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Feasibility study of flushing To Lich River with Red River water through West Lake

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Preface

This study is done in response to a research proposal of the Hanoi University of Natural Resources and Environment (HUNRE). We are six students from the Delft University of Technology in the Netherlands and conducted this research as a part of our master study program, called ''Civil Engineering Consultancy Project". Our study backgrounds are Hydraulic engineering, Water management and Geo-engineering respectively. All of us were seeking to gain experiences abroad, in a sector related to our expertise and with a social value. This multidisciplinary project contains these aspects. For the purpose of this project, we lived and worked in Hanoi during the months of September and October in the year of 2019.

We would like to express our appreciation for those who provided us with the possibility to complete this project. In particular, we thank our supervisors from the TU Delft, Dr. Thom Bogaard and Dr. Ir. Erik Mosselman, for their active involvement and guidance during the project. Furthermore, we would like to acknowledge the crucial role of Msc. Thuy Nguyen and Prof. Pham Quy Nhan and the others from the FAWARRE Department. They helped us to understand the culture of Vietnam and were accessible for questions every day of the project. Finally, a special thanks to Juliette Eulderink, for being our mentor at HUNRE and our experienced friend in Vietnam.

We hope you enjoy your reading.

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Abstract

Hanoi is coping with a serious water quality problem of the To Lich River (TLR). This river flows through the center of the city where many sewer gates have its outfall in it. The government of Hanoi has proposed a solution to clean the river by flushing it with Red River (RR) water through the West Lake (WL). The goal of this study is to examine the feasibility of this solution, from a water quality and hydraulic point of view.

Firstly, the current state of the three water bodies was investigated and a stakeholder analysis was conducted to look into the social and political context.

Secondly, the effect of the solution on the water quality in the WL and TLR was researched. The most important water quality parameters were qualitatively discussed and after that, the quantitatively changes in the WL were modelled. A convection-diffusion model was set up for different parameter concentrations in R. R is a free language for statistical computations and graphics, the use of it can be extended with the use of open source packages. The convection-diffusion equation was solved with the open source package 'ReacTran', this package contains routines that develop models that describe reaction and advective diffusive transport. In this study two dimensional models were made with the use of the central difference method. The initial parameter concentrations were gathered by field measurements and extensive online research.

The water quality assessment shows that the Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), turbidity and Total Suspended Solids (TSS) concentrations in the RR have a better value than in the WL. Concentrations of other parameters do not show significant differences. The model itself shows for every parameter that after 100 days of mixing the water is not completely mixed in the WL. The water in the TLR is flushed with WL water and its quality is therefore more or less equal to WL water.

It is concluded that the proposed solution improves the water quality in the WL and the TLR. However, long and frequent mixing is necessary for the WL water to reach the RR water quality level. Nevertheless, the quality of the lake bed sediment is unknown and should be looked into in more detail in future research.

Thirdly, a hydraulic analysis was carried out by investigating the hydrological and geometrical characteristics of the three water bodies. Thereafter, the hydraulic impact was examined by comparing six different flushing scenarios, each with a different opening height of the sluice gates between the WL and the TLR. The flow, water depth and sediment transport rates for different time intervals were modelled in R over the distance of the TLR. The river flood wave was modelled as a dynamic flood wave. A Multi Criteria Analysis was done to interpret the results on the consequences in the TLR. The outcome of the optimum scenario is when the

gate has an opening height of 5%. The total transported sediment volume is significantly larger in this scenario, which is beneficial. The hydraulic effects on the WL and the morphological changes in the RR are for all scenarios negligible.

From a hydraulic perspective the proposed solution is feasible for all water bodies. However, more extensive research on for example the impact on the hydraulics in the TLR is needed to get more conclusive results.

In addition to the research on cleaning the TLR, there is a trend that the number of students in the water resources faculty at HUNRE is decreasing. This happens despite the increasing need for experts in this field. Our project therefore aims to contribute to educational capacity for HUNRE and raise awareness about water quality issues.

As a spin-off, our project (co-)developed educational tools that can be used within the HUNRE curriculum and as awareness raising activities in Hanoi with citizens, schools and the like. The decision on the content of these tools was made in close collaboration with the HUNRE staff. Fieldwork with Vietnamese students was conducted to start with building a data base on water quality of the water bodies in Hanoi.
The tools that are created are manuals, instruction videos and an introduction lecture. Furthermore, the database, that is built, can be extended with more fieldwork in the future.
The extent to which the educational tools and the database integrate in the study program of HUNRE remains unsure, however the awareness among Vietnamese students on the importance of water quality has increased. Furthermore, the OKP project strives to realize the integration of the educational tools in the future. Therefore, this research objective is expected to be achieved.

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Nomenclature

Abbreviations and acronyms

ADCP	Acoustic Doppler Current Profiler
AFDW	Advective Finite Difference Weighing
BOD	Biological Oxygen Demand
CENM	Centre for Environment & Nature
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
EC	Electro Conductivity
FAWARE	Faculty of Water Resources
FTU	Formazin Turbidity Unit
HS&DC	Hanoi Sewerage & Drainage Company
HUNRE	Hanoi University of Natural Resources and Environment
ICEM	International Centre for Environmental Management
JVE	Japan-Vietnam Environment Improvement Company
MCA	Multi Criteria Analysis
MONRE	National Ministry of Natural Resources and Environment of Vietnam
MPN	Most Probable Number
MSL	Mean Sea Level
NTU	Nephelometric Turbidity Unit
RR	Red River
TDS	Total Dissolved Solids
TLR	To Lich River
TSS	Total Suspended Solids
TUD	Delft Technical University

UNDP	United Nations Development Program	
URENCO	Hanoi Urban Environment Company	
VF	Volume Fraction	
WL	West Lake	
WRI	The World Research Institute	

English symbols

a	Sluice gate opening	$[m]$
A_{lake}	Lake surface area	$[m^2]$
b	Sluice gate length	$[m]$
$B_a v$	Average width concerned river section	$[m]$
$BOD5$	Biological Oxygen Demand	$[mg/L]$
C_d	Contraction coefficient	$[-]$
CO_2	Carbon Dioxide	$[mg/L]$
COD	Chemical Oxygen Demand	$[mg/L]$
D	Diffusion Coefficient	$[m^2/s]$
d_r	Inverse relative distance Earth-Sun	$[m]$
DO	Dissolved Oxygen	$[mg/L]$
E_0	Penman open water evaporation	$[mm/day]$
e_a	Actual water vapor pressure calculated with air temperature and humidity	$[Pa]$
e_s	Saturated water vapor pressure calculated with the air temperature	$[Pa]$
E_{lake}	Evaporation from lake	$[mm/day]$
EC	Electric Conductivity	$[uS/cm]/[\Omega^{-1}]$
g	Gravitational acceleration	$[kNm^{-2}]$
G_i	Groundwater inflow	$[mm^3/day]$
G_o	Groundwater outflow	$[mm^3/day]$
G_{sc}	Solar constant	$[Jm^{-2}s^{-1}]$
h_0	Upstream water depth	$[m]$
J	The number of the day in the year	$[-]$
k_{Rs}	Adjustment coefficient for radiation	$[degC^{0.5}]$
L_{reach}	Total length of the reach over which the wave propagates	$[m]$

$N0^{2-}$	Nitrite	$[mg/L]$
$N0^{3-}$	Nitrate	$[mg/L]$
NH^{4+}	Ammonium	$[mg/L]$
O_2	Oxygen	$[mg/L]$
O_{lake}	Surface outflow from the lake	$[mm^3/day]$
$P0_4^{3-}$	Phosphate	$[mg/L]$
P_{lake}	Precipitation on lake surface	$[mm/day]$
Q	Discharge	$[m^3/s]$
q_b	Depth integrated bed load transport	$[kg/ms]$
q_s	Suspended load transport	$[kg/ms]$
R_a	Extraterrestrial radiation	$[Jm^{-2}day^{-1}]$
R_s	Incoming solar radiation	$[Jm^{-2}day^{-1}]$
R_{land}	Surface inflow	$[mm^3/day]$
S	Mean sediment transport	$[m^3/s]$
T_{max}	Maximum daily temperature	$[\circ C]$
T_{min}	Minimum daily temperature	$[\circ C]$
t_{wave}	Wave length	$[m]$
TSS	Turbidty	$[mg/L]$
u	Wind speed	$[m/s]$
V_{lake}	Lake volume	$[m^3]$
Z	Site elevation	$[m]$

Greek symbols

α	Albedo coefficient	$[-]$
δ	Solar decimation	$[rad]$
γ	The psychometric constant calculated with air temperature, humidity and air pressure	$[Pa/K]$
λ	Latent heat of vaporisation calculated with the air temperature	$[Jkg^{-1}K^{-1}]$
ν	Kinematic velocity	$[m^2/s]$
ω_s	Sunset hour angle	$[rad]$
ϕ	Latitude	$[rad]$
ρ_s	Average sediment density	$[kg/m^3]$
ρ_w	Average water density	$[kg/m^3]$

Chapter 1

Introduction

Hanoi is the capital of Vietnam, located in the Red River delta in the North of the country. In the past two decades, the city of Hanoi has been dealing with a rapid domestic growth and industrialization [8]. Parallel to these developments, the surface water quality in Hanoi has been decreasing [5]. The To Lich River (TLR) is one of the heavily polluted rivers that flows through the center of Hanoi. The TLR is connected to the largest surface water area in Hanoi, the West Lake (WL). The TLR and the WL are connected with sluice gates, which are closed for normal conditions. Seventy kilometers south of the WL, the TLR flows back into the Red River (RR). Many sewer gates have their outfall in the TLR and the wastewater often is untreated. The water quality of this river is very poor and therefore the Hanoi government considers it as a 'dead river' [77], mainly due to a low dissolved oxygen concentration.

Possible solutions to improve the water quality of the TLR have been proposed by the government in the past few years [48]. One of the possibilities is to flush the river by opening the sluice gates between the WL and the TLR. In order to maintain a certain water level in the WL, a pumping station between the RR and the WL has to be installed. The pumps withdraw water from the RR and discharge it into the WL. The feasibility of this solution is investigated within this research. [1]

Another trend occurring in Hanoi was the decrease in popularity of technical water related study programs. The number of students in the field of water resource engineering is decreasing despite the fact that the need for experts in water quality in Hanoi is increasing. Activities to increase the awareness regarding the importance of water quality are conducted within this project.

The goal of the research is divided in three main objectives.

The first objective is to examine the current water quality of the three water bodies (RR, WL and TLR) and determine the impact of the proposed solution on the quality levels. The latter is done with the use of a model. The second objective is to determine the effects regarding the hydraulic characteristics of the water bodies. The current hydraulic and hydrological system is investigated, whereafter a model is built to research the hydrodynamic changes. On the basis of this model, the optimum flushing scenarios are determined. The third and final

[1] In this report the cleaning of the TLR by pumping RR water into the WL and then rinse the TLR is abbreviated as 'the proposed solution'.

objective for this study is to contribute to the educational program of HUNRE and help raising awareness about water quality issues.

The three main research questions are:

1. *'What are the consequences for the water quality in the West Lake and in the To Lich River of the proposed solution?'*
2. *'What is the optimal flushing scenario considered the hydraulic effects on the Red River, the West Lake and the To Lich River?'.*
3. *'How can this study contribute to the educational program of HUNRE and help raising awareness about water quality issues?'*

This report is structured as follows: Chapter 2 covers a general description of the WL, the TRL and the RR and a stakeholder analysis. This is followed by chapter 3 about the water quality, which is subdivided in parts on the theory, on the used methodology and on the results. In Chapter 4 an hydraulic assessment is conducted with the same structure as chapter 3. The educational purpose of this project is discussed in chapter 5. The discussions on the results are drawn in chapter 6. In chapter 7, the conclusions and recommendations for further research are given.

Chapter 2

General description

The implementation of the proposed solution has an effect on three different water bodies, namely the RR, the WL and the TLR. This chapter aims to describe the current situation. Firstly, the current state of the three water bodies is described. Secondly, a stakeholder analysis of the water management system for these water bodies explains the social and political context. This integral approach enables a complete examination of the disadvantages and advantages for the system.

2.1 Description Red River

The reach of the RR flows from Southwest China, across Laos, through the Northern part of Vietnam, into the Gulf of Tunkin. Fifty-one per cent of the total area lies in Vietnam, which is equal to 86660 km^2. The delta of the RR has an area of 16444 km^2 [28]. The RR Delta in Northern Vietnam is low-lying, more than half of the area lies less than two meters above mean sea level (MSL) [28]. This area is densely populated and highly relies on the water supply from the RR for the development of the economy, food security and social activities. During the monsoon season, the flow fertilizes the RR delta. The RR plays an important role for the agriculture of that area. The agricultural sector employs 70% of the population. The color of the river turns reddish in the monsoon season, because of the silt sediment transportation. This is the reason why the river is called the Red River [36]. Furthermore, during the monsoon season, the RR often floods, this flooding supports fisheries and other aquaculture. Nevertheless, in the past there have been many devastating floods. Especially in Hanoi the consequences were severe, an estimation in costs from the United Nations Development Program (UNDP) resulted in 50 million US dollars on average per year for the Hanoi government [28].

To mitigate the costs of flooding for the Vietnamese government, dams and reservoirs have been implemented upstream of Hanoi. This is supplementary to the dike systems of 2700 km [28]. Another function of those dams is to secure water supply during dry periods. However, the operation of these dams results in conflicts between stakeholders. E.g. when dams are closed, the fish migration is blocked up- and downstream which is disadvantageous for fisherman. On the other hand, maintaining high levels in the reservoirs is beneficial for hydro power plants and the security of water supply [36]. An important consequence of the upstream dam is trapping of sediment [20]. This, combined with extensive sand mining in river channels upstream from the dam in the RR, causes erosion problems downstream the dam [24]. Lastly, an international conflict occurred between China and Vietnam on October 1st 2015. China discharged a large part of its reservoir water volume in a hydro electricity dam upstream. The increased water level caused serious flooding in Hanoi. Vietnam is dependent on the choices made upstream, showing the importance of international cooperation. A regular exchange of information is needed to overcome future conflicts. [11]

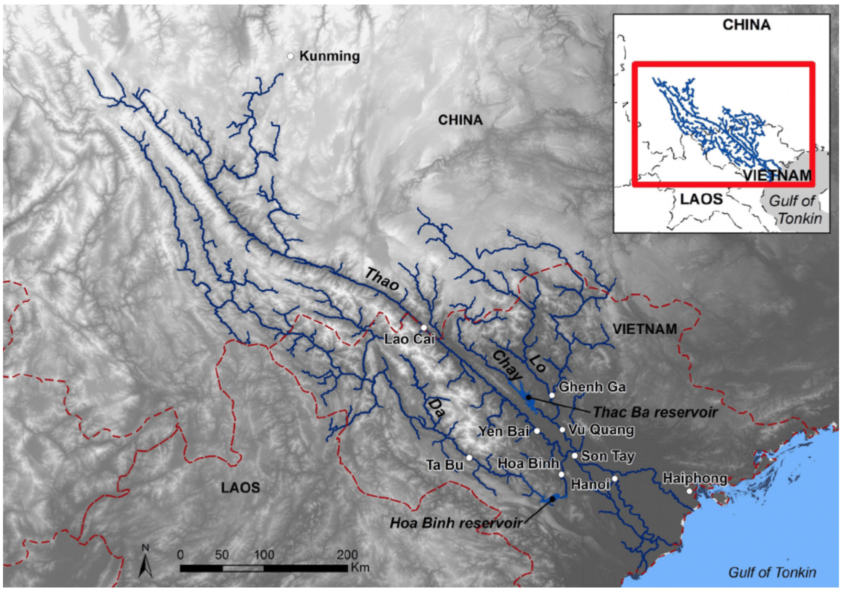


Figure 2.1: Red River Basin

2.2 Description West Lake

The WL (Ho Tay in Vietnamese) is situated northwest of Hanoi city center, in the Tay Ho district [55]. It originally was a part of the RR and throughout history there have been many different legends about the origin of the lake, each resulting in a different name. Eventually it became a semi-enclosed water body. Around the WL there are many recreational activities and the area is known for its historic relics. This makes the lake of a cultural and social importance for Hanoi. The lake receives untreated domestic-, industrial wastewater and storm water runoff from the surrounding area and the city center. The management board of WL estimates that ca. 4000 cubic meters of untreated wastewater per day flows into the WL. This number came out in 2009. The estimated volume of the WL is 5.2 km^2 (see section 4.1.1). After this the Hanoi's People Committee authorised the Tay Ho district as the only authority responsible for the water quality of the WL. The purpose was to tackle down the pollution problem. Up until 2009, many authority departments were involved in regulations for the WL, which resulted in many rule violations. E.g., the direct dumping of waste and waste water of businesses into the lake [78].

A catastrophic fish kill occurred in 2016, which shocked the country and the government. Around 200 tons of dead fish were floating on the surface of the WL and collected between October 1st until October 4th [80]. This event was followed by other fish deaths in 2017, 2018 and 2019. In 2017 the authority of Hanoi asked the Tay Ho People's Committee to shut down all the businesses and farming activities on the WL and to remove all the boats from the WL for the first quarter of 2017. The businesses were shut down, however not all boats were removed and some are now abandoned on the WL [2]. Additionally, the Hanoi authorities installed oxygen supply systems. In 2016 the Phu Dien Construction Investment and Trading

Joint Stock Company started with the installation of four sprinkler systems [79] and in 2018 the authorities announced their plans to implement forty more aeration systems to provide oxygen for the aquatic life [81].

2.3 Description To Lich River

The TLR originated as a distributary of the RR and it was initially used to transport RR water to the southern parts of Hanoi. In 1889 the French started a re-organisation of Hanoi, during this time the TLR was disconnected from the WL and the RR by filling the TLR with soil [29]. After this re-organisation the TLR had the function of a discharge river for runoff water. In 2002, the TLR was embanked by the local authorities. The total length of the river is approximately 15 kilometers [49]. The system consists of four canals and flows through four districts of Hanoi. Because the TLR is mainly used for discharging domestic and industrial waste water, it is heavily polluted [69]. A more detailed description about the pollution sources around the TLR system is presented in section 4.1.2. The TLR is so low in oxygen that it is classified as a "dead" river, the river has turned black and has a bad odor [32]. According to the Natural Resources and Environment department of Hanoi the oxygen level was 2.5 times below the accepted standard [31]. The Hanoi People Committee is putting effort in educating and creating awareness amongst citizens about water quality. However, the situation of the TLR has not significantly changed.

Several international companies have offered help to clean the TLR [58][29]. In 2019, Japan has installed a bio-reactor in the TLR and in the WL with the purpose to increase the oxygen level in the water [48]. Another measure that has been taken by the city of Hanoi is to dredge the TLR [38][26]. After a heavy rain event in May 2019, the water level in the WL was so high that the sluice gates (separating WL and the TLR) could be opened up for a while. This significantly reduced the black color of the water of the TLR and the smell also got better. Unfortunately, after a couple of days the situation in the TLR was more or less the same as before. There is not enough information available to say something useful about the discharge trough the TLR for this event.

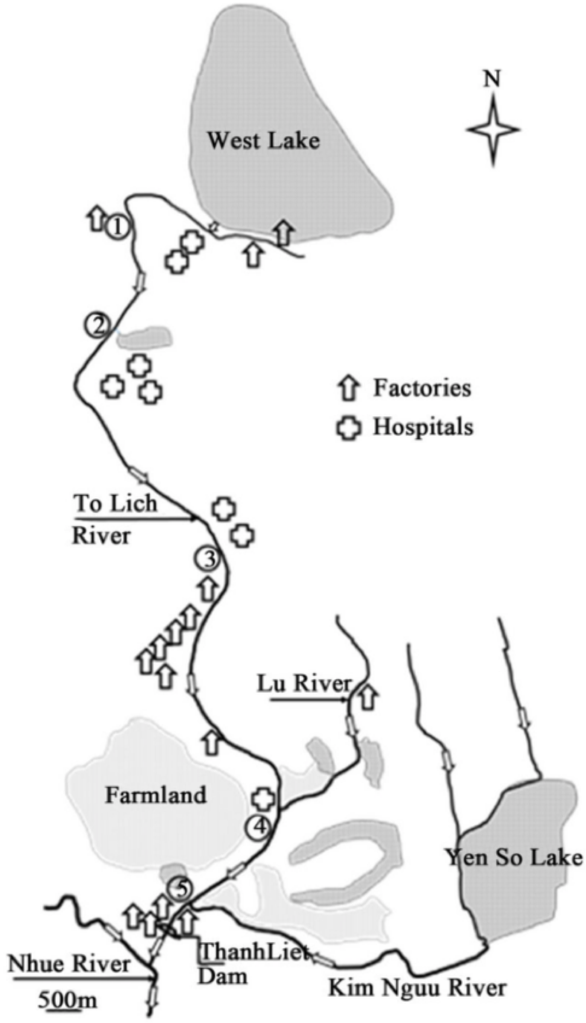


Figure 2.2: To Lich River with its pollution sources

2.4 Stakeholder analysis

The stakeholder analysis is carried out to create a better understanding of the social and political context. It leads to an overview of the current situation. To start with, an overview of the the stakeholders is given.

- Centre for Environment & Nature Management (CENM) - An organisation that continuously measures the water quality of the water bodies. Reports to ENRE.
- Domestic Polluters (Households) - Daily polluters of the TLR, they are depended on the Hanoi Sewerage & Drainage Company (HS&DC) to create a better sewage system that treats their wastewater in an orderly manner.
- Environment & Nature Resources Department - Department that is working under the supervision of the Hanoi People's Committee. This department especially focuses on carrying out the national strategy of Ministry of Natural Resources and Environment of Vietnam (MONRE). Multiple smaller executive organizations work under the ruling of this department (Hanoi Sewerage & Drainage Company & CENM).
- Fishermen - Fisherman on the RR and WL benefit from a solution to the problem that occurs. The solution should provide an increase in aquatic life and their condition.

- Hanoi People's Committee - Head of all municipal departments and regulative administrations in Hanoi. Controlling the budget of the municipality and implementing the national strategies. The controlling party over almost all official institutions and departments in Hanoi.
- Hanoi Sewerage & Drainage Company (HS&DC) - Operational managing board of the drainage system of the city of Hanoi. Responsible for the wastewater treatment plants that are located in Hanoi. HS&DC execute the proposed solution and are be the project manager.
- Hanoi Urban Environment Company (URENCO) - Regulators of the local policies. Finding people who litter in the lake. They play a big role in creating awareness.
- Hotels - Hotels are responsible for a large part of the pollution in the sewage system, and are in impact comparable to restaurants.
- Industries - Industries surrounding the TLR which dump their wastewater in the TLR. Depending on their level of self-cleaning they are partly responsible for the degradation of the TLR water.
- International Centre for Environmental Management (ICEM)- independent technical service centre that gives advice for governments and private companies. They help with implementing sustainable strategies. ICEM did research on the large-scale river system around Hanoi.
- The Japan-Vietnam Environmental Improvement Company (JVE) - JVE is currently executing a project in the WL and TLR that should improve the water quality of both water bodies. By using a nano-bioreactor that increases the amount of oxygen present in the water. The project proposed can interfere with their current work.
- Ministry of Natural Resources and Environment of Vietnam (MONRE) - This national institution is responsible for developing and implementing national strategies on Natural Resources and Environment. MONRE is responsible for legislation and policies at a national level.
- Neighboring inhabitants - The neighbouring inhabitants are negatively influenced by the bad odor and bacterial growth in the water bodies. Their hygienic condition can improve with the solution provided.
- Restaurants - Restaurants form a big source of pollution as they often dump their waste products untreated in the sewage system, ending up in the TLR or the WL.
- Recreational users - The WL could potentially be extensively used for recreational purposes. This is now limited by the condition the water body is in. The solution should provide an increase in recreational use of the water body
- Tay Ho District (People's Committee) - Residential people's committee who is responsible for running the local policy in the district of Tay Ho. This particular Committee is a decision-maker in all the matters containing the WL.
- Universities (Thuyloi, FAWARE) - Civil engineering universities in Hanoi. Both Universities are consulted about their research on the subject. Thuyloi is originated from MARD (Ministry of Agriculture and Rural Development), while FAWARE is originated from MONRE.
- Worldbank - An international financial organization that can help and invest in sustainable solutions for a wide range of problems. This organization has researched the water situation of Hanoi during the massive fish deaths in 2017.
- World Research Institue (WRI) - The World Research Institute is a non-profit organization that focuses on environmental sustainability, economic opportunity, human health, and well-being. It does research on and invests in sustainable projects all around the world.

