	Acc.		Acc.	Acc.				1.5-30 x incr.	Acc.		2
	Sediment	41.2	19.2	25.9	18.4		6.9	11.8			6.1	4
	Sediment at site	4.47	22.6	94.6	0.004	0.224	0.92	0.95			6.45	4

Acc. Accumulation

1 (Meck;Love;& Mapani, 2006)
2 (Palheta & Taylor, 1995)
3 (U.S. EPA, 1994b)
4 (Almås;Kweyunga;& Manoko, 2009)
5 (Liang;Yang;Dai;& Pang, 2011)

Table 11 above and Table 12 below give examples of the environmental effects of gold and copper mining respectively. Potential adverse effects to surface waters from gold mining operations include AMD, leaching of cyanide and mercury used in the process, increased sediment load on the river and release of heavy metals (U.S. EPA, 1994b)

Table 12. Average values of water quality analyses near a copper mining site in China. (He, Wang, & Tang, 1997)

	Ref site	Mine site	20km	50km	84km	230km (lake mouth)
Cu in sediment (mg/kg)	36	2878	2173	1012	733	215
Conductivity (mS/cm)	86	390	164	196	133	
Alkalinity (CaO, mg/l)	20.88	0	20.88	19.9	16.11	
Turbidity (SiO2, mg/l)	3.12	24.31	40.12	23.45	116.1	
pH	7.05	5.18	6.74	6.86	7.01	
Minimum pH	6.55	3.24	6.3	6.3	6.5	

As shown in chapter 264, NN2 shows signs of strong stratification. Anoxia, lowering of pH and leaching of metals from the bottom sediments will occur in the reservoir. The quality of water drawn from the reservoir flows straight in to NN1 reservoir. The mouth of NN1 is an important fish spawning site (Schouten, 1998) and the discharged water has a direct influence on the success of fisheries.

5.3.4 Nam Ngum 1 Reservoir

NN1 reservoir is fed via three main inlets; Nam Ngum, Nam Sane and Nam Song through a water transfer via a diversion dam. The mining-related pollution from NN2 reservoir is negligible, which leaves the other two rivers as the main risk for pollutants.

Lead and lead-zinc mines and limestone quarry are the main sources of mining related pollution to the NN1 via Nam Song diversion. This inlet was sampled in the NREI water quality campaign of 2013, but it yielded no evidence of detectable metal pollution. Conductivity from this source corresponds well with the measures conductivity from NN2R and falls in with natural levels (Conductivity in the inlet is 196 uS/cm).

Nam Sane inlet has not been sampled and therefore evidence of metal pollution entering the reservoir could not be determined. According to Idom (2013), a copper mine operates in the Nam Sane watershed, but for this thesis the site could not be located.

The amount of metal pollution arising from mining operations that finds its way to NN1 is negligible. In situations where substantial amounts of metals enter the reservoir, they are likely to quickly sediment near the inlet. The high residence time of the reservoir (130-190 days, see Table 7, page 39) suggests that the pollutants will stay in the reservoir bottom indefinitely.

5.4 Nam Song

Lead-zinc mines, limestone quarries (and cement factories) operate in the Nam Song catchment area, upstream from Nam Song diversion dam. Downstream from the diversion, First Pacific Mining operates a coal mine. Figure 34 shows a map of the Nam Song water shed until Nam Song diversion dam.

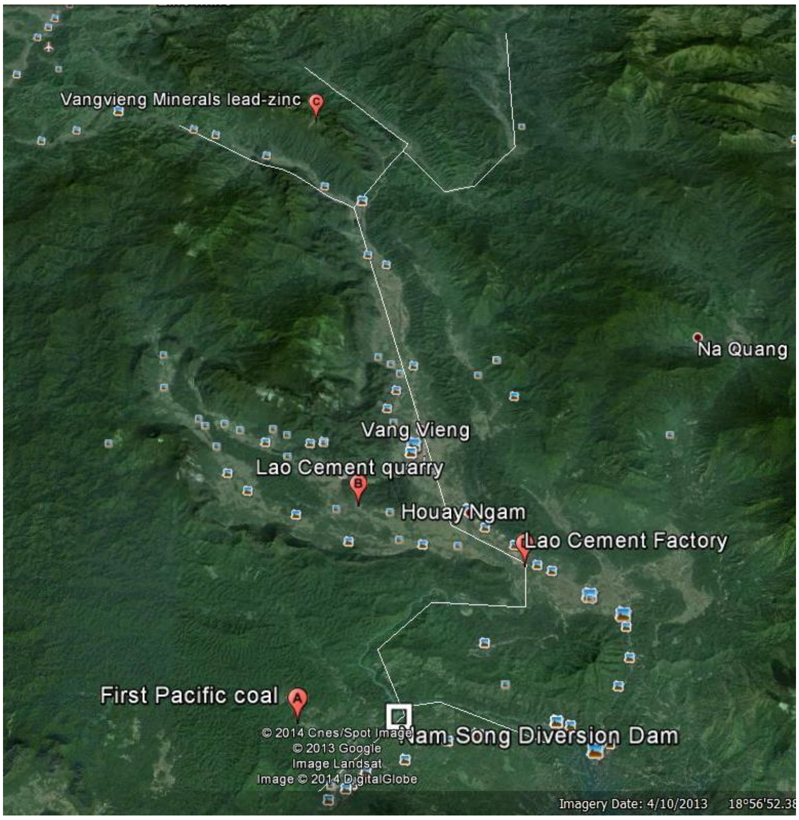
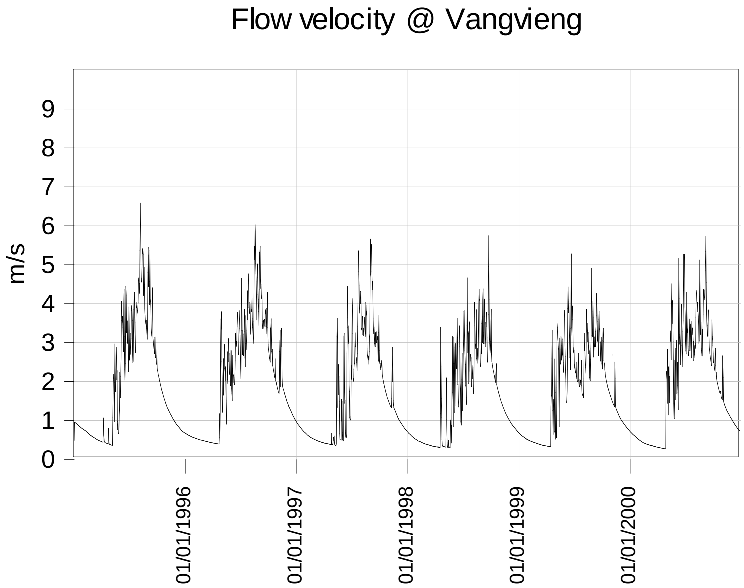


Figure 34. Map of Nam Song area with the most important (located) mining operations. The white line corresponds to the approximate river course.

The diversion dam feeds extra water to the NN1 reservoir. Limestone quarries, cement factories and industry operating in the Vangvieng area therefore affect the water quality of the reservoir.



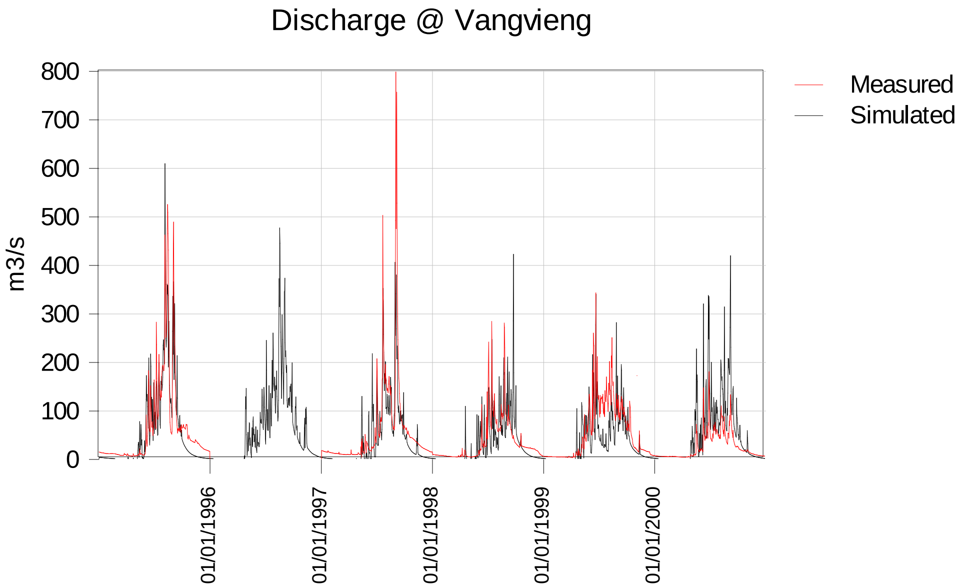


Figure 35. Measured and simulated discharge and simulated flow velocity at Vangvieng.

