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Wastewater Treatment and Reuse through Constructed Wetlands in Vientiane, Lao PDR

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List of Abbreviations

ADB	Asia Development Bank
BDEA	Berlin Digital Environmental Atlas
BOD	Biological Oxygen Demands
CWs	Constructed Wetlands
DLWC	Department of Land and Water Conservation New South Wales
DPCTC	Department of Post, Communication, Transport and Construction Vientiane Capital City
EEPSEA	Economy and Environment Program for Southeast Asia
EPA	United States Environment Protection Agency
ESCAP	UN Economic and Social Commission for Asia and the Pacific
FWS	Free Water Surface Wetland
FAO	Food and Agriculture Organization of United Nation
GEC	Global Environment Centre Foundation
GTZ	German Agency for Technical Cooperation
HRT	Hydraulic Retention Time
JICA	Japan International Cooperation Agency
Laos/Lao PDR	Lao People's Democratic Republic
MPWT	Ministry of Public Works and Transport Lao People's Democratic Republic
MRC	Mekong River Commission
PCB	Polychlorinated Biphenyl
PTI	Public Works and Transport Institute
PPCPs	pharmaceuticals and personal care products
SSPC	Symposium Scientific Programme Committee
SF	Suburface Flow Wetland
TLM	That Luang Marsh
TP	Total Phosphorus
TSS	Total Suspended Solids
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
VCC	Vientiane Capital City
VIUDP	Vientiane Integrated Urban Development Project
WBSD	World Business for Sustainable Development
WELL	Water and Environmental Health at London and Loughborough
WWF	World Wild Found

Summary

The massive infrastructure investments of the last 10 years in Vientiane (capital of Lao PDR) saw the city's drainage network and wetlands being replaced by hydraulically more efficient cement-lined channels designed to ensure flood protection. As a result, water quality entering the receiving That Luang wetland has significantly degraded. It was initially intended that sewage water from the city centre would be prevented from entering the drainage network and pumped to large facultative wastewater stabilization ponds when stormwater contribution was low. Nowadays, this treatment system is inoperative and housing and commercial buildings have started to appear around the upper part of the site (*i.e.*, inflow area). Considering that agriculture is still a significant activity toward the lower part of the site (*i.e.*, outflow area) located in the That Luang wetland, this project demonstrates that simple designs improvement could in theory produce 8 000 to 50 000m^3 of treated wastewater per day suitable for reuse. The highest water quality level, necessary for irrigation of crops likely to be eaten uncooked, could be achieved if a vertical subsurface-flow component was added. This however means that the hydraulic retention time would have to be kept to a minimum of 2,7 days (< 30,000 m^3/d) to accommodate a security margin for bot BOD_5 and TSS. Only a less restrictive reuse could be achieved if only a free water surface flow design is maintained. Finally, a reversal of the original flow direction is suggested to ensure that air quality and amenity is maintained in the section surrounded by habitations.

Acknowledgments

First of all, I would like to thank my supervisor Dr. Jean O. Lacoursière for his support, guidance and patience throughout the whole project. I'm deeply grateful to Pauline Gerrard from WWF Laos, who provided me guidance and valuable advices during my fieldwork in Vientiane. I'm also very grateful to Dr. Lena Vought from Kristianstad University, Prof. Ian Guymer from Warwick University and Dr. Sally MacKenzie from Wildfowl & Wetlands Trust (WWT) for counsel, suggestions and encouragements. I also wish to convey my gratitude to all my WWF's colleagues, especially Khek, who helped me a lot when I was in Vientiane. I'm very obliged to the Department of Science and Technology (STO) of Vientiane Capital and all the organizations who helped me with information collection in Laos.

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1. Introduction

Wetlands are shallow water system, usually with water level lower than 1.5 m. Wetlands are found in every climate zone, and are known by terms such as marshes, bogs, fens, swamps and mires (Mitsch & Jørgensen, 2004). Due to the functions of food production and water security protection, wetlands had for a long time a very “close relationship” with cities, of which Vientiane is a very good example.

1.1 Development of Vientiane Capital City

Vientiane is the capital city of Lao PDR, with a total area of 3 920 km^2 (after the administrative reform). It is composed of 189 villages (ban) and contains almost 1 500 km^2 of permanent and seasonal water bodies, floodplains, swamp and marshes (Gerrard 2004, Sengtianthr 2005).

The urban area of Vientiane grows fast. From the historical data (Figure 1), the population has grown more than 45 times during the past 80 years. Population has grown continuously during the past few decades.

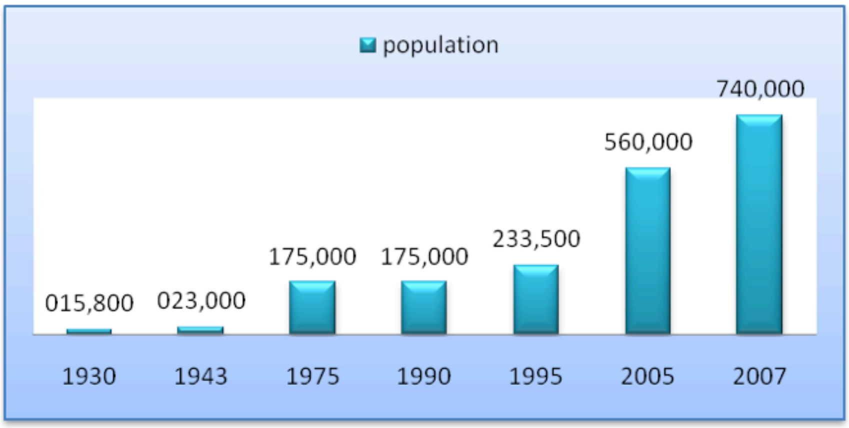


Figure 1: Population developing of Vientiane City (Established based on data from Rafiqui *et al.*, 2009, Müller *et al.*, 2006 & ADB 2008)

Until 2007, there were about 300 km of roads within Vientiane Capital City area, and only less than one third of them were paved. The rest of them were mainly earth or gravel. In order to pick-up the pace of the urbanization, major urban infrastructure development projects were initiated (ADB, 2008).

1.2 That Luang Marsh

That Luang Marsh (TLM) is the largest remaining urban wetland in Vientiane Capital City (Figure 2), which is located on its eastern boundary. The area of TLM is about 20 km^2 (Claridge, 1996) and it is surrounded by 16 villages and more than 7 000 households (Müller *et al.*, 2006). It drains eastward to the Mekong River through the ca. 54 km long Houay Mak Hiao River system.

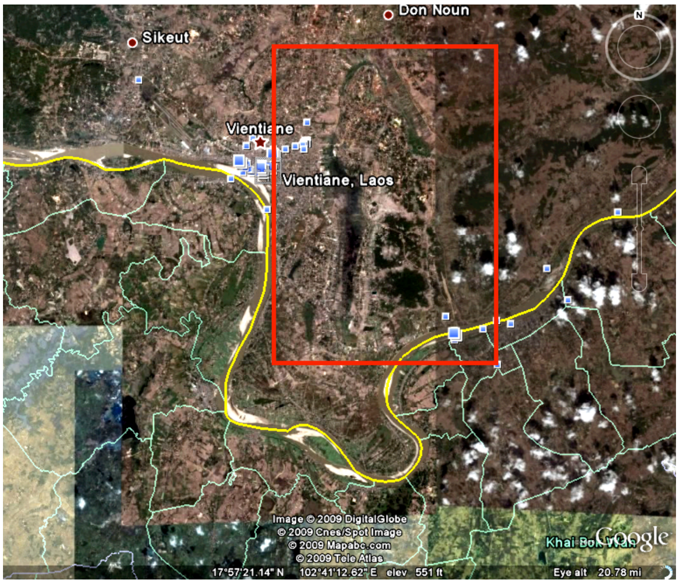


Figure 2: Location of That Luang Marsh in Vientiane (Source from Google Earth)

The That Luang Marsh has been modified during the last 20 years. Forests were removed and agricultural fields became the major component of TLM (Gerrard, 2004). Table 1 shows the dry seasons land use of TLM in 2006. Rice filed cover 8 000 hectares, and occupies 47% of the area. Other plantation such as vegetable gardening, banana and teak farming are also important agriculture production.

In TLM, rice production is a large water consumer. As in most of Laos, most of it is still done through 'pounded' water culture. Because of shortage in irrigation water however, about 30% of the rice field in TLM are unproductive during dry season (Kyophilavong, 2007).

Table 1: The land use of TLM in 2006 (dry season)

Area type	Area (Ha)	Percentage%
Rice filed	8,300	47
Green area*	4,500	26
Banana	25	0.1
Teak	30	0.2
Constructed area	450	2.5
Other area*	3,900	22
Water area	450	2.5
Total	18,000	100

Note: Table 1 is established by the GIS data from WWF Laos and MRC, 2006 (See Appendix 1 for details)

Meanwhile, the population density around the TLM has more than tripled during the 1990s (Gerrard, 2004). Nowadays, more than half of the population there depends on the resources from the marsh. Wetland based agriculture activity, such as rice production, vegetable and fruits farming, fishing, aquatic vegetation harvester and animal catching are the major living mode and incoming sources for local people (Figure 3).

Figure 3: TLM provides natural resources to people who live around it. Left: Rice farming. Right: Fishing in TLM is not only the incoming sources for the people, but also a living style.

Large biological diversity is another treasure of this wetland. There are about 20 species of fish, among witch 7 are harvested regularly. Seventeen species of aquatic plants are also found there, of which half are commonly collected. Five species of amphibians and reptiles live in and around the marsh. Nevertheless, the number of bird species went down during 1999 - 2005 and only four species were found during the survey in 2005 (Müller *et al*., 2006).

TLM also provides a large range of ecological services. Flood control, natural wastewater treatment and sanitation processes (JICA & MTPC, 2002). Since there is no centralized wastewater treatment in Vientiane, domestic sewage discharges into wetlands without or with only partial treatment at best (treatment is available through septic tanks and soak pits, but lack of maintenance reduces their efficiency). Because of its large area and storage capacity, TLM can still offer the service of pollutants removal. Gerrard´s research (2004) shows that TLM is bringing huge economic benefits (Table 2).

Table 2: Direct and indirect benefits from That Luang Marsh (Gerrard, 2004)

Direct Benefits	
Type of Use/Benifit	Annual Value (US$/yr)
Rice cultivation	350,000
Vegetable gardens	55,000
Aquaculture	180,000
Capture fisheries	1,100,000
Non-fish wetlands	350,000
Indirect Benefits	
Flood protection	2,800,000
Wastewater pruification	71,000
Total	4,906,000

1.3 Urban wetlands in Vientiane Capital City

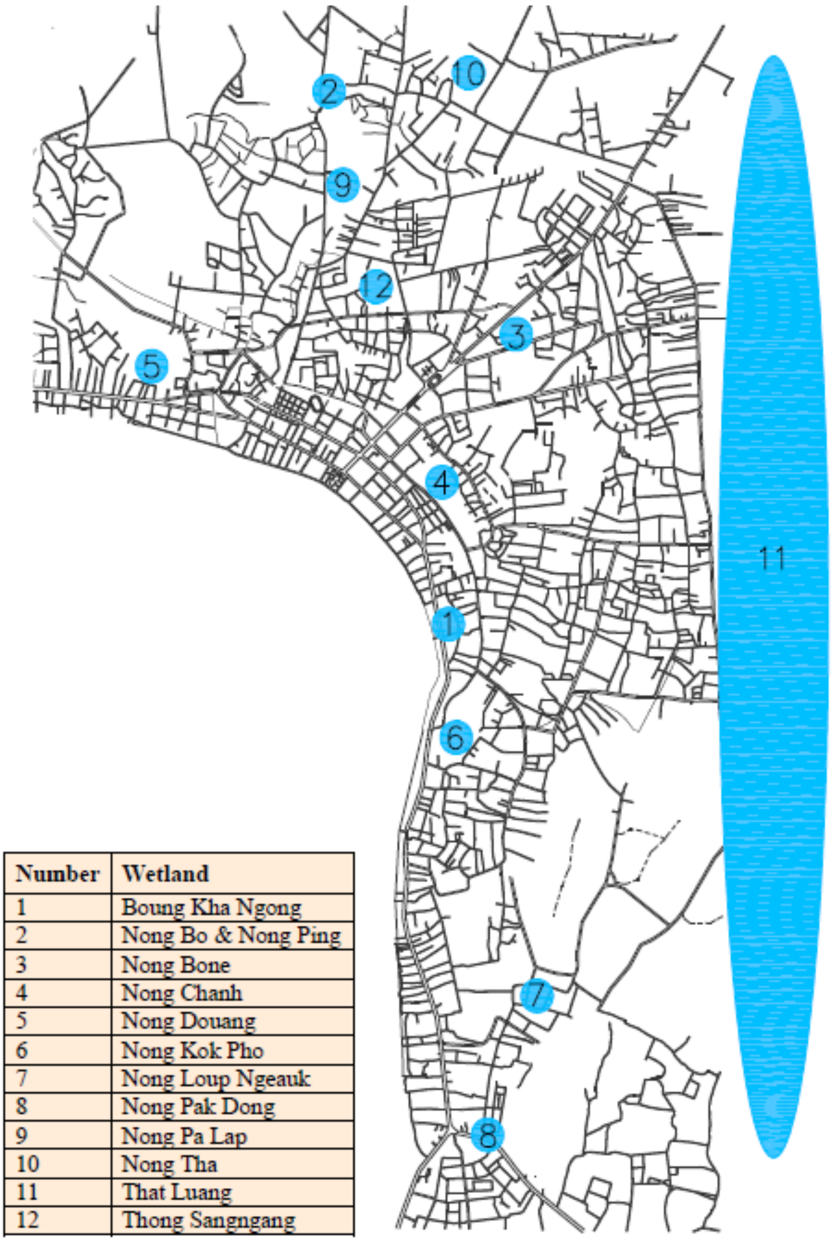
That Luang Marsh is not the only wetland of the city providing economic value and contributing to the surrounding inhabitants livelihood. However, they are regularly being filled with construction wastes and rapidly become commercial or residential areas (Figure 4).