2.4.1 Classification of the stakeholders

In order to make a comprehensive analysis of the stakeholders, the stakeholders with the same position are coupled. The subgroups in which they are divided in are listed below and the stakeholders that belong to these groups can be seen in figure 2.3.

- Legal
- Political
- Research institutes
- Executive party
- Polluters
- Clients
- Financial supporters
- Other

Legal
MONRE
Political
Hanoi People's Committee
Ho Tay District (People's Committee)
Environment & Nature Resources Department
Centre for Environment & Nature
Research Institutes
Universities (Thuyloi, FAWARE)
WRI
ICEM
Executive Party
Hanoi Sewerage & Drainage Company
Hanoi Urban Environment Company (URENCO)
Polluters
Industries
Restaurants
Hotels
Domestic Polluters (Households)
Clients
Fisherman
Recreational Users
Neighboring inhabitants
Financial supporters
Worldbank
Alternatives
JSE, JVE

Figure 2.3: Stakeholder classification

2.4.2 Power interest grid

The power interest grid divides the stakeholders on the basis of their interest compared to their power. The different quadrants allow one to differently approach each stakeholder according to their role in the project. Figure 2.4 illustrates the power Interest grid of this project.

1. High Power, High Interest - Stakeholders to manage closely. These are the most important set of stakeholders as they are highly interested and have a lot of influence and power. These stakeholders should be fully engaged and informed from the beginning of the project onward [67].
2. High Power, Low Interest - Stakeholders to keep satisfied. Members of this group can gain influence if they seem necessary or if they are negatively influenced. So it is important to keep these stakeholders informed about possible dilemmas and solutions [67].
3. High Interest, Low Power - Stakeholders to keep informed. Keep this group of stakeholders informed and keep contact to make sure no big issues arise [67].
4. Low Interest, Low Power - Stakeholders who need minimal effort. These stakeholders are influenced by possible solutions, but don't have a lot of influence themselves. It's good to monitor this group, but as they have low interest and power, minimal effort is needed to maintain a good relationship [67].

Figure 2.4: Power-Interest Grid

2.4.3 Formal relations diagram

The formal relations diagram visualises and gives insight in the relations between the stakeholders. It is used to create a better stakeholder strategy. Furthermore, it gives insight in the hierarchy of the different institutions.

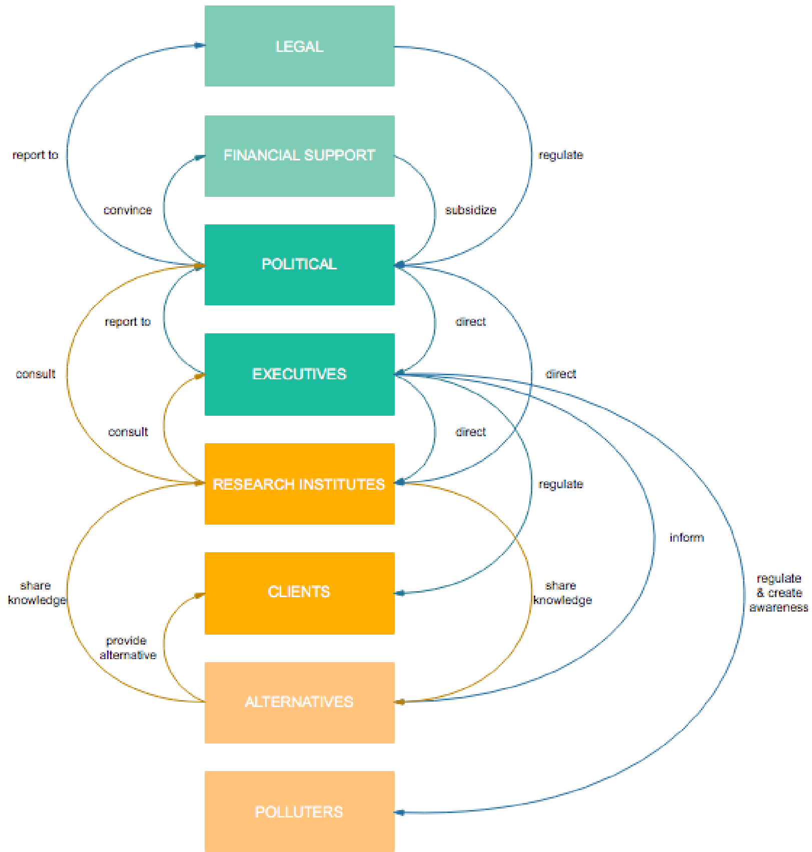


Figure 2.5: Stakeholder Relations Diagram

Chapter 3

Water Quality Analysis

Water quality is one of the two main aspects that are investigated in this research. This chapter contains an introduction, theory, methodology and result. The goal is to understand the water quality of the three water bodies (i.e. RR, WL and TLR) and how water quality parameters interact with each other. The focus is on the interaction between RR and WL, since after flushing the water in the TLR is ”replaced” by WL water. This interaction prediction is conducted with a advection-dispersion model programmed in R. The combination of theoretical knowledge, data and the model leads to the final results and interpretations on the water quality of the water bodies.

3.1 Regulations Vietnam

The surface water quality regulations in Vietnam are described in the 'National technical regulation on surface water quality' (QCVN 08-MT:2015/BTNMT) [76]. Within these regulations, a distinction is made between 4 categories, each with another water quality standard: A1, A2, B1 and B2, ordered from high to low quality. Category A1 is water that, after it has been treated, can be used for domestic water supply, the preservation of flora and fauna and for other purposes. Category A2 is water that, before it can be used for domestic water supply, needs to be treated with more treatment techniques than water from category A1. Both categories B1 and B2 are not feasible for domestic water supply. Water classified as B1 is used for irrigation and other similar agricultural purposes. Category B2 is water that only has the function of being transported. For the TLR, the desired water quality level category is B1. For each category the regulations formulate a range of values in between which a quality parameter must be. The classification and the limit values per class are depicted in Appendix A figure A.1.

3.2 Water quality theory

In this chapter the theory behind the water quality of the three water bodies is established. It contains an explanation of different limnological processes and feedback loops occurring in lakes. Further insights in the water quality parameters are listed and explained in more detail in appendix H.

3.2.1 Limnological processes & feedback loops

Lakes are very complex and changing ecosystems. Limnological processes describe the different feedback loops that occur in such an ecosystem. The feedback loops sustain on a balance between chemical properties, physical properties and climate. In this section the important limnological processes of the WL are explained. The feedback loops and parameter explanation together allow one to draw the conclusions between several observed parameter values and their implication when flushing.

Carbon Cycle

As discussed and described in appendix H, the processes that interfere with the oxygen concentration in lakes are: day & night fluctuations of oxygen level, temperature fluctuations and depth fluctuations in space. The oxygen content of a turbulent lake is determined by its amount of mixing due to this turbulence. However, the WL is a lentic water body, so the water is still standing. It could be even referred to as a reservoir, having limited inlets and outlets. Therefore, next to the previous named processes, photosynthesis and respiration play an important role. Combined they form the carbon cycle of a lake [84].

Photosynthesis

Photosynthesis is the process of green plants, bacteria and algae turning dissolved CO_2 into O_2 and sugars by the influence of sunlight. Therefore, photosynthesis creates higher dissolved oxygen levels and a 'food base' for all plants and organisms. The process mainly occurs in the epilimnion, which is the top layer of a lake. Due to the high temperature and shallow depth of the WL, photosynthesis is an important process [84].

Respiration

Respiration is the reversed process of photosynthesis where organisms take O_2 out of the water and create CO_2. Overnight the respiratory processes take over the photosynthesis. This creates an oxygen balance in a lake [54] [53].
The carbon cycle is an equilibrium which is the basis of the oxygen balance in a lake. As is described in section H, the oxygen level is crucial to the aquatic conditions of living organisms and plants [84], a concentration of less than 5 mg/L would put the aquatic life under stress. In the results, the effects of an increased or decreased DO level has a big impact on the oxygen balance thus aquatic life within the water bodies.

Limiting Nutrient Concept

A lake ecosystem contains various types of nutrients. All nutrients (Phosphate, Ammonium, Nitrate eg.) are present in different amounts. Too low or too high amounts of nutrients have negative effects on a lake, as discussed in the sections below. The limiting nutrient concept describes that one nutrient that is limiting will limit biomass production/and or growth rate. A nutrient can become the limiting nutrient if it is depleted. This absence of nutrients can prevent growth of living organisms or prevent chemical reactions. Several nutrients can be limited in a lake environment. However, TP (Total Phosphate) and TN (Total Nitrogen) are the most common nutrient to be limiting. If there are too many nutrients present, the nutrients will act as fertilizer. In other words, this leeds to excessive growth of algae. In severe cases this could also lead to a decrease in DO.

Phosphate Cycle

In figure 3.1, the phosphate cycle is illustrated. Three main processes can be identified. First of all, the phosphate cycle within the water column. In this process phosphate is used by phytoplankton. Via the phytoplankton the phosphate enters and exits the foodweb. Secondly, phosphate is present in sediments causing the process in which it is constantly interacting with these sediments. In-depth studies can be conducted on the role of phosphate levels by absorption by the sediment. This is not in the scope of this project but could be recommended as a future research topic. Finally, the phosphate levels increase due to the effects of human interference. Especially domestic waste, which is a large input in the mentioned water bodies, has a big effect on the phosphate levels [15] [45].

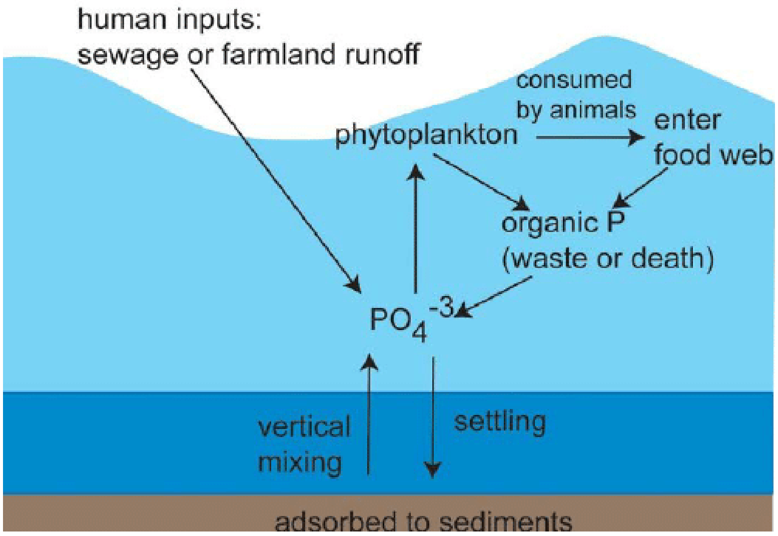


Figure 3.1: Phosphate cycle in marine environments

Nitrogen Cycle

Figure 3.2 describes the nitrogen cycle in marine environment. As discussed in appendix H, nitrogen occurs in several forms in lakes. The nitrogen cycle consists of nitrification, denitrification and ammonification. These are the three interaction processes between NO_3^-,NO_2^- and NH_4^-. These reactions occur in the presence of oxygen and hydrogen. An increase or decrease in nitrogen levels directly impacts the balance of the nitrogen cycle. If an equilibrium between concentrations is not reached, one form of nitrogen could become dominant. As discussed, NO_3^- & NO_2^- are nutrients that have a positive influence on eutrophication. The presence of a high ammonium concentration can cause harm and even death to aquatic life, due to its toxic properties. The extend to which ammonia is toxic is also dependent on the environment (pH, temperature) [3] [27].

Eutrophication

High concentrations of nutrients, in this case phosphate, can lead to excessive growth of plants and algae blooms. This growth phenomenon is caused by the high concentrations of nutrients, named eutrophication. Eutrophication is especially common in lakes, because the nutrient supply does not flush away. Furthermore, eutrophication is easily visible because a thick layer of

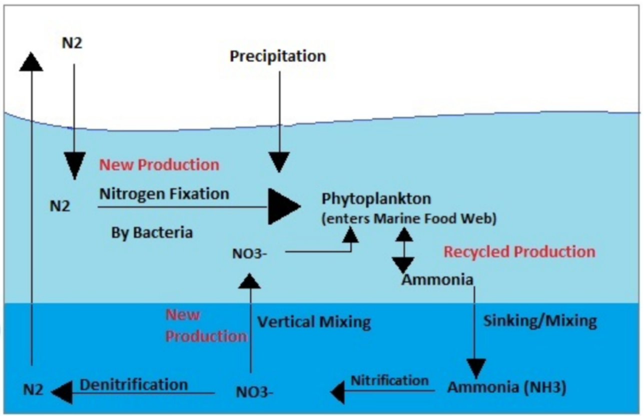


Figure 3.2: Nitrogen cycle in marine environments

green algae, scum and foam is formed on the water surface. As a consequence of eutrophication, the dissolved oxygen level of water drops, especially during night when the high oxygen demand for respiration of the plants does not get compensated with photosynthesis. This can cause organisms to die and in the worst case scenario form areas with oxygen arm water in which species are depleted. Another effect of eutrophication is an increasing pH value, which is harmful for fish but also makes present ammonium more toxic [44]. Controlling the phosphate levels in a water body is therefore very important.

Acidification

Acidification is when a lake gets a higher or lower acid concentrations due to the effects of acidic precipitation. The most common pollutants that cause this acidification are NO_X and SO_X. Studies in 2001 have shown that there is a form of acid rain in the Northern Vietnam region [75]. Furthermore, the acidification is also affected by the soil type and bedrock characteristics. pH levels indicate if acidification is occurring in the WL.

Salinity

As the WL is a rain fed lake, the salinity levels of the lake are naturally low. The effect of increasing the water level in the WL with RR water cannot (significantly) change this salinity as the RR is also rain fed. Changes in salinity levels are definitely not expected. However, they could be observed using electric conductivity meters.

pH

pH is an equilibrium of the free OH^- and H^+ ions, described by the negative logarithm of the concentration of H_+ ions. The change of pH when mixing two water bodies can only be qualitatively analysed, as the chemical reactions are not taken into account in this study. The analysis is based on the measured pH levels and their ΔpH. Assuming there is a one-on-one relation between the dilution of the water body and the pH level.

3.3 Methodology of modeling the WQ

This section focuses on the consequences for the water quality in the WL. The selection procedure of the model is elaborated. Thereafter, the details of the chosen model are explained. The changes of the water quality of the TLR are not studied explicitly. The current water quality of the TLR is so bad, that flushing it with cleaner water would surely improve the water quality. To verify this, the current water quality status of the WL and TLR are tested for this study.

3.3.1 Model selection

The following options for model methodologies have been investigated:

- Mixing model: The theory behind this model is based on instant mixing of two volumes with different concentrations. No (chemical) reactions between the parameters are taken into account. This simplified representation of the mixing gives a first impression on how the water quality can change. However, the mixing process in the WL will not be instantaneously and thus the results that would come from this model are not sufficient for the scope of this research.

- Advection-dispersion model: This type of model estimates the dispersion of a volume water into a water body with different concentrations. The dispersion term consists of multiple factors. This option is more advanced than using a mixing model, since it takes into account the dispersion characteristics in a lake of each parameter into the water. The chemical interaction between parameters is neglected. 'Phython' or 'R' are programming software that can be used for this model.

- Chemical model: For this model, next to the convection- and diffusion principles, all the chemical reactions between parameters are considered as well. The outcome gives the most representative impression of reality. Ready-to-use modelling packages, e.g. Qual2K, are available online [12].

For this research the options mentioned above have been considered. The advection-dispersion model is chosen. The advection-dispersion principles are modelled in the programming software 'R'. The mixing model is not chosen, because the mixing process in the WL is not instantaneously. The results would therefore not be representative. The chemical model is not chosen, because the theory behind the chemical model is too detailed for the scope of this research. Since the parameters COD, BOD, TSS, pH, EC,total coliform and E.coli are not single molecules, they are be described qualitatively. The other parameters (ammonia, free oxygen, nitrite, nitrate, total iron and phosphate) are modelled with the advection and dispersion principles.

3.3.2 Advection-dispersion equation

For modeling water pollution and flow in a lake the general convection-diffusion equation is used. It will be used as the advection-dispersion equation in this report [64]:

$$\frac{\delta C}{\delta t} = D * \bigtriangledown^2 * C - v * \bigtriangledown * C + k * C \tag{3.1}$$

The left hand side of the equation expresses the change of concentration over time at a given location. The right side expresses the different parts of this equation. The right first part of equation 3.1 describes the dispersion term. In other words, how would the substance (small ion or molecule) diffuse over a certain area in a certain amount of time. Variable 'D' is the dispersion coefficient $[m^2/s]$. The variable 'C' is the concentration of the substance. The concentration of each substance is measured in $[mg/L]$ The $\nabla * C$ represents the concentration gradient. The second term on the right side describes the advection, this is the dispersion due to the velocity. The convection is described by the velocity (v $[m/s]$) and the gradient of the concentration $[\nabla * C]$. The last term 'k' on the right hand side represents a consumption rate, this takes into account some (chemical) reactions. This consumption rate is a simplification per parameter. This consumption rate is left out in the next solutions of this subsection, as it is not implicated to most parameters in this research. Later in the report is discussed which parameters are modelled with a consumption rate.

Two-Dimensional Solution

The two-dimensional equation has an x- and y component. The equation is given as:

$$\frac{\delta C}{\delta t} = D * \frac{\delta^2 * C}{\delta x^2} + D * \frac{\delta^2 * C}{\delta y^2} - v * \frac{\delta C}{\delta x} \tag{3.2}$$

To solve the analytical solution it is assumed to be constructed of two one-dimensional parts g_1 & g_2.

$$C(x, y, t) = g_1(x, x_0, t), g_2(y, y_0, t) \tag{3.3}$$

Inserting the default boundary conditions as $x_0 = 0$ and $y_0 = 0$ allows it to be integrated over the whole domain. The integration results into the analytical solution in two-dimensions.

$$C(x, y, t) = \frac{1}{4\pi Dt} * exp[-\frac{(x - vt)^2 - y^2}{4Dt}] \tag{3.4}$$

The advection-dispersion equation gives the basis of how the model in R works. R uses different numerical approximation to approach the result, there is a huge amount of numerical approximation techniques. Equation 3.1 is the basis of the model ReacTran, which is discussed later on. Analytical methods used in ReacTran are described by the books of Pietrzak (1989) and Hundsdorfer and Verwer (2003) [37].

3.3.3 Modelling in R

The advection-dispersion equation is modelled in 'R'. The staff at HUNRE is familiar with this programming software, which enables the code to be used for further research or education. R is a free language for statistical computations and graphics, the use of it can be extended with the use of open source packages.

Model setup

Within 'R', the package called 'ReacTran' is described as: "Routines for developing models that describe reaction and advective diffusive transport in one, two or three dimensions". [37] ReacTran includes the package "tran.2D" which enables the modeling of transport in a two dimensional grid field with the advection-dispersion equation.

The input values for the model can be found in table B.1 [37]. The code itself can be found in appendix B. Some explanation will be given in this subsection.

The surface of WL is schematized using cell of 100m2. The West Lake is divided into cells which make up a grid; every cell has the same surface area. The width of the matrix is 1500 m and the length 3300 m. This results in a matrix with N_x cells in the x-direction and N_y cells in the y-direction. It is important to allocate sufficient space in order to run the code. As a cell size of 1 m^2 requires too much memory space, a cell size of 100 m^2 is chosen for this study.

As computations are performed with the central difference method, the value assigned to AFDW is equal to 0.5. Central differences is used since the dispersion is larger than the advection and the solution is second order accurate [37]. Since the central method is not universally stable, the time step size should not be too big. The volume fraction is set to 1.

This model considers a time dependent 'if'-statement. In the case that the time interval (t) is smaller than 1, the formula uses a relatively large advection coefficient indicating the inflow due to pumping of the RR water (the pump is on for one day). Once the time step has taken place, the pumping stops and the advection coefficient returns to its original value.

For the simulation time in this research 100 days is taken. With a time step of 1 day. This simulation time is approximately the dry period in Hanoi.

Initial- and boundary conditions

Initial conditions are required at the point where the pumps are installed. This is the starting point of the changes in concentration; this point on the grid holds a different value in concentration compared to the rest of the grid. However, this is not modeled as one single grid point: the area in which RR water enters the WL is larger than just 1 point. The size of the area in which RR water 'replaces' WL water depends on the power and impact that the pumps have. Therefore, instead of a single point, multiple grid cells are chosen as the area to define the initial concentration. The amount of cells is determined by looking at a probable pumping scenario (elaborated in chapter 4). This scenario describes an increase of the WL water level with 0.3 m, which is equal to a volume increase of 1.560.000 m^3. To get a 2D area, this volume is divided by the mean water depth of 1.5 m (estimated from section 4.1.1, hence an area of 780.000 m^2 is obtained. In R this is equal to 7800 grid cells.
Also the initial concentration of the entire WL is an input. This is be the concentration of the rest of the grid cells
Last, this model is applicable to only one parameter at a time, the dispersion coefficient for each parameter should be specified.

For simplicity reasons the boundary conditions of the grid are non-gradient. This means that there is no flux or gradient at the edge of the grid.

The model set up described above is schematized in figure 3.3.