Nam Song is an unregulated river; therefore it exhibits the extremely high and extremely low discharges annually. The measured and simulated discharge from the station Vangvieng are shown in Figure 35 above. Minimum measured flow between 1995 and 2000 was 4 $m^3 s^{-1}$.

The low dry season discharge and flow velocity creates the same problems as described earlier for the other unregulated streams. The capacity to neutralize acids and receive effluent from mining operations and industry is extremely limited compared to wet season.

5.4.1 Vangvieng Minerals Lead-Zinc Mine

Vangvieng Minerals has mining concessions for one lead-zinc (Pha Luang) mine and two ferrous concessions in the Nam Song watershed, north of Vangvieng City.

Pha Luang site produces 300 000 tons and 200 000 tons of Zn and Pb concentrates respectively, over its predicted lifetime. The mining effluents flow down steep hillslope into unregulated stream above Pha Tang (a town north of Vangvieng). Some examples of mine effluents from Pb-Zn mines are given in the Table 13 below.

Table 13. Examples of average concentrations of metals and pH in waters associated with Pb-Zn mines.

Sample media	Sample location	Average concentration mg/l						pH	Source
		Cu	Zn	Pb	Cd	Ni	Fe		
Water (mg/l)	Discharge min	10	6		0.1		50	2.6	1
	max	12	30		0.1		240	2.9	
	Discharge min	2	3		2		9	2.9	1
	max	13	12		12		140	3.8	
	Water downstream min	3	10		0.05		50	3	1
	max	15	80		0.3		350	3	
	Water downstream min	0.009	0.047	0.0013	0.002				1
	max	0.034	0.57	0.0077	0.009				
	Discharge	0.15	0.75	0.3	0.05			7.8	1
Sediment (mg/kg)	Water downstream		0.18			0.73			2
	Sediment downstream		0.83			1.36			2
	Sediment upstream		202	29				7.08	3
	Sediment at site		878	208				6.86	3
	Sediment 30km downstream		664	94				7.01	3
	Sediment 200km downstream		226	81					3
	Upstream sediment (mg/kg)	112	289	92	2.3				4
	At site sediment (mg/kg)	509	6714	6915	36				4
	10km downstream sediment		1724	739	6.4				4

1 (U.S. EPA, 1994c)

2 (Ntengwe & Maseka, 2006)

3 (He, Wang, & Tang, 1997)

4 (Giddings, Hornberger, & Hadley, 2001)

As with other types of mining pollution, the resultant concentrations in water and sediments are the result of the mining methods and mineral quality. The polluted metal particulates flow downstream towards Vangvieng only 20-30 km away. Nam Song flows fairly slow and with small amount of water near the mining site (see Figure 36), which limits sediment transport downstream. High concentrations of metals can be expected along the river north from Pha Tang.

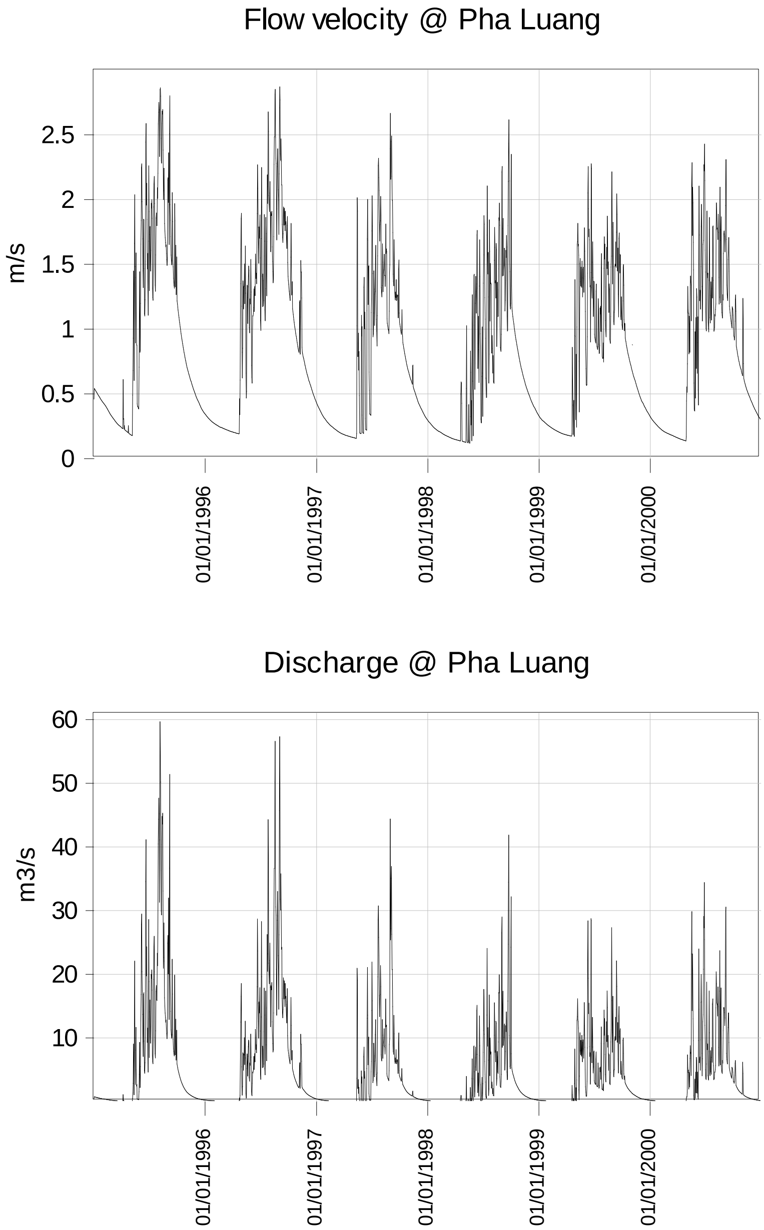


Figure 36. Simulated discharge and flow velocity of Nam Song at Pha Luang Pb-Zn mine.

No measurements of water quality along Nam Song were available at the time of writing this thesis.

5.4.2 First Pacific Coal Mine

First Pacific Mining Limited (FP) operates a coal mine near the town of Vang Khi downstream from the Nam Song Diversion Dam.

Coal mining effluents and AMD are often very acidic. Examples of effluent water quality are provided in Table 14. Streams affected by coal mining usually have high levels of one or more heavy metal and phosphate, nitrate and ammonia. (Mason, 1996)

Table 14. Examples of average concentrations of metals and pH in waters associated with coal mining.

Sample location	Average concentration (mg/l)						
	Zn	Mn	Mg	Sulfate	Fe	pH	Source
AMD				4.54	1.25	2.9	1
0.5km downstream				2	0.11	2.9	1
1km downstream				1.02	0.27	3.1	1
2km downstream				0.92	0.12	3.2	1
Mine water	0.07	2	60	247	14	5.8	2
AMD	0.8	24.5	115	2475	43	3.7	2
Abandoned mine water	0.08	2.3	73	595	40	6	2

1 (Bigham, Tuovinen, Brady, & Logan)
2 (Younger, 2001)

The resultant effluent and AMD quality is, like in other mining operations, determined by the quality of waste mineral and the operation of the mine. A good point of comparison are coal mines in Vietnam. Table 15 shows average values of various environmental variables from coal mining sites in Vietnam, collected by Chinh et.al. (2007).