Figure 4: Many of the city's wetlands are being filled by construction wastes.

In order to illustrate and follow the impacts of urbanization, a city-wide wetlands status project was carried out by students from Kristianstad University (Sweden). This study by Müller *et al*. (2006) shows that about 30% of the urban wetlands area was lost between 1999-2005 (Figure 5). Among the twelve selected wetlands, half of them had seen significant area loss (> 25%). What's more, the Nong Chanh marsh situated in the city centre had by then already lost more than 50% of its area.

Table 3: Estimated degrees of wetland area lose (Müller *et al.*, 2006)

Wetland name	Slight (0-10%)	Medium (10-25%)	Great (>25)
Boung Kha Ngong	X		
Nong Bo, Nong Ping	X		
Nong Bone			X
Nong Chanh			X
Nong Douang			X
Nong Kok Pho			X
Nong Loup Ngeauk			X
Nong Pak Dong			X
Nong Pa Lap	X		
Nong Tha	X		
That Luang	X		
Thong Sangngang		X	



Number	Wetland
1	Boung Kha Ngong
2	Nong Bo & Nong Ping
3	Nong Bone
4	Nong Chanh
5	Nong Douang
6	Nong Kok Pho
7	Nong Loup Ngeauk
8	Nong Pak Dong
9	Nong Pa Lap
10	Nong Tha
11	That Luang
12	Thong Sangngang

Figure 5: City wetland location (Müller *et al.*, 2006)

Losses in wetland area and associated aquatic vegetation directly resulted in significant water quality reduction, which led to an increase in nutrients discharge from the city. Based on Lacoursière *et al.* (2004), the ammonia to nitrate ratio (an indicator of sewage pollution) increased rapidly after the drainage network rectification as exemplified in Figures 6 and 7. This means that natural filtration capacity of the drainage system was greatly reduced when the vegetation and soft sediment profile were lost.

Figure 6: Nong Chanh, the central wetland of Vientiane in 1990 (left) and 2003 (right). Marsh area and vegetation lose due to the drainage rectification work and city development. (Reproduced with the permission of Drs. Lacoursière and Vought)

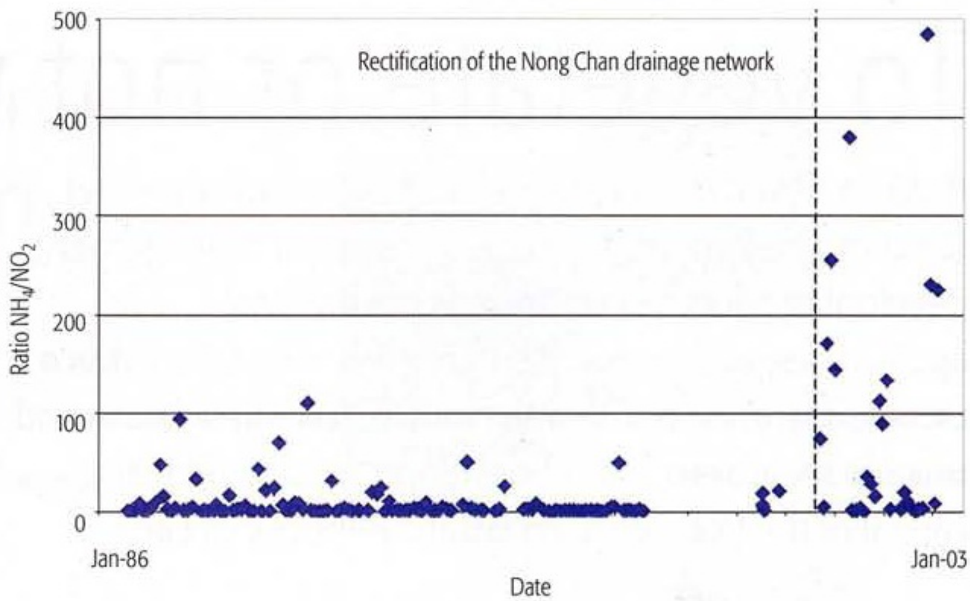


Figure 7: Change in ammonium:nitrate ratio at the Nong Chanh wetland outflow before and after rectification work (Reproduced with the permission of Drs Lacoursière and Vought).

Nowadays, a new development plan is being formulated in Vientiane. According to the new project, the government plan to transform the area in TLM from wetland into an urban centre with tall buildings, hotels and businesses. The total new TLM developing area will be 670.0 ha (pink area in Figure 8), and about 200 household will be moved into this area (Souksakhone Vaenkeo, 2008; JICA & MPWT &PTI, 2009).

Figure 8: New town project planning area

Information provided by the DPCTC shows that, a pond is going to be used to meet the demand of flooding storage capacity in the new town project, and a new wastewater treatment plant is going to be built to treat the wastewater in new town. Nevertheless, city wastewater treatment is not included in the new town project, and TLM still will be the major wastewater receiver of Vientiane. Therefore, large area loss of the wetland will bring a dramatic change to the city water environment.

1.4 Vientiane Capital City's drainage network

Vientiane located in a flood-prone zone with a 1,700 mm average annual precipitation (Visvanathan & Sato, 1996). The whole city is mainly drained by the Hong Ke and Hong Xeng channels (Figure 9). Urban wetlands, such as the Nong Chanh and Nong Bone, are included into the original network design. Total catchment area of Hong Ke and Hong Xeng are 9.6 km^2 and 53 km^2 respectively. To reduce the flooding damage, all drainage channels were improved during the past few years. The main drainage channels are all channelized and deepened in order to increase their water evacuation velocity and capacity.

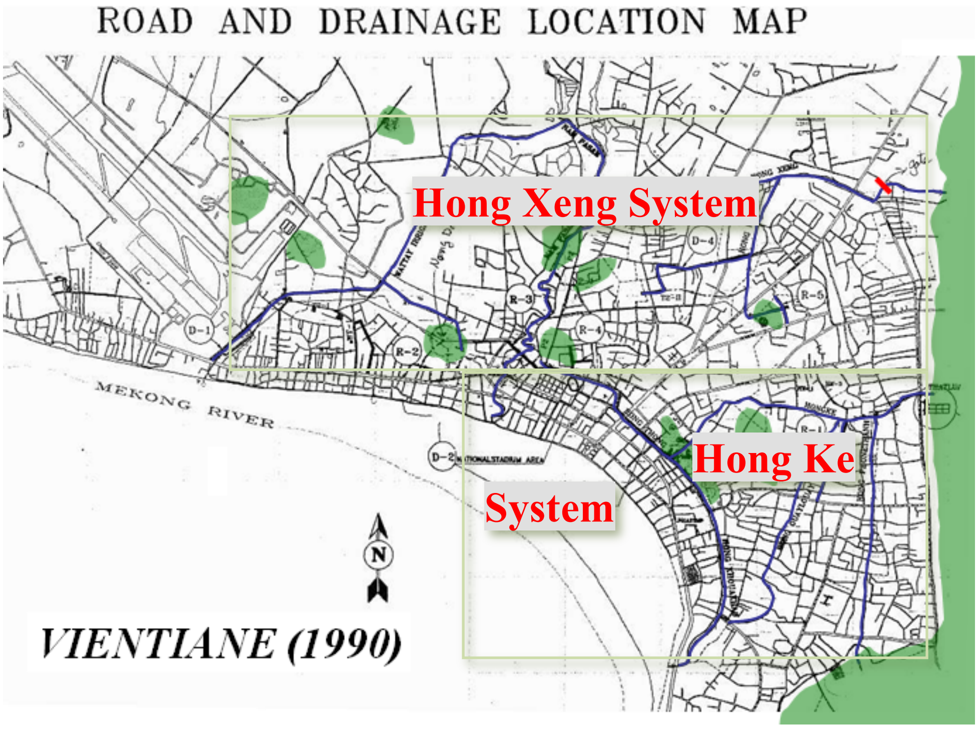


Figure 9: Drainage channel location and drainage system in Vientiane Capital City (Reproduced with the permission of Drs Lacoursière and Vought).

1.5 Urbanization leads to an increased runoff

Planned urbanization of Vientiane Capital City will bring new challenges stormwater management. Large permeable area of what is now countryside will become impervious and large scale of the wetland will be filed up. Thus, more stormwater runoff will occur in the city. Flooding might be more serious during the raining season. Figure 10 shows that a shorter lag-time and a higher peak flow of stormwater runoff should be expected after urbanization.

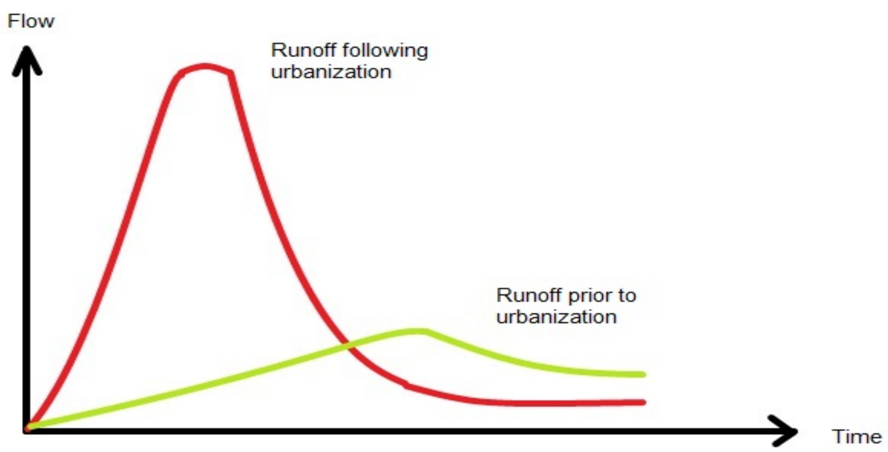


Figure 10: Urbanization causes a change of the runoff pattern. (Stahre 2006)

Nevertheless, flooding control and wastewater treatment objectives should to be balanced. Under classic engineering approach, stormwater need to be evacuated out of town rapidly by a straight canal of shortened length. A meandering watercourse on the other hand provides more treatment potential as well as superior habitats for aquatic flora and fauna. In a meandering canal, wastewater is led away in a manner that offers better protection of canal side and bed than a straight one.

More wastewater will be generated from urbanization. Meanwhile, wetlands area is continuously lost. This means that, without any water treatment facilities, polluted water will eventually flow into the Mekong River if pollution is not reduced at the sources and the That Luang Mash is not protected. I a worst-case scenario, where most of the marsh would be urbanized and its draining Houay Mak Hiao River system entirely channelized to ensure maximum flood protection, large amount of nutrients could contribute to the eutrophication risk of the Mekong River.

1.6 Vientiane Capital City wastewater treatment

As mentioned earlier, Vientiane Capital City does not have an integrated sewage treatment system. All buildings are supposed to have on-site wastewater disposal and treatment facilities such as septic tanks and soak pits. Although most of the facilities are properly designed, many are poorly constructed and/or managed, therefore poorly working. Cracks and permeable bottom of the failing septic tanks make groundwater contaminated by sewage leakage easy. Septic tanks blockage happens frequently. Somehow, although not conformed to regulations, part of the household sewage water is lead directly to open ditches (Figure 11).

Figure 11: Sewage collected by septic tanks and open ditches.

Situation goes worse during the rainy season, flooding raises the groundwater level and poorly constructed septic tanks become water storage tanks. With the growing of the water level, faeces are flushed out from the septic tanks to the lower area of the street.

In order to treat household sewage water from the city centre, facultative lagoons were built in 1993 with a 0.9 million US dollar grant from the European Union. This "That Luang Wastewater Management Project" (often referred to as "the EU-ponds") was planed and managed under the Department of Post, Communication, Transport and Construction (DPCTC) of Vientiane. The location of pumps intake draining the centre of the city by the Nong Chang wetland and the EU-ponds right at the edge ot the That Luang Marsh are shown in Figure 12.

The dimensioning of the waste stabilization ponds was based on a total organic load of 1,003 kg BOD/d and an inflow of less than 14,000 m^3/d (JICA & MTPC, 2002).

Figure 12: Vientiane city treatment ponds. Water intake is located in Nong Chan marsh, and pumped to the EU ponds near Hong Ke cannel. (Google Earth)

According to the design, sewage and stormwater were to be collected upstream of a low-head dam built with the intent of pumping all wastewater during the dry season and to prevent floating solid wastes from going downstream (Figure 13 left). Bar screens are built to prevent large waste from going into the pumps intake (Figure 13, right). No long-term flow measurement is readily available at this location, but a dry-weather measurement made in February 2005 recorded an average discharge of ca. 125 l/s (ca. 10,800 m^3/d) (Dr. Jean O. Lacoursière, pers. com 2009).

Figure 13: Water intake of EU ponds. Water dam and bar screen are built to trap large waste (with permission of Drs Lacoursière and Vought).

The original layout of the waste stabilization ponds is shown in Figure 14, with wastewater circulating from left (upper portion) to right (lower portion) to finally empty by gravity into Hong Ke Canal just before it outflows to the centre of the That Luang Marsh.