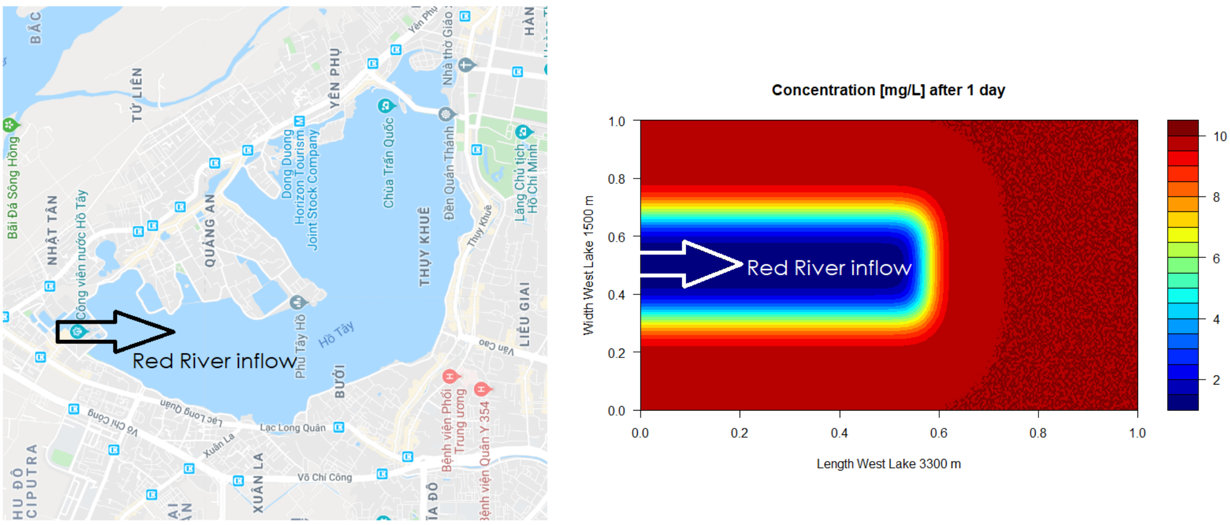


Figure 3.3: R model set up of Red River inflow in West Lake

3.4 Input parameters for model in R

For each water quality parameter used in this report, five different factors are needed, namely: dispersion coefficient, advection coefficient, consumption rate, initial concentration WL and initial concentration RR. The initial concentrations are found by literature research and field-work. The dispersion coefficients and consumption rates are found by literature research and interpretation. In this chapter the steps taken in order to obtain all the values together with the validation are described.

3.4.1 Dispersion coefficient

The diffusion coefficient, as in the general convection-diffusion equation 3.1, is very small compared to the advective-disperion mixing and negligible in an environment as a lake. The mixing of a lake consists of multiple forces: incoming and outgoing streams in a lake, thermal gradients, wind forces, Coriolis effects and diffusion [46]. The diffusion coefficient should be replaced by a dispersion term which includes all the forcing terms mentioned above. Many studies are done to define this dispersion coefficient, ranging between 0.01 - 5 m^2/s. This coefficient is an empirical coefficient. For the model a value of 5 m^2/s is used. The assumption is made by the fact that the WL is a small lake and in small lakes there is often more mixing. Besides this, the lake gets influenced by the pumping inflow of the RR and outflow to the TLR, which increases the mixing. So the parameter dependent diffusion coefficient is replaced by a parameter independent dispersion coefficient.

3.4.2 Advection coefficient

The advection coefficient or advective velocity describes the transport or velocity of a particle or substance due to bulk motion. In rivers the advective velocity is higher than in lakes as there is a bigger bulk motion. In section 3.3.2 the advection coefficient is an input parameter for the advection-dispersion equation with the units $[m/day]$. In lakes the flow velocity is really low, so the advection coefficient is close to zero. In this model the advection in the lake is equal to 0 $[m/day]$. However, due to the pumping of RR water into the WL the advection coefficient starts to increase. As the pumping is causing bulk motion, in the first day an advection coefficient of 200 $[m/day]$ is chosen to model the pump velocity. Considering the fact that the pumping is only in one direction, the advection coefficient can only alter in the x-direction. This advection coefficient is easy adjustable in the model, so for bigger pumps a higher initial advection coefficient can be chosen.

3.4.3 Consumption rate

The consumption rate discussed in section 3.3.2 in this model is a simplification factor of how the concentration changes over time. The concentration is changed over time due to chemical reactions as described in section 3.2.1. The consumption rate is defined as relative change over time [%/time]. If possible, for every parameter a consumption rate should be chosen that simplifies the change in concentration over time due to chemical reactions. This estimation is however very difficult. Only a consumption rate for DO is used in this research.

3.4.4 Initial concentrations Red River & West Lake

To define the initial concentrations of the RR and WL online data and data from field measurements is used. In the optimal scenario, all the online parameter values are used, because this saves a lot of time in doing additional field measurements. In order to validate the online data, test strips and various meters are used. The accuracy of these measurement methods is discussed extensively in chapter 6.

Final initial concentrations

Combining both sources of information results in a determination of the initial concentration values of the WL and the RR. Once all necessary data is retrieved, an interpretation is made on this data and a mean value for each parameter was established (see table 3.1).

In order to set the RR and WL initial conditions in perspective, an average parameter value of the TLR is considered. This average value is produced from a combination between field measurements and online data. These values are meant for comparison of the current situation. Average TLR values are not taken into account in the R model.[1] Some values in the table stand out: the RR nitrate concentration and the TLR phosphate concentration. The RR nitrate concentration is higher than the one in WL, this is not expected since the WL is overall more polluted than the RR. This could be caused by an upstream nitrate source like a industrial site or agricultural runoff. Nevertheless, the difference is too small to say this with confidence. Second the phosphate concentration in TLR is lower relative to the WL. It was expected that the TLR would have higher phosphate concentrations since it is directly connected with households effluents. Furthermore phosphate can be stored in high concentrations in sediments, TLR and the WL both have a thick of layer of sediments. What stands out is the enormous difference in DO level of the TLR compared to the other two water bodies. In addition to that, the COD and BOD levels of the RR and WL also alter significantly with respect to the TLR.

Table 3.1: Average concentrations Water bodies and Vietnam Regulations

	Red River	**West Lake**	**To Lich River**	**Regulations B1**
DO [mg/L]	5.0	4.9	0.1	>4.0
COD [mg/L]	57.7	104.3	202.7	<30
BOD5 [mg/L]	1.8	11.3	90	<15
E.Coli [MPN/100ml]	>100	>100	>100	<100
Turbidity [mg/L]	18.3	57.0	66.2	-
pH [-]	7.2	7.4	7.4	5.5 - 9
EC [μ S/m]	205.5	322.8	832	-
Nitrate [mg/L]	1.8	1.0	2.3	<10
Nitrite [mg/L]	0.0	0.0	0.0	<0.05
Phosphate [mg/L]	1.3	1.9	1.3	<0.3
Ammonium [mg/L]	0.2	0.9	27.2	<0.9
Total Iron [mg/L]	0.3	0.2	-	<1.5

Online data

The Hanoi Environment and Natural Resources Department installed several water quality stations which record live data of multiple parameters that are taken into account in this report [22]. One station is located in the WL and one station is located in the TLR. The live data was

[1] The online source measured the turbidity in [mg/L] and the Hach turbidity is given in [NTU]. This unit difference is solved by a conversion rate [41].

copied every 24 hours from the 9th of September 2019 until the 14th of October 2019 in order to generate a hand-made database. This database will from now be referred as the online data.

Unfortunately, there was no real-time online data available for the RR. However, some data has been found via CEMN. This is data from various boreholes around the RR. From this data, only a small portion could be used, because the majority of the data was on ground water. Furthermore, the measurements were only done twice a year, one in the dry season and one in the rainy season. In other words, it is rater difficult to use since the values vary a lot. Similar as for the WL online data, the available online data per water body is shown in table 3.2.

Validation online parameter values

The online data is measured using a professional measurement station, however, the precision and error propagation was not retrieved from the company. Considering the possibility of errors contained in the online data, the data gathered by the online monitoring tool is validated. The validation is done by comparing the online hourly data to field measurements, these field measurements are done over 2 days. The location for these measurements is chosen close to the online measurement tool. For each parameter a value has been determined during the field measurements. With these values, a range is made for every parameter, which includes the accuracy of the tools used during the field measurements. The accuracy range of the measurement is discussed in chapter 6. In table 3.2 it is stated whether the online data is within the range or not.

Table 3.2: Choice of data retrieval + validation (Y=Yes, N=No, '-'=unknown/not measured), only online data needed validation

	Red River		**West Lake**	
Parameter	Online/Measured	Within range Y/N	Online/Measured	Within range Y/N
DO	Measured	-	Online	Y
COD	Online	N	Online	N
BOD5	Measured	-	Online	N
E.Coli	Measured	-	Measured	-
Turbidity	Measured	-	Online	N
pH	Measured	-	Online	N
EC	Measured	-	Measured	-
Nitrate	Online	N	Online	N
Nitrite	Online	N	Measured	-
Phosphate	Online	N	Online	N
Ammonium	Online	N	Online	N
Total Iron	Online	N	Measured	-

Field measurements

For the missing parameters in table 3.2, a set of field measurements is done. To estimate the missing parameter values of the RR, three measurements are done. The outcomes of these three measurements are compared and a mean value of each parameter is defined and taken as the input value for the model. As the RR is a fast flowing river, three measurements are sufficient for finding a representative mean of a river. As for the WL, a mean is taken of all the measurements taken in the WL. The mean value of each parameter in the WL consists of at least 5 different measurements. The mean is representative for the whole lake.

3.5 Results

In table 3.1, the current average concentrations are compared to the Vietnam regulations. The results show that the proposed solution has a positive influence on all described parameters in the TLR. Especially an improvement of the conditions of DO, BOD5, and ammonium is observed. The parameters that stand out are E.Coli, phosphate, and COD. The values of these parameters in the WL water are lower than in the TLR , however, they are still too high to meet the regulative condition.

For the parameters DO, nitrate, nitrite, phosphate, ammonium and total iron the R model is used. The initial condition of each parameter is determined and listed in table 3.1. The plots of the R model per parameter can be found in appendix A. The remaining parameters are discussed qualitatively because the advection-dispersion equation is not applicable to these parameters. Below, the different impacts of the proposed plan are explained.

General interpretation output

In appendix A, it can be seen that after 100 days of mixing, the RR water is not homogeneously mixed with WL water. The figures show this is the case for all the parameters, since the dispersion coefficient is the same for all. Further details on this part are discussed in section 6.1.1.

Dissolved Oxygen

In figure A.2c the concentration DO is plotted in the 2D grid after 100 days. For the modelling of DO, a consumption rate of 0.05 $\%/day$ is assumed [37]. The consumption rate is deducted from the fact that the DO concentration decreases over time, as it is consumed due to high BOD5 and COD concentration. High BOD5 and COD values indicated a high consumption rate of DO in the WL.

The current input values do not display a big difference in DO, see table 3.1. Water samples were taken at the edge of the lake where the water column height is rather shallow. Even though the sample is collected halfway in the water column, its interaction with the atmosphere is still significant. It is estimated that the DO levels in WL drop significantly with depth due to the low rate of mixing. Where the DO concentration in the RR is assumed to be quite depth uniform due to turbulent mixing. This is discussed more extensively in chapter 6.

The figure A.2c shows a lower mean concentration than there was initially. This is due to the fact that the model assumed only initial concentrations with a consumption rate. No interaction with the atmosphere during simulation time or other (chemical) interactions were considered. These two interactions would influence the DO concentration, leading to a higher concentration than shown in figure A.2c. In chapter 6, this is further elaborated.

Taking everything in consideration, the proposed plan causes the DO level of the WL to increase due to higher DO and lower COD/BOD5 concentrations in RR. Increased DO levels can cause the eutrophication (algea bloom) to reduce and the conditions for aquatic life to improve.

Chemical- and & Biological Oxygen Demand

The COD & BOD5 are not suitable parameters to insert in the R model. However, a qualitatively judgement is made. Low values of COD and BOD5 are observed in the RR. The WL has BOD5 and COD values which are significantly higher than the RR, see table 3.1. In other words, if water of the RR water is mixed with WL water, the quality of the WL water improves due to dilution.

COD
The observed values of the COD in the two water bodies show the expected results. The COD value of the RR has a mean value of 57.7 mg/L and the WL has a mean value of 104.3 mg/L. The proposed plan caused a drop in COD levels of the WL. It is preferable for an aquatic ecosystem to keep the COD values as low as possible. Lower COD levels causes the DO consumption of the WL to lower, thereby improving aquatic life conditions (section 3.2.1). Although an improvement is seen, regulation level B1 is not met. Implementation of extra treatment measures should be taken into account.

BOD5
The WL and RR BOD5 levels show a value of 11.3 mg/L and 1.8 mg/L respectively. As discussed in section 3.2.1, it is preferred to keep the BOD5 level of a water body as low as possible.

E. coli

The results of the E.Coli tests were similar for both the WL and RR. The input values of both parameters have a range indication of >100 [$MPN/100ml$]. This result is classified by Akvo as "Very High Risk, Unsafe" [9]. The measurements can be found in figure A.7a. As all water bodies contained this increased level of E.coli, care should be taken when handling the water.

Turbidity

Since the RR water is from a river, the TSS concentration is higher due to advection and heavier mixing. TSS is not suitable for the R model, however a qualitatively judgement is made. The concentrations stated in table 3.1 are different then expected. The WL concentration has a higher value than the RR concentration. This could be explained by the fact that the concentrations TSS per water body contain different kind of solids. Whereas the RR has a turbidity caused by sediment transport, WL's turbidity is probably caused by algae bloom (eutrophication). This is visually confirmed during the fieldtrips. When water is pumped into the WL, it should be sieved first, leaving out the sediment particles. Then, the proposed solution has a positive impact on the TSS concentration in WL.

pH

The difference in pH between the different water bodies is not significant. It is not expected that the pH-level of the WL changes when the proposed plan is executed. Current pH levels do not indicate acidification (section 3.2.1).

Eletric Conductivity

The average EC values of the water bodies are: 205.5 $\mu S/cm$ and 322.8 $\mu S/cm$, for RR and WL respectively. (EC(RR) $<$ EC(WL)) These values show an increase in EC when looking at the flushing direction. The more polluted, the higher EC values are expected. The concentrations nitrate, nitrite, phosphate, ammonium and total iron are present in WL as ions. As these concentrations did not differ that much from the RR, the higher value of EC in the WL should be caused by other ions. Concluding, the proposed solution has thus a positive influence on the EC concentration of WL.

Nitrate / Nitrite

Nitrate
The average value of nitrate found in RR water is 1.8 mg/L and 1.0 mg/L in the WL water. The RR has a value almost twice as big as the WL. When running the model with these input values, the convection process for nitrate is observed. As the difference in $NO3^-$ concentration between the RR and WL is small, the effects on the WL, when mixing, are minimal. However, the higher nitrate level flowing into the WL results in a boost in the nitrogen cycle as described in section 3.2.1. With the concentration used in this study, the proposed solution is considered not optimal with respect to nitrate as can be seen in figure A.3c, where the mean concentration increases.

Nitrite
For both the RR and WL, nitrite levels are present in significantly low levels. It is not expected that these nitrite levels effect the nitrogen cycle and nitrite level in WL.

Phosphate

The phosphate concentration in the RR is lower than in the WL, with 1.3 and 1.9 mg/L respectively. Since phosphate is also included in the nitrogen cycle, the lower inflow concentration has a positive influence on the water quality of the WL. Although the result has a positive influence, the regulation standards B1 are not met. Measures have to be taken in order to lower phosphate levels to the regulatory standard.

Ammonium

The initial values used for RR and WL are 0.2 and 0.9 mg/L, respectively. Ammonium has a big influence on the eutrophication, as a higher ammonium concentration increases eutrophication. The lower inflow concentration of the RR water improves the water quality of the WL. The results of the ammonium strips are based on the eyesight, as the results could not be acquired by the Akvo app.

Total Iron

The total iron content of the RR has a mean value of 0.3 mg/L. The WL has a mean value of 0.2 mg/L. This minimal change is not expected to cause severe consequences after the proposed solution has been executed.

Chapter 4

Hydraulic Analysis

In addition to what happens to the water quality, when implementing the proposed solution, it is also important to know what happens to the hydraulics of the water bodies. First, the three water bodies are analysed on a hydrological and geometric level. Next, it is explained which methods have been used for the hydraulic analysis. Furthermore, the results are analysed and discussed.

4.1 Analysis of the water bodies

First the water balance and the bottom topography of the WL are discussed. Next, it is discussed how the TLR is schematized for this study and what dimensions this entails. Finally, the discharge in the RR is be discussed.

4.1.1 West Lake

The WL plays a major role in the proposed solution. The water balance, bottom topography and water level fluctuations of the WL are discussed below.

Water balance

The water balance of the WL is described in the following way [19]:

$$\frac{dV_{lake}}{dt} = R_{land} + A_{lake} * (P_{lake} - E_{lake}) + G_i - G_0 - O_{lake} \quad (4.1)$$

With:
$\frac{dV_{lake}}{dt}$ = The change of water volume over a time period in the lake $[mm^3/day]$
R_{land} $[mm^3/day]$ = Surface inflow
A_{lake} $[mm^2]$ = Surface area
P_{lake} $[mm/day]$ = Precipitation on the surface
E_{lake} $[mm/day]$ = Evaporation
G_i $[mm^3/day]$ = Groundwater inflow
G_O $[mm^3/day]$ = Groundwater outflow
O_{lake} $[mm^3/day]$ = Surface outflow

For the WL there is minor groundwater inflow and outflow [21]. Therefore, these parameters are neglected (G_i and G_O) in this report.

Surface inflow and outflow

The inflow of the WL is mostly sewage water and storm water runoff [21]. The inflow and outflow of various sewers to the WL for every month of the year are plotted in figure 4.1 [18]. The related locations of those sewer gates at the WL can be found in figure 4.3. [71] The sewage runoff around the WL is a combined system, this means that the waste water and the storm water are discharged together [39]. Therefore, the discharge into the lake increases during the rainy season. This is clearly visible in figure 4.1, where the sum of the inflow and outflow of sewage runoff is plotted per month of the year. All the surface in- and outflows (from figure 4.1) are added together, the final inflow can be seen in figure 4.2.

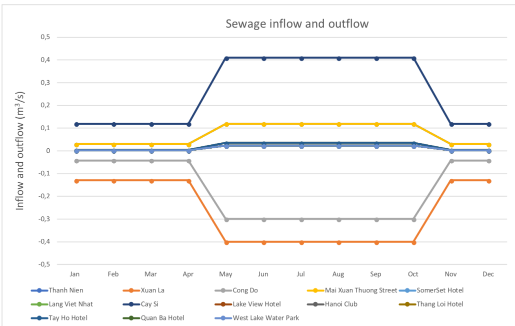


Figure 4.1: The sewage in- and outflow [18]

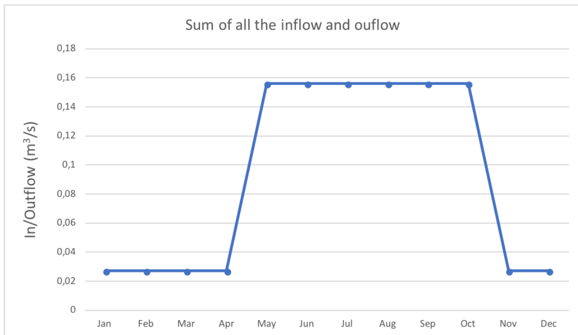


Figure 4.2: Sum surface in- and outflow[18]

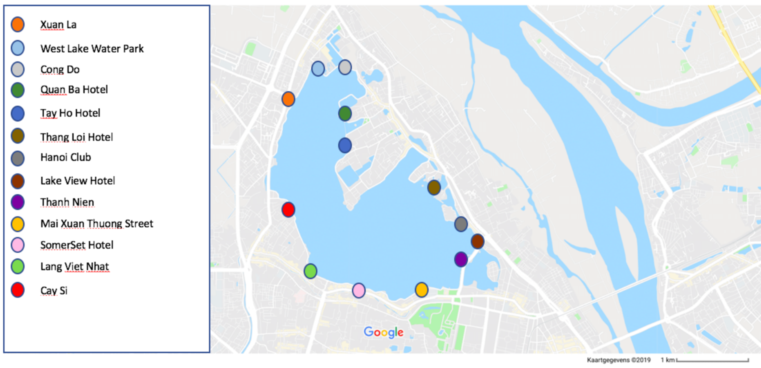
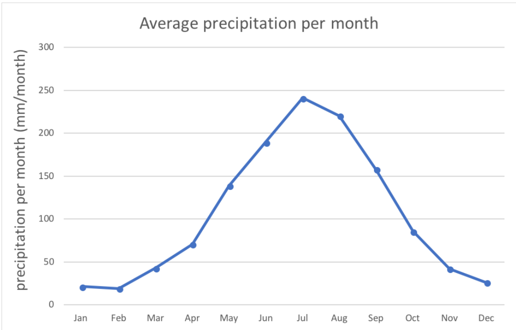


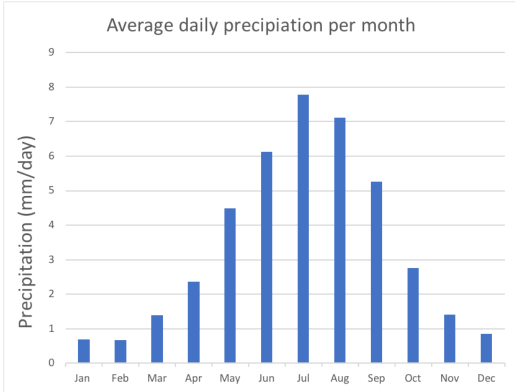
Figure 4.3: Locations sewer gates [71]

Precipitation over the surface of the lake

The average monthly precipitation and average daily precipitation are are shown in figure 4.4a and 4.4b. This data is based on weather reports collected from 2005 until 2015. All the data has been measured at Hanoi Airport which is twenty-one kilometers from Hanoi [70]. All data (e.g. air temperature, humidity, air pressure, wind speed etc) in this chapter is obtained from this meteo station, unless stated otherwise.



(a) Average monthly precipitation in Hanoi [70]



(b) Average daily precipitation per month in Hanoi [70]

Figure 4.4: Precipitation in Hanoi

Evaporation from the lake

A simplified version of the Penman Formula is used to calculate the evaporation rate of the WL [83].

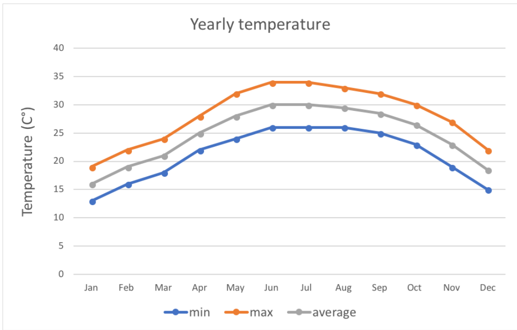
$$E_0 = \frac{R_{net} * \Delta}{\lambda * (\Delta + \gamma)} + \frac{6430000 * E_a * \gamma}{\lambda * (\Delta + \gamma)} \tag{4.2}$$

$$R_{net} = (1 - \alpha) * R_s - (0.75 + 2E - 5 * Z) * R_a \tag{4.3}$$

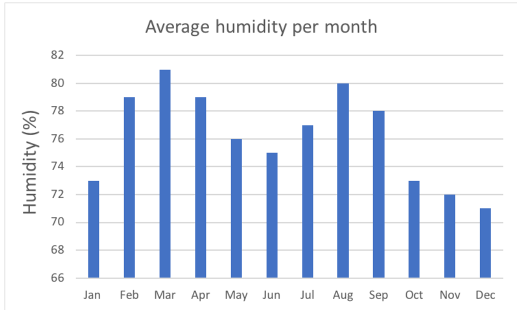
$$E_a = (1 + 0.536 * u) * (\frac{e_s - e_a}{1000}) \tag{4.4}$$

The parameters of these formulas are:
E_0 $[mmday^{-1}]$ = Penman open water evaporation
Δ $[PaK^{-1}]$ = The slope of the temper
γ $[PaK^{-1}]$ = the psychometric constant calculated with air temperature, humidity and air pressure
λ $[Jkg^{-1}K^{-1}]$= the latent heat of vaporisation calculated with the air temperature
α $[-]$= Albedo coefficient, value of 0.8 is chosen [83]
R_s $[Jm^{-2}day^{-1}]$= Incoming solar radiation
R_a $[Jm^{-2}day^{-1}]$= Extraterrestrial radiation
Z $[m]$= Site elevation, set at 0
u $[ms^{-1}]$= Wind speed
e_s $[Pa]$ = Saturated water vapor pressure calculated with the air temperature
e_a $[Pa]$ = Actual water vapor pressure calculated with air temperature and humidity

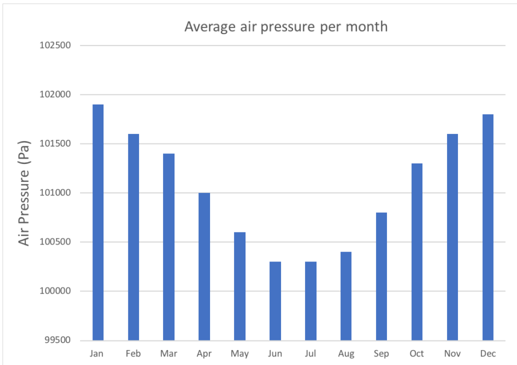
With formula 4.2, the evaporation is calculated in mm/day.