Table 15. Water quality at coal mining sites and waters discharged from the mining sites in Vietnam. (Chinh, Gheewala, & Bonnet, 2007)

No.	Parameter	Coal mine[a]	Coal cleaning[b]	Uncontaminated river[a]
1	pH	3.5	6.2	6.5
2	BOD_5 (g/m^3)	52.4	13.6	42.6
3	Total suspended solid (g/m^3)	103	68	4
4	Total solid (g/m^3)	278.47	NA	6.30
5	Arsenic (As) (g/m^3)	0.0056	0.0046	0.0021
6	Total Nitrogen (N) (g/m^3)	1.75	NA	1.12
7	Total Phosphorus (P) (g/m^3)	1.40	NA	0.26
8	Cadmium (Cd) (g/m^3)	0.11	0.012	0.03
9	Total Chromium (Cr) (g/m^3)	0.0046	0.0002	0.0029
10	Copper (Cu) (g/m^3)	0.34	0.012	0.05
11	Iron (Fe) (g/m^3)	234	2	0.6
12	Manganese (Mn) (g/m^3)	12.02	0.86	0.46
13	Mercury (Hg) (g/m^3)	0.0008	0.0005	0.0001
14	Lead (Pb) (g/m^3)	0.056	0.006	0.003
15	Nitrates (NO_3^-) (g/m^3)	6.85	1.64	0.67
16	Sulfates (SO_4^{2-}) (g/m^3)	745	351	32
17	Oils (g/m^3)	1.4	0.2	0.0

[a] Sampling in mining site.
[b] Summarized wastewater discharge from all screening/preparation plants, monitoring in 2001.

If operated irresponsibly, coal mining can result in complete devastation of streams and rivers for decades. In Pennsylvania, chronic and episodic AMD pollution from coal mining area reduced the amount of benthic macroinvertebrae from 1268 individuals/m^2 (reference site) to 61 individuals/m^2 (sites with episodic pollution) or 39 individuals/m^2 (sites with chronic pollution). Any large scale recovery of the polluted streams in Pennsylvania took at least 60 years, and is attributed to the exhaustion of pyrite (acid forming) materials. In Scotland, coal mining has impacted some streams so severely, that water has been rendered unusable indefinitely. (Younger, 2001; MacCausland & McTammy, 2007; Raymond & Oh, 2009)

Possible pollution from the FP coal mining site flows through a small stream to Nam Song, just upstream from the village of Vang Khi. The mining site was expected to produce approximately 32 000 ton/month over 6.5 years. (Choochang, 2006) Coal production produces wastewater of approximately 2400 m^3 per ton produced. Most of the wastewater is produced in processing plants, which are not operating at the FP site. However, the mine waters contain high concentration of heavy metals and have very low pH, which means that there is a high risk of water pollution near the town of Vang Khi.

The very low pH of coal mine waters (pH of 3.4 from Table 15) has severe effects on the stream biota. Figure 37 shows the pH tolerance of benthic macroinvertebrae in Norwegian lakes. The pH of the Vietnamese coal mine waters is so low that it may be expected to have very low amount of biota present.

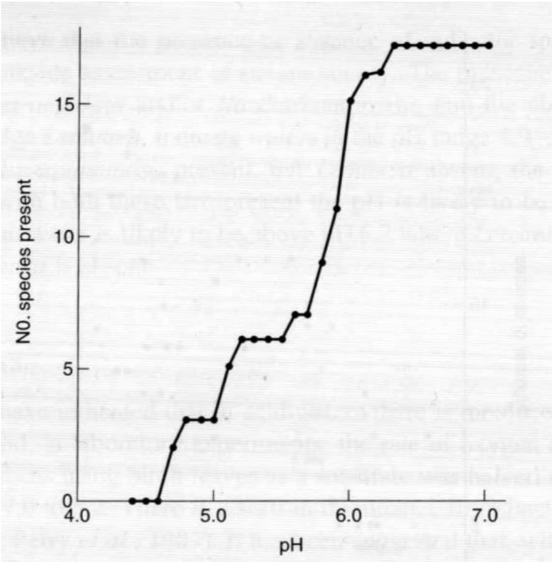


Figure 37. pH tolerance of 17 species of crustaceans, bivalves and snails in Norwegian lakes. Based on data from 1500 lakes. (Mason, 1996)

The coal is mined in an area with small streams and no regulation, so the previously explained risks of low dry season water quantity and high wet season precipitation apply here. The exact location of the mine could not be determined; however simulation suggest that in the approximate location discharge does not exceed 5 $m^3 s^{-1}$ even in the wet season. This makes the surrounding streams have very high risk of disastrous pollution.

No data on the water quality in the area was available for the writing of this thesis.

5.5 Nam Lik

There is only one major mining operation on-going in the Nam Lik watershed. Concession areas of operating mines overlap Nam Lik watershed, but it was not possible to confirm whether these operate within the drainage basin or not. A copper mine exploration area is also located in the southern part of the watershed.

A zinc mine is operated 5 km to the east from the town of Kasi. As with most of the other mining sites, the stream here is unregulated. Being in headwaters region, the water quantity and stream velocity here are low (simulated discharge go near zero, while maximum discharge is around 60 $m^3 s^{-1}$). The mine drains via a stream to the farmlands and villages around Kasi. This creates a high risk for water when water is withdrawn from the river to be used in irrigation or drinking water.

Pollution is unlikely to travel further than the NL1-2 dam, approximately 60km downstream from the town of Kasi. The reservoir has a residence time of 98-129 days. The high residence time results in sedimentation of SS to the bottom. Due to the depth at the dam (the dam wall is 101.4 m high) stratification is likely to occur and previously described anoxia and metal leaching may possibly happen.

Further downstream Nam Lik receives pollution from FP coal mining site on the Nam Song. The confluence of the two rivers is located approximately 30 km downstream from the coal mine. Nam Song is half-regulated in this stretch by NSD. The river in here experiences the same extreme high and low discharges (Figure 38) as many other mining sites in the NNRB.

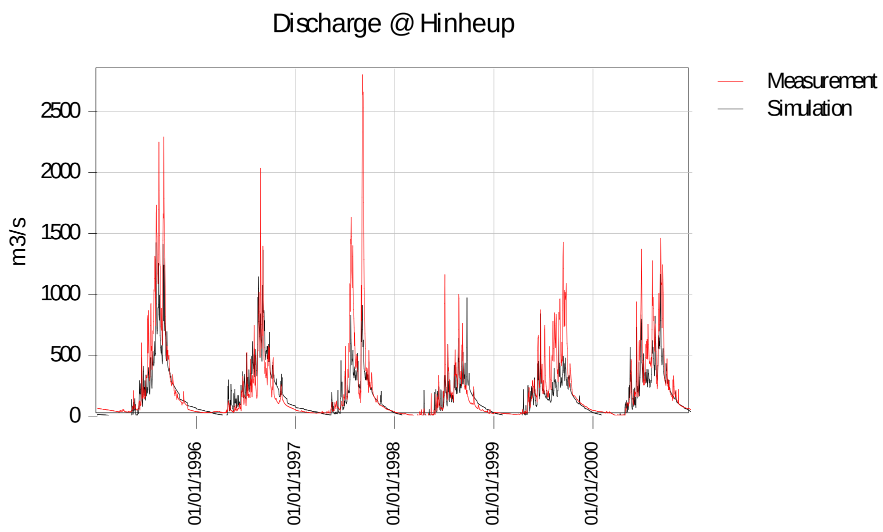


Figure 38. Simulated and measured discharge of Nam Lik at Hinheup. Station located a few kilometers downstream from the confluence with Nam Song.

The potential metal pollution from the coal mining site are transported downstream to (to be built) NL1 reservoir at Hin Heup. NL1 is a shallow reservoir (dam wall height of 30 m) with small storage capacity. Sediment retention efficiency is likely to be small; therefore metal pollution may pass through the reservoir and be discharged downstream.

5.6 Lower Nam Ngum

The Lower Nam Ngum is relatively unimpacted by mining operations of the upper part of the basin judging from recent monitoring data by EMSP/NREI (2014). Most of the population and industry of the NNRB is located in the Vientiane Plains through which Nam Ngum flows. The stress induced by the industrial operations is far more important in terms of their effect on water quality in the area than mining operations. This can be seen in, for example increasing iron concentration in downstream direction (see section 4.1.4).