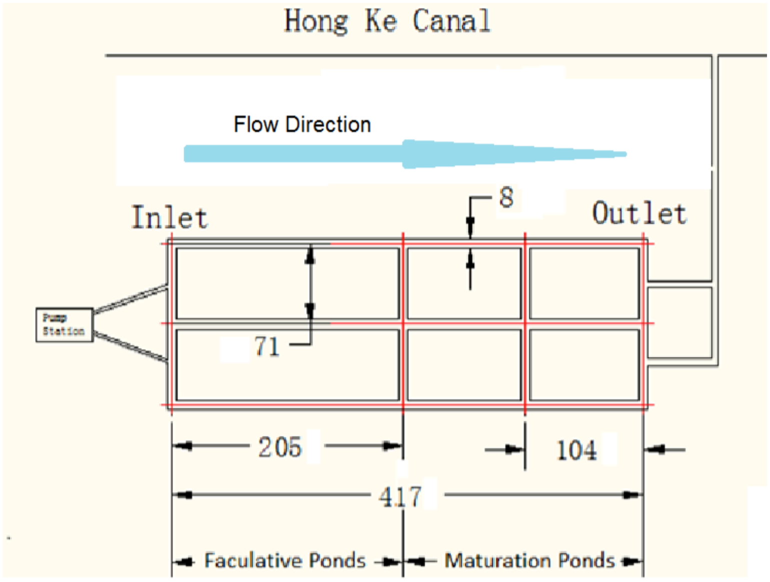


Figure 14: Original design of EU ponds (Source VUISP, Final Report 2001)

For various reasons, the EU ponds were not fully operational for long and are not used for sewage treatment anymore. A restaurant was later opened near the inlet and more buildings are now under construction along the facultative lagoons (Figure 15).

Figure 15: Construction sites and buildings near the faculative lagoons

1.7 Safety of treated wastewater reuse in agriculture

Owing to population growth, industrial development and expansion of irrigated peri-urban agriculture, water demand in urban area has been increasing steadily. Meanwhile, the water cycle of the Mekong River Basin is affected by the changing of climatic conditions. The flood season in 2009 was drier than normal, and the water level in the Mekong River was among the 5th lowest water levels in the record of past 98 years (MRC, 2010). Facing to these challenges, and for both environmental and economic reasons, wastewater reuse becomes more and more important in discussing water resources management. Wastewater reuse has a long history of application and has been practiced in many aspects, which includes agriculture, industrial, household and urban usage. Of them all, agriculture consumes the largest volume of reused wastewater and this is expected to increase further (UNEP & GEC, 2004).

Benefits of wastewater reuse in irrigation have been approved by ancient practice in many countries. Wastewater contains plenty of organic matter and nutrients (Langergraber & Muellegger, 2005), which maintains soil fertility by irrigation. Nutrient such as nitrogen (N), phosphorus (P) and potassium (K) in the wastewater can be used to replace artificial fertilizer (Vinnerås et al., 2004).

Nevertheless, researches show that raw wastewater reuse in irrigation will cause parasitic infestations and toxic contamination. The use of raw wastewater leads to contamination by parasites such as *Giardia* cysts and *Ascaris* eggs (Amahumid et al, 1999). Intestinal *Helminth* eggs are found on raw-wastewater irrigated vegetables in India (Gupta et al, 2009). Figure 16 indicates that a minimum of 10 days hydraulic retention time (HRT) is necessary to allow for *Helminth* eggs removal, while ca. 15 days are required to reduce bacteria by a factor of 10,000x.

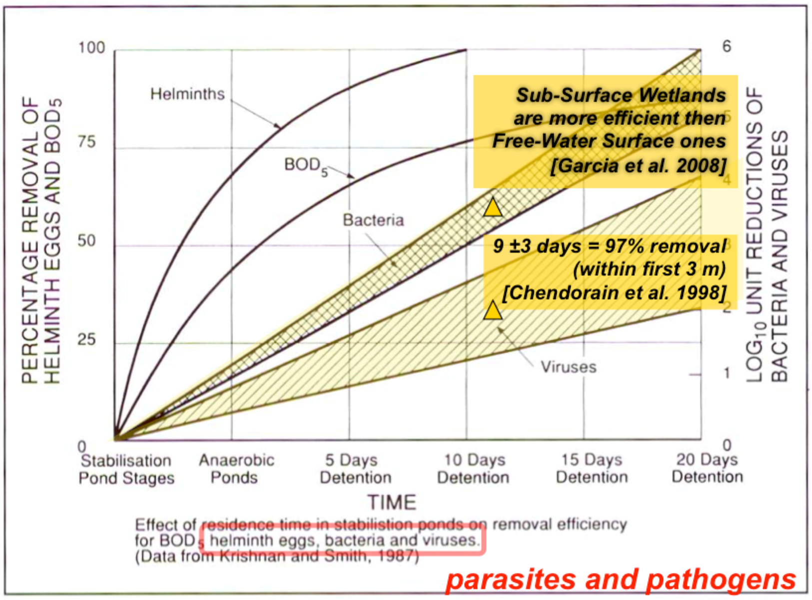


Figure 16: Generalized removal rates of different pathogen in relation to hydraulic retention time (HRT) in treatment wetlands (source: constructed wetland hand-out, Dr. Lacoursière, Kristianstad University 2009)

Plants can further get contaminated by PCBs through raw wastewater irrigation (Naglaa et al, 2010). WHO published in 1989 its “Guidelines for the Safe Use of Wastewater and Excreta in Agriculture and Aquaculture” which were revised in 2006 as “Guidelines for the safe use of wastewater, excreta and greywater, volume 2: wastewater use in agriculture”. The guidelines include irrigation recommendations for crops to be consumed uncooked, and crops to be cooked or used as feed, as well as for parks and localized irrigation (Table 4).

Table 4: WHO guidelines for using treated wastewater in agriculture (WHO, 2006; Wescot, 1997)

Category	Reuse condition	Exposed group	Intestinal nematodes[b] (arithmetic mean no. of eggs per litre[c])	Faecal coliforms (geometric mean no. per 100 ml[c])	Wastewater treatment expected to achieve the required micro-biological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers, consumers, public	≤ 1	≤ 1000[d]	A series of stabilization ponds designed to achieve the microbiological quality indicated, or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[e]	Workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in cat. B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

a) In specific cases, local epidemiological, socio-cultural and environmental factors should be taken into account, and the guidelines modified accordingly.
b) *Ascaris* and *Trichuris* species and hookworms.
c) During the irrigation period.
d) A more stringent guideline (200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
e) In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

The Environmental Protection Agency of United States (US-EPA) has also provided the guideline of wastewater reuse in agriculture. In the guidelines, routine parameters are included (Table 5).

Table 5: US-EPA/USAIS guidelines for wastewater reuse of agricultural irrigation (adapted from US-EPA/USAID, 1992; Blumenthal et al. 2000).

Type of Reuse	Reclaimed Water Quality	Recommended Monitoring	Setback Distances
AGRICULTURAL	pH = 6-9	pH weekly	300 ft from potable water supply wells
Food crops commercially processed	BOD ≤ 30 mg/l	BOD weekly	
	SS = 30 mg/l	SS daily	
Orchards and Vinerds	FC ≤ 200/100 ml	FC daily	100 ft from areas accessible to public
	Cl_2 residual = 1 mg/l min.	Cl_2 residual continuous	
PASTURAGE	pH = 6-9	pH weekly	300 ft from potable water supply wells
Pasture for milking animals	BOD ≤ 30 mg/l	BOD weekly	
	SS ≤ 30 mg/l	SS daily	
Pasture for livestock	FC ≤ 200/100 ml	FC daily	100 ft from areas accessible to public
	Cl_2 residual = 1 mg/l min.	Cl_2 residual continuous	
FORESTATION	pH = 6-9	pH weekly	300 ft from potable water supply wells
	BOD ≤ 30 mg/l	BOD weekly	
	SS ≤ 30 mg/l	SS daily	
	FC ≤ 200/100 ml	FC daily	100 ft from areas accessible to the public
	Cl_2 residual = 1 mg/l min.	Cl_2 residual continuous	
AGRICULTURAL	pH = 6-9	pH weekly	50 ft from potable water supply wells
Food crops not commercially processed	BOD ≤ 30 mg/l	BOD weekly	
	Turbidity ≤ 1 NTU	Turbidity daily	
	FC = 0/100 ml	FC daily	
	Cl_2 residual = 1 mg/l min.	Cl_2 residual continuous	
GROUNDWATER RECHARGE	Site-specific and use-dependent	Depends on treatment and use	Site-specific

In this project, the most stringent recommendations by WHO (2006) for BOD_5 and TSS of <15 mg/l is used as an upper limit for irrigation of crops likely to be eaten uncooked (or for water used in public park watering).

1.8 The WWF "Water Project" in Vientiane Capital City

Filling-up of the city's wetlands makes TLM receives more pollutants. Water quality degradation has become a serious problem, which directly impacts the aquatic species diversity. Wastewater also significantly impacts the agriculture irrigation by increasing health risk (Kyophilavong, 2007). Meanwhile, a lack of irrigating water in the dry season is a major factor in reduced agricultural productivity.

In order to achieve a better living environment for the Vientiane residents and to improve the livelihood for the TLM residents, a water-related project was carried on in Vientiane Capital City sponsored by the Asia ProEco Programme of EuropeAid. The name of the project was "Wastewater Treatment through Effective Wetland Restoration of That Luang Marsh (WATER project)". The WATER project was initiated on 1st June 2007 following the signing of a Memorandum of Understanding between the Government of Lao PDR and WWF. The project was coordinated by WWF-Lao and based at one of the Government agencies of Lao PDR (Department of Science and Technology of Vientiane Capital City). Vientiane Urban Development Administration Authority (VUDAA) and the Department of Communication, Transportation, Post and Construction (DCTPC) were two of the major partners of the WATER project. In the WATER project, capacity and awareness building were emphasized, and maintaining the "natural sanitation" capacity in the urban wetland was the goal. In order to rebuild the aquatic ecosystem self-cleaning capacity, wetland restoration was put into practice. Consequently, the TLM would be able to have a sustainable delivery of wetland goods and services (e.g. flood protection, water quality improvement, natural-resources production). In order to reduce wastes discharging into city wetlands, the WATER project mainly focused on establishing small-scale wastewater treatment facilities. In the project, wastewater from households, schools and factories is treated by constructed wetlands locally and discharged into city wetlands.

However, water quality in the drainage network would not be improved immediately. Wastewater from some households, which are not suitable for setting small-scale wastewater treatment facilities, would still be discharge into the drainage network directly. What's more, small-scale wastewater treatment facilities need time to establish. From CWs' construction to stabilization usually needs several months, and it's going to take longer time for the approach to be popularized. Meanwhile, water shortage becomes a problem of the city, and wastewater reuse should be part of the solution.

2. Thesis Objective

As a contribution to WWF's WATER project, this thesis attempt to answer one of the recommendations of the project's Mid-Term Review (carried out by Dr. Jean O. Lacoursière of Kristianstad University), namely: "*Could rehabilitating the inoperative EU-Facultative Lagoons simultaneously reduce the impact of untreated wastewater on the That Luang Marsh and provide a secure source of agriculture irrigation during the dry season?*"

The specific objective of this thesis is to establish if, within the available area of the original facultative lagoons complex, it is possible to construct a treatment wetland system able to generate water suitable for irrigation of crops likely to be eaten uncooked (*i.e.*, the most stringent health requirement).

This project was carried out under the local supervision of WWF-Lao and its consulting group to contribute to the WATER Project's objectives. In order to find the best solution, a four months trip of information collection and discussions was carried out in Laos.

2.1 Background of this Thesis Project

This project was introduced to me by Dr. Lena B.-M. Vought and my supervisor from Kristianstad University who have been studying the urban aquatic ecosystems of Vientiane for over 2 decades. Their contact with the WATER Project team allowed me to get integrated in the project activities and gather the information required to produce a reliable design proposal. A large part of this project took place in the field in Vientiane and its surroundings. During the investigation, water supply situation and water drainage systems were inspected. Water samples were taken from major drainage channels and wetlands to define my assumptions on wastewater quality inflow to the proposed design. Relevant information was received from local people and the WATER project unit's interviews. The restoration design of the wetlands is based on the disused EU-Facultative Lagoons' construction structures. In order to reduce the cost, the pump station and the water intake have been kept. In this project, two sets of wetland design plans are proposed. Treatment efficiencies of these two designs are compared by estimating outflow water quality and quantity.

3. Theoretical Background

3.1 Wetland for wastewater treatment

Wetlands are shallow system, usually with water level lower than 1.5m. Constructed wetlands have extensively vegetated water bodies that use enhanced sedimentation, fine filtration and pollutant uptake processes to remove pollutants from wastewater (Melbourne Water, 2005).

With flexibility in location, low operation cost and high pollutants removal efficiency, constructed wetlands (CWs) are highly sustainable methods for wastewater treatment. They can be designed to fit complex landscapes (Alvarez-Cobelas *et al.*, 2001) and can be put into operation with neither energy supplement nor additional chemical and artificial carriers (Lin *et al.*, 2002; Jou *et al.*, 2009). CWs have been commissioned to treat various types of wastewater worldwide, as they show significant removal rates of nutrient rich wastewater such as agricultural runoff (Zhang, *et al.,* 2009; Polomski *et al.*, 2009; Sim *et al.*, 2008), animal farms wastewater (Stone, *et al.*, 2004; Poach, *et al.*, 2004; Cronk, 1996). Studies also show that CWs can be used to treat landfills leachates (Aluko & Sridhar, 2005) as well as removing pharmaceuticals and personal care products (PPCPs) (Matamoros *et al.*, 2009). High standards of wastewater reuse, nutrients recovery and biomass production can be achieved with CWs (Rousseau, et al., 2008; Masi, 2009).