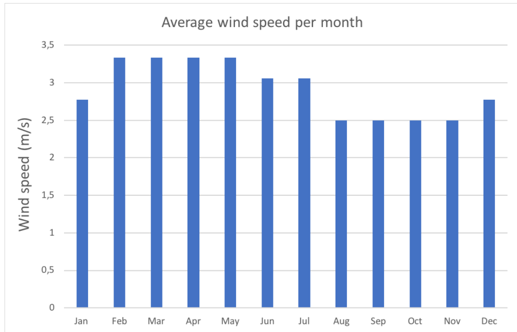
(a) Average temperature per month in Hanoi [70]



(b) Average humidity per month in Hanoi [70]



(c) Average air pressure per month in Hanoi [70]



(d) Average air wind speed per month in Hanoi [70]

Figure 4.5: Average monthly weather data Hanoi

The extraterrestrial radiation has been calculated with the following formulas [6]:

$$R_a = \frac{86400}{\pi} * G_{sc} * d_r * (w_s * \sin(\phi) * \sin(\delta) + \cos(\phi) * \cos(\delta) * \sin(w_s)) \tag{4.5}$$

$$d_r = 1 + 0.033 * \cos\left(\frac{2\pi}{365} J\right) \tag{4.6}$$

$$\delta = 0.409 * \sin\left(\frac{2\pi}{365} J - 1.39\right) \tag{4.7}$$

$$w_s = \arccos(-\tan(\phi) * \tan(\delta)) \tag{4.8}$$

Where:
R_a $[Jm^{-2}day^{-1}]$= Extraterrestrial radiation
G_{sc} $[Jm^{-2}s^{-1}]$= Solar constant (=1367 $Jm^{-2}s^{-1}$)
d_r [m] = Inverse relative distance Earth-Sun
ω_s [rad] = Sunset hour angle
ϕ [rad]= Latitude
δ [rad]= Solar decimation
J [-]= The number of the day in the year between 1 and 365 (or 366)

The necessary data for solving the above formula are the latitude (in radians) and the day number (between 1 and 365/366). The latitude of Hanoi in radians is equal to 0.37 rad (latitude of 21° 01’ 28.20"N) [42]. The middle day of the month is chosen as the average day number of each month. The extraterrestrial radiation is presented in figure 4.6a.

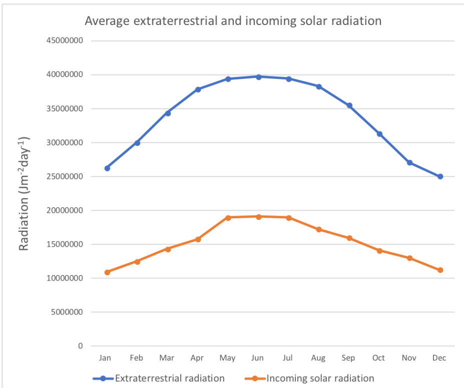
The incoming solar radiation is calculated with the Hargreaves radiation formula [6]:

$$R_s = k_{Rs} * \sqrt{T_{max} - T_{min}} * R_a \tag{4.9}$$

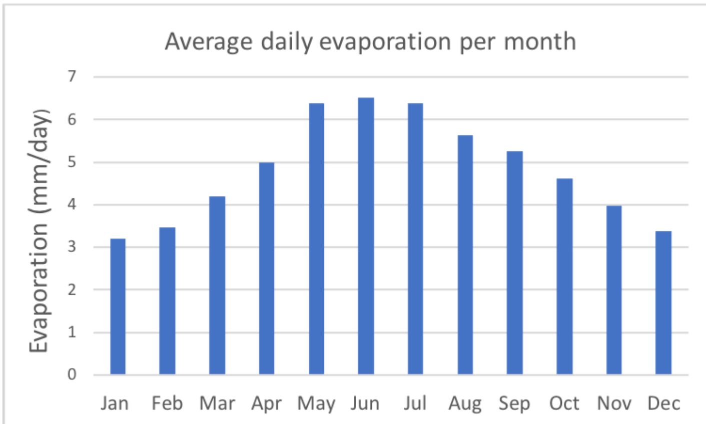
With:
R_s $[Jm^{-2}day^{-1}]$= Incoming solar radiation
k_{Rs} [deg $\mathrm{C}^{-0.5}$]= Adjustment coefficient for radiation (0.16-0.19)
T_{max} [°C]= Maximum daily temperature
T_{min} [°C]= Minimal daily temperature
R_a $[Jm^{-2}day^{-1}]$= Extraterrestrial radiation

With the extraterrestrial radiation calculated with formula 4.5 and the minimum and maximum temperatures taken from figure 4.5a the incoming solar radiation has been calculated and is presented in figure 4.6a.

Now that the daily average extraterrestrial and incoming solar radiation per month are calculated, the evaporation can be calculated with formula 4.2. The average daily evaporation per month is presented in figure 4.6b.



(a) Average daily extraterrestrial and incoming solar radiation for Hanoi

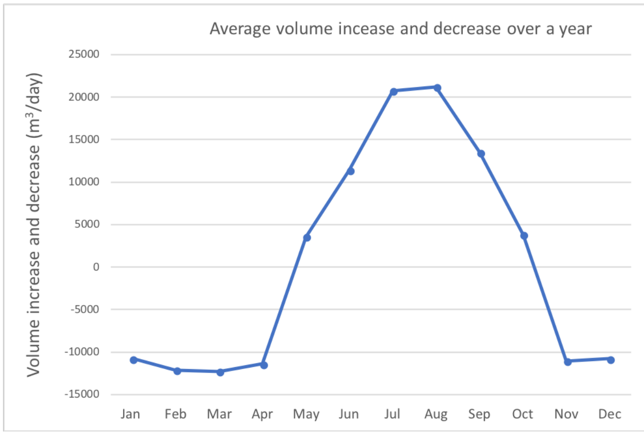


(b) Average daily evaporation for Hanoi

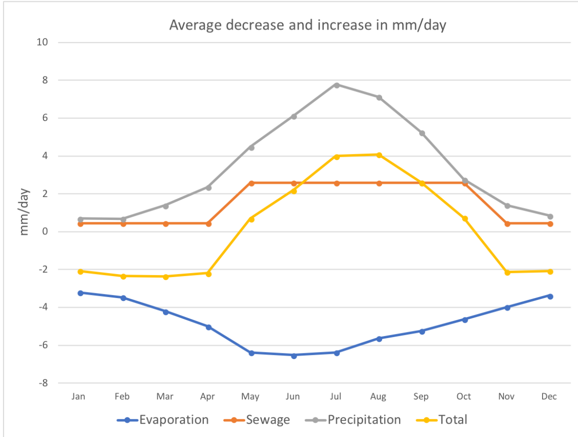
Figure 4.6: Average daily radiation and evaporation Hanoi

Result water balance

The change in lake water volume over a time period is shown in figure 4.7a. The average decrease and increase in mm/day is represented in figure 4.7b.



(a) Average daily increase or decrease of the volume of West Lake



(b) Average daily surface level change in mm/day for the West Lake

Figure 4.7: Change in volume and surface level West Lake

Bottom topography and water level analysis

The bottom topography of the WL is found in the 'Bathymetry Study Report, West Lake, Hanoi, Vietnam' by Dynamics Solutions-Internation [21]. The bottom topography is investigated in 2013 by means of an ADCP mounted on a boat. No more recent information is available. In figure 4.8, the outcome from this report is depicted with some simplifications.

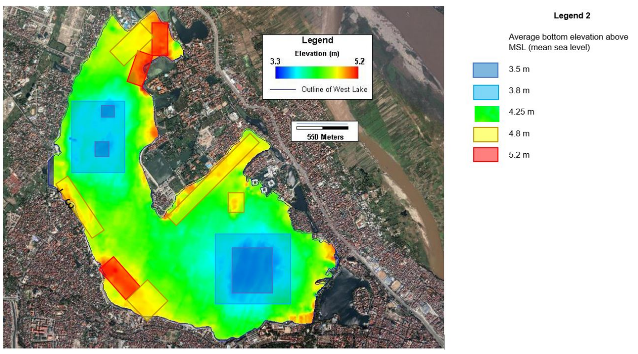


Figure 4.8: Bottom topography of the West Lake, Hanoi [21] (schematized, adjusted in Word by author)

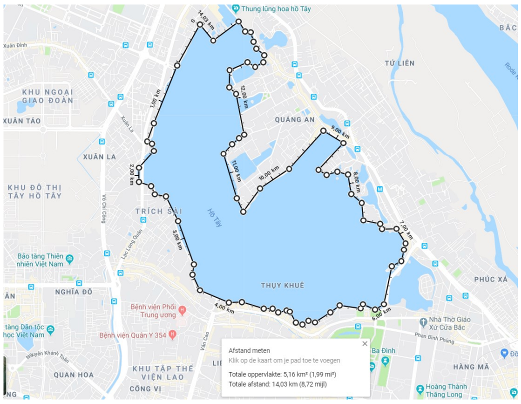


Figure 4.9: Average surface area of the West Lake, Hanoi [deducted from Google Maps]

Regulations for the water level in the WL state a water level of MSL (Mean Sea Level) +5.7m [35]. This means that at the most shallow parts of the lake (bottom level MSL +5.2m), the water depth is aimed to be circa 0.5m. Even though the water level sometimes deviates from this prescription, in this research it is assumed the water level does not differ more than 0.5m from the prescriptive value of 5.7m. As a consequence, the 'bottom' of WL is never 'dry'. Therefore, it can be assumed that the total surface area is constant: 5.2 km^2 (deducted from Google Maps, depicted in figure 4.9.
From the averaged depths, the total volume of water in the lake at a water level of MSL +6m can be calculated. This comes down to a total volume of about 9282500 m^3.

Water level fluctuation

With the implementation of the pumps from the RR to the WL the water volume of the WL can be controlled. The consequences of changing this volume must therefore be assessed. As mentioned in section 4.1.1, the surface area of the lake is assumed to be constant, provided that the surface elevation is above 5.2m +MSL. Therefore, for this scenario, the relation of the volume and the water level is linear. This can be seen in figure 4.10.

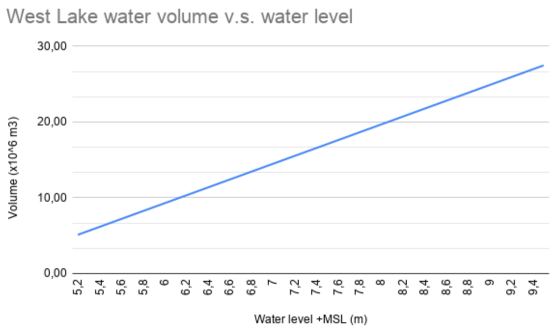


Figure 4.10: Water level per water volume in the West Lake [21]

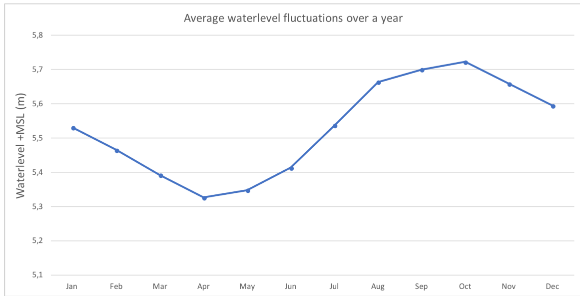


Figure 4.11: Average yearly fluctuation of the water level (+MSL) of the West Lake

From multiple realtime online measurements [50] it is conducted that the average water level in the month September is equal to 5.7m +MSL.

With the information from figure 4.7b the average fluctuation of the water level (+MSL) over a year are calculated. This is represented in figure 4.11.

4.1.2 To Lich River

This subsection is divided in a description and a simplification of the TLR system.

Description To Lich River system

The TLR system consists of four rivers; The TLR, the Lu River, the Kim Nguu River and the Set River. The TLR has the largest discharge and is approximately 15.5 km long, receiving wastewater of the western part of Hanoi. The other three rivers receive wastewater from the eastern part of Hanoi, before discharging it in the TLR downstream. All these rivers are heavily polluted, as can be seen from figures 4.12a, 4.12b, 4.12c 4.12d. Upstream, the TLR is connected to the WL via two sluices, each with 2 gates. Only one sluice is currently in use, sluice gate 'A' at Trich Sai Street. The focus is on this sluice gate. The dimensions and further specifications are listed in appendix E. When the gates of sluice A are opened, the water runs into a closed sewer for approximately 1.5 kilometers. Here-after the embanked, open, reach of the TLR starts and continues for another 15 kilometers. The whole TLR system covers a basin area of approximately 77.5 km^2. Fifteen kilometers downstream from the WL, the TLR confluences into the Nhue River.
The upstream reach of the TLR receives mostly domestic wastewater and the downstream reach receives both domestic and industrial wastewater. The TLR is approximately connected to 240 point sources of wastewater. Additionally, there are also illegal point sources that are not registered. There are approximately 5 industrial zones located in the system. In the downstream reach of the TLR is the Thuong Dinh industrial zone, this zone consists of 30 factories that discharge their wastewater to the TLR. The other 4 industrial zones (consisting of approximately

70 factories) discharge their wastewater to the Lu river, Kim Nguu river and Set river [69]. The location where the TL river joins the Nhue River the water flow direction is controlled by the Thanh Liet gate. In the downstream reach of the Nhue River there is a lot of agricultural production, therefore the dam is closed if the water in the TLR is too polluted. The Thanh Liet gate also closes when the water level in the TLR is higher than approximately 4 metres [17]. The latter only happens in practice when there has been such heavy rainfall that the storm water can not be drained anymore and the risk of flooding is very high. The exact regulation rules and dimensions of the Thanh Liet Gate are listed in appendix E. When the dam is closed the water runs through the reach of the Kim Nguu River towards the Yen So lake, where the water is pumped into the RR. The maximum capacity of this pumping station is 90 m^3/s [14]. For the proposed solution, it is assumed that the Thanh Liet gate is open and the water flows into the Nhue river. After the Thanh Liet gate, the Nhue river continues for 60 kilometers before it reaches the RR.

(a) To Lich River

(b) Lu River

(c) Kim Nguu River

(d) Set River

Figure 4.12: Polluted rivers in Hanoi [77]

Simplification of To Lich River system

Firstly, the embanked reach starts right behind sluice gate A from WL. The actual 1.5 kilometers of closed sewer is neglected, because the dimensions and type of waterway could not be defined with enough certainty. Elaboration on how this area would effect the results is discussed at the end of the report. A sketch of the simplified upstream connection between the WL and the TLR can be seen in figure 4.13 . The dimensions of the gate sluices are obtained from the director of the management board of these sluice gates (appendix E). Sluice gate A has two gate doors of 3 by 3 meters. When the gates are 100 % opened, the opening height is 3.1 meters. Further specifications are to be found in appendix E.

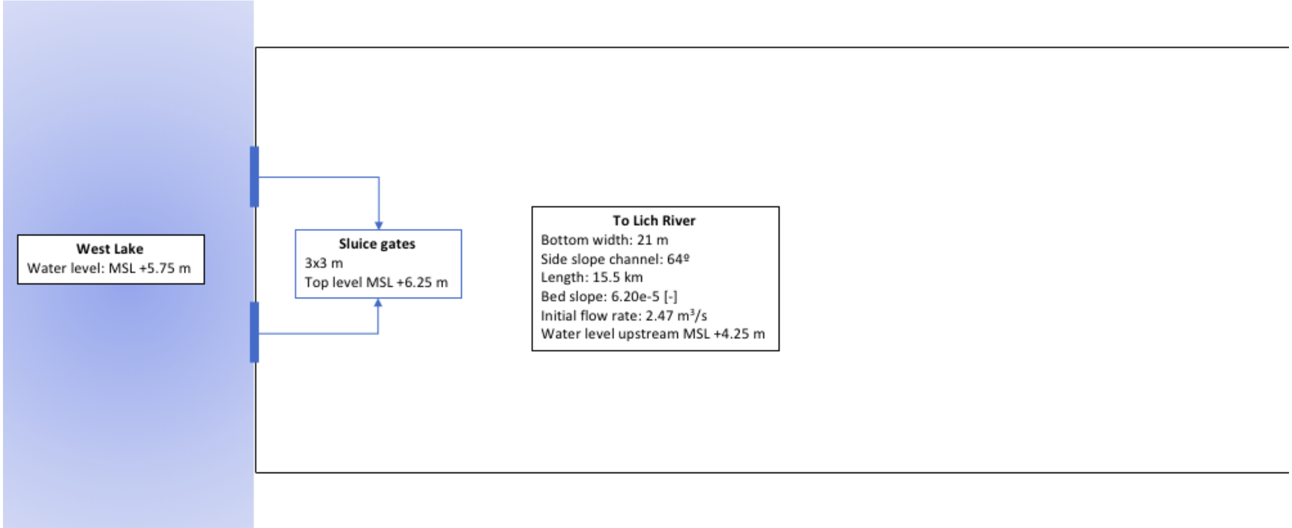


Figure 4.13: Schematised upstream reach To Lich

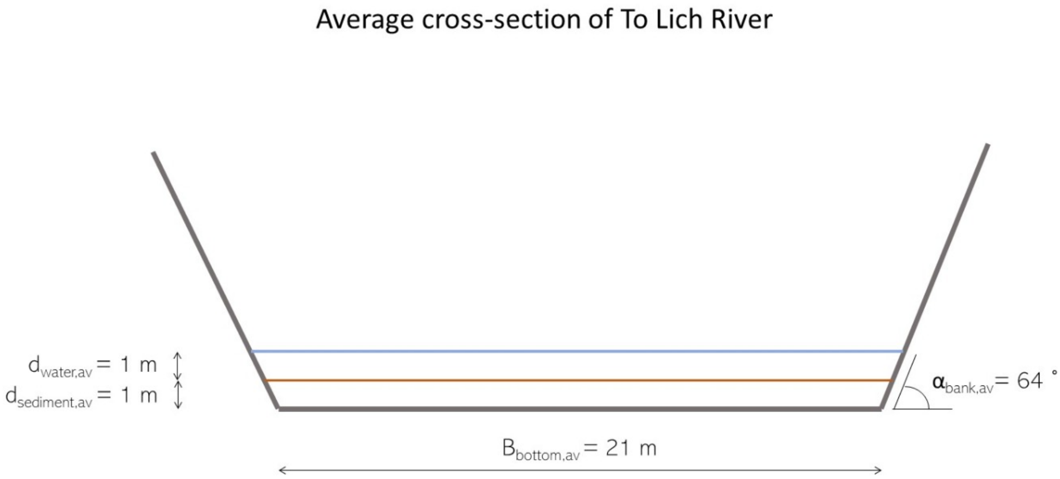


Figure 4.14: Average cross section To Lich

In figure 4.16 the longitudinal view of the embanked TLR is visualized. The five locations are obtained from figure 4.15, location number 5 is at the Thanh Liet gate. The numbers are ordered in downstream direction. Information about these reaches can be found in table 4.1 [69]. The average cross-section dimensions of the TLR that are used for further calculations are defined in figure 4.14. On average the sludge layer in the embanked TLR is one meter thick with one meter of water on top.

The surface water level slope is the difference between the TLR water level upstream and downstream, divided by the distance. Upstream real time data has been used at location S1 (Hoang Quoc Viet, obtained 30 September: 3.17 meters) and downstream real time data has been used at location S5 (Thanh Liet gate, obtained 30 September: 2.21 meters). For the initial situation the flow is assumed steady, the slope of the water surface is equal to the bed slope. For the scope of this research the geometry of the Nhue River is assumed the same as the TLR.

$$Slope = \frac{3.17 - 2.21}{15500} = 6.19E - 5[-] \tag{4.10}$$

The average discharge in the TLR is based on the following formula:

$$Q_{average} = \sum_{i=1}^{5} \frac{s_i - s_{i-1}}{S_{total}} * Q_i \tag{4.11}$$

This results in 2.47 m^3/s. The initial flow rate in the river is very low, especially compared to the flow needed for flushing (see section 4.3.1).

Table 4.1: General characteristics of specific reaches of the TLR [69]

Characteristics	**S1**	**S2**	**S3**	**S4**	**S5**
Distance from upstream (km)	3.1	5.1	9.1	13.8	15.5
Water depth (m)	0.75	0.84	0.98	1.05	1.34
Area of water cross section (m^2)	11.91	14.50	23.83	30.25	50.97
Water velocity (m/s)	0.015	0.039	0.049	0.117	0.131
Flow rate (m^3/s)	0.18	0.57	1.16	3.53	6.68
Sediment depth (m)	1.2	1.2	1.2	0.9	0.6
Area of sediment cross section (m^2)	16.16	18.00	26.57	23.60	21.03
Total sediment volume in a specific reach (m^3)	–	34,161	89,139	117,888	42,395
Average sediment density in a specific reach (kg/m^3)	–	1053	1195	1242	1357

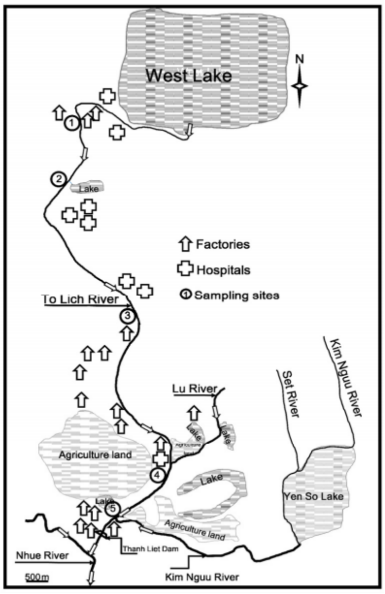


Figure 4.15: Map of TLR study area, showing the sampling sites [68]

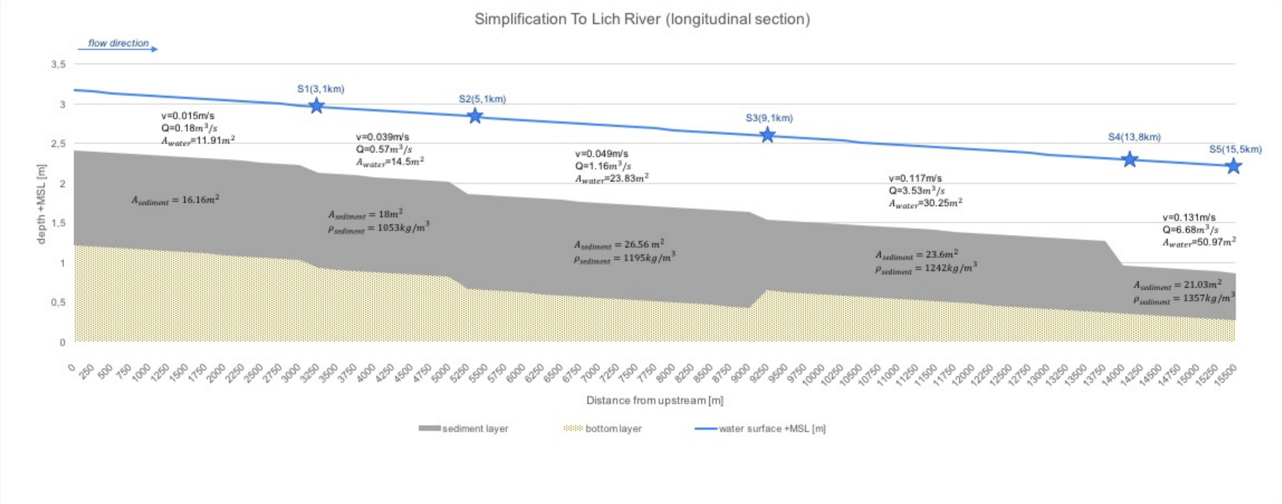


Figure 4.16: Longitudinal view To Lich

4.1.3 Red River

For this report the consequences of the water extraction to the morphological profile of the RR are determined. Therefore, the annual average discharge of the RR is studied and from this the significance of the water subtraction is explained.