However, a few sites do exist in the LNN. Lao-China Potassium operates two potassium mines in the eastern part of the LNN, close to the outlet of NN to Mekong River. The population density in the eastern part of Vientiane Plains is lower than in the west that is close to Vientiane City. There is no evidence, however, that there would be a great impact on Nam Ngum itself from these plants. Streams near the mine sites probably have high amounts of nutrients and sediments originating from the sites.

Nam Ngum in this stretch is a meandering river with a very small slope, which reduces the flow velocity and increases sedimentation. Erosion of stream bed and banks becomes increasingly important factor in the concentration of suspended sediments. (Gordon, McMahon, Gippel, Finlayson & Nathan, 2004) In an event of a significant input of mining related pollutants, the sedimentation reduces the area affected. Erosion may transport pollutants further on over time.

6 Discussion

NNRB currently has 39 registered and a number of smaller mining operations going on. Only a few of them could be located for this project. Mining can have a wide range of environmental effects which are different for each individual mine. In general, only large and medium sized mines have environmental considerations in place. Pollution from mining could not be determined in detail because of lack of data. Information on mine production or environmental surveys is difficult to obtain, apart from Australian owned operations. (MINDECO, 2006) Often exact locations of the mining sites could not be found, neither by data or (outdated) satellite imagery.

Environmental pollution from mining operations in the area is highly dependent on the seasonality of weather. The water quantity during winter dry season is a problem because mines are operated all year and mine waste water has a much higher relative impact during low water period than during wet season. AMD on the other hand is a bigger problem during wet season because of water availability to waste rock heaps in mining sites (He, Wang, & Tang, 1997).

It can be expected that all mining operations have impacts on water bodies in their surroundings. The large mining operations that are operated using best available techniques may pose a problem due to the large quantities of minerals mines. Large production quantities also produce large amounts of waste water. Mines operated in a modern way can usually meet the World Bank effluent criteria given in Table 16. Meeting this criteria is also a requirement for World Bank loan for a mining operation. (World Bank, 1998)

Table 16. Effluent limits from base metal and iron ore mining set by the World Bank. Values in mg l-1 except for pH. (World Bank, 1998)

Parameter	*Maximum value*
pH	6–9
TSS	50
Oil and grease	10
Cyanide	1.0
Free	0.1
Weak acid dissociable (WAD)	0.5
COD	150
Arsenic	0.1
Cadmium	0.1
Chromium (hexavalent)	0.1
Copper	0.5
Iron	3.5
Lead	0.2
Mercury	0.01
Nickel	0.5
Zinc	2
Total metals	10

Smaller mines have a high impact on their surroundings due to the lack of environmental protection measures. Streams where effluent and AMD is released will be highly polluted and low on species richness (and population). Low quality water from these streams can pollute receiving streams.

How far the pollution spreads from each mining site is largely governed by the hydrology and sediment transport of the area. Where wet season flow velocities are high, polluted sediments are likely to be transported far. The area of the watershed where most mining operations are located is mountainous with high rates of erosion. Pollution from mining sites are effectively diluted by natural sediment load and water quantity in the larger streams.

In riverine environment metal pollution is likely to stay in particulate phase in suspended or bottom sediments. Metal particles end up in reservoirs in the deep reservoirs of NN1, NN2 and NN3 that trap most of the sediments. However, since the metals readily adsorb to small clay and silt particles which stay in suspension, some particulate metal will be discharged from the reservoirs. Also, due to stratification, anoxia and possible low pH some metals leach out of the sediments in deeper parts of the reservoirs and may be discharged downstream. Metals in solution, will not stay in solution for long periods of time due to high acid neutralization capacity of the catchment.

The area of NNRB where most of mining operations are located is very low in population (WREA, 2008), see Figure 13 in page 21. Villages close to the mine locations may experience deterioration of important water sources for drinking water and agriculture. Stakeholders have reported this to happen (Idom, 2013).

6.1 Suggestions

In order to reliably evaluate the amount of metal entering (and their effects on) streams and reservoirs, information on mining practises, quality of waste minerals and water quality data of effluents from mining sites is required. In addition, monitoring data in water bodies near mining sites should be available to determine the actual impact on water quality.

For the sustainable management of important water resources, cooperation with industry, mining and energy sector is needed. Collection of all available data and a creation of (preferably) permanent water quality network and exchange system with stakeholders are required. Good water quality yields benefits to all aforementioned stakeholders and to the local communities which depend on the NN for water source. A suggestion of said water quality monitoring network is given in the section below.

It would also be advisable to adopt an environmental condition index for a few sites in the NNRB. These indexes are useful for the communication of the stream health to the general public. An index to be adopted could be for example the Water Quality Index that MRC is using (easy comparison with MRC data on NN and other rivers in the Mekong area) or the Index of Stream Condition (ISC) developed in Australia. The advantage of the ISC is that it is designed in a way that allows people with limited scientific training to apply it, reducing its costs. Overall there are more than 100 river health indices developed, many of which are designed to be used in a tropical context. (Gordon, McMahon, Gippel, Finlayson & Nathan, 2004)

6.1.1 Water Quality Monitoring Network for the NNRB

The water quality network presented here is based on the EMSP/NREI network of monitoring stations of 2013. The network consisted of 5 stations in the LNN, 3 stations in NN1R and 2 more in the NN2. The presented network also assumes that the hydropower companies responsible of the operation of the reservoirs have their own monitoring programs in place and that the data is shared with the party responsible of the water quality monitoring for Nam Ngum (EMSP/NREI). Figure 39 below shows a map of the existing and proposed new stations in the NNRB.

Figure 39. A suggestion of a Water Quality Monitoring Network based on the findings of the study. Yellow circles correspond to the established water quality stations of EMSP, red stars correspond to hydropower dams in the NNRB. Green boxes indicate new stations. Base map of sub-basins by Idom (2013).

The new stations proposed are chosen with ease of access in mind, and all of them are accessible with a car. Each of the new stations are described below.

1. NNT

   This station is the furthest upstream on Nam Ngum. It is located on a bridge between villages of Ban Tang and Lat Boua, close to the origin of NN. The station serves as a reference point for the stations in the Plain of Jars. Coordinates are 19°36'36.63"N and 103°12'40.22"E.

2. BPL

   The station is located in the village of Phieng Luang along national road 7. The village is close to the point where Nam Kho from the city of Phonsavan enters Nam Ngum. Nam Ngum can be sampled from a bridge at 19°31'18.18"N 103° 4'1.09"E. Nam Kho can be accessed via a trail that leads to about 50 m away from the confluence of the two rivers. See Figure 40 below. Coordinates for this location are 19°31'4.24"N 103° 4'33.13"E.

Figure 40. A map of the BPL monitoring station. Map from Google Earth.

The sampling location is located downstream from the Lao-Yong ferrous metal mine.

3. PHT

   Station is located in the village of Pha Tang along Nam Song. The sampling location is on a bridge on road 13. The station is located downstream from mine concessions and the operating Vangviang Minerals lead-zinc mine. Coordinates are 19° 4'38.11"N and 102°25'46.17"E.

4. VGV

   VGV is located in Vang Vieng which is the location of a weather station. The site has also been used to measure discharge of Nam Song. This provides an excellent opportunity for measurements of both discharge and relevant water quality variables. The sampling location is on a bridge at 18°55'17.02"N 102°26'40.26"E.

5. KSI

   Kasi is a town in north-western NNRB along Nam Lik. The station is located downstream from a stream which flows through a zinc mining area. Here again the station is easily accessible via a bridge along national road 13. The coordinates are 19°14'2.05"N 102°15'9.19"E.

6. KKH

   This station is located at a confluence of Nam Lik and a stream from population centres of south-western NNRB. It is in the village of Keng Khikhouay and can be used to sample both Nam Lik and the stream originating from the south. The location does not have a bridge, but a ferry across Nam Lik. The river is easily accessed with a car. Coordinates are 18°43'32.34"N 102° 7'39.71"E.

7. HNH

   Hin Heup station is located where hydrological measurements have been made, as in the station VGV. As with the station in Vang Vieng, the combination of hydrological data (discharge) with water quality variables is extremely valuable to the management of the river resources. The station is located downstream from the confluence of Nam Lik and Nam Song. Sampling point is on a bridge at 18°38'12.77"N 102°19'39.18"E.