3.1.1 Free Water Surface and Subsurface Flow Wetlands

Two types of wetlands designs are used to treat wastewater: free water surface wetland (FWS) and subsurface wetland (SF). Water surface of the free water surface wetland is exposed in the atmosphere. The water level of subsurface flow wetland is lower than the surface of wetland bed (EPA, 1993). FWS (Figure 17a) mimic natural wetlands and can be a better habitat for certain wetland species. However, SF (Figure 17b) is closer to wastewater treatment plants than wetlands. In a SF system, the water flow through a porous medium and only few relatively narrow lists of macrophytes such as *Phragmites australis* are able to live within (Mitsch & Jørgensen, 2004). A vertical flow wetland (VF) (Figure 17c) is a combination of a filter bed and an SF. Wastewater is poured or dosed onto the system surface using a mechanical delivery system. Wastewater flows vertically down through the filter matrix (Akvopedia, 2009).

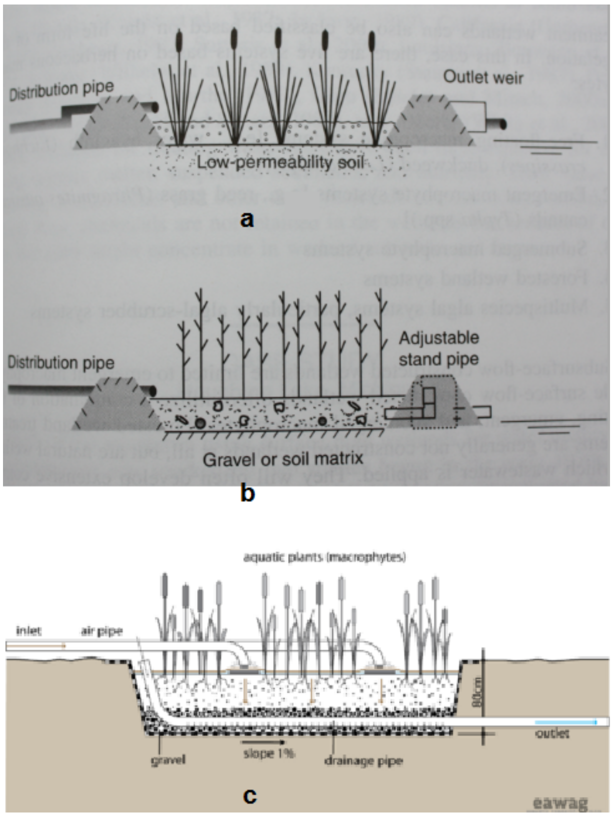


Figure 17: Three types of wetland treatment systems: a. free water surface wetland (Mitsch & Jrøgensen, 2004); b. subsurface flow wetland (Mitsch & Jrøgensen, 2004); c. vertical flow wetland (Akvopedia, 2009)

Wetlands are characterized by a range of properties making them attractive for pollutants management (Bavor and Adcock, 1994). The properties include (adapted from DLWC New South Wales, 1998[a]):

- a large buffering capacity for nutrients and pollutants;
- high biomass productivity;
- large adsorptive capacity of the sediments;
- large biodiversity; *and*
- high rates of oxidation by micro flora associated with the plant biomass.

The removal processes of pollutants in a wetland are shown in Table 6.

Table 6: Overview of Pollutant Removal Mechanisms (Brown *et al.*, 1998 & Mitchell, 1996)

Pollutant	Removal Processes
Organic material (measured as BOD)	Biological degradation, sedimentation, microbial uptake
Organic contaminants (e.g. pesticides, PCB)	Adsorption, volatilization, photolysis and biotic/ abiotic degradation
Suspended solids	Sedimentation, filtration
Nitrogen	Sedimentation, volatilization, nitrification/denitrofication, microbial and plant uptake
Phosphorus	Sedimentation, filtration, adsorption, plant and microbial uptake
Pathogens	Natural die-off, sedimentation, filtration, predation, UV degradation, adsorption
Heavy metals	Sedimentation, adsorption, plant uptake

3.1.2 The Nitrogen Cycle

Usually wastewater contains three kinds of nitrogen: organic nitrogen, ammonia nitrogen and nitrate nitrogen. Four types of biological reactions are happened in the wetland system, and the processes of the reactions are shown in Figure 18.

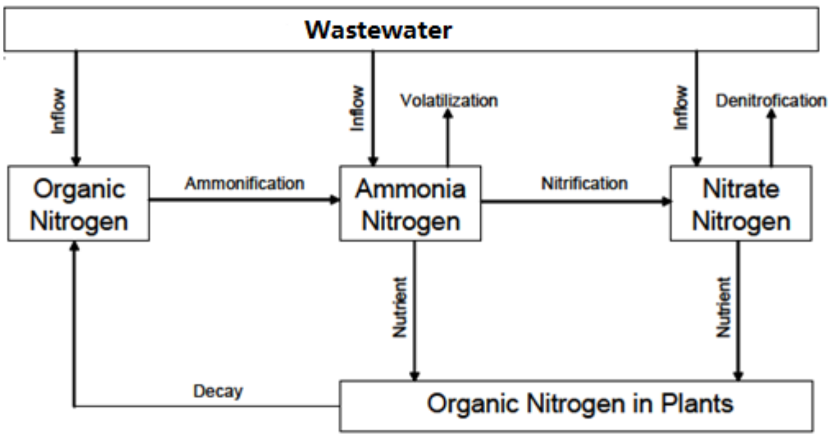


Figure 18: Mass balance for nitrogen transformation and removal (Wang Y. *et al.*2009)

During organic matter degradation, organic nitrogen transforms into ammonia nitrogen through the ammonification process. Ammonia nitrogen then can turn into nitrate nitrogen by microorganism through the reaction of nitrification. Denitrification is also a biological reaction, which generates nitrogen gas and nitrous oxide from nitrate nitrogen. At the same time, the plants that provide substrates to nitrification and denitrification organisms also uptake nutrient from the wastewater and assimilate inorganic nitrogen for their structure. The processes of nitrogen cycle are show in Figure 19.

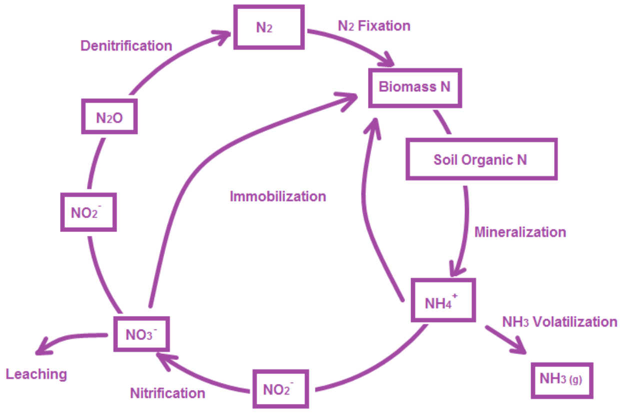


Figure 19: the Nitrogen cycle

3.1.3 Phosphorous removal

Phosphorus is an essential element for biological growth. However, because it is a limiting factor, an excess of phosphorus in the aquatic system may lead to eutrophication and possible algal blooms. Because phosphorous has to be mined and that its availability is expected to decline within the next decades or so, recycling it is becoming critical.

Phosphorus cycling is efficient and extensive in wetlands (Figure 20). It is stored in sediment, biota (plants, biofilms and fauna), detritus and water. Phosphorus cycling is influenced by the environment conditions such as the redox chemistry, pH and temperature (Brown M. *et al.* 1998 & Kadlec and Knight, 1996).

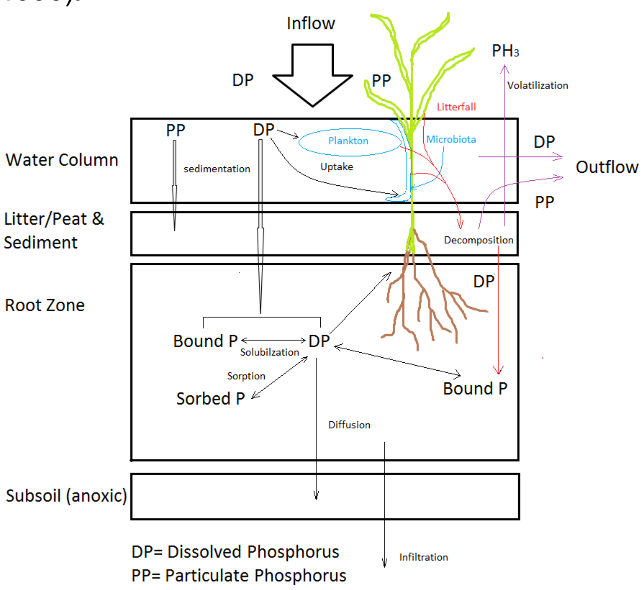


Figure 20: Phosphorus cycling in a wetland (adapted from Kadlec and Knight, 1996)

3.1.4 Importance of vegetation in constructed wetlands

Vegetation in a wetland is an integral component of the wastewater treatment system, and in the system, vegetation has several functions such as the following. (DLWC New South Wales, 1998[b])

- provide a protection to avoid bank erosion and stabilize the substrate;
- provide a surface area to trap suspended solids;
- provide a biologically active root zone to remove the nutrients and pollutants;
- maintain infiltration rate and reduce soil compaction;
- decrease the flow velocities; *and*,
- create a diverse and prominent landscape element in the development and enhance local biodiversity.

3.2 Facultative wastewater stabilization ponds

Facultative waste stabilization ponds (facultative lagoon) are usually 1.2 to 2.4m in depth and are not mechanically mixed or aerated as shown in Figure 21. Due to atmospheric re-aeration and algal primary production, the surface layer of water contains dissolved oxygen. This layer, with high dissolved oxygen (DO), creates a condition that supports aerobic and facultative organisms. The bottom layer of lagoon is anaerobic layer, which contains sludge deposits and supports anaerobic organisms. The intermediate anoxic layer (facultative zone) ranges from aerobic near the top to anaerobic at the bottom (EPA, 2002).

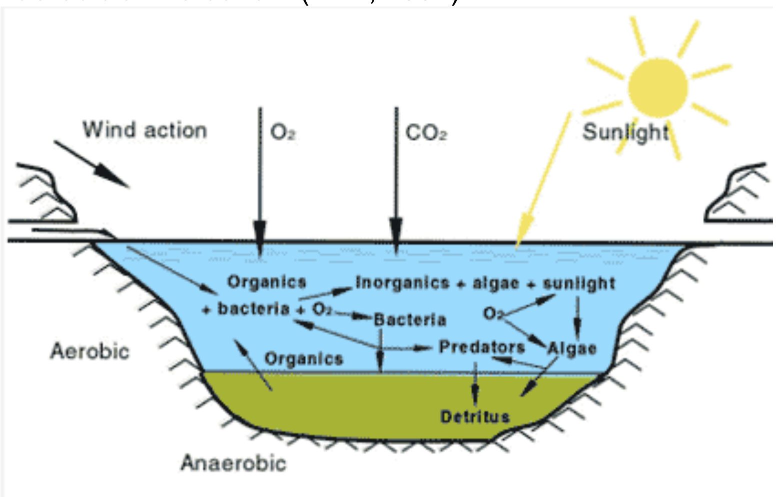


Figure 20: Facultative waste stabilization ponds (The Water Treatment, 2009).

4. Methodology

4.1 Data Collection

Both primary and secondary data were collected in Vientiane Capital City, Lao PDR. Primary data includes water environment survey, canal water sample collection and field-testing (water quality 2009 Aug.3). Secondary data was collected from Governmental and Non Governmental Organisations in Vientiane.

Long-term average water quality data of the EU-Ponds inflow was not available. In order to get realistic outflow (i.e., treated values), the inflow characteristics were based on the tables of typical average contents of pollutants in domestic wastewater found in the literature.

4.2 Restoration Dimensioning Procedure

4.2.1 Key Design Issues

The key design criteria are selected and ranged based on "The Constructed Wetland Manual" (DLWC New South Wales, 1998), namely:

- ✓ Wetland construction design
- ✓ Inlet zone design
- ✓ Layout of macrophyte zone
- ✓ Hydraulic structure calculation
- ✓ Plants recommendation
- ✓ Monitoring, management and maintenance providing
- ✓ Outflow expectation and parameter design

4.2.2 Reed's Method for Wetland Parameter Design

The equations of the Reed's Method (Reed *et al*., 1995) are based on the first-order plug flow assumption for pollutants' removal primarily by biological processes. The selected parameters include biochemical oxygen demand (BOD), ammonia (NH_4) and nitrate (NO_3). The separate equations for total suspended solids (TSS) and total phosphorus (TP) are based on regression analyses by Knight *et al*. (1993).

The dimensioning equations based on Reed *et al*. (1995) used in this thesis are presented below.

Dimensioning of the wetland's basic characteristics:

The hydraulic retention time (HRT) is determined by the inflow rate (Q) and the design volume of the wetland (V). With a certain wetland design volume, the hydraulic retention time is in the inverse ratio of inflow volume.

(Eq. 1) $$HRT = \frac{V}{Q} = \frac{A_s \cdot y \cdot n}{Q}$$

where:

HRT: hydraulic retention time in days (d);
V: design volume of wetland, m^3;
A_s: treatment area of wetland, m^2;
y: average depth of wetland, m;
n: porosity (percent, expressed as a decimal fraction);
Q: average flow rate through the wetland, m^3/d.

The surface area of wetland (A_s) is conformed to plane geometry, and the equations are chosen by the wetlands' design shape.