The yearly average discharge of the RR is shown in figure 4.17. This data is measured at the town Sontay, 40 kilometers upstream of the planned pumping location. The minimum discharge is 900 m^3/s (march, 2003) [10]. To verify this data, more recent data on the river discharge is taken into consideration as well. ADCP data from an environmental station, 7 km downstream of the future pumping location, is visualized in figure 4.18. However, this location is downstream of the bifurcation with the Duong River. The pumping location is upstream of this bifurcation, therefore the discharge at the environmental station is significantly smaller. The minimum discharge measured at this location was 500 m^3/s in 2018. Taking this discharge as the minimum occurring discharge at the pumping location (in other words: being extremely conservative), the most extreme effects of pumping can be deduced. The effect of the water withdrawal is determined by the time in which the volume is pumped into WL. The expected effects are discussed in section 4.4.3.

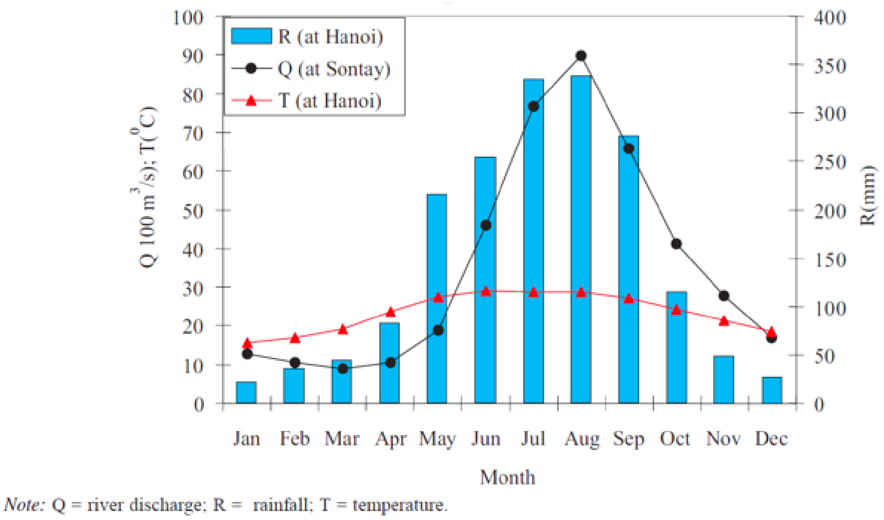


Figure 4.17: Discharge of the Red River measured at Sontay [10]

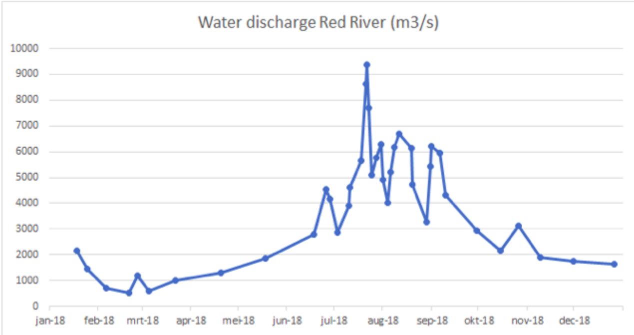


Figure 4.18: Discharge of the Red River measured with ADCP

4.2 Methodology

This section discusses the models that are used for the hydraulic analysis, what these models are representing and with which program these models are made.

4.2.1 River flood wave

According to this study the difference between the water level in the TLR and the WL is sufficiently large when the TLR is flushed. The TLR is flushed when the water surface level in the WL is at a height of approximately 6m (+MSL) [35], the water depth of the WL at the sluicegate is equal to 2.75 meters. Under the circumstances that the TLR needs to be flushed, the water depth in the TLR is very low (approximately 1 meter [69]). The difference between the 2 water levels (in WL and TL) is then so large, that the fall over the gate is larger than the water depth in the TLR, hence a river flood wave occurs when opening the gates.

This river flood wave determines the maximum water level that occurs in the river, the sediment transport that occurs in the river and the time it takes for the river to return to its original state.

The parameter that determines how long it takes to flush the TL is the discharge that enters the TLR. This flow rate is determined by how high the gate is opened. To investigate what situation is most efficient, several alternatives are examined, all with a different gate opening, hence discharge. The opening of the gate is expressed as a percentage of the maximum opening height. The different alternatives studied in this report are: 5%, 10%, 15%, 20%, 30% and 40%. These alternatives are referred to as 'the flushing scenarios'. For every flushing scenario a river flood wave model is made.

4.2.2 Sediment transport

From section 4.1.2 it can be concluded that there is a thick layer of sediment in the TLR. That is why it is also important to look at the sediment transport rate along the river stretch.
To compute the sediment transport rates along the river during the flood wave, the sediment transport rate formulas of Van Rijn are used [59]. These formulas are the basis of the criterion of Shields for sediment motion. The depth-integrated bed-load transport q_b as well as the suspended load transport q_s, both in $kg/s/m$ are calculated, according to formulas 6.1 and 6.4 in this article. The calculated q_b and q_s are converted to a mean sediment transport S in $[m^3/s]$ by dividing it by the average sediment density $\rho_s[kg/m^3]$ and multiplying it by the average width of the concerned river section $B_{av}[m]$.

Next to reducing the sediment layer by flushing the TLR, the People Committee of Hanoi started a dredging project. The task to conduct the dredging is assigned to the Sewage and Drainage Company. This year, in 2019, the aim is to dredge forty-thousand cubic metres of mud. Last year, one meter of sludge (equal to ten-thousand cubic metres) was dredged in the upstream reach of the TLR [38]. The results of sediment transport by flushing and by dredging are compared in section 4.4.3.

4.2.3 Modelling in R

The river flood wave and sediment transport models are made in R. The choice for R is based on the fact that HUNRE is familiar with this software and so the code can be used for further research in the future. R is a free language for statistical computations and graphics. It is also easy accessible by extending it with the use of open source packages. The full code made in R for this study is presented in appendix G.

Model set up

The river flood wave models are made in R with the package 'rivr'. The description of this package is: 'This package is designed as an educational tool for students and instructors of undergraduate courses in open channel hydraulics. Functions are provided for computing normal and critical depths, steady (e.g. backwater curves) and unsteady (flood wave routing) flow computations for prismatic trapezoidal channels' [40].

Theory model

With the package 'rivr' a kinematic wave model and a dynamic wave model can be made. For a kinematic wave the wave length and wave height stay the same during the whole propagating period of the flood wave, there is however steepening of the wave. For a dynamic wave model, the pressure component is taken into account, this effect causes the wave to damp out; the wave height will decrease and the wave length will increase over the propagating period. Hence, the flood wave will flatten out over the propagating length. The kinematic wave model is a simplification of the dynamic wave model. For this study a dynamic wave model is chosen, this model is chosen to examine if the damping of the river flood wave is significant. The normal equilibrium depth is calculated with the Manning equation. The package 'rivr' has the choice between two numerical schemes; The MacCormack scheme and the Lax diffusive scheme. The MacCormack scheme is a second order accurate predictor-corrector scheme that provides efficient flood wave routing. The Lax diffusive scheme provides smooth solutions for boundary conditions with discontinuities, e.g. a sudden gate closure [40]. In this study there are no sudden changes in the boundary conditions, hence the dynamic flood wave model is made with the MacCormack scheme.

In the dynamic flood wave model, the upper boundary and lower boundary conditions must be defined, this is because of the use of the Method of Characteristics (MOC) to compute the flow regime at the model boundaries [40]. The temporal resolution of the model is defined by the chosen time step, a value of 10 seconds is chosen for this study. The spatial resolution of the model is defined by the distance between two nodes in the model domain, a value of 250 meters is chosen for this study.

With the data set obtained from the dynamic wave model the sediment transport equations are solved in R and sediment transport models are made.

4.3 Input parameters in R

For the model in R different input parameters are needed. First, the geometry of the river stretch is needed. The input values for the dimensions of the river stretch are the width $B = 21$ m, the side slope $\alpha = 64°$,the bed slope $i_b = 0.000062$ and the river length $L = 75000$ km. These values are equal to the values determined in section 4.1.2. Furthermore, a manning coefficient is also required for the model, this is a coefficient which represents the friction applied to the flow by the channel. The TL river is man made, that is why a manning coefficient has been chosen that represents a constructed brick channel, this value is equal to 0.015 [66]. However, it is known that there is a thick layer of sediment in the TL river, therefore it is assumed that the value of the manning coefficient is slightly higher. Eventually a value of 0.025 has been chosen as input parameter for this study. The other input parameters are described below.

4.3.1 Initial conditions and boundary conditions

The initial condition used in the model is the initial flow in the river stretch. The value for the initial discharge is determined in section 4.1.2 and is equal to 2.47 m^3/s.

The dynamic flood wave model needs two boundary conditions. One upstream boundary condition and one downstream boundary condition, both conditions are defined for the full duration of the model.

The upstream boundary condition is defined as a flow rate during a specific time. For the model the sluice gates are opened at t = 0 and the sluice gates close when the WL water surface level has decreased 0.3 meters (the surface water level is decreased from + 6m MSL to + 5.7m MSL [35]). This duration is calculated with the discharge through the gates, which depends on the gate opening. The discharge under the gate is calculated with the following formula [65]:

$$Q = C_d ab * \sqrt{2gh_0} \tag{4.12}$$

The 'a' stands for the sluice gate opening height [m], the 'b' for the sluice gate length [m], the 'g' for the gravitational acceleration [kN/m^2], the 'h_0' for the upstream water depth and the C_d for the contraction coefficient. The contraction coefficient differs a lot for free flow and submerged conditions. For submerged conditions the discharge coefficient is dependent on the tail-water depth and the discharge under the sluice gate decreases. For flee flow the discharge only depends on the dimensions of the opening and the upstream water depth; the tail water depth stays constant. Theoretical and empirical experiments have been conducted to formulate an accurate value for the discharge coefficient. This results in the following relation for a sluice gate in free flowing conditions[65]:

$$Q = 0.864ab * \sqrt{gh_0}(\frac{h_0 - a}{h_0 + 15a})^{0.072} \tag{4.13}$$

The condition for which free flow occurs is:

$$h_0 \geq 0.81h_2(\frac{h_2}{a})^{0.72} \tag{4.14}$$

The free flow condition is met for the initial conditions of all scenarios, even when the equilibrium depth in the TLR is reached. This condition is depicted in figure 4.19 However, in between these situation, the river flood wave can cause a high tail water depth which creates submerged conditions. However, the implementation of the entire submerging effect on the discharge in our model would be outside the scope of this project. Therefore, the effect of submerge is taken into account by dividing the initial discharge for each gate by two to get the average discharge, with which the calculations are done.

Table 4.2: Discharge and time that gates are open for the flushing scenarios

Scenario	**1**	**2**	**3**	**4**	**5**	**6**
Percentage of maximum opening height (%)	5	10	15	20	30	40
Initial flow through 2 gates (m^3/s)	4.00	7.70	11.28	14.74	21.34	27.58
Average flow through 2 gates (m^3/s)	2.00	3.85	5.64	7.37	10.67	13.79
Average time the gates are open (s)	784567	404874	276582	211731	146155	113083

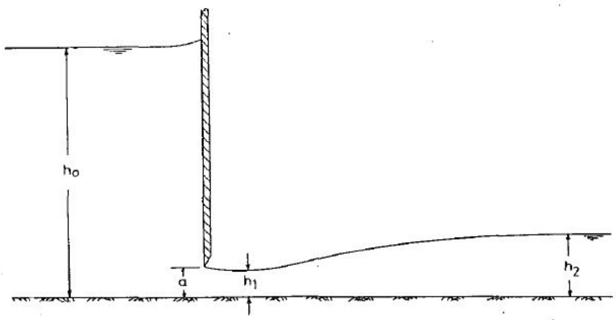


Figure 4.19: Sluice with free flow conditions [65]

The average discharge through the gates and the opening time of the gates is calculated for every scenario and are presented In table 4.2. This is done with the dimensions of the gate (3 x 3 m), the maximum opening height of a gate (3.1m) and the water depth in the WL when flushing starts (2.75m) (see appendix E). An example of an upstream boundary condition is (for scenario 20%):

$$Q(t) = \begin{cases} 2.47 + 7.37, & \text{if } t \leq 211731 \\ 2.47, & \text{otherwise} \end{cases} \tag{4.15}$$

For a dynamic flood wave model, a downstream boundary condition must also be specified. Physically, the water level (+MSL) in the RR is increasing when the flood wave arrives downstream. Caused by the large discharge ratio between the RR and the TLR, the water level increase is not very large in the RR. Actually, the total system of the two rivers should be modelled to obtain a detailed overview of the situation. Within the scope of this project, only the TLR is modelled in R, and the effects of the flood wave downstream are reproduced within this model as good as possible. The downstream boundary condition in R can be specified in three ways; a water depth, water discharge or depth gradient. During the flood wave the water depth is not constant downstream, neither is the water discharge. Therefore, the downstream boundary condition is set to a zero depth-gradient. To support the choice, the outcomes are validated in section 4.4.1, using hand calculations.

4.3.2 Sediment transport input parameters

To be able to compute the transported sediment along the river during the river flood wave according to Van Rijn, first the average sediment size must be determined. The TLR is a man-made river and has therefore no natural sediment layered bottom. However, on top of the surface which is made of stone, a layer is formed. The exact composition of this layer is not investigated in this study. It is expected that this layer consists of a combination of sediment from the RR basin and shattered solid waste parts. The area around the RR and Hanoi has a soil composition of clayey-silt [72] [1]. Based on this information, a mean sediment size $d_(50) = 0,002mm$ is assumed for the sediment layer in the TLR.

The average sediment density of the river sediment is based on a Japanese study on the TLR (2013) [48], and comes down to a $\rho_s = 1213kg/m^3$. The water density is assumed to be $\rho_w = 1000kg/m^3$. Further input values are taken from the Van Rijn article: kinematic viscosity $\nu = 1 * 10E - 6[m^2/s]$, coefficient $\alpha_b = 0.015$ and exponent $\eta = 1.5$.

4.4 Results

In this section the results from this chapter are presented, validated, interpreted and evaluated.

4.4.1 Final results

For each scenario a river flood wave model is made in R. Six graphs are made for each scenario, representing:

- The flow over the distance for different times
- The depth over the distance for different times
- The depth over the time for different distances
- The velocity over the distance for different times
- The sediment load transport over the distance for different times
- The sediment transport over the distance for different times

All the graphs are presented in appendix F, in figure 4.20 and figure 4.21, two examples are shown for scenario 20%.

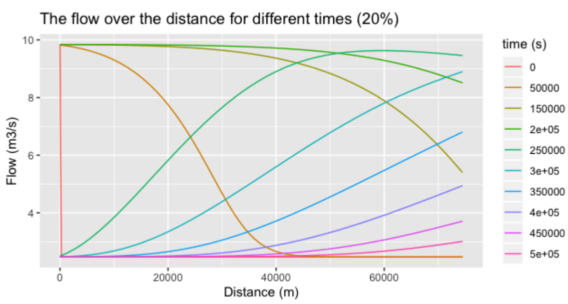


Figure 4.20: The flow over the the distance for different times for scenario 20%

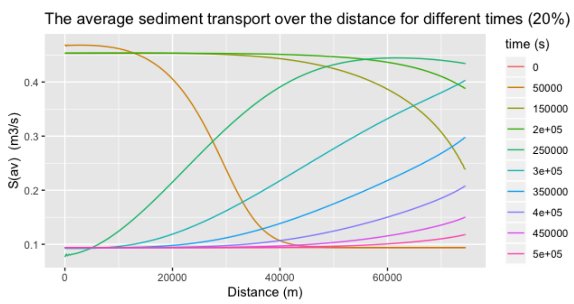


Figure 4.21: The sediment transport over the distance for different times for scenario 20%

Analytical validation results

The output graphics of the model are validated with hand calculations, to make sure that the chosen downstream boundary condition (defined as a zero depth gradient) is valid. The size of the wave translation speed and diffusion (damping) can be deduced from the continuity equation 4.16:

$$\frac{\delta h}{\delta t} + \frac{\delta q}{\delta x} = 0 \tag{4.16}$$

This equation is combined with the Chézy equation for a specific discharge with varying surface slope for a passing high water wave.

$$q = Ch^{\frac{2}{3}}\sqrt{i_b - \frac{\delta h}{\delta x}} \tag{4.17}$$

Substituting equation 4.17 into equation 4.16 and differentiating to x, gives equation 4.18 in the form of an advection-diffusion equation:

$$\frac{\delta h}{\delta t} + \frac{3}{2}u\frac{\delta h}{\delta x} - \frac{q}{2i_b}\frac{\delta^2 h}{\delta x^2} = 0 \tag{4.18}$$

in which wave translation speed $c = \frac{3}{2}u$ and diffusion coefficient $K = \frac{q}{2i_b}$. Next, a sinusoidal form and a coordinate system that moves with the wave is assumed for the river flood wave. Then, the term with the translation speed can be set to zero and the following equation is obtained:

$$\frac{\delta h}{\delta t} = -\frac{q}{i_b}\frac{4\pi^2}{L_{wave}^2}h \tag{4.19}$$

This results in an exponential damping function. However, in this study a relative short reach is being studied (the length of the reach is smaller than the length of the wave), so a linear approximation is valid.

$$\frac{\Delta h}{h} = -\frac{q}{i_b}\frac{4\pi^2}{L_{wave}^2}t_{passage} = -\frac{q}{i_b}\frac{4\pi^2}{L_{wave}^2}\frac{L_{reach}}{c} = -\frac{4\pi^2 h}{3i_b}\frac{L_{reach}}{L_{wave}^2} \tag{4.20}$$

in which
Δh $[m]$ = Maximum wave height difference during wave propagation
h $[m]$ = Wave height at x = 0 (start of wave)
L_{Reach}[m] = Total length of the reach over which the wave propagates
L_{Wave} $[m]$ = Wave length

Using equation 4.20, the peak height reduction of the wave (Δh) can be approximated for different lengths and heights of the high water wave. For each scenario, this is done in an Excel sheet. The results from the excel sheet are compared to the outcomes of R. The outcomes more or less have the same magnitude. However, when analyzed in more detail it can be seen in figure 4.22 that the modelled results are lower than the analytical results when the WL gate is opened for 0-30%. For larger gate openings ($> 30\%$) the modelled damping height is larger than the analytical values. The most representative modelled results are found for a gate opening of 30%. However, the differences between the analytical and the modeled values are not significant, hence the choice of the boundary condition is validated.

Table 4.3: Damping height Δh [m] per sluice height scenario

Opening height of sluice	**5%**	**10%**	**15%**	**20%**	**30%**	**40%**
Analytical value damping height Δh [m]	0,001	0,005	0,017	0,038	0,107	0,220
Modelled value damping height Δh [m]	0,0	0,0	0,005	0,0024	0,107	0,224

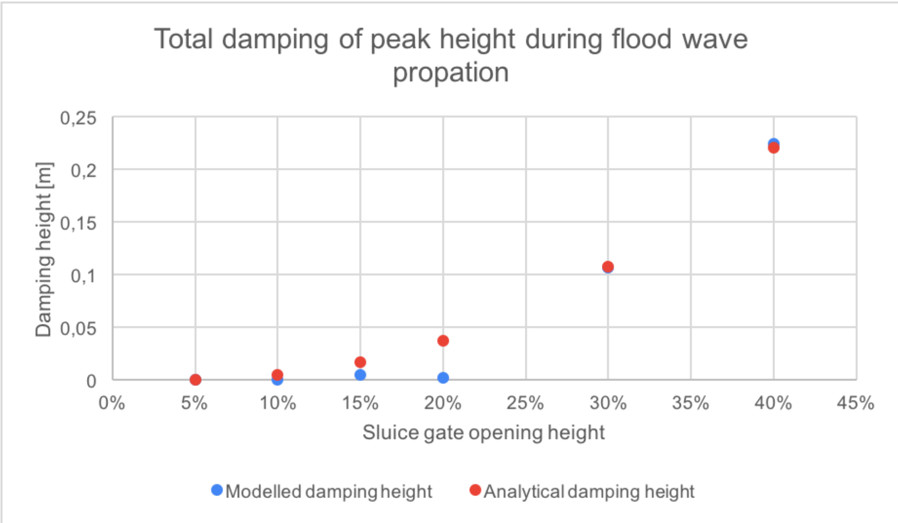


Figure 4.22: Difference of reduction in peak height of flood wave model vs. analytical calculation

4.4.2 Interpretation results

The aim of the hydraulic analysis is to draw a conclusion about the optimum flushing scenario. For that purpose, a multi criteria analysis (MCA) is carried out in this chapter. Five criteria aspects are chosen where the six different flushing scenarios get a score for between 1 and 5. Furthermore, each criterion has a weight factor (1-5) that reflects the importance of this criteria. The outcome of the MCA is depicted in table 4.5 and figure 4.23.

Comparison of scenarios

To interpret the results, the most significant aspects are determined and listed in table 4.4. Below, the different aspects and the methodology of how they are obtained are explained. The flushing time is not included in the MCA, this is explained below.

Table 4.4: Results of MCA for different sluice opening heights

Percentage open WL gate A	**5%**	**10%**	**15%**	**20%**	**30%**	**40%**
Max water depth Thanh Liet (m)	0.80	1.00	1.20	1.30	1.50	1.70
Flow velocity WL gate A (m/s)	2.20	2.10	2.00	2.00	1.90	1.90
Total transported sediment (m^3)	$32e+4$	$27e+4$	$21e+4$	$21e+4$	$17e+4$	$17e+4$
Effective flushing time $(days)$	12.70	8.70	7.50	6.40	5.80	5.80
Flushing period $(days)$	9.08	4.69	3.20	2.45	1.69	1.31
Dilution factor $(-)$	1.21	1.38	1.53	1.66	1.86	2.00

The **factor of dilution** of the TLR flow with WL water is of importance in comparing the flushing scenarios. This factor is of importance because the higher dilution factor, the more the smell and appearance of the TLR improves. The factor is computed as follows: the average increase of the water depth during flushing ($\Delta h_{av,eff}$ [m]) divided by the initial depth of the TLR 'in rest' (h_e [m]). A dilution factor between 0-20 % is scored with 1 and a value in the range of 80-100% is scored with a 5 respectively.