The sampling stations marked in yellow in Figure 39 have been described in section 4. Station PKN (Pakkanjung) is another station that has been used for hydrological measurements. These measurements should be continued as with stations VGV and HNH.

Hydropower stations in the NNRB have their own water quality monitoring programs which can be integrated into the network. NN1R is covered by the EMSP program. The reservoirs marked with stars in the map need to be integrated into the program (even though NN3 has not been built yet, agreements of data exchange should be already in place when the operation starts).

Some mining companies in the area already have environmental monitoring programs set. Australian Phu Bia Mining is already cooperating with the EMSP/NREI and their data can be included in the monitoring network. Other companies should be requested to start monitoring of water quality and to include any existing data with EMSP/NREI database to ensure efficient management of water resources in the NNRB.

EMSP program has started monitoring of the following parameters:

- Temperature of air and water
- pH
- Conductivity
- Dissolved Oxygen
- Biological and Chemical Oxygen Demand
- Secchi depth
- Total Dissolved Solids
- Total Solids
- Total Hardness
- Total Suspended Solids
- Alkalinity
- Chlorine
- Sulphates
- Nitrogen (NO_2, NO_3) and Total Nitrogen
- Phosphates (PO_4P) and Total Phosphorus
- Calcium, Magnesium, Sodium and Potassium
- Chromium, Copper, Manganese, Nickel, Lead, Iron, Zinc and Cadmium.

The same parameters should be monitored in the new sampling stations as well. In addition to these parameters, the measurements of chlorophyll and faecal coliforms should be included, especially in sampling stations close to towns and villages.

Established sampling frequency in conducted surveys by EMSP/NREI has been set at one sample per month, which is also the basis for rivers in the suggested plan. Deep basins in reservoirs can be sampled only twice a year, once during dry season and once in the wet season (Mäkelä & Meybeck, 1996).

Additionally, sediments need to be sampled at selected stations due to their importance in the uptake, storage, release and transport of nutrients and contaminants. (Ongley, 1996) Grain size fractions, and chemical analyses should be made for heavy metals (at least Cr, Cu, Mn, Ni, Pb, Fe, Al, Zn and Cd) and nutrients.

Suggested stations for sediment analysis are; BHB (Ban Hai Bridge, last station before outlet to Mekong), PKN (Pakkanjung, Station in the northern Vientiane Plains), PHT (Pha Tang, sampling of Nam Song downstream from mining area), KSI (Kasi, a town downstream from a mining area), BPL (Phieng Luang, downstream of a mining area in the Plain of Jars) and NNT (most upstream station that can be used as a reference). Sampling should be done at least once a year in the dry season, when suspended sediment load is at its lowest. Preferably, also wet season analysis should be made, including suspended sediment quality analysis.

6.2 Findings in a Mekong Context

Mining operations in the NNRB do not have any noticeable effect on Mekong. As seen before, the water quality from Nam Ngum has problems with DO and, to an extent, nutrients. However, pollution from mining is a problem in the Upper NNRB. Metals are confined to the upper reaches by reservoirs and sedimentation in the LNN.

Results of the study, however, point out that an efficient monitoring and management of the rivers in the Mekong River Basin is needed. The whole watershed is under heavy hydropower development. Without careful considerations on responsible mining operations and building of dams, there is a danger of the slowing down of economic development and irreparable damage to the environment and the livelihood of the people living in the area.

With the current rapid developments in hydropower and mining industries in the NNRB and recent projects in the area, Nam Ngum has the potential to become a benchmark watershed when it comes to monitoring and management of the water resources. This requires hard work and resources. All the necessary pieces exist, if the support of stake-holders and politicians is gained.

7 Conclusion

The information and data concerning water quality and quantity in the NNRB is fragmentary and difficult to obtain. This thesis was written based on data only in the Lower Nam Ngum, NN2 and NN1 reservoirs. Hydropower and mining companies, the environmental authorities of Lao PDR and the MRC all have data, but it has not been collected together and it is sometimes difficult to get a hold of.

The calibration of the IWRM water quality model had to be based on sparse, monthly sampling. In reality the concentrations of TSS and P have high daily fluctuations. One sample per month on a river that is highly seasonal results in a big risk of error when it is used for calibration purposes. Lack of data from recent years (2000-2012) is also a problem when evaluating potential effects of mines in the area.

Overall, the conclusions made in this thesis are based largely on assumptions and on simulations instead of actual measurement data. To confirm the results of the thesis, more field data need to be collected.

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Appendix 1. Example of the MRC Data Sheets (Tha Ngon, 1995-2000).

STATID	SDATE	TIDEHL	FLOW_m3/s	TEMP_°C	pH	TSS_mg/L	COND_mS/m	Ca_meq/L	Mg_meq/L	Na_meq/L	K_meq/L	ALK_meq/L	Cl_meq/L	SO4_meq/L
H230102	13-2-1995			26.0	7.45	3.0	13.9	0.934	0.234	0.281	0.022	1.096	0.103	0.158
H230102	23-3-1995			27.0	7.52	2.0	10.7	0.890	0.127	0.181	0.023	0.922	0.127	0.106
H230102	24-4-1995			29.1	7.19	3.0	10.6	0.719	0.230	0.156	0.018	0.842	0.042	0.161
H230102	16-5-1995			28.2	7.21	6.0	15.4	0.964	0.216	0.275	0.026	1.035	0.156	0.256
H230102	20-6-1995			29.3	7.92	21.0	14.1	0.811	0.366	0.239	0.020	1.120	0.156	0.079
H230102	17-7-1995			28.8	7.65	63.0	10.6	0.734	0.214	0.152	0.018	0.827	0.111	0.092
H230102	15-8-1995			26.1	6.99	99.0	6.7	0.469	0.123	0.078	0.013	0.524	0.035	0.061
H230102	18-9-1995			29.2	6.97	55.0	7.9	0.503	0.184	0.088	0.020	0.578	0.034	0.118
H230102	17-10-1995			27.6	8.52	42.0	14.1	0.802	0.354	0.086	0.017	1.019	0.154	0.173
H230102	20-11-1995			25.9	7.83	21.0	15.2	0.975	0.325	0.090	0.014	1.112	0.166	0.190
H230102	20-12-1995			25.3	7.56	12.0	13.4	0.810	0.300	0.086	0.015	1.078	0.183	0.074
H230102	22-1-1996			24.4	7.68	7.0	10.9	0.730	0.246	0.161	0.019	0.831	0.120	0.247
H230102	19-2-1996			22.8	7.52	12.0	11.1	0.685	0.262	0.157	0.016	0.786	0.067	0.175
H230102	18-3-1996			26.1	8.85	10.0	9.9	0.602	0.217	0.152	0.013	0.740	0.058	0.108
H230102	18-4-1996			27.5	7.37	10.0	10.2	0.641	0.213	0.181	0.056	0.719	0.161	0.111
H230102	20-5-1996			28.6	7.46	33.0	11.7	0.684	0.261	0.168	0.046	0.851	0.132	0.152
H230102	19-6-1996			28.3	7.47	51.0	10.1	0.730	0.243	0.155	0.040	0.792	0.126	0.159
H230102	23-7-1996			28.1	7.25	48.0	11.5	0.692	0.256	0.143	0.028	0.790	0.097	0.164
H230102	20-8-1996			25.3	7.17	183.0	10.2	0.718	0.239	0.093	0.027	1.046	0.033	0.093
H230102	24-9-1996			25.8	7.00	240.0	7.5	0.527	0.176	0.094	0.013	0.693	0.052	0.179
H230102	23-10-1996			26.7	7.03	194.0	11.5	0.705	0.235	0.230	0.025	0.664	0.045	0.180
H230102	19-11-1996			25.3	7.11	116.0	13.5	0.834	0.278	0.238	0.030	1.018	0.127	0.236
H230102	17-12-1996			25.3	7.24	95.0	12.4	0.786	0.262	0.233	0.035	0.962	0.155	0.312
H230102	20-1-1997			24.6	7.39	52.0	13.4	0.813	0.271	0.285	0.036	0.984	0.162	0.322
H230102	17-2-1997			24.0	7.45	40.0	12.2	0.780	0.261	0.222	0.034	0.950	0.158	0.296
H230102	19-3-1997			21.5	7.74	10.0	11.2	0.728	0.276	0.208	0.026	0.904	0.159	0.271