(Eq.2) $$A_s = L \cdot W$$

where:

L: wetland length, m;
W: wetland width, m.

The hydraulic load rate changes with the inflow rate, when the surface area of the wetland is given.

$$\text{(Eq.3)} \quad HLR = \frac{100 \times Q}{A_s}$$

where:

HLR: Hydraulic load rate, cm/s.

Assessing BOD, NH_4 and NO_3 removal

Environment temperature and hydraulic retention time (HRT) of the wetland influence the removal result a lot. In a certain climate condition, the adjusting of hydraulic retention time will lead to a better outflow.

$$\text{(Eq.4)} \quad \ln\left(\frac{C_i}{C_o}\right) = K_T \cdot HRT$$

where:

C_i: influent polluant concentration, mg/L;
C_o: outlet effluent pollutant concentration, mg/L;
K_T: rate constant at temperature T_w/d;

Different Θ_R and K_R are used to calculate K_T for different parameters. Rate constant at temperature (K_T) refers the operation rates of different parameters are varying under different temperature. Table 7 shows the parameters for the design of the two types of constructed wetlands based on the Reed *et al.* (1995) equation.

$$\text{(Eq.5)} \quad K_T = K_R \cdot \Theta_R^{(Tw-T_R)}$$

where:

K_R: rate constant at reference temperature;
Θ_R: temperature coefficient for rate constant;
T_W: water temperature, °C;
T_R: reference temperature.

Table 7: Parameters of wastes removal (Reed *et al.*, 1995)

Parameter	BOD removal	Nitrification[b] (NH_3-H removal)	Denitrification[b] (NO_3 removal)	Pathogen removal
T_R, °C	20	20	20	20
Residual, mg/L	6	0.2	0.2	-
For free water surface wetlands				
K_R, d^{-1}	0.678	0.2187	1.000	2.6
Q_R	1.06	1.048	1.15	1.19
For subsurface flow wetlands				
K_R, d^{-1}	1.104	K_{NH}[c]	1.000	2.6
Q_R	1.06	1.048	1.15	1.19

a) All rate coefficients are for temperatures greater than 1°C.
b) Nitrification/ denitrofication are not possible at temperatures below 0°C.
c) K_{NH}=0.01854+ 0.3922$(r_z)^{2.6077}$
d) K_{NH}: Subsurface flow nitrification rate constant, d^{-1};
e) r_z: Depth of bed occupied by root zone, percent expressed as a decimal fraction.

4.2.3 Weirs Design

In this project, weirs are designed to control water going through from one section of the wetland to another. Free flow condition is chosen for weir calculation.

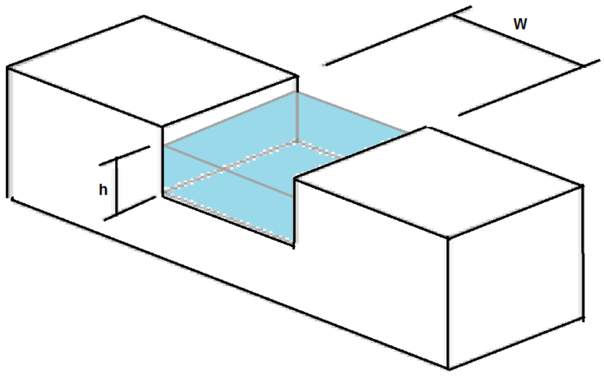


Figure 21: Free flow weir

The flow rate through weirs (Q_{weir}) can be determined by setting size and shape of the weir (Figure 22).

$$\text{(Eq.6)} \quad Q_{weir} = B \times C_w \times L \times h^{\frac{3}{2}}$$

$$\text{(Eq.7)} \quad L = 2h + w$$

where:

Q_{weir}: flow through weirs, m^3/s;
B: blockage factor (0.5);
C_w: weir coefficient (1.7);
L: wetted parameter, m;
h: flow depth above the weir, m.
w: weir length.

5. Results and Discussions

5.1 Establishing Inflow Water Quality

According to the historical data from WWF, the concentrations of heavy metal are very low in Vientiane's water bodies. Therefore, they are not considered in setting water quality parameters.

In order to get a reliable outflow assumption for the constructed wetland, rational input data of inflow water quality is important. Wastewater quality varies daily and, because of the traditional combined sewage overflow system (CSOs), it would be diluted during rain events. Unfortunately, due to budget restriction, removal of the sampling station associated with the EU-Ponds pumping inflow made that long-term water quality data is not available to establish the actual average inflow values. Parameters concentrations were therefore chosen from Henze (1995) table of "Typical Average Contents of Pollutants in Domestic Wastewater". Because it is known that groundwater enters the city's drainage network, the wastewater type is chosen as diluted.

Table 8: Inflow water quality (established from Henze, 1995)

Parameters	Concentration (mg/L)
TSS,	190
NH_3-N	18
NO_3-N	0.5
TP	10
BOD	150

5.2 Proposed Wetland Restoration Designs

In this project, two alternative designs (A and B) were prepared. In both cases, constructed wetlands are used to replace the original facultative stabilization ponds but, although with some modifications, sewage water is still pumped to the wetlands inlets using the existing system. As for the previous design, water exits the constructed-wetlands through gravity.

Since restaurants and living facilities are now built along the original inlet, the original flow direction is reversed (hence the need to extend the inflow pipes) and wastewater will go into the wetland from the old outlets, and come out through the old inlet as shown in Figure 23.

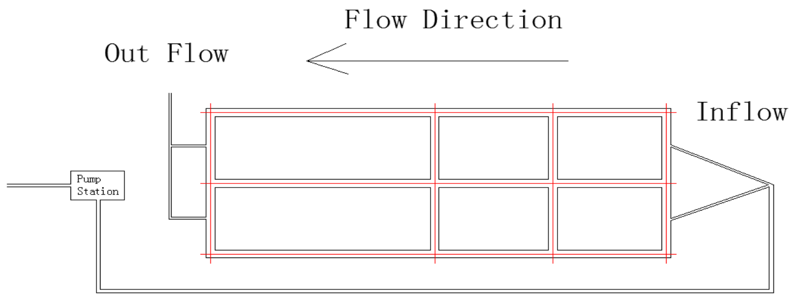


Figure 22: New flow direction of wetland

5.2.1 Alternative-A: Free Water Surface (FWS) Wetland only

Two groups of free water surface constructed wetlands (FWS) are designed to work in parallel. Each group contains three free surface flow sub-wetlands (Figure 24).

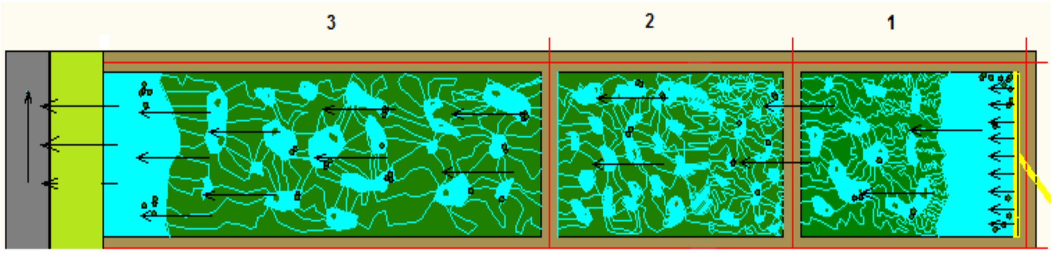


Figure 23: Layout of the Free Water Surface Wetland groups

5.2.1.1 Inlet Zone design

The inlet zone (section 1 in Figure 24) of the FWS wetland groups is made of a deep-water area followed by some shallow marsh, where the deep area serves as sediment trap. Access space along the inlet zone is set for sediment removal operation as seen in Figure 25.

5.2.1.2. Macrophyte Zone Layout

5.2.1.2.1 Zonation

The overall layout sets the wetland with one macrophyte zone divided in shallow and deep marshes (respectively sections 2 and 3 on Figures 23 and 24). Because of it slowly increasing depth, the deep marsh has submerged vegetation and an open-water zone (> 1.5 m) free of anchored vegetation (Figure 25).

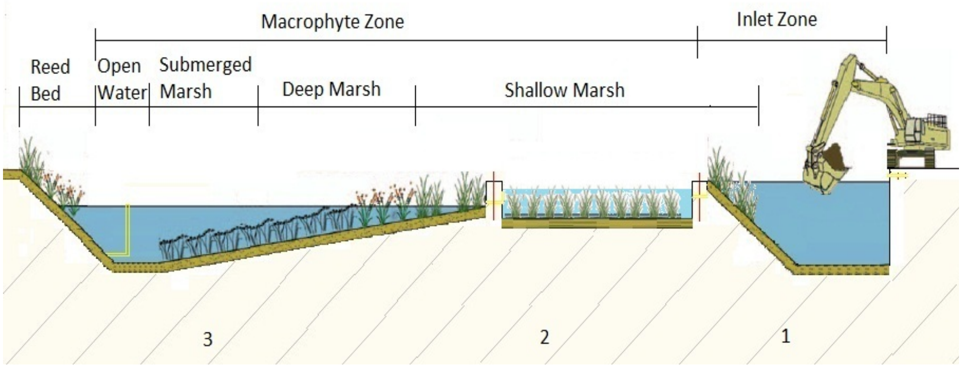


Figure 24: FWS wetland rendered with zonation definition

5.2.1.2.1 Longitudinal Profile

Precipitation in Vientiane city has significant difference during the raining season and the dry season. An extended detention depth of 0.5 m has been adopted for the whole area of wetland to prevent system overload during a heavy rainfall, which sometimes also happens during the dry season. As to prevent the risk of fauna being isolated in shallow depressions if the pumps stop working during drought periods, the wetlands' beds are designed to gradually deepen over the macrophyte zones in sub-wetlands 1 and 3 (Figure 26).

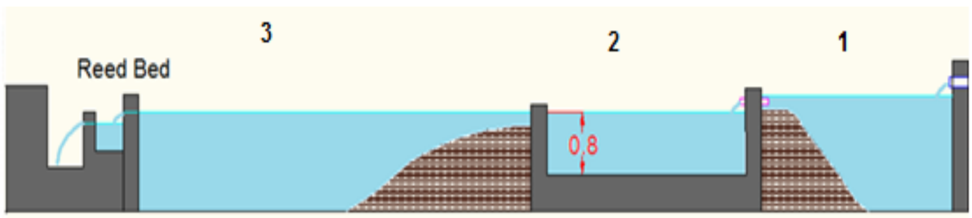


Figure 25: Side cross section of FWS wetlands

The construction parameters of the FWS wetlands are shown in Table 9. The total volume of the constructed wetland is 80,074 m^3 and the total surface area is 49,518 m^2.

Table 9: FWS wetlands design parameter

Wetland No.	Surface Area (m^2)	Average Depth (m)	Volume (m^3)
1	6,050	2.5	15,000
2	6,300	1	6,300
3	12,500	1.5	18,600

5.2.1.3 Flow Diversity

A diagram of possible surface water diversity is shown in Figure 26. Deep-water zones are designed at both inlet and outlet. As mentioned earlier, the deep-water area of the inlet zones functions as a settling trap for incoming particles. Alternating shallow and deeper paths are arranged to optimize water distribution and ensure extended residence time. A dense reed bed is set as a buffer zone at the outlet of the wetlands. As shown in Figure 27, water then overflows into the water collection channel.

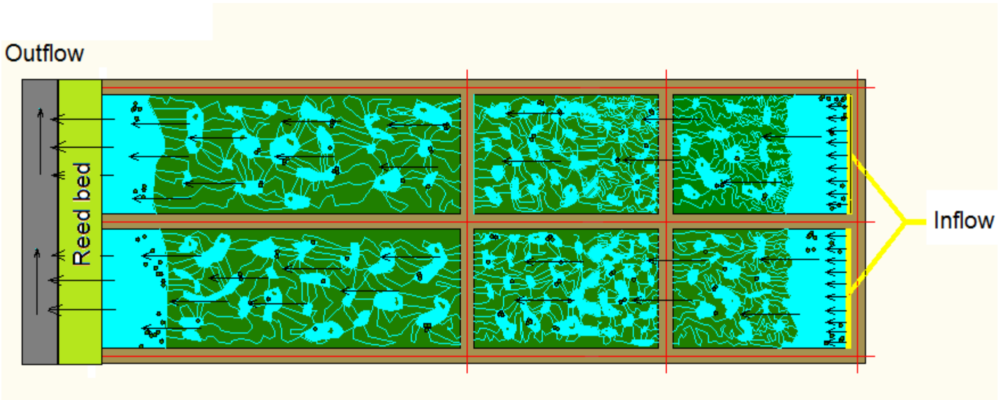


Figure 26: Surface water flow direction of FWS wetlands

5.2.1.4 Vegetation Specifications

Vegetation specifications and plants density recommendation of the macrophyte zone are shown in Table 10.

Table 10: Vegetation specifications of FWS wetlands (adapted from Melbourne Water, 2005)

Zone	Plant species	Planting density (plants/m^2)
Littoral berm	*Persicaria decipens*	3
Ephemeral marsh	*Blechnum minus*	6
Shallow marsh	*Cyperus lucidus*	6
Marsh	*Bolboschoemus caldwellii*	4
Deep marsh	*Juncus ingens*	8

5.2.1.5 Expected Removal Performance Assessment

Using Reed's method to determine removal performance from the set sewerwater quality characteristics (inflow) and the established dimensions of the selected wetland design, a theoretical water quality outflow can be assessed for different hydraulic loading rates (Table 11). Results show that, in accordance to an upper limit of 30 mg/l for BOD and TSS set by

USEPA for irrigation water, the hydraulic loading rate for this FWS-only design (Alternative-A) should not be larger than *ca.* 20,000 m^3/d.