The **effective flushing time** is the time from when the gates open until when the initial condition in the TLR is restored. This represents the total time for which effects of flushing, such as sediment transport and dilution, are present. Therefore, a larger effective flushing time is favourable for the TLR and this criterion is weighted the second most important. The effective flushing time is determined from the graphs in appendix F, by looking at the time it takes until the river is in its original state again. The results of the effective flushing time varies between approximately 5 days (40 %) and 13 days (5%). The difference between the results is divided in five steps and scored from 1 to 5 respectively.

The amount of **sediment** flushed downstream for every scenario, expressed in cubic metres, is considered as well. The sediment transport is determined by looking at the graphs in appendix F that show the sediment transport over distance for different time intervals. From these graphs the average sediment transport rate is subtracted for each wave at a specific time. This value is multiplied with the duration of that specific wave and a volume of transported sediment is obtained. The total volume for each scenario of transported sediment is shown in table 4.4. In the section 4.4.1, the damping height for each scenario is determined, from this can be argued that the damping of the waves is not significant compared to the length of the river stretch (the maximum value is approximately 20 cm over 75 km). With this assumption it is concluded that the sediment transport upstream and downstream does not differ significantly. Therefore, no distinction is made in this report between sediment transport upstream and downstream.

The **flow velocity at gate A at WL** is taken into account, as high flow velocities can cause structural damage to the gate. For a cement concrete sewer the non-scouring or limiting velocity is, very roughly approximated, 2,5 - 3 m/s [25]. All scenarios have flow velocities below this limit. However, the 'safe' range of 2,5 to 3 m/s is investigated for this particular situation to guarantee the structural safety of the sluice. Therefore, the flow velocities of the scenarios are scored between 1 to 5. The considered scale of velocities is between 0 and 2,5 m/s, divided by 5 gives the reach for every score. The velocity under the gate is calculated by taking the average discharge through 1 gate and dividing it by the gate opening area.

The **largest occurring water depth at the Than Liet gate** is compared with the maximum water depth at that location. The regulation rules are specified per season in appendix E. The smallest allowed water depth (in the rainy season) is 2.8 m. If one of the scenarios exceeds this value, it has a score of 1. If not, then the scenario scores a 5. The maximum water depth for each scenario at 15 km (location Thanh Liet dam) is determined from the graphs and is presented in table 4.4.

The **flushing period** in table 4.4 is the amount of days that the WL gate A is open per scenario. The effective flushing time is more important for the hydraulic effects on the TLR and therefore the flushing period is not included in the MCA. However, the flushing period is used to determine the hydraulic effects on the RR. The time difference between the flushing period and the effective flushing time is the minimal time the WL gate is closed. From this the maximum pumping capacity is deduced which provides insight into the morphological effect, explained in section 4.4.3.

Table 4.5: Multi Criteria Analysis on flushing scenarios

Criterion	**Weight factor**	**5%**	**10%**	**15%**	**20%**	**30%**	**40%**
Max water depth Than Liet $[m]$	1	5	5	5	5	5	5
Flow velocity WL gate A $[m/s]$	2	1	1	1	2	2	2
Total transported sediment $[m^3]$	3	3	2	2	2	1	1
Effective flushing time $[days]$	4	5	3	2	1	1	1
Dilution factor $[-]$	5	2	2	3	4	5	5
	Total score	**49**	**38**	**36**	**39**	**41**	**41**

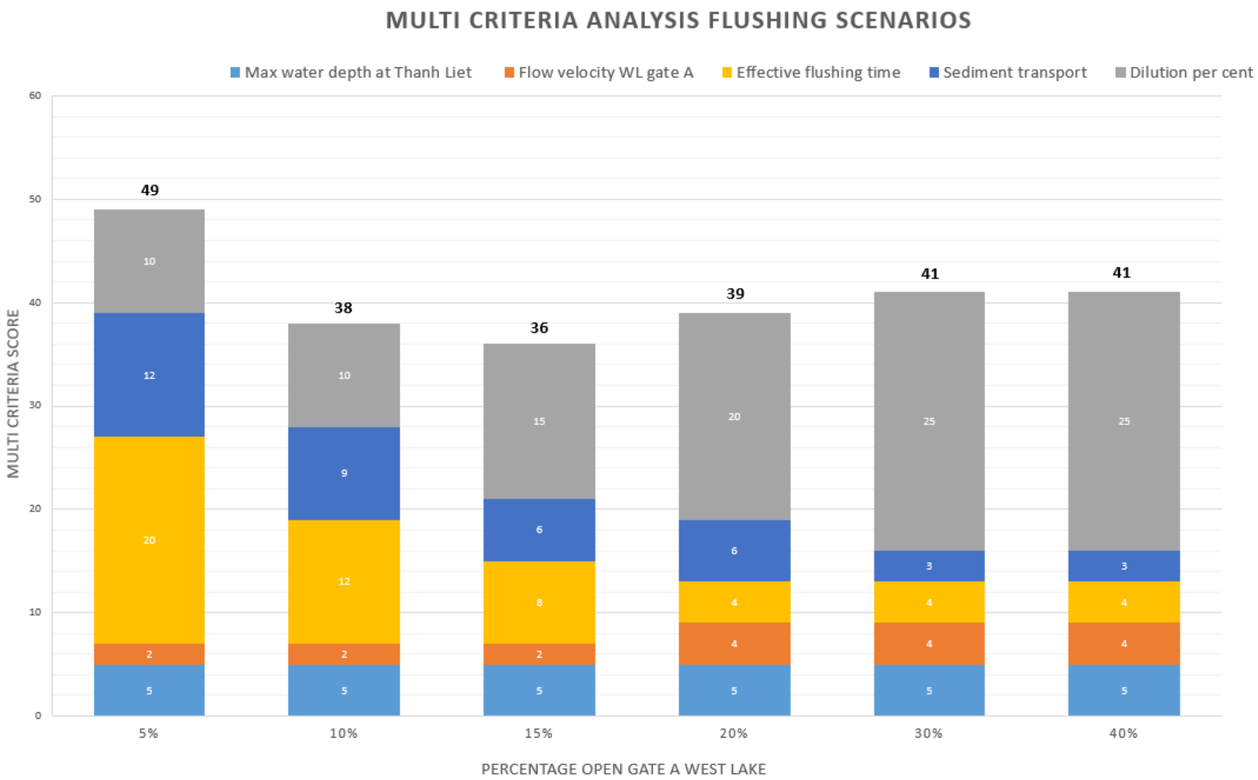


Figure 4.23: Multi Criteria Analysis on flushing scenarios

4.4.3 Optimum scenario

According to the MCA performed in section 4.4.2, the optimum scenario is 5 % with a total score of 49, see figure 4.23.

Flushing scenario

With a gate opening height of 5%, the effective flushing time is approximately 13 days and the flushing period (the time that the gates are open) is approximately 9 days. The most critical flushing scenario is that the gates immediately open again when the TLR is returned to its original state. This means that the minimum time needed for the WL water level to be heightened is the effective flushing time minus the flushing period. In other words this is the period in which the sluice gate is closed and the pumps can fill up the WL. This comes down to approximately 4 days. This means that if the WL water level is at 5.7m + MSL there are 4 days left to fill the WL up to 6m + MSL, hence 4 days to increase the surface level with 0.3m. Because the TLR is a very polluted river, it is assumed in this study and for this scenario that the TLR therefore is flushed once every two weeks. The water level in the WL determines how much water needs to be extracted from the RR. In the rainy months it is likely that less water needs to be extracted from the RR to increase the water level of the WL to +6m MSL than in the dry months. Besides increasing the water surface level to +6m MSL, the water level of WL also needs to be managed and maintained at a level of +5.7m MSL.

Sediment

In this part, the effect of the 5% scenario on transported sediment is explained and brought into perspective.

For the 5% scenario, the total volume of mobilized sediment is $V_{mobilized,5\%}$ = 32e+4 m^3 per flushing event. The corresponding mobilized sediment height in metres is:

$$\Delta d_{sed,mobilized,5\%} = \frac{V_{sed,mobilized,5\%}}{L_{reach} B_{average}} = \frac{32e+4}{75000 * 21} = 0.20m \tag{4.21}$$

The outcome can not be interpreted as a net sediment transport over distance and time as a part of the mobilized sediment deposits downstream in the river reach. From the mobilized sediment material that clumps together, the d_{50} increases and the mobilization rate decreases. This model however assumes a constant sediment diameter. To give an idea of the erosion rate in the river, a rough estimated possibility is discussed. If one assumes that three-quarter of the mobilized sediment deposits before it reaches the RR, then the total erosion depth comes down to $\Delta d_{sed,eroded,5\%} = \frac{1}{4}\Delta d_{sed,mobilized,5\%}$ = 0.05 m / flushing event. A more detailed elaboration on this topic is discussed in chapter 6.

According to the schedule of one flushing event per fourteen days, the total erosion depth per year comes to:

$$\Delta d_{sed,eroded,5\%,yearly} = \frac{t_{year}}{t_{flushingcylce}} * \Delta d_{sed,eroded,5\%} = \frac{365}{14} * 0.05 = 1.30m/year \tag{4.22}$$

The Hanoi Sewage and Drainage company aim to dredge 40,000 m^3 sediment in 2019, as referred to in section 4.2.2. These dredging activities are done in the TLR (0 - 15.5 km, upstream of the Than Liet Dam). The height of the dredged sediment layer from these activities, averaged over the TLR, is:

$$\Delta d_{sed,dredged,2019} = \frac{V_{sed,dredged,2019}}{L_{reach} B_{average}} = \frac{40e+3}{15500 * 21} = 0.12m/year \tag{4.23}$$

The total decrease of the sediment layer in the TLR is therefore

$$\Delta d_{sed} = \Delta d_{sed,eroded,5\%} + \Delta d_{sed,dredged,2019} = 1.3 + 0.12 = 1.42m/year \tag{4.24}$$

Even though the average sediment depth is currently 1 m, the outcome of equation 4.24 does not imply a full 'cleaning' of the river bed. There are two important aspects that need to be considered. Firstly, the increase and deposition of new sediments throughout the year leads to an increase of the sediment depth. This is discussed in chapter 6. Secondly, the sediment layer probably exists of larger waste particles such as bottle caps which is simulated in R. To model the mobilization of larger particles the same density is used as in section 4.3.2: $\rho_s = 1213 kg/m^3$, as this is more or less equal to the density of polyvinyl plastics [63]. In R, the maximum particle size of particles that moves in the 5% scenario is found as $d_{50,max,mobilized} = 0.003$ m. In figure 4.24, the sediment transport over distance for this d_{50} is depicted. However, most plastics and other waste particles are larger [63], which means those do not get mobilized for the 5% scenario. This is discussed in chapter 6.

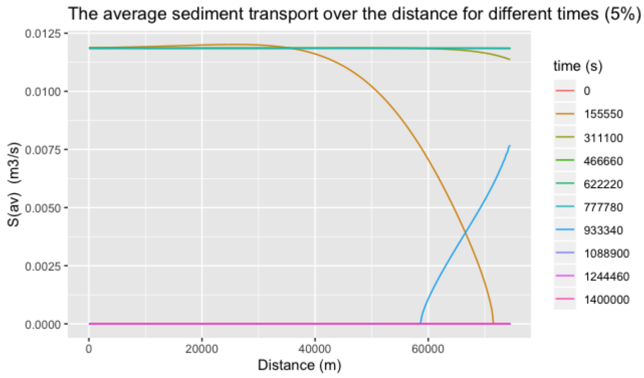


Figure 4.24: Sediment transport over distance for a $d_{50,max,mobilized} = 0.003$ m, scenario 5%

Morphological response Red River

As discussed in section 4.1.3, the potential morphological changes in the RR are to be investigated. The maximum water withdrawal from the RR is therefore:

$$Q_{withdrawal,RR,average} = \frac{\Delta h_{WL} A_{WL}}{t_{eff,flushing} - t_{gateopen}} = \frac{0.3 * 5.2E6}{4 * 24 * 3600} = 4,5 m^3/s \tag{4.25}$$

In the case of a discharge of $Q_{RR} = 500 m^3/s$, which was stated in section 4.1.3 as very conservative, the water withdrawal is less than 1 % of the total discharge. So even in this most extreme case (the minimum time for the WL water level to be heightened for 5%), morphological changes in the RR are assumed to be not significant. Furthermore, if the minimum time required to fill up the WL for all the other scenarios is considered (the effective flushing time minus the flushing period), it is determined that the minimum value belongs to scenario 5%. Hence, this scenario provides the most critical condition, the morphological response of the RR can thus be neglected for every alternative.

Chapter 5

Education

This research is conducted in relation with the TUD and HUNRE. Funded by the Orange Knowledge Programme, in 2019 TUD deployed a long-term project, named 'Climate Proof Vietnam: Educating together for sustainable change in Vietnamese deltas'. Amongst other objectives, the project aims to build educational capacity. This involves creating opportunities for HUNRE through offering students and staff new educational tools, and starting up new research projects. Therefore, as part of this larger project, this multidisciplinary research had an educational component. Besides delivering a finished research report, this multidisciplinary project aims to raise awareness about water quality issues and teach students about measurement techniques. To ensure the continuation of water quality monitoring in the studied water bodies, and to allow some of the methods to be adopted into the current education system, the work has been done in close collaboration with HUNRE staff and students.

5.1 Methodology

As this project has a time-span of eight weeks, it was decided to deliver a set of educational tools to ensure the study program continues in the future. The set of educational tools consists of a manual, instruction video's and an app with a database. The tools are supplied in such a way that they can easily be used by students in the (near) future and altered when deemed necessary. Furthermore, certain educational activities are set up in such a way that they can be integrated in to the study program as practicals in the future. There was a swift collaboration with the Vietnamese students during the educational activities that were held in the eight week time-span. The activities involved an introduction lecture that prepared the students for the water quality practical and a fieldwork trip. The application of the educational tools that are established and how the activities are set up, is described below.

5.1.1 Educational tools

Manual

A manual was made that consists of a description of each water quality parameter that was measured for this study and a step-by-step plan on how to use each measurement tool. The manual can be found in appendix C. Furthermore, the manual also contains questions related to the content of the manual. The questions must be answered by the students while using the manual. In order to encourage the students not to immediately look at the answers of the questions and to start a discussion between the students, no answer form has been made for the questions in the manual.

Instruction video's

For water quality measurement devices it is important that they are used in the right way to ensure that the accuracy of the measurements is as good as possible. To guarantee this accuracy of action, a set of instruction videos is created, supported by English and Vietnamese subtitles. Also, the steps in the video are in line with the steps explaining the usage of each tool in the manual.

Next to these instruction videos, two other videos are established. The first one is about the procedure on how to take a water sample. The second one covers the process on how to install the Akvo application (explained below) on a mobile phone.

Akvo application and database

Akvo is a non-profit organisation with the aim to create an open source data platform on water quality [9]. This organisation has created a mobile phone application which offers support using HACH test strips and stores the measured data as well. In this report, this mobile phone application is referred to as 'Akvo app'. HUNRE is authorized to use the TUD license for the Akvo app. Through repetitive water quality measurements, a database can be generated by HUNRE.

5.1.2 Educational activities

Introduction Lecture

To prepare the students for the fieldwork a Powerpoint presentation was made and an introduction lecture about the fieldwork was given. The purpose of this lecture was to help the Vietnamese students understand the various aspects of fieldwork and to explain where and why the fieldwork is done. The presentation explains the current status of the TLR and the proposed solution. In addition, the importance of doing water quality tests was explained. Furthermore, some details about the fieldwork were discussed.

Fieldwork

The fieldwork conducted for this study is multi-purpose. First of all, the fieldwork helps to verify the real-time online data used in this study. Secondly, the result of the fieldwork is the basis of the first data base of the three water bodies used in this study. The fieldwork for this study was conducted in cooperation with the students and staff of HUNRE. In this way they were actively involved in the process of analysing, collecting and interpreting data. To ensure that the fieldwork will continue in the future, educational tools were made with a detailed step-by-step approach for the fieldwork, described in section 5.1.1.

In order for the students to learn how to handle the tools and how to do different measurements, various types of equipment were used during the fieldwork.

An important aspect for the fieldwork conducted in this study is the determination of the fieldwork locations, which is discussed below.

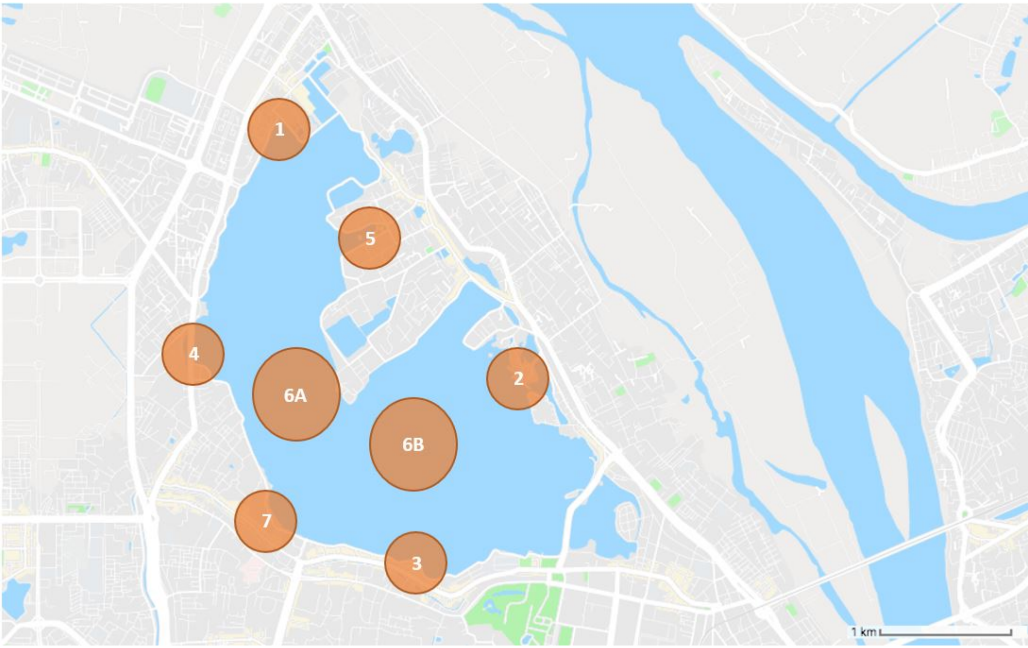


Figure 5.1: Map of Hanoi with sample locations in West Lake (created by author)

Determination of fieldwork locations

West Lake

The water samples were taken to give a representative value of the water quality of the water body. For a lake this is usually a sample taken in the middle of the water body: samples in the edges will show biased values due to the lack of flow, different temperature and a higher waste concentration [56]. In the WL however, taking measurements in the middle of the lake on a regular basis turned out not to be ideal for the practical, as it included renting a boat. Therefore, water samples were taken at six different locations at the edge of the lake and compared to the values of the water samples that were taken in the middle during a one-time trip. Out of these six test locations, the three most representative locations were selected as practical sites. The values for these parameters can be found in appendix D. A short explanation of how the the sample sites are determined is given below.

Test location 5 clearly shows high values for phosphate and EC. This indicates a lack of flow and chances of eutrophication, hence it is an undesirable location for field tests. Location 3 has high pH and turbidity values. This makes it an unfavourable location to represent the water quality of the WL. As for location 7, there was no turbidity measured and a out of range DO value was obtained. The chosen measurement locations around the WL are locations 1,2 and 4. The locations can be seen in figure 5.1.

Red River and To Lich River

The best sampling locations for both the RR and the TLR were determined on the basis of three criteria: the water must be representative for the whole river section (i.e. water must flow), there must be no upstream pollution sources close to the sample location and the location must be easily accessible to take a water sample.

For the RR there is an extra criterion: the sampling location at the RR must be close to

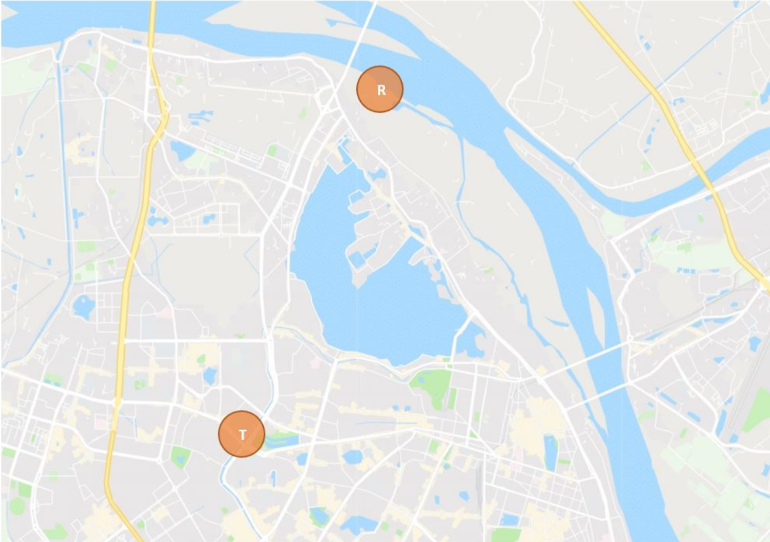


Figure 5.2: Map of Hanoi with sample locations in the Red River and the To Lich River

the WL. This is a criterion because in this study it is considered to pump RR water into the WL. In order to keep the pipelines that transport this water as short as possible (hence, as cheap as possible), they will be installed at the part where the distance between the WL and the RR is smallest. If the sampling location of the RR would be chosen downstream of this point, the water quality measured there would not be representative for the water quality of the water that is actually pumped into the WL. The chosen locations are depicted in figure 5.2. As for the TLR, the test location was taken relatively far upstream. It is unknown what the water quality is downstream, although it is not expected that the water quality improves downstream, as many sewers have their outlet in the downstream section of the river.

5.2 Results

The results are listed below:

- Manual (see appendix C) (+ transcript in Word)
- Akvo app to do water quality measurements
- Akvo database where outcomes of measurements can be stored
- Instruction video on how to install Akvo app
- Instruction video on how to take a water sample
- Instruction video's on how to use measurement tools (EC, pH, DO and (HACH) turbidity)
- Introduction lecture about water quality practical

Chapter 6

Discussion

The results obtained in this project will be discussed in this chapter. Some simplifications and assumptions led to the results. These simplifications and the results will be discussed.

6.1 Water quality

6.1.1 Model in R

The first point of attention is the fact that the WL is modelled as a 2D matrix, in which the geography of the WL is simplified to a rectangular shape. The shape of the WL will have an influence of the transport of concentrations in the lake. In addition to that, an optimum representation of the flow in the WL would have been modelled in 3D instead of in 2D. However, within the scope of this project, 2D modelling was chosen.

The second point of attention is the fact that the advection-dispersion equation was used. This function only includes the mixing of different concentrations for which no (bio)chemical reactions are taken into account. This is a simplification, as many reactions take place in lakes.