SDATE	Fe_mg/L	NO32_mg/L	NH4N_mg/L	TOTN_mg/L	PO4P_mg/L	TOTP_mg/L	Si_mg/L	DO_mg/L	CODMN_mg/L
13-2-1995	0.185	0.157	0.063		0.009	0.016	6.40	7.86	1.40
23-3-1995	0.222	0.329	0.049		0.004	0.015	5.60	8.77	0.20
24-4-1995	0.162	0.100	0.047		0.011	0.006	6.40	6.35	0.80
16-5-1995	0.181	0.172	0.034		0.005	0.014	4.10	4.80	2.10
20-6-1995	0.133	0.119	0.013		0.011	0.030	5.60	4.60	2.20
17-7-1995	0.560	0.181	0.023		0.024	0.034	5.30	4.90	1.30
15-8-1995	0.373	0.032	0.047		0.007	0.019	5.10	6.90	1.90
18-9-1995	0.111	0.099	0.033		0.024	0.045	5.30	8.20	1.50
17-10-1995	0.095	0.004	0.023		0.011	0.013	5.40	7.26	1.10
20-11-1995	0.086	0.074	0.024		0.008	0.026	6.20	8.02	1.70
20-12-1995	0.091	0.028	0.014		0.005	0.015	6.90	8.43	0.50
22-1-1996	0.094	0.041	0.048		0.006	0.008	5.50	7.30	0.60
19-2-1996		0.103	0.011		0.005	0.009	5.70	8.70	8.80
18-3-1996		0.096	0.020		0.005	0.008	5.00	7.30	2.10
18-4-1996		0.098	0.053		0.018	0.035	5.70	7.50	2.20
20-5-1996		0.126	0.037		0.014	0.021	5.80	4.90	1.20
19-6-1996		0.133	0.047		0.019	0.027	5.70	2.50	1.70
23-7-1996		0.129	0.044		0.022	0.031	5.70	5.70	1.10
20-8-1996		0.123	0.024		0.015	0.024	5.70		0.40
24-9-1996		0.078	0.023		0.011	0.021	4.80		1.40
23-10-1996		0.070	0.023		0.011	0.015	5.10	6.70	0.60
19-11-1996		0.026	0.022		0.013	0.018	4.90		3.50
17-12-1996		0.002	0.217		0.002	0.012	4.80	6.10	1.00
20-1-1997		0.036	0.018		0.008	0.013	5.00	7.20	0.50
17-2-1997		0.003	0.012		0.004	0.010	7.00	6.00	0.40
19-3-1997		0.007	0.017		0.002	0.007	7.60	6.00	1.10

STATID	SDATE	TIDEHL	FLOW_m3/s	TEMP_°C	pH	TSS_mg/L	COND_mS/m	Ca_meq/L	Mg_meq/L	Na_meq/L	K_meq/L	ALK_meq/L	Cl_meq/L	SO4_meq/L
H230102	23-4-1997			24.2	7.60	4.0	11.3	0.722	0.265	0.200	0.024	0.953	0.141	0.238
H230102	26-5-1997			29.3	7.40	16.0	13.6	0.961	0.326			1.163	0.030	0.202
H230102	18-6-1997			29.0	8.29	50.0	13.8	0.995	0.332			1.020	0.030	0.180
H230102	16-7-1997			27.1	7.20	82.0	10.0	0.610	0.220			0.735	0.036	0.127
H230102	20-8-1997			28.0	7.17	93.0	9.5	0.637	0.213			0.701	0.038	0.130
H230102	23-9-1997			27.4	7.16	80.0	10.5	0.700	0.233			0.722	0.022	0.125
H230102	22-10-1997			27.5	7.17	71.0	11.2	0.713	0.228			0.810	0.028	0.133
H230102	24-11-1997			27.4	7.28	10.0	13.6	0.798	0.262			0.965	0.092	0.141
H230102	23-12-1997			26.3	7.71	7.0	13.3	0.884	0.295			1.120	0.117	0.137
H230102	21-1-1998			25.4	7.72	11.0	12.7	0.865	0.288			1.014	0.121	0.120
H230102	18-2-1998			25.6	7.38	6.0	6.8	0.517	0.201			1.151	0.120	0.280
H230102	19-3-1998			28.3	7.46	15.0	10.7	0.831	0.277			1.009	0.125	0.297
H230102	23-4-1998			28.4	7.24	18.0	9.5	0.721	0.240			0.869	0.083	0.237
H230102	19-5-1998			28.6	7.99	20.0	9.4	0.711	0.237			0.822	0.075	0.230
H230102	16-6-1998			30.8	7.22	28.0	10.6	0.836	0.280			1.357	0.074	0.233
H230102	27-7-1998			28.2	7.20	46.0	11.7	0.964	0.322			1.038	0.076	0.240
H230102	18-8-1998			25.4	7.15	96.0	9.5	0.589	0.243			0.772	0.020	0.115
H230102	28-9-1998			29.0	7.74	128.0	13.2	0.899	0.370			1.166	0.035	0.106
H230102	15-10-1998			29.6	7.31	90.0	13.5	1.114	0.033			1.122	0.153	0.199
H230102	24-11-1998			27.3	7.69	50.0	13.2	0.851	0.248			1.109	0.165	0.056
H230102	18-12-1998			27.5	7.34	3.0	13.0	0.817	0.227			1.019	0.136	0.052
H230102	21-1-1999			25.4	7.49	2.0	12.2	0.766	0.378			1.006	0.149	0.052
H230102	18-2-1999			26.5	8.10	4.0	11.0	0.730	0.244			0.925	0.060	0.086
H230102	22-3-1999			25.9	8.20	2.0	11.6	0.972	0.324			0.903	0.113	0.080
H230102	19-4-1999			29.0	7.45	3.0	12.7	0.865	0.429			1.072	0.059	0.149
H230102	17-5-1999			28.3	7.21	6.0	11.5	0.816	0.329			0.990	0.040	0.189
H230102	21-6-1999			27.0	7.49	9.0	10.1	0.692	0.237	0.107	0.037	0.801	0.028	0.118
H230102	20-7-1999			27.3	7.84	26.0	12.6	1.089	0.206	0.168	0.032	1.268	0.050	0.123
H230102	17-8-1999			27.5	7.64	86.0	12.0	0.917	0.437	0.132	0.031	1.048	0.049	0.119
H230102	27-9-1999			27.5	7.22	90.0	9.0	0.631	0.527	0.095	0.032	0.748	0.045	0.053

SDATE	Fe_mg/L	NO32_mg/L	NH4N_mg/L	TOTN_mg/L	PO4P_mg/L	TOTP_mg/L	Si_mg/L	DO_mg/L	CODMN_mg/L
23-4-1997		0.010	0.019		0.001	0.006	6.80	6.20	1.00
26-5-1997		0.041	0.034		0.005	0.009	7.10	5.60	1.00
18-6-1997		0.066	0.037		0.003	0.025	7.10	6.50	0.70
16-7-1997		0.075	0.031		0.014	0.021	7.00	6.80	1.10
20-8-1997		0.082	0.015		0.012	0.014	7.10	5.60	0.70
23-9-1997		0.054	0.028		0.002	0.019	6.80	5.80	1.10
22-10-1997		0.073	0.024		0.002	0.005	7.00	4.70	0.80
24-11-1997		0.084	0.017		0.002	0.003	7.20	6.40	1.70
23-12-1997		0.072	0.019		0.001	0.005	8.00	7.60	0.60
21-1-1998		0.066	0.020		0.004	0.006	7.20	7.10	0.90
18-2-1998		0.039	0.021		0.002	0.006	6.00	6.20	0.90
19-3-1998		0.026	0.098		0.018	0.029	6.30	6.20	1.20
23-4-1998		0.059	0.029		0.003	0.005	5.50	7.50	0.80
19-5-1998		0.028	0.013		0.002	0.006	5.80	6.10	
16-6-1998		0.031	0.020		0.003	0.008	6.20	5.30	0.70
27-7-1998		0.084	0.055		0.004	0.017	6.00	7.50	0.80
18-8-1998		0.042	0.015		0.005	0.019	6.40	6.40	0.40
28-9-1998		0.092	0.093		0.004	0.013	6.00	6.00	1.00
15-10-1998		0.030	0.187		0.003	0.012	6.10	6.00	1.30
24-11-1998		0.029	0.039		0.009	0.016	7.00	6.10	0.40
18-12-1998		0.001	0.010		0.008	0.021	9.50	7.90	0.40
21-1-1999		0.030	0.018		0.006	0.011	8.00	5.90	0.30
18-2-1999		0.003	0.008		0.005	0.006	6.00	7.80	0.50
22-3-1999		0.007	0.014		0.002	0.007	6.00	8.20	0.05
19-4-1999		0.024	0.029		0.003	0.010	7.00	4.90	0.20
17-5-1999		0.094	0.017		0.006	0.012	2.00	4.60	0.40
21-6-1999		0.110	0.037		0.007	0.009	4.00		0.69
20-7-1999		0.076	0.018		0.005	0.007	5.00	6.50	1.50
17-8-1999		0.093	0.019		0.018	0.029	7.00	5.90	2.00
27-9-1999		0.001	0.016		0.003	0.015	8.00	5.50	2.70