Table 11: Theoretical outflow water quality of FWS wetland (Alternative-A) under different hydraulic loading rates.

		Estimated Outflow Concentration, mg/L					
Q m3/d	**HRT days**	**BOD**	**NH_3-N**	**NO_3-N**	**TSS**	**TP**	
2,000	*40*	0	0	0	22.50	2.59	**Too large HRT (algal growth)**
3,000	*26.7*	0	0	0	22.90	4.06	
4,000	*20*	0	0	0	23.28	5.09	
6,000	*13.3*	0	0.003	0	24.09	6.37	
8,000	10	0	0.03	0	24.91	7.13	
10,000	8	0	0.11	0	25.73	7.63	
15,000	5.3	0.001	0.60	0	27.77	8.35	
20,000	4	0.03	1.41	0	29.81	8.74	
30,000	2.7	0.47	3.29	0	*33.90*	9.14	**TSS over limit (30mg/l)**
40,000	2	1.98	5.03	0	*37.99*	9.34	
50,000	1.6	4.71	6.50	0	*42.07*	9.47	

Figure 28 shows removal rates for the set parameters under different hydraulic retention time. Results show that removal rate would not significantly increase after 7 days, with removal rates of NH_3-N and TP being more sensitive to Hydraulic Loading Rate.

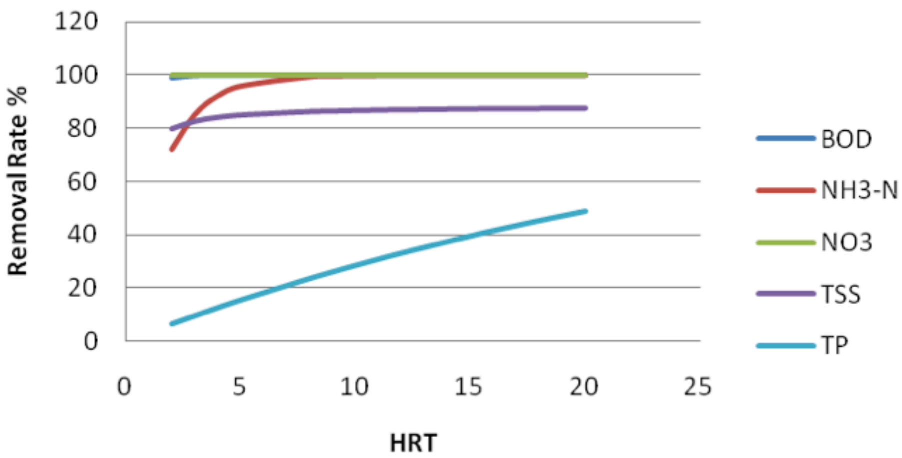


Figure 27: HRT and removal rate of selected elements by FWS-only wetland group

Vientiane Capital City has a high year-around average temperature, over growing of algae has to be taken into consideration. Since its common temperature is above 25, a 10 days limitation of HRT is chosen from Figure 29 (Melbourne Water, 2005). Therefore, the hydraulic loading rate of the wetland groups should not be less than 8,000 m^3/d.

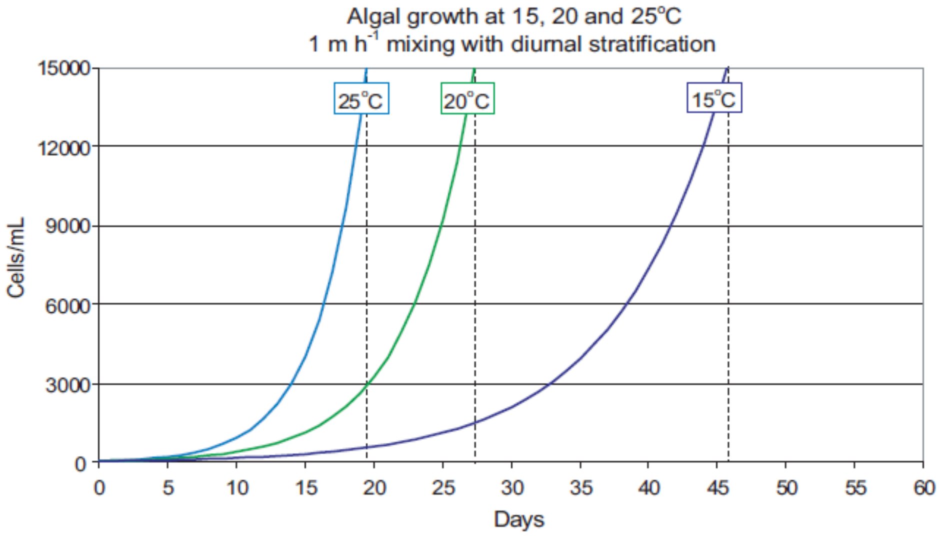


Figure 28: Algal growth at 15, 20 and 25 ℃ 1m/h mixing with diurnal stratification (Melbourne Water, 2005)

5.2.1.6 Dimensioning of the Inter-Cells and Outflow Weirs

A total of twenty weirs, are set on each wetland diversion dam of both wetlands groups. Assuming the largest inflow of 20,000 m^3/d and no evaporation for simplification, free-flow condition dictates that those weirs could be of a width and depth of 0.2 m.

5.2.2 Alternative-B: Combination of Free Water Surface (FWS) and Subsurface Vertical Flow (VF) wetlands

Two groups of free water surface (FWS) and subsurface flow (SF) combined wetlands are proposed, with a vertical-flow (VF) subsurface flow wetlands replacing part of the free surface wetland in sub-section 2 of each wetland group (Figure 30).

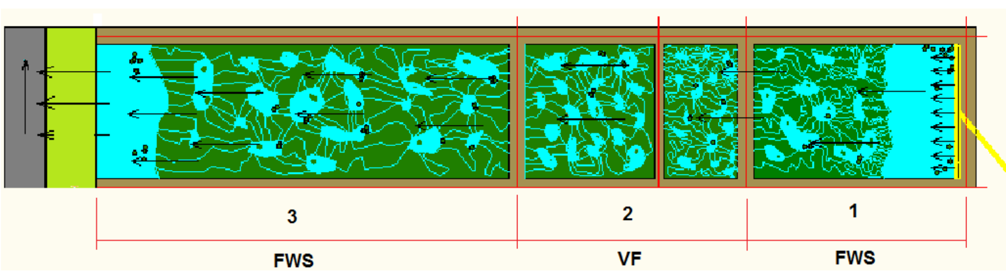


Figure 30: Free water surface and subsurface flow wetland group. Wetland 1 and wetland 3 are free water surface wetlands, and wetland 2 is a vertical-flow wetland (subsurface flow wetland).

5.2.2.1 Inlet Zone design

The inlet zones of the VF wetlands group has the same design as the FWs wetlands group in Alternative-A. Sediment basins and shallow marshes are both included in the design.

5.2.2.2 Macrophyte Zone layout

5.2.2.2.1 Wetland zonation

The wetland has one macrophyte zone, and the macrophyte zone includes wetland 2, wetland 3 with shallow marsh, deep marsh, submerged marsh and open water area (Figure 31). Surface of the whole vertical-flow wetland (wetland 2) is covered by shallow marsh. Root zone depth is assumed to be 30 cm.

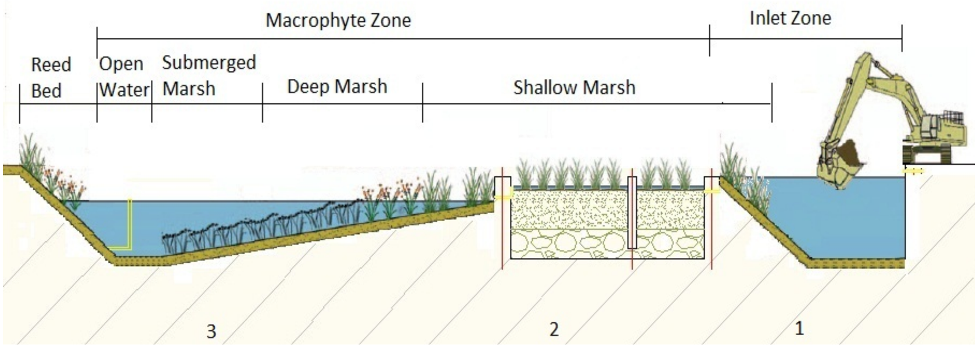


Figure 29: Wetland render with zonation instruction

5.2.2.2.2 Longitudinal Profile

As for the previous alternative, an extended detention depth of 0.5 m has been adopted for the whole area of wetlands to prevent system overload during the raining season. Similarly, a gradually deepening wetland' bed is designed to protect fauna in case of pump-stoppage induced drought.

The construction parameters of the VF wetlands are shown in Table 9. The total volume of the constructed wetland is 80,174 m^3. Wetland 2 is filled up by gravel and sand (Figure 32). The designed depth of wetland 2 is 3 m, and the porosity of the filler is 0.35. The designed parameters of wetland 1 and wetland 3 are the same as the Alternative-A alternative and the design volume of wetland 2 is 6,350 m^3.

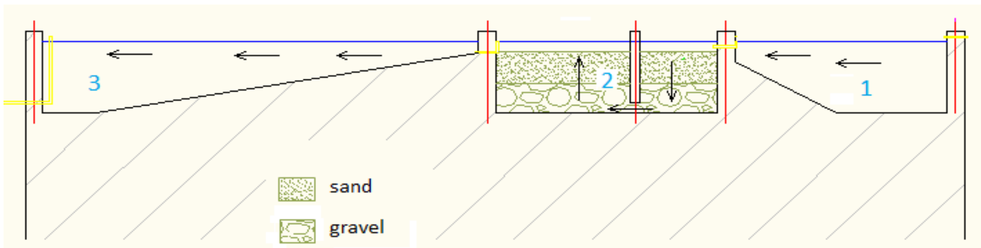


Figure 30: Construction layout of VF wetland

5.2.2.3 Flow Diversity

Surface water diversity of the VF wetland is shown in Figure 31. Shallow water traps, water paths and reed beds are set as in Plan A. Partition walls (B-B and C-C in Figure 33) separate the surface flow and subsurface flow wetlands. A wall is added to the subsurface wetland (A-A) as a diversion dam. As seen in Figures 33 and 34, water is not supposed to go over the diversion dam, but to flow vertically down to the bottom. Water goes through the gravel layer to reach the second part of vertical-flow wetland.

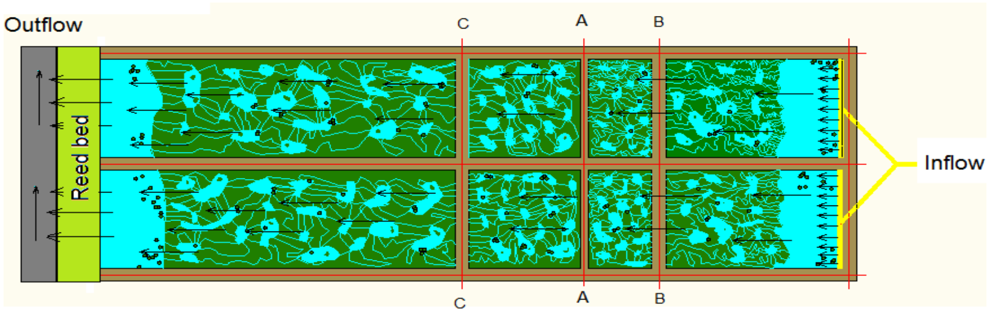


Figure 31: Surface water flow direction of VF wetland

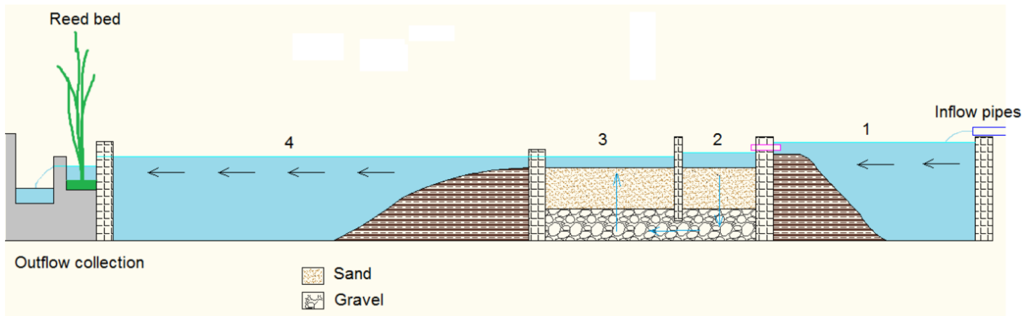


Figure 32: Cross section and the water direction of the VF wetland

5.2.2.4. Vegetation Specifications

Vegetation specifications and plants density recommendation of the macrophyte zone are shown in Table 12.

Table 12: Vegetation specifications of VF wetland (adapted from Melbourne Water, 2005)

Zone	Plant species	Planting density (plants/m^2)
Littoral berm	*Persicaria decipens*	3
Ephemeral marsh	*Blechnum minus*	6
Shallow marsh	*Cyperus lucidus*	6
Vertical-flow zone	*Vetiveria zizanioides* Nash, *Cyperus flablliformis* Rottb (Kantawanichkul, *et al.*, 1999)	6
Marsh	*Bolboschoemus caldwellii*	4
Deep marsh	*Juncus ingens*	8

5.2.2.5 Expected removal performance assessment

As for the previous alternative, the Reed's method is used to estimate outflow water quality based on different hydraulic loading rates (Table 13). For the concentration of TSS and BOD_5 should not be higher than 30 mg/L, and HRT should not be longer than 10 days, the ideal water inflow of the wetland groups should be between 8,000 m^3/d and 60,000 m^3/d.