Before using a model it needs to be calibrated. This calibration was very difficult since there was no data of a similar scenario to compare with. Calibration is very important to say something about the reliability.

Moreover, only pumped RR water was taken as inflow input. No other inflow of sewers were considered as significant input for the model. These inflows could differ over time, leading to other final concentrations.

For ReacTran, the finite difference method was chosen. This choice is based on a short study on this topic. Other methods with a higher order of accuracy, faster computation time and difference in stability could be used.

The outcomes of the model show the advection-dispersion of a single parameter with an initial inflow from RR. It would be interesting to determine for how long flushing is necessary to significantly change the WL concentrations. In chapter 3, a single flush of RR water and a retention time of 100 days was discussed. After these 100 days no significant changes have taken place.

A water quality model has a more reliable outcome when it is based on a hydraulic model. First the hydraulics should be modelled and understood. Second the water flows in a hydraulic model can be assigned with different water quality parameters to see what the impact of a solution is on the water quality.
The last point to be mentioned is the fact that the model can only assess the mixing of a single parameter. Better insight in the lake processes are obtained when chemical reactions are taken into account. This is, however, not within the scope of this project.

6.1.2 Input parameters R

The five input parameters in R are the following: dispersion coefficient, advection coefficient, consumption rate, initial concentration WL and initial concentration RR. The first three parameters are discussed in this subsection. Section 6.1.3 contains the discussion on the latter.

Dispersion coefficient

For the dispersion coefficient, an assumption based on other studies is made. This causes some uncertainty regarding the modeled dispersion. Since lake mixing is a very difficult topic, more research about this dispersion is advised. Another uncertainty is the fact that the dispersion coefficient is assigned to all the grids, creating a homogeneous field. In practice, the dispersion per location will differ due to different circumstances.

Advection coefficient

As discussed before is the advection in lakes is significantly small, therefore the advection coefficient is set to zero. An advection coefficient of non-zero could have been chosen (as it probably would be the case).

Consumption rate

The consumption rate is an approximation for chemical reactions influencing the concentration of a parameter. This consumption rate is only approximated for DO, as discussed in the chapter 3. First, this consumption rate should be combined with an inflow, saturation component or atmospheric interaction leading to more reliable outcomes. The outcomes of DO in figure A.2c were lower than they would be in practice, as there was only consumption and no production. Second, the consumption rate is a simplification of the actual consumption due (chemical) reactions.

6.1.3 Initial concentrations

In the upcoming paragraphs, the possible errors in acquiring the values for the initial concentration of WL and RR water are discussed. Errors propagate trough-out the whole process of acquiring data, due to measurement inaccuracy, calibration inaccuracy, environmental factors, instrument resolution and instrumental drift [52].

Field measurements

The measured data contains two types of errors: manufacturing errors in the tool and errors made during testing. The HACH teststrips have an error between 10%-25%. The Greissinger tools have different errors. The EC-meter has an error of 1%, the pH-meter has an error of +- 0.02 digits and the DO-meter has an error of 1.5% mg/L. These errors could influence the final results. Continuing, the WL testing site was very close by the data tool of the HENR Dept.

The EC measurement was conducted and processed correctly. However, the result showed some interesting outcomes. The increased level of the EC in the WL compared to the RR could not be explained by the measured nutrients levels. This indicated that different ions (that affect the EC) were present in the WL. With the data that is gathered in this report, there is no way of determining the origin of these ions.

As stated in 3.4.4, some parameters have shown values against the expectations. The most logical reason for these values, is that the amount of measurements was too small to find accurate and more representative parameter values.

Online data

From the validation of the initial conditions in chapter 3, it becomes clear that there is a difference between the online data and the test strip values. The online data is measured by the the HENR Dept. The methodology and correctness of the HENR Dept's online data tool could not be measured nor checked.

6.1.4 Aquatic Life

Water quality conditions, therefore aquatic life conditions, improve when the proposed solution is executed. However, the migration of aquatic species is not touched upon in this report.

6.2 Hydraulic Analysis

In this section, a discussion is being held on the hydraulic analysis. Prior to that, the following must be stressed. This research is based on one 'flushing scenario', in which the WL water level is increased from 5.7 m +MSL to 6 m +MSL, while more situations are possible. For example, the water level can be raised from 5.3 m +MSL as well, which is likely to be the case in dry seasons when evaporation rates are high and flushing would be most feasible. Another example is the possibility to turn on the pumps and open the gate simultaneously. When taking into account these kind of alternate scenarios, different aspects should be elaborated. It is important to keep in mind that there are multiple possibilities of flushing, of which one is worked out in this research.

6.2.1 To Lich River

Model accuracy and limitations

To begin, the dynamic flood wave model made in R uses the MacCormack scheme which is second order accurate in time and space. The method of characteristics is used to solve the boundary conditions, this method is first order accurate in time and space. Because of this accuracy, the approach of the model for a dynamic flood wave is reliable.

The 'rivr' package needs all the input data expressed in feet. This means that all the input parameters are converted from meter to feet which entails rounding errors. Subsequently, the temporal resolution is equal to 10 seconds and the spatial resolution is equal to 250 meters.

To get a higher accuracy these values could be reduced. However, a disadvantages of this is that it takes longer to run the model.

Thereby, a limitation of the model is that the downstream boundary condition cannot be set as a water surface level, as explained in section 4.3.1. Instead, the downstream boundary condition of the model is set to a zero depth-gradient. The validation of the outcomes, using this boundary condition, is done in section 4.4.1 by hand calculations. However, the model result is compared to an analytical approach of linearized functions and only 6 scenarios are checked. Therefore, the results of this are not taken into account for the determination of the optimal flushing scenario.

Another remark on the model accuracy are the input values for the river geometry. Only the average values of the width B, bed slope i_b, side slope α, discharge Q and Manning coefficient n are possible to specify in the model. In fact, these values vary for different parts in the river. The output of the model is therefore less accurate than if it was possible to define different input parameters over the length of the river reach.

Upstream reach of the TLR

The upstream part of the TLR consists of a closed sewer of about 1.5 km length. This sewer starts at a short distance from the WL gates (1 to 2 meters). The cross sectional dimensions, length and other specifications of this sewer area are not known and could not be obtained despite several attempts. Since the sewer is built beneath the surface level it was also not possible to make a grounded estimation. Therefore, the assumption is made for this study that the average cross-section of the open reach starts directly behind the WL gates. This average cross section has a bottom width of twenty-one metres, depicted in figure 4.14, whereas the width of the closed sewer is expected to be smaller. The limiting discharge through the sewer is therefore expected to be smaller than modeled in R. If the maximum discharge of the sewer is exceeded, water accumulation before the gate can cause damage to the structure and in an extreme case even flooding. Therefore, the strength and capacity of the closed sewer is important information about the feasibility of the proposed solution. However, the optimal flushing scenario according to this study happens when the WL gates are open for five percent. This is a very safe scenario regarding the limiting discharge through the sewer. Furthermore, records of the past flushing events claim that the gates were opened by twenty percent and no indications of damage or floodings are found.

River reach downstream of Thanh Liet Gate

It is assumed that for the reach behind the Thanh Liet Gate the average cross section and bed slope of the Nhue river are similar to the TLR. However, the accuracy of this rough estimation is not assessed. In fact, Google maps shows that the Nhue River has a length of approximately sixty kilometers in which it has branches and confluences with other river streams.

Sediment characteristics

About the sediment characteristics, multiple aspects are arguable. These are listed below.
First of all, the average sediment particle diameter (d_{50}) is taken as 0.00002 m. This value is based on previous studies on the soil composition of the RR basin. However, the TLR bed sediment is likely to contain a lot of waste: soil particles can be accumulated and other larger pieces due to waste dumping can occur. Secondly, the discharge through sluice A is assumed to be only a water discharge. However, it is likely that this water discharge contains a sediment

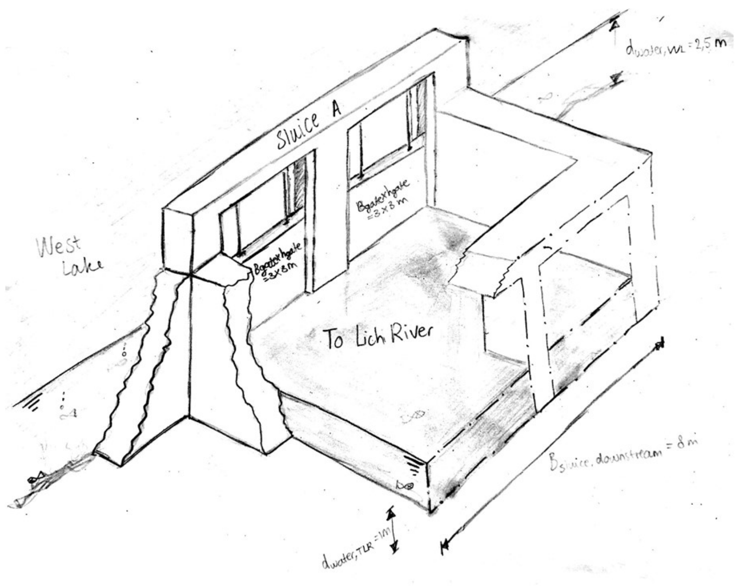


Figure 6.1: Schematic view sluice A, 3D

discharge as well. Lastly, only some of the dimensions of the Than Liet sluice are known. However, the type of sluice and details about the sediment discharge capacity of the sluice are not known. In this studies it is assumed that all the mobilized sediment upstream of Than Liet can pass the sluice.

Interpretation of the model

The model is interpreted by a MCA, this takes into account the total transported sediment and the effective flushing time. Both variables are deduced from the obtained graphics of the model. The model is based on the entire reach from the WL to the RR, which is seventy-five kilometers. However, the TLR covers only the first fifteen kilometers of this total reach. The time of the river flood wave and the total sediment transported in only the TLR would therefore result in much smaller values. However, since this study considered the water bodies as one hydraulic system it was considered incomplete to neglect the reach that connects the TLR to the RR. For the interpretation of the results it is important to keep this in mind.

6.2.2 West Lake

Hydraulic parameters

For the hydrological analysis of WL a lot of different parameters have been considered, it is of importance to examine the parameter reliability.

First of all, the surface inflow and outflow of the WL are discussed. This data is based on assuming seasonal inflow and outflow, as real-time measured data is unavailable. In addition, this data has been obtained in 2015. This makes the data even more unreliable since in the mean time new regulations, new sewer gates etc. may have been implemented. Also a lot of meteorologic data is used to obtain the water balance of the WL. All this data is based on weather reports collected from 2005 until 2015 and has been measured twenty-one kilometers from Hanoi. Meteorologic data, such as wind speed, can quickly become inaccurate if not measured at the exact location.

Subsequently, taking climate change into account, it is expected that the current average meteorological data differs from the average data measured from 2005 until 2015. The evaporation of the WL is calculated with the Penman formulas. These formulas use different parameters (i.e. radiation) that are estimated for this study, this decreases the reliability of the formulas. The study on which the bottom topography of the WL is based has been made in 2013, the study has also been simplified in this report. Based on these simplifications various assumptions have been made in this rapport. Hence, it can be concluded that the parameters used for the hydrological study of the WL are fairly unreliable.

Water surface level regulations

A lot is said in this study about the water surface level regulations of the WL. Results are based on the information that, for the proposed solution, the water surface level of the WL needs to be increased from +5.7m MSL to +6m MSL. However, some of these values have been taken from newspaper articles. Furthermore, it is assumed that the surface level of +6m MSL is equal to a water depth in WL of 2.75 meters. This information is also estimated on the basis of the bottom topography of WL combined with information from various newspaper articles.

6.2.3 Red River

Discharge data

The main parameter that has been examined for the RR is the discharge. The discharge data that has been examined consists of two data sets: the first data set was obtained from a station at the city Sontay, which is 40 kilometers upstream of the planned pumping location and it was measured in 2003. The second data set is obtained at an environmental station downstream of the planned pumping station and it was measured in 2018. Because both locations are quite far from the proposed pumping location, this report uses the minimum discharge that occurs in the data set obtained at the downstream location.

Water withdrawal

The proposed solution is about pumping water into the WL. For the pumps it is important that only water will be extracted and no sediment. This is of importance because of several reasons: If not only water, but also sediment is pumped into WL, the WL bottom will aggregate and this will lead to an increase of the ground level. This can lead to a decrease in water depth of the WL. The depth of WL is around 2 - 2.5 meters and it is not desirable that the lake becomes shallower. Furthermore, there is a lot of sand extraction happening upstream in the RR, this causes erosion problems. If water and sediment is extracted from the RR, the erosion would only worsen. If only water is extracted, the erosion problem would in fact be reduced. However, it has also been determined in section 4.4.3 that the morphological changes in the RR will be so small that they can be neglected. Lastly, sediment extraction also ensures that more maintenance is needed for the pipes. Because, there is more chance of damage and blockage of the pipes

Chapter 7

Conclusion & Recommendations

7.1 Water Quality Assessment

The proposed solution positively influences the water quality of the West Lake and the To Lich River.

The aim to 'clean' the To Lich River by dilution and meet the water quality standards for rivers (classification B1) in Vietnam is already almost met when considering the current status of the West Lake. All the water quality characteristics values of the West Lake meet the regulation limits, except for the E.coli and phosphate concentrations.

Furthermore, the proposed solution improves the water quality of the West Lake. However, this change occurs slowly. Complete flushing takes more than 100 days. To improve the water quality of the West Lake significantly, it is advised to switch on the pumps more often or constant throughout the year.

The dissolved oxygen level in the West Lake is considered as the most important parameter for the water quality status. If the proposed solution is implemented, the eutrophication in the West Lake is expected to decrease and the water will be cleaner. This cleaner water with less eutrophication will lead to less oxygen depletion and thus higher dissolved oxygen levels. Besides that, lower BOD and COD levels in the Red River will cause the dissolved oxygen to increase in the West Lake.

The impact on the nitrite, total iron, ammonium and phosphate concentrations in the West Lake is minimal. All nutrients have not shown significant differences between the Red River and the West Lake. Next to this, high levels of E.coli are found in all the water bodies. Therefore, to meet the regulation standards for phosphate and E.coli, other treatment measures need to be implemented. The effect on turbidity, pH and EC is expected to be positive after implementation of the proposed solution.

7.2 Hydraulic Assessment

From a hydraulic engineering point of view the proposed solution is feasible for all the water bodies.

The hydraulic assessment results in an optimal flushing scenario for the To Lich River, occurring when the West Lake gates have a opening height of 5%. This scenario scores highest in the MCA, mostly due to the long effective flushing time. This indicates the time in which the benefits of flushing occur and therefore has a high weighing factor. The least favourable aspects of the 5% scenario are the dilution factor and the fact that large waste particles (d_{50} >0.003m) do not get mobilized.

The hydraulic and morphological consequences for the Red River are not significant for any of the flushing scenarios. The maximum Red River pump capacity is based on the time difference between the flushing time and the effective flushing time. This is the time the gates of the West Lake are closed. The scenario of 5% results in the shortest time difference and therefore is the most critical for the subtraction of Red River water.

The hydraulic state of the West Lake allows to flush the To Lich River. The minimum surface level must be maintained at MSL +5.7 meters. The water level can be increased to MSL +6 meters, which gives the possibility to flush the To Lich River. A decrease of 0.3 metres in the water level is sufficient to flush the To Lich River.

7.3 Education

The results listed in section 5.2 are emerged from the cooperation with the board of HUNRE. It is not yet possible to conclude if the educational goals are achieved. I.e. the extent to which the tools will be used and the database will be extended in the future is unknown. In addition, the future awareness among Vietnamese students about the importance of water quality is unknown as well.

Based on the eight week during project, however, it can be concluded that the cooperation between the board and students of HUNRE and TUD is successful. The results of this project will be integrated by the OKP project in the future, therefore the educational goal is expected to be achieved.

7.4 General conclusion

The proposed solution is feasible from both the hydraulic and the water quality perspective. However, further research is needed to draw a final, indisputable conclusion on the optimal flushing scenario. Furthermore, it is difficult to understand the exact point of perspective of each stakeholder. Especially since there are so many of them.

For this research the aim is to make a feasibility study of the proposed idea. For the interpretation of the results and the drawn conclusions, some points have to be kept in mind. First of all, some general comments about the proposed solution are made in section 7.5.1. Thereafter, points of criticism and the subsequent recommendations are pointed out per chapter.

7.5 Recommendations

In this chapter all recommendations are given on how to continue this research in the future.

7.5.1 General view on proposed solution

The proposed solution is imposed to improve the water quality of the TLR. However, by diluting it, the cause of the pollution is not taken away. Therefore the proposed solution does not solve the core of the problem. A more sustainable approach to improve the water quality is to treat the wastewater before it flows into the TLR. This effectively solves a part of the problem instead of mitigating the effects of the problem, as the proposed solution would.

Furthermore, the proposed solution requires extensive cooperation between different provinces. It is advised to look into the scenario when the Thanh Liet Gate is closed, as this would keep the water flow in the province of Ha Noi. All the important stakeholders that are related to this water pollution issue, should be incorporated in order to ensure that implementation of the proposed solution is supported by all parties.

7.5.2 Water Quality

As the idea of the proposed solution is an extensive project that includes various shareholders, the recommendations after this research are numerous and are therefore subdivided in 3 paragraphs.

Obtaining data

More precise tools could be used in future research and the sample size could be increased to decrease the size and the amount of errors.

For future research, it is advised to do measurements regularly on the water quality of the WL to show monthly, seasonal and annual changes. This should be done on different locations, preferably on the lake it self rather than on the sides. Verify that the HENR tool is generating unbiased results and that certain sensors are not outdated. If this indeed is true, do more measurements close to the HENR tool.

If this is not true, it is advised to find a way to automatically download data from another website for future research or extend the database that was set up from an educational point of view.

Modeling WQ

The exact advection in WL per location is something to consider in further research. This could be done by measuring the velocities in the water column at representative locations.

Flushing time and retention time of WL is something to look into in further research. This should contain a full study of the mixing processes in the lake by combining the hydraulic model with the water quality model. Furthermore, the 3D model of flow in the lake and chemical reactions between variables, by plotting all the parameters simultaneously, should be investigated. Next the consumption rate that is used in the model should be fine-tuned. It now only covers the consumption of DO while it should also take into account the consumption rates of other parameters.

Other recommendations

Future research about the (bio)chemical interaction between parameters is recommended to gain better insight into the effects of the proposed plan. In addition, further research must be done on how to maintain the current ecosystem in the WL when the solution is carried out.

Another aspect that must be stressed is the fact that flushing of the TLR causes a severe decrease in water quality of the Nhue river downstream the Than Liet gate. The rate to which this causes problems for the local residents downstream should be investigated. As the Nhue river streams through three different provinces, it is important to include the municipalities of these areas in the stakeholder analysis as well.

Last but not least, a sediment study should be done. As it is still unclear how much sediment should be sieved out from the incoming RR water, this is something that should be investigated. Also, as the soil could contribute for a large part on the contamination, the exact composition of the sediment in the WL and the TLR and their states of pollution should be examined. This might also provide more insight on the values of nitrate and phosphate.

7.5.3 Hydraulic Analysis

For the hydraulic part, the recommendations are also subdivided into 3 paragraphs.

Obtaining data

To be able to make the model of the TLR more accurate, more data must be obtained. The upstream part of the TLR that lies under the ground must also be examined extensively. Furthermore, to properly analyze the effects over the entire river stretch, more data must also be obtained from the Nhue River downstream.

More information and data about the Than Liet gate should be obtained to verify that all the mobilized sediment upstream of Than Liet gate can pass the sluice.

The water surface regulations of the WL are based on values taken from newspaper articles. It is recommended to compare and validate these values with the official regulation documents, this data needs to be obtained.

For the RR, it is advised to measure the discharge consistently at the proposed pumping location.

Modeling river flood waves

To get better insight in the accuracy of the model, a non-linearized equation should be used and more damping heights should be calculated to obtain a more accurate validation.

More research needs to be done into different models for the river flood wave. Ideally, a model needs to be found where the downstream boundary condition can be set as a water surface level.

Other recommendations

The main function of the Thanh Liet Gate, which separates the Nhue River from the TLR, is to protect the Nhue River from floods. This could be for example an indication that the Nhue River is narrower and therefore more prone to floodings. Therefore, it is advised to include the Nhue River into the scope of future research.

An empirical research on the composition of the 'sludge layer' in the TLR is recommended. If the d_{50} appears to be larger, a flushing scenario with higher velocities is probably the outcome.

A study on WL sediment and the bottom topography around sluice A is required. It is needed to say something about the sediment discharge from WL into the TLR when flushing.

For the analysis of the WL various parameters are based on the simplification of the bottom topography. For later studies it is advised to do more research into the bottom topography of the WL, for these parameters to become more accurate.