STATID	SDATE	TIDEHL	FLOW_m3/s	TEMP_°C	pH	TSS_mg/L	COND_mS/m	Ca_meq/L	Mg_meq/L	Na_meq/L	K_meq/L	ALK_meq/L	Cl_meq/L	SO4_meq/L
H230102	20-10-1999			26.2	7.03	53.0	12.4	0.830	0.269	0.188		0.428	0.110	0.137
H230102	9-11-1999			27.1	7.96	46.0	13.5	0.863	0.349	0.205	0.031	1.129	0.094	0.285
H230102	20-12-1999			24.7	7.84	20.0	12.5	0.925	0.185	0.200	0.030	1.099	0.132	0.098
H230102	17-1-2000			24.6	7.50	10.0	9.6	0.897	0.263	0.196	0.029	1.125	0.108	0.189
H230102	21-2-2000			25.2	7.36	6.0	12.1	1.005	0.233	0.106	0.018	1.057	0.213	0.062
H230102	20-3-2000			26.2	7.49	7.0	10.5	0.915	0.153	0.100	0.013	0.966	0.009	0.713
H230102	18-4-2000			27.3	7.50	12.0	10.5	0.985	0.171	0.102	0.030	0.974	0.164	0.161
H230102	16-5-2000			29.3	7.53	23.0	11.4	1.079	0.311	0.110	0.033	0.970	0.104	0.217
H230102	20-6-2000			26.6	7.84	39.0	6.5	0.835	0.143	0.106	0.027	0.972	0.081	0.099
H230102	17-7-2000			32.2	7.64	60.0	9.8	0.738	0.185	0.095	0.024	0.971	0.116	0.170
H230102	18-8-2000			27.3	7.13	82.0	9.9	0.783	0.195	0.089	0.026	0.876	0.045	0.302
H230102	19-9-2000			27.7	8.57	96.0	8.9	0.706	0.304	0.093	0.022	0.826	0.039	0.113
H230102	23-10-2000			26.8	7.24	101.0	10.9	0.900	0.134	0.084	0.019	0.933	0.123	0.157
H230102	20-11-2000			27.0	7.75	92.0	13.1	0.967	0.226	0.080	0.018	1.313	0.156	0.185
H230102	20-12-2000			26.8	7.80	83.0	12.4	0.764	0.193	0.090	0.025	1.093	0.166	0.189

SDATE	Fe_mg/L	NO32_mg/L	NH4N_mg/L	TOTN_mg/L	PO4P_mg/L	TOTP_mg/L	Si_mg/L	DO_mg/L	CODMN_mg/L
20-10-1999		0.023	0.010		0.002	0.008	8.00	4.50	3.00
9-11-1999		0.021	0.019		0.026	0.039	7.00	5.50	0.70
20-12-1999		0.025	0.010		0.001	0.005	6.00	6.80	0.60
17-1-2000		0.030	0.032		0.002	0.003	9.00	6.80	0.10
21-2-2000		0.002	0.014		0.002	0.009	3.50	6.45	1.10
20-3-2000		0.007	0.021		0.002	0.009	3.80	6.70	1.00
18-4-2000		0.002	0.010		0.002	0.005	4.00	6.30	0.10
16-5-2000		0.004	0.009		0.016	0.006	5.00	6.20	0.70
20-6-2000		0.010	0.047		0.023	0.032	6.40	6.30	0.09
17-7-2000		0.357	0.026		0.003	0.013	6.00	5.00	0.97
18-8-2000		0.176	0.090		0.007	0.017	2.70	5.60	1.30
19-9-2000		0.120	0.045		0.026	0.047	5.40	6.20	2.00
23-10-2000		0.123	0.049		0.029	0.047	5.10	6.80	0.50
20-11-2000		0.001	0.015		0.020	0.041	5.30	6.80	0.20
20-12-2000		0.018	0.013		0.004	0.014	5.60	7.00	0.30

Appendix 2. Introduction to the Nam Ngum IWRM Model

The model used in the thesis, provided by Environmental Impact Assessment Finland Ltd. (EIA), is a distributed grid-based GIS application. The model runs with inputs of geographical, meteorological and infrastructure data. In addition to hydrology and water quality modelling, it is capable of the simulation of groundwater, crops, irrigation, floods, erosion, reservoir sediment trapping etc.

The Nam Ngum model is based on a 1km resolution grid that incorporates basin topography, land use and soil characteristics. Topography and the meteorological stations used in the model are shown in Figure 1.

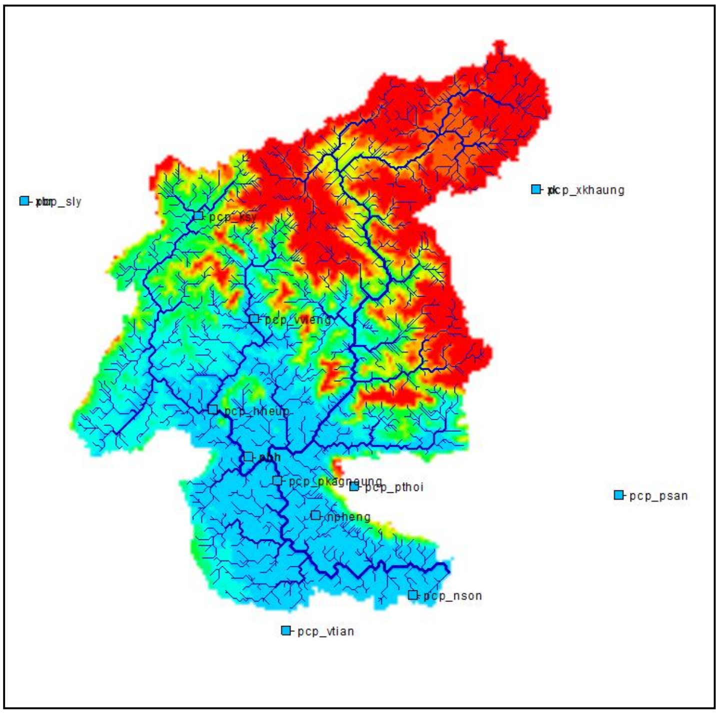

Figure 41. Topography of the Nam Ngum River Basin and the weather stations incorporated to the model.

Variables of the water quality component of the model are soluble phosphorus (DPO4), Total P (TOTP) and suspended solids divided in three categories: mud, silt and sand. The concentration of the variables is calculated by flow along a river network. The concentration is affected by:

- runoff
- river discharge
- soil and land use
- sedimentation along the river network and in reservoirs and lakes.

The soil and land use data of the model are shown in figures 2 and 3.