Table 13: Outflow water quality of VF wetland under different inflow

		Outflow Concentration, mg/L					
Q m^3/d	HRT	BOD_5	NH3-N	NO_3-N	TSS	TP	
2,000	*40.1*	0	0	0	0.4	2.13	Too large HRT (algal growth risk)
3,000	*26.7*	0	0.01	0	0.49	3.57	
4,000	*20.0*	0	0.08	0	0.58	4.49	
6,000	*13.4*	0	0.47	0	0.79	5.97	
8,000	10.0	0	1.18	0	1.03	6.79	
10,000	8.0	0.01	2.03	0	1.33	7.34	
15,000	5.3	0.26	4.2	0	2.22	8.14	
20,000	4.0	1.28	6.04	0	3.4	8.57	
30,000	2.7	6.27	8.69	0	6.75	9.02	
40,000	2.0	13.86	10.43	0	11.61	9.24	
50,000	1.6	22.32	11.65	0	18.24	9.4	
60,000	1.3	30.66	12.51	0.01	26.88	9.49	BOD over limit (30mg/l)

Figure 35 shows the pollutants removal rates under different Hydraulic Retention Times. Calculations are carried out with the same parameter as FWS wetlands. Results indicate that the removal rate of NH_3-N and TP will be higher under longer HRTs, with VF wetlands demonstrating higher TSS removal rates.

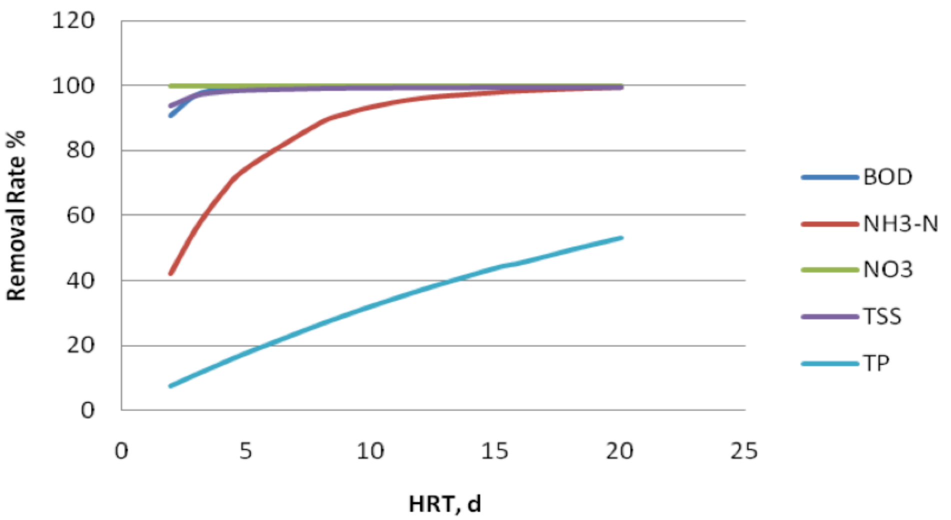


Figure 33: VF wetland pollutants removal rate under different HRT

5.2.2.5 Dimensioning of the inter-cells and outflow weirs

Discharge weirs are used to transport water in the rest of the structures. Discharge weirs calculations are the same as the FWS wetland of Alternative-A. In each group, ten weirs are set on wall C-C, D-D and E-E (Figure 36) with depth set at 0.2 m and width at 0.5 m.

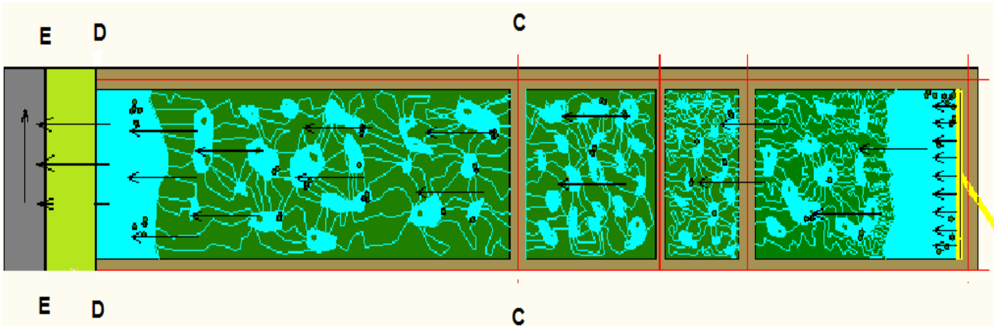


Figure 34: Weirs are locating on the diversity dams

5.3 Comparison alternatives A (FWS) and B (FWS-VF)

Removal rates show that, at similar Hydraulic Retention Time, the free-water surface wetland design (Alternative-A) is more efficient in removing BOD^5 and NH_3-N, while the design combining FWS and a vertical-flow wetland (Alternative-B) is more efficient in removing TSS and TP (Figures 37). This is not surprising as VF works both as a subsurface wetland and a sand-filter, leading to a rapid removal of most particles. However, FWS systems are more efficient at removing organic material and ammonia at shorter HRTs.

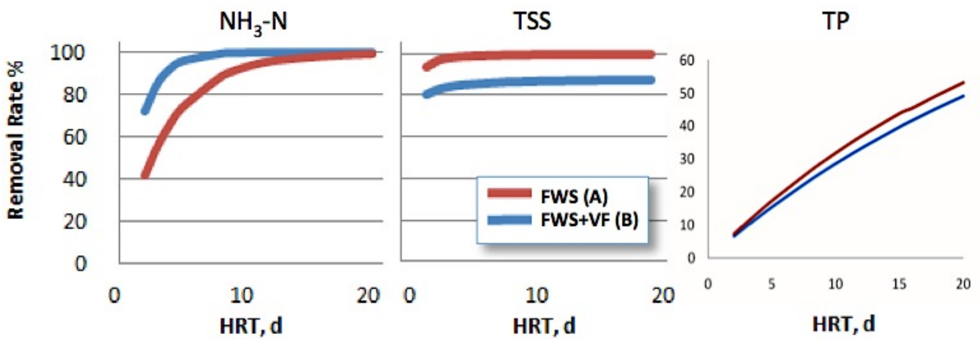


Figure 35: Compare of NH3-N and TSS of FWS wetland and VF wetland

Based on the outflow overall water quality, the design containing a vertical-flow wetland (Alternative-B) is more suitable to meet WHO's most stringent recommendation of < 15 mg/l BOD_5 and TSS for treated sewagewater reuse on crops likely to be eaten raw (Table 14, where numbers in red indicate values exceeding the limit). To ensure suitable removal of parasites and pathogens, HRT should however be longer then 10 days (green zone in Table 14). Although both BOD_5 and TSS values would remain within the stringent limit until *ca.* 40,000 m^3/d (*i.e.*, about 4 times the 10,800 m^3 dry-weather flow observed in February 2005; yellow zone in Table 14), only part of the dry-weather flow generated by the city-centre can be processed for a low-risk parasites and pathogens standard to be maintained.

Table 14: Comparison of theoretical outflow water quality of Plan A (FWS) and *Plan B (FWS+VF)* under different hydraulic loading rates. Numbers in red indicate values above the WHO (2006) upper limit of 15mg/l BOD5 and TSS for water reuse on crops likely to be eaten raw. Area shaded green indicates HRT more suitable to remove parasites and pathogens. Area shaded in yellow indicates an average dry-flow (February 2005) passing the pumping station.

		Estimated Outflow Concentration, mg/L Plan A (FWS) and *Plan B (FWS+VF)*				
Q m3/d	**HRT days**	**BOD**	**NH_3-N**	**NO_3-N**	**TSS**	**TP**
2,000	***40***	0 / *0*	0 / *0*	0 / *0*	22.5 / *0.4*	2.59 / *2.13*
3,000	***26.7***	0 / *0*	0 / *0.01*	0 / *0*	22.9 / *0.49*	4.06 / *3.57*
4,000	***20***	0 / *0*	0 / *0.08*	0 / *0*	23.28 / *0.58*	5.09 / *4.49*
6,000	***13.3***	0 / *0*	0.003 / *0.47*	0 / *0*	24.09 / *0.79*	6.37 / *5.97*
8,000	**10**	0 / *0*	0.03 / *1.18*	0 / *0*	24.91 / *1.03*	7.13 / *6.79*
10,000	**8**	0 / *0.01*	0.11 / *2.03*	0 / *0*	25.73 / *1.32*	7.63 / *7.34*
15,000	**5.3**	0.001 / *0.26*	0.60 / *4.20*	0 / *0*	27.77 / *2.22*	8.35 / *8.14*
20,000	**4**	0.026 / *1.28*	1.41 / *6.04*	0 / *0*	29.81 / *3.40*	8.74 / *8.57*
30,000	**2.7**	0.47 / *6,27*	3.29 / *8.69*	0 / *0*	33.90 / *1.75*	9.14 / *9.02*
40,000	**2**	1.98 / *13.86*	5.03 / *10.43*	0 / *0*	37.99 / *11.61*	9.34 / *9.24*
50,000	**1.6**	4.71 / *22,32*	6.50 / *11.68*	0 / *0.01*	42.07 / *18.24*	9.47 / *9.40*

5.4 Management and further design suggestions

5.4.1 General Management

Plants in wetlands take up nutrients during growth, especially phosphorus, from the sediments and water column as it is a very important component of plant cells. During plants decomposition however, 35~75% of tissue phosphorus will be released to the system (Kadlec & Knight, 1996). For this reason, aquatic-plants harvest is very important to the wetland management. To avoid disruption in the system efficiency and considering the climate in Vientiane Capital City, plants harvest should be systematic and continuous (*eg.*, partial removal in weekly designated plots). Accumulated biomass could then be used as fertilizer after composting, or used in biogas production. An example of maintenance form is shown in Table 15).

Table 15: Maintenance form of EU wetlands

EU WETLANDS- MAINTENANCE FORM			
Wetland No:			
Description:	CWs and sediment		
SITE VISIT DETAILS			
Site visit date: Site visit by: Weather:		____________________ ____________________ ____________________	
Purpose of the site visit	Tick Box	Complete Sections	
Routine inspection	☐	Section 1 only	
Routine maintenance	☐	Section 1 and 2	
Cleanout of sediment	☐	Section 1, 2 and 3	
Annual inspection	☐	Section 1, 2, 3 and 4	
SECTION 1- INSPECTION			
Depth of sediment		_____________m	
Any weeds or litter in wetland (If yes, complete Section2-Maintenance)		Yes/No	
Any visible damage to wetland or sediment basin? (If yes, complete Section 4- Condition)		Yes/No	
Inspection comments:			
SECTION 2 - MAINTANCE			
Are there weeds in the wetlands	Yes/No		
Were the weeds removed this site visit?	Yes/No		
Is there litter in the wetland?	Yes/No		
Was the litter collected this site visit?	Yes/No		
SECTION 3 - CLEANOUT OF SEDIMENT			
Have the following been notified of cleanout dates?		Yes	No
Coordinator-open space and/or drainage		☐	☐
Local residents		☐	☐
Other (specify….)		☐	☐
Methods of Cleaning (Excavator or educator)			
Volume of sediment removed (apporoximate estimate)		m3	
Any visible damage to wetland or sediment forebay? (If yes, complete Section 4-Condition)		Yes/No	

SECTION 4 - CONDITION

Component	Checked?		Condition OK?		Remarks
	Yes	No	Yes	No	
Inlet weir or pipes					
Outlet riser/s and weir/s					
Sediment forebay					
Wetland vegetation					
Wetland banks					
Wetland floor					
Surrounding landscaping					
Comments:					

5.4.2 Further Suggestion for improved performance

If alternative-A is selected, the FWS wetlands would work more effectively if inflow is kept under 20,000 m^3/d to at least meet the USEPA limit of 30 mg/l TSS (as stated earlier, only alternative-B can meet the more stringent WHO limits). To solve this problem, an extra sedimentation basin is suggested as a forebay the to the wetland inflow distribution system (Figure 38). However, such large area of open water may bring the problem of mosquito reproduction. Mosquito control could therefore be another challenge of management.

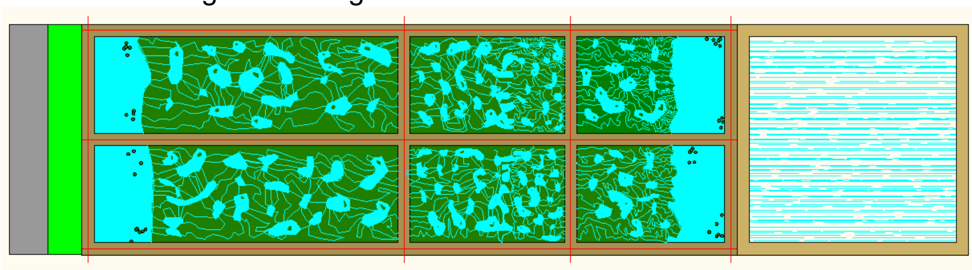


Figure 36: FWS wetland (alternative-A) with large sedimentation basin

If alternative-B is selected, less area is required and the risk of mosquito problem is reduced. However, substrate clogging can be a serious management challenge if not addressed properly (Akvopedia, 2009). To reduce this risk, a define zone for regular cleaning is suggested (Figure 37). Cells are set as the inflow part of the wetland 2 to isolate VF wetlands into small scale. The system is still able to work when one of the cells is being cleaned.

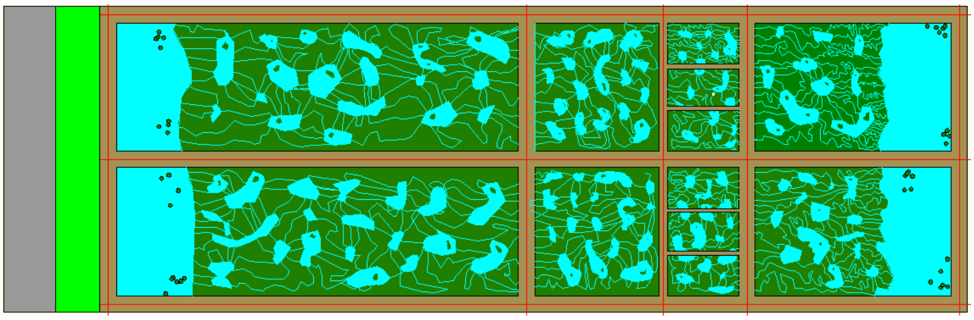


Figure 37: Addition of an area facilitating surface cleaning of VF wetlands.

6. Conclusions and final remarks

To the question raised in this thesis… "*Could rehabilitating the inoperative EU-Facultative Lagoons simultaneously reduce the impact of untreated wastewater on the That Luang Marsh and provide a secure source of agriculture irrigation during the dry season?*"… the answer is YES.

6.1 Constructed Wetlands vs. Facultative Lagoon

Although both constructed wetlands (CWs) and facultative lagoons (FLs) are economical and energy saving wastewater treatment processes, results of my study indicates that CWs are more suitable for wastewater reuse than FLs in Vientiane. For the same area, the simulation show that both proposed CWs designs are able to treat more wastewater per day than the actual FLs design flow (13,000 m^3/d) and still treat sewage water to BOD_5 and TSS levels suitable for reuse in agriculture. It also indicates that alternative-B design (FWS+VF) can produce up to 40,000 m^3/d of irrigation water for crops likely to be eaten raw for BOD_5 and TSS (<15 mg/l; WHO 2006), while alternative-A (FWS) could produce up to 30,000 m^3/d within the <30 mg/l limits set by USEPA (1992) for crops commercially processed. In both cases however, the daily availability could have to be reduced to less then 8,000 m^3/d (HRT > 10 days) if it was determined that the level of pathogens and parasites in the treated sewage water was still too high.

6.2 Wastewater Reuse in the That Luang Marsh

At the time of starting this thesis project, about 45% of the total area of the That Luang Marsh was rice field during the dry season, with about 30% of producing under drought condition (Kyophilavong, 2007). Other, less water demanding crops like grazing pastures, fruit-trees, cereals and vegetables can also be produced there. Thus, wastewater reuse for irrigation within and around TLM would be a large benefit for the agriculture economy.

However, the reuse of wastewater is sometime not so easily accepted in some countries. Fortunately, people in Laos have open minds for nature resources reusing. Local people should therefore welcome treated wastewater for agriculture irrigation, back yard watering or car washing. Nevertheless, awareness building and proper regulatory frameworks will have to be in place to ensure that both production and usage is done in a proper and secure way.

Environment pollution, nature resources limitation have been discussed all over the world. For a long time wastewater has been regarded as a large problem as it brings both hygienic hazards and excess organic matter and substances as nitrogen and phosphorus, which brings the problem of eutrophication in natural water bodes. Protection of That Luang Marsh natural resources is one more reason to promptly implement treated wastewater reuse. Although a larger area of constructed wetlands would be necessary to treat all the sewage water the actual pumping system can bring for treatment, any reduction in pollution reaching the TLM is positive.

6.3 Vientiane Capital City long-term development

The increase of pollution and steady decline in drainage water quality is becoming a serious challenge in managing Vientiane's water resources as it becomes more and more urbanized. The situation could be worse due to the continuous loss of the city wetlands. As flooding is still a very big problem during the raining season, traditional combined sewage overflow (CSOs) is not suitable for Vientiane Capital City. Heavy rainfall will cause system overload, which will lead to raw wastewater overflow by dysfunctional septic tanks.

Although the construction of a centralized treatment system should be part of the long-term planning of the city, a decentralized approach should be immediately promoted as well outside the city centre. As demonstrated by the WATER Project, combination of properly functioning septic tanks (primary treatment) and small individual or communal treatment wetlands (secondary treatment) would be highly suitable. The EU-ponds restoration, topic of this thesis, could be seen as an example of an approach to build a larger neighbourhood treatment system that would not require household septic tanks. In all designs, raw wastewater would be treated and reused locally.

Finally, any sustainable development of Vientiane Capital City should also include the long-term implementation of Sustainable Urban Drainage System (SUDS) and of Resource-Based Sanitation (Ecological Sanitation). Such approaches would not only help protecting the remaining urban wetlands, but would also contribute to both renewable energy production (e.g. biogas from septic tanks sludge and aquatic plants cropping) and food security (e.g., urine as fertilizer and biogas residues as soil conditioners).

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Appendix 1: GIS data of land use of TLM

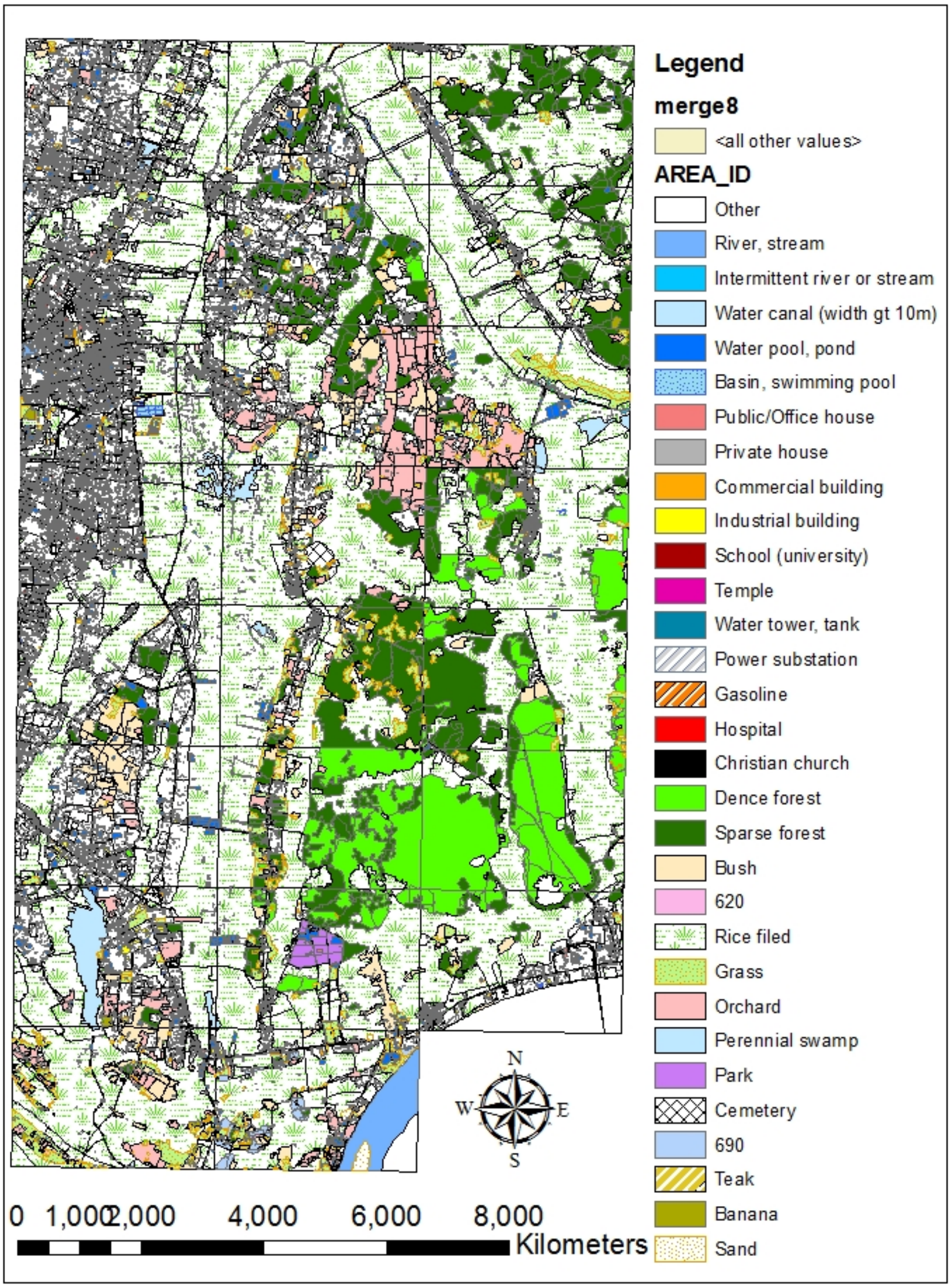


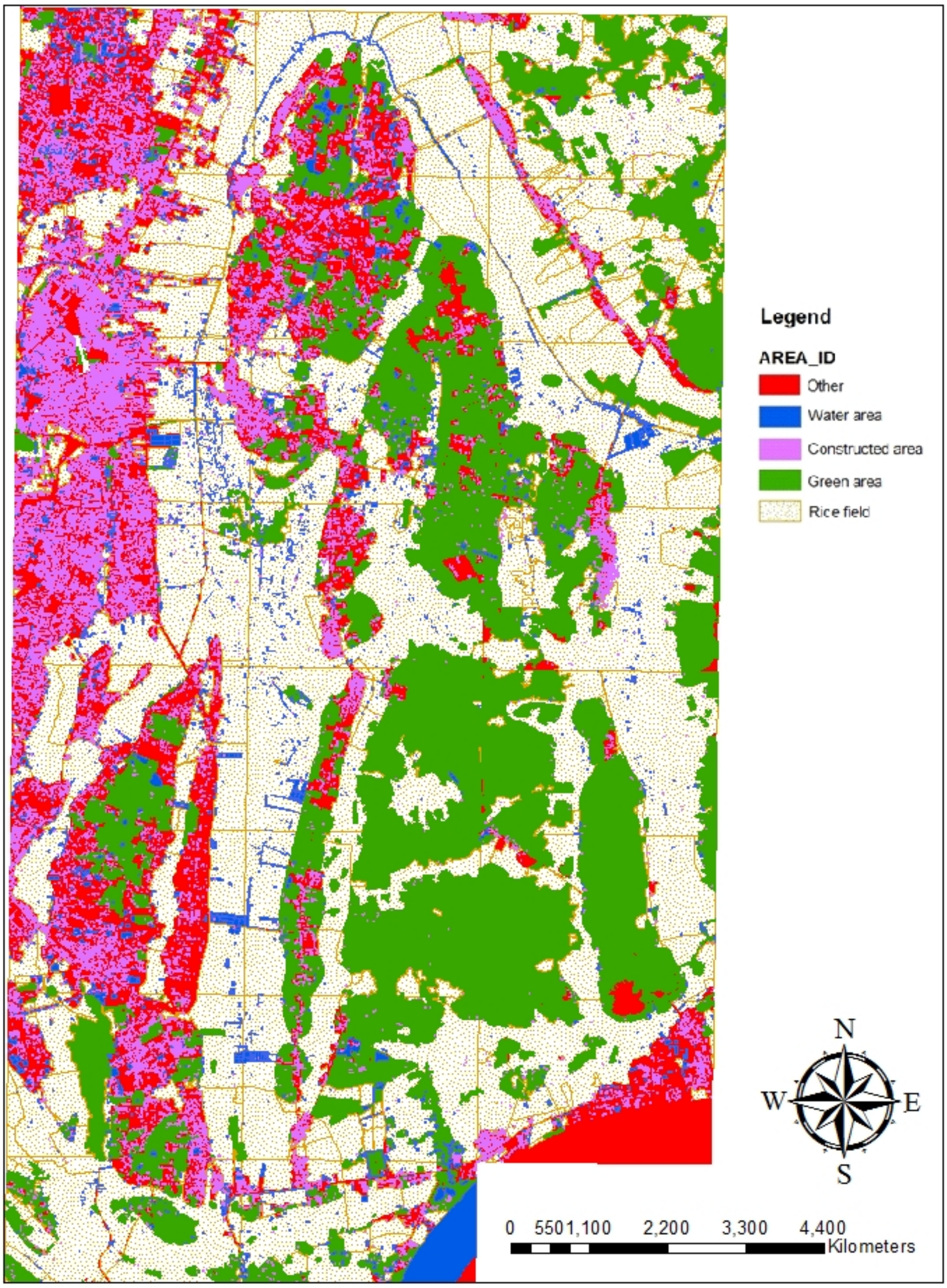
Figure 38: Original GIS data of TLM (WWF restricted data)

Appendix 2: Land use of That Luang Marsh

Land use of TLM summarized by GIS metadata (WWF restricted data)

Land Use	Area (Ha)
Other	3900
Public/Office house	40
Private house	300
Commercial building	22
Industrial building	36
School (university)	13
Temple	6
Water tower, tank	0.2
Power substation	0.2
Gasoline	0.6
Hospital	4.8
Christian church	0.3
Dense forest	1000
Sparse forest	1750
Bush	450
Green	0.7
Grass	450
Other	3.5
Orchard	550
Perennial swamp	160
Park	40
Cemetery	43
Green	34
Teak	28
Banana	24
Sand	18
Intermittent river or stream	9
Water canal (width great than 10m)	1
Water pool, pond	290
Basin, swimming pool	7
River, stream	140
Rice filed	8300

Appendix 3: GIS data for land use calculation



Edited GIS data for land use calculation

***Green area indicated all permeate surface except rice filed include forest, bush, grass, swamp, park, cemetery, cash crop, and send. Other area includes bared surface, city green area and missing data.**