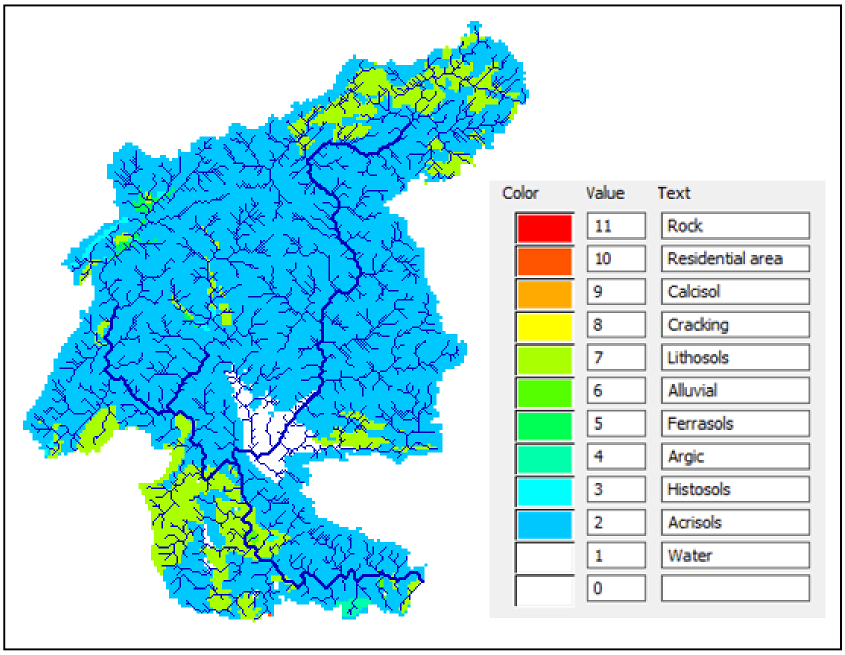

Figure 42. Soil data of the Nam Ngum model.

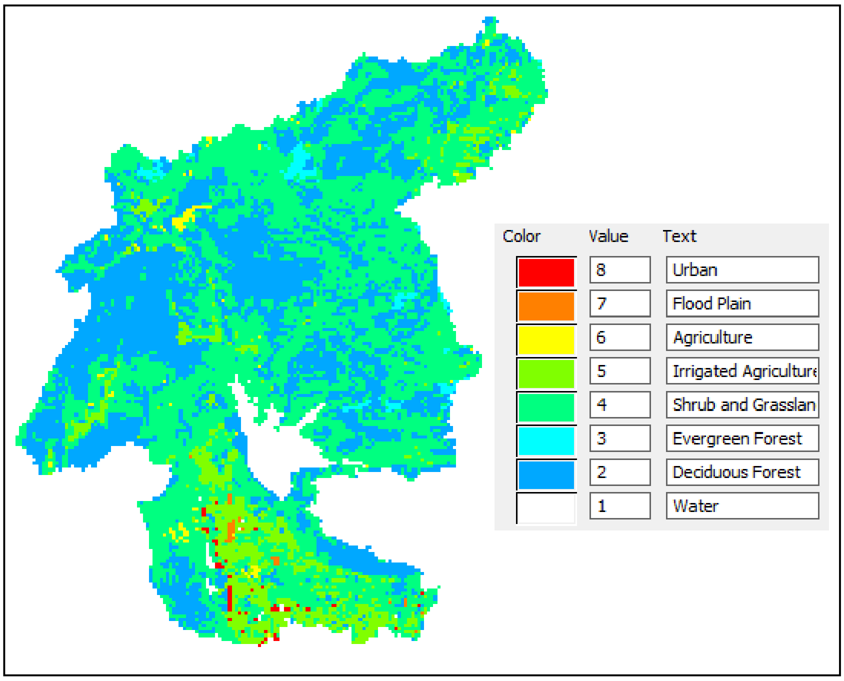

Figure 43. Land use data of the Nam Ngum model.

The model includes all the present operating reservoirs and two new ones currently being built. Nam Ngum 3 (NN3) is planned to start operation in 2015 and Nam Lik 1 (NL1) in 2018. The model also includes a water transfer scheme from Nam Song to NN1 and from Nam Leuk to Nam Sane (to NN1).

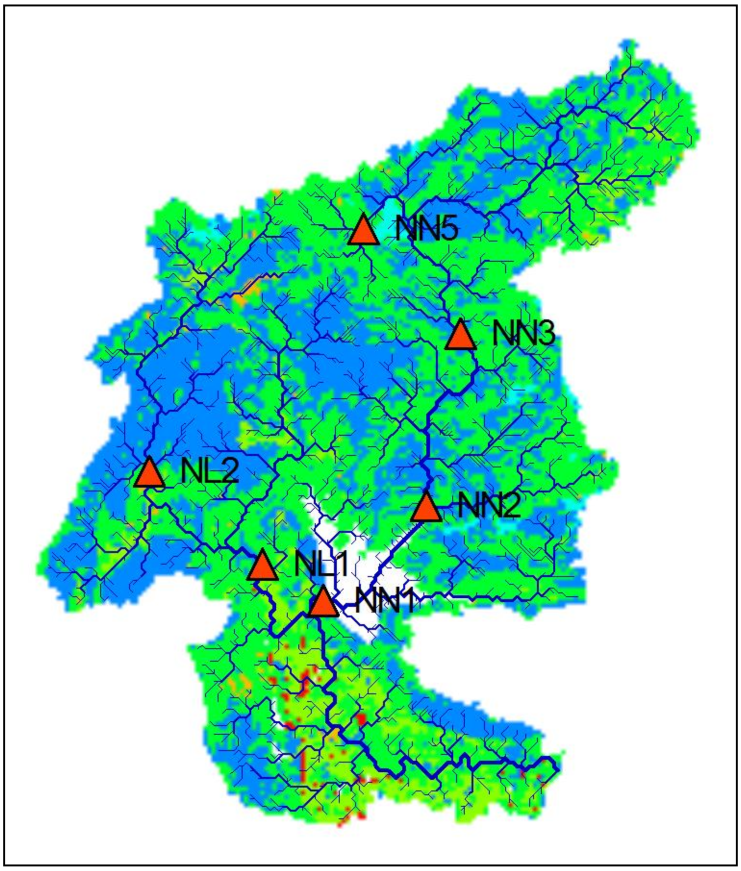

Figure 44. Reservoirs in the model.

The model outputs can be accessed through user defined Time Series Points (TSP) which can be seen figure 5 below. Also map outputs for large number of indicators are produced by each model run.

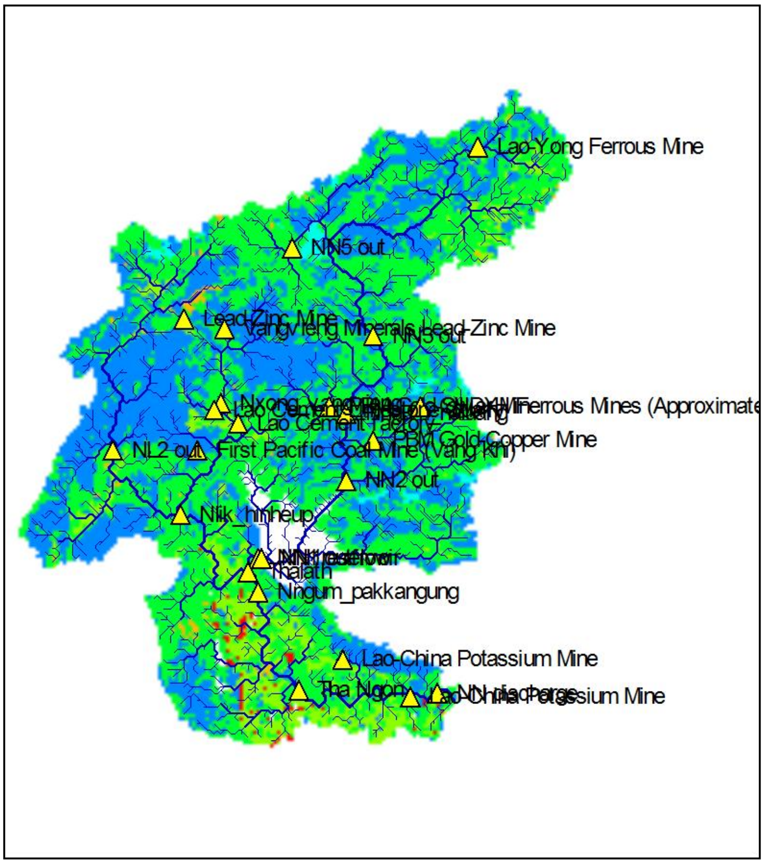

Figure 45. Time series points of the Nam Ngum model.

The TSP’s serve a number of functions. Each reservoir in the basin has been assigned a TSP in order to monitor the quality of the discharged water. TSPs related to mining operations are used to evaluate the effluent sediment load and metal pollution in the receiving streams. Other TSP’s serve mainly calibration and validation purpose.