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Appendix A

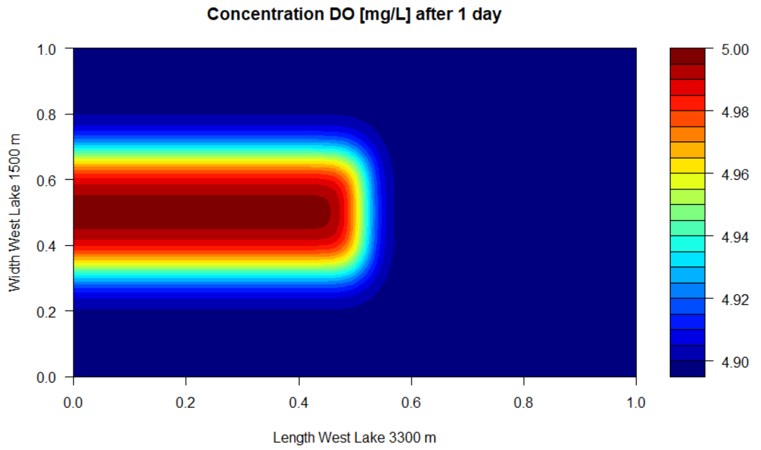
Results Water Quality

Bảng 1: Giá trị giới hạn các thông số chất lượng nước mặt

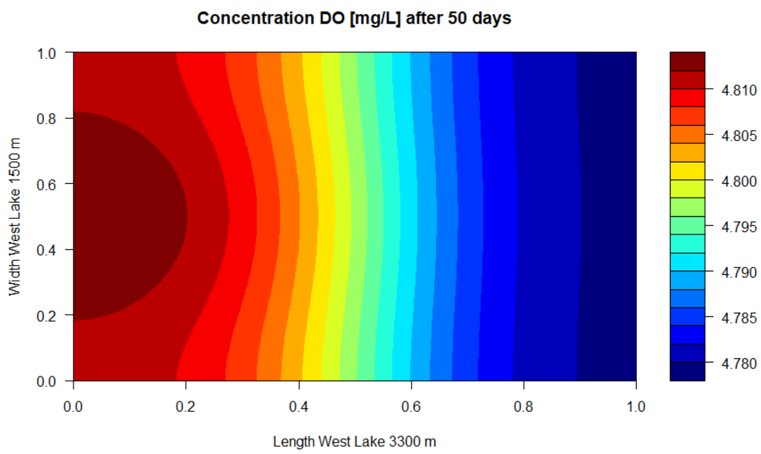
Table 1: Limit values of surface water quality parameters

TT	Thông số Parameter	Đơn vị Unit	Giá trị giới hạn Limit value			
			A		B	
			A_1	A_2	B_1	B_2
> 1	pH		6-8,5	6-8,5	5,5-9	5,5-9
> 2	BOD_5 (20°C)	mg/l	4	6	15	25
> 3	COD	mg/l	10	15	30	50
> 4	Ôxy hòa tan (DO)	mg/l	≥ 6	≥ 5	≥ 4	≥ 2
5	Tổng chất rắn lơ lửng (TSS)	mg/l	20	30	50	100
> 6	Amoni (NH_4^+ tính theo N)	mg/l	0,3	0,3	0,9	0,9
7	Clorua (Cl^-)	mg/l	250	350	350	-
8	Florua (F^-)	mg/l	1	1,5	1,5	2
> 9	Nitrit (NO_2^- tính theo N)	mg/l	0,05	0,05	0,05	0,05
>10	Nitrat (NO_3^- tính theo N)	mg/l	2	5	10	15
>11	Phosphat (PO_4^{3-} tính theo P)	mg/l	0,1	0,2	0,3	0,5
12	Xyanua (CN^-)	mg/l	0,05	0,05	0,05	0,05
13	Asen (As)	mg/l	0,01	0,02	0,05	0,1
14	Cadimi (Cd)	mg/l	0,005	0,005	0,01	0,01
15	Chì (Pb)	mg/l	0,02	0,02	0,05	0,05
16	Crom VI (Cr^{6+})	mg/l	0,01	0,02	0,04	0,05
17	Tổng Crom	mg/l	0,05	0,1	0,5	1
18	Đồng (Cu)	mg/l	0,1	0,2	0,5	1
19	Kẽm (Zn)	mg/l	0,5	1,0	1,5	2
20	Niken (Ni)	mg/l	0,1	0,1	0,1	0,1
21	Mangan (Mn)	mg/l	0,1	0,2	0,5	1
22	Thủy ngân (Hg)	mg/l	0,001	0,001	0,001	0,002
>23	Sắt (Fe)	mg/l	0,5	1	1,5	2
24	Chất hoạt động bề mặt	mg/l	0,1	0,2	0,4	0,5
25	Aldrin	µg/l	0,1	0,1	0,1	0,1
26	Benzene hexachloride (BHC)	µg/l	0,02	0,02	0,02	0,02
27	Dieldrin	µg/l	0,1	0,1	0,1	0,1
28	Tổng Dichloro diphenyl trichloroethane (DDTs)	µg/l	1,0	1,0	1,0	1,0
29	Heptachlor & Heptachlorepoxide	µg/l	0,2	0,2	0,2	0,2
30	Tổng Phenol	mg/l	0,005	0,005	0,01	0,02
31	Tổng dầu, mỡ (oils & grease)	mg/l	0,3	0,5	1	1
32	Tổng các bon hữu cơ (Total Organic Carbon, TOC)	mg/l	4	-	-	-
33	Tổng hoạt độ phóng xạ α	Bq/l	0,1	0,1	0,1	0,1
34	Tổng hoạt độ phóng xạ β	Bq/l	1,0	1,0	1,0	1,0
> 35	Coliform	MPN hoặc CFU /100 ml	2500	5000	7500	10000
>36	E.coli	MPN hoặc CFU /100 ml	20	50	100	200

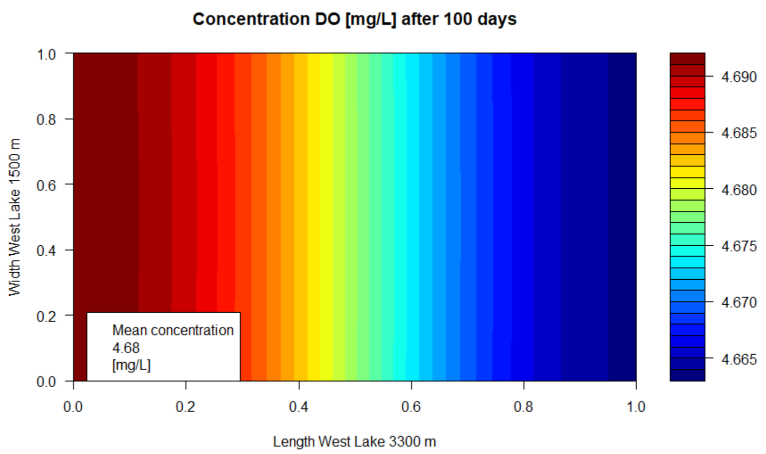
Figure A.1: Limit values of surface water quality parameters, according to National Technical Regulation on Surface Water Quality, Vietnam. [76] NB: English translation in blue and parameters applicable to this research are indicated with a blue triangle



(a) DO [1 day]

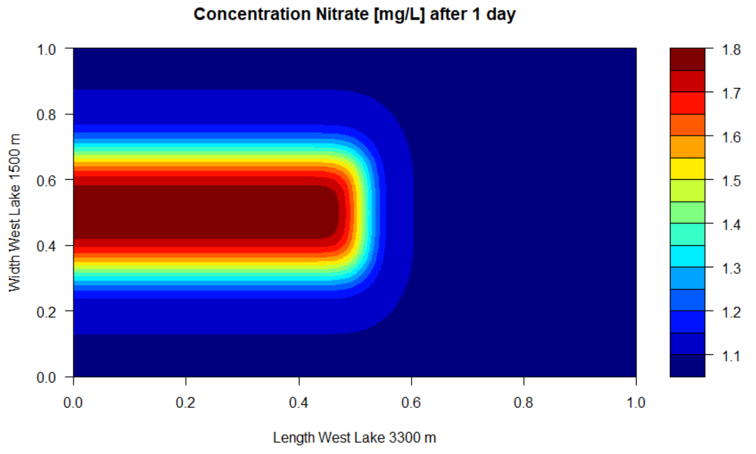


(b) DO [50 day]

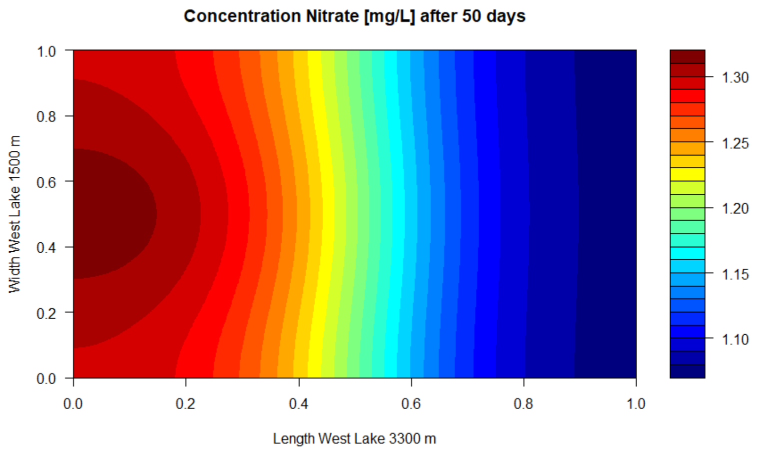


(c) DO [100 day]

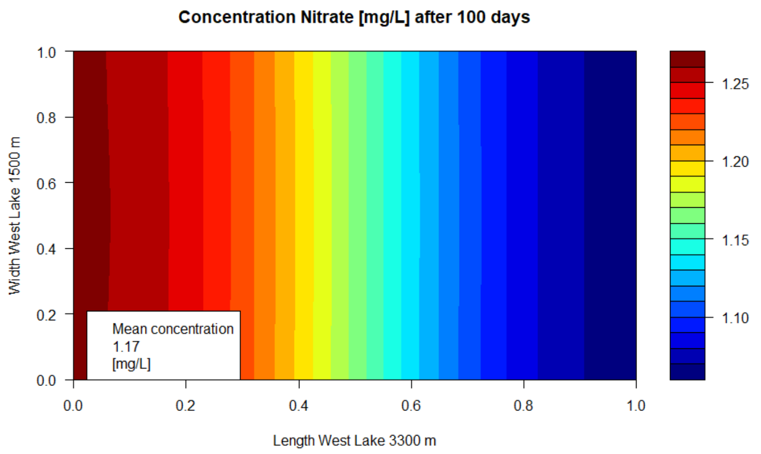
Figure A.2: Convection-Diffusion DO for 1, 50 and 100 days



(a) Nitrate [1 day]

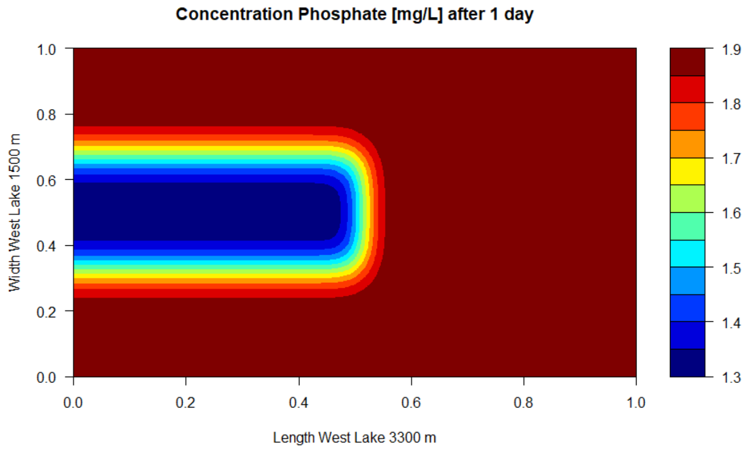


(b) Nitrate [50 day]

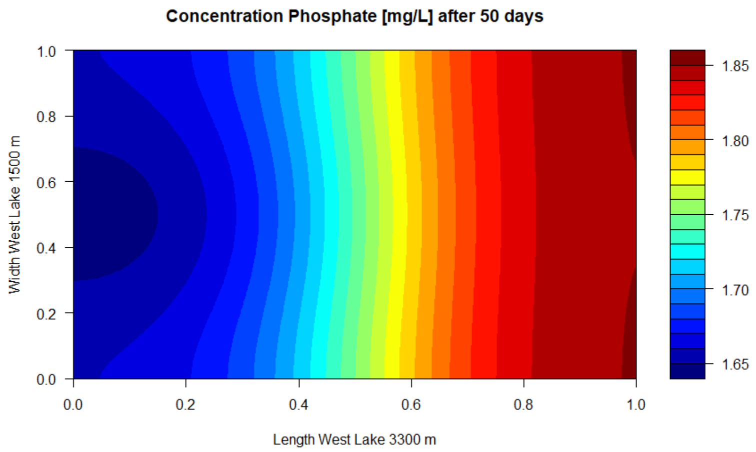


(c) Nitrate [100 day]

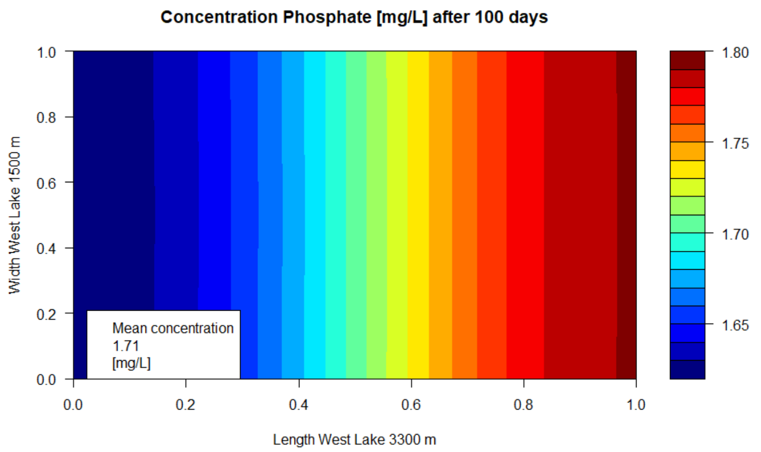
Figure A.3: Convection-Diffusion Nitrate for 1, 50 and 100 days



(a) Phosphate [1 day]

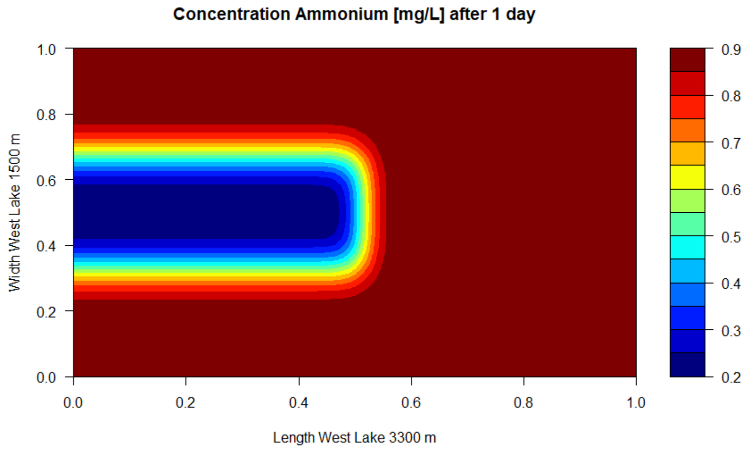


(b) Phosphate [50 day]

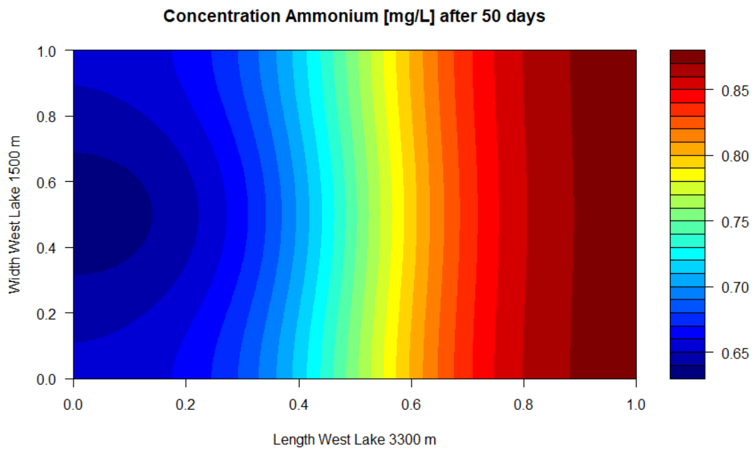


(c) Phosphate [100 day]

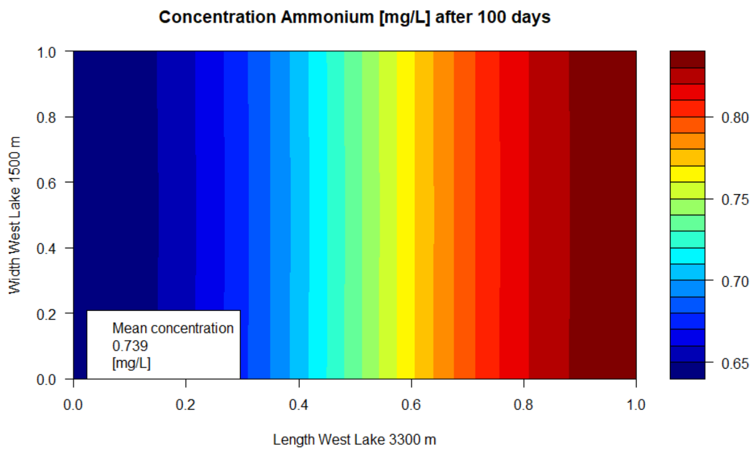
Figure A.4: Convection-Diffusion Phosphate for 1, 50 and 100 days



(a) Ammonium [1 day]

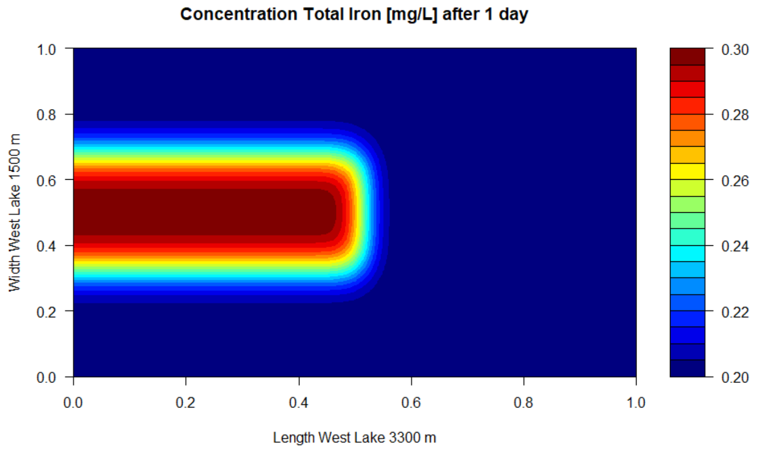


(b) Ammonium [50 day]

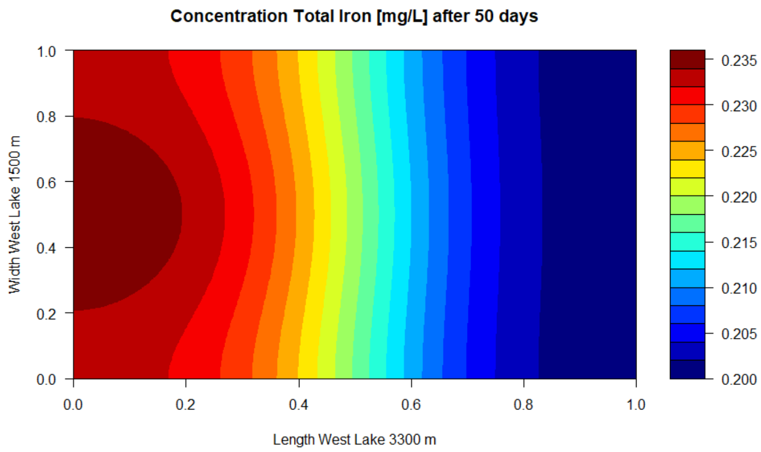


(c) Ammonium [100 day]

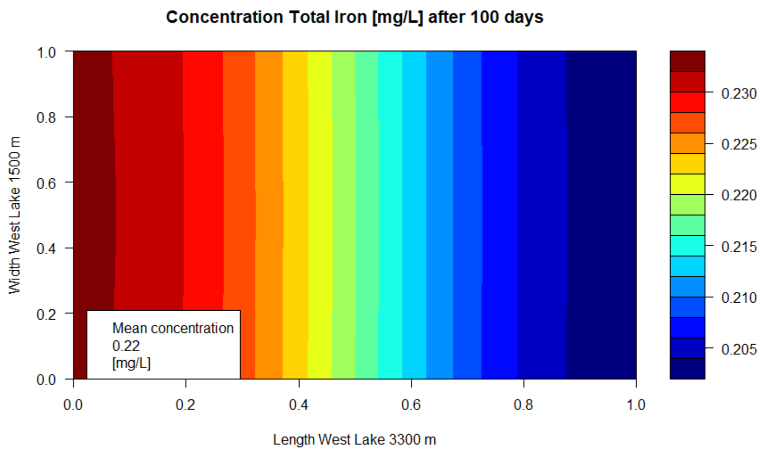
Figure A.5: Convection-Diffusion Ammonium for 1, 50 and 100 days



(a) Total Iron [1 day]



(b) Total Iron [50 day]



(c) Total Iron [100 day]

Figure A.6: Convection-Diffusion Total Iron for 1, 50 and 100 days

(a) E. Coli Result (similar results for each water body)

(b) E. Coli Result (UV light)(similar results for each water body)

Figure A.7: Ecoli results in normal- and UV-light

Appendix B

Water quality model in R

```
#Clear workspace
dev.off()
rm(list=ls())

#Loading packages for use code
library("deSolve")
library("rootSolve")
library("shape")
library("ReacTran")

#vALUES CAN BE CHANGED BY USER
Lenx = 3300      # length of X, width [m], length of West Lake
Leny = 1500      # length of Y, length [m], width of West Lake
Nx = Lenx/10     # number of grids in X direction
Ny = Leny/10     # number of grids in Y direction
Dy = Dx = 5*3600*24/100   # dispersion coeff, X- and Y-direction [$m^2$/day] per grid cell
vgrid = 0       # advection coefficient [m/day]
r = 0.0005     # consumption rate [%/day]
v.x1 = 200     # advection coeff [m/day] in X direction initial due pumping
InitialRR = 0.2  # initial value at t=0 at pump [mg/L]
InitialWL = 0.9      # initial westlake value at t=0 [mg/L]
days = 100    # simulation time [days]
Agrid = 100 # interface area [$m^2$]
AFDWgrid = 0.5 # weight used in finite difference schemes,backward = 1, centred = 0.5, forward = 0
VFgrid = 1      # volume fraction


#AUTOMATIC MODEL SETUP
x.grid = setup.grid.1D(x.up = 0, x.down = Lenx, N = Nx) #set up grid in x direction
y.grid = setup.grid.1D(x.up = 0, x.down = Leny, N = Ny) #set up grid in y direction
xmid = x.grid$x.mid
ymid = y.grid$y.mid
grid2D = setup.grid.2D(x.grid, y.grid)
v.grid = setup.prop.2D(value = vgrid, grid = grid2D)
D.grid = setup.prop.2D(value = Dx, y.value = Dy, grid = grid2D)
A.grid = setup.prop.2D(value = Agrid, grid = grid2D)
AFDW.grid = setup.prop.2D(value = AFDWgrid, grid = grid2D)
```

```r
VF.grid = setup.prop.2D(value = VFgrid, grid = grid2D)

# The model equations - using the grids
Diff2Db <- function (t,y, parms) {


    # Higher advection velocity due to pumping
    if (t <1) {
      CONC = matrix(nrow = Nx, ncol = Ny, data = y)

      dCONC = tran.2D(CONC, grid = grid2D, D.grid = D.grid,
                      A.grid = A.grid, VF.grid = VF.grid, AFDW.grid = AFDW.grid,
                      v.x=v.x1)$dC - r * CONC
    }

    # No advection
    else{

    CONC = matrix(nrow = Nx, ncol = Ny, data = y)
    dCONC = tran.2D(CONC, grid = grid2D, D.grid = D.grid,
                    A.grid = A.grid, VF.grid = VF.grid, AFDW.grid = AFDW.grid,
                    v.grid = v.grid)$dC - r * CONC
    }

  return (list(dCONC))
}


# initial concentrations
y = matrix(nrow = Nx, ncol = Ny, data = InitialWL)
y[0:150,50:101] = InitialRR # initial concentration at pumping InitialRR
# solve time units
times = seq(0, days, by = 1)
outb = ode.2D(y = y, func = Diff2Db, t = times, parms = NULL,
              dim = c(Nx, Ny), lrw = 16000000)

par(mfrow=c(1,3))
image(outb, ask = FALSE, main = paste("Concentration Ammonium [mg/L] after ", head(times,1)+1, "day"), subset = time == times[2], method = "filled.contour",
    add.contour = TRUE,xlab="Length West Lake 3300 m", ylab="Width West Lake 1500 m")


image(outb, ask = FALSE, main = paste("Concentration Ammonium [mg/L] after ", median(times), "days"), subset = time == median(times), method = "filled.contour",
      add.contour = TRUE,xlab="Length West Lake 3300 m", ylab="Width West Lake 1500 m")

image(outb, ask = FALSE, main = paste("Concentration Ammonium [mg/L] after ", tail(times,1), "days"), subset = time == tail(times,1), method = "filled.contour",
      add.contour = TRUE,xlab="Length West Lake 3300 m", ylab="Width West Lake 1500 m")
legend("bottomleft", c("Mean concentration",format(mean(tail(outb,1)), digits=3),"[mg/L]"),
```

```
        col=c("black"))
```

Listing B.1: Convection-Diffusion in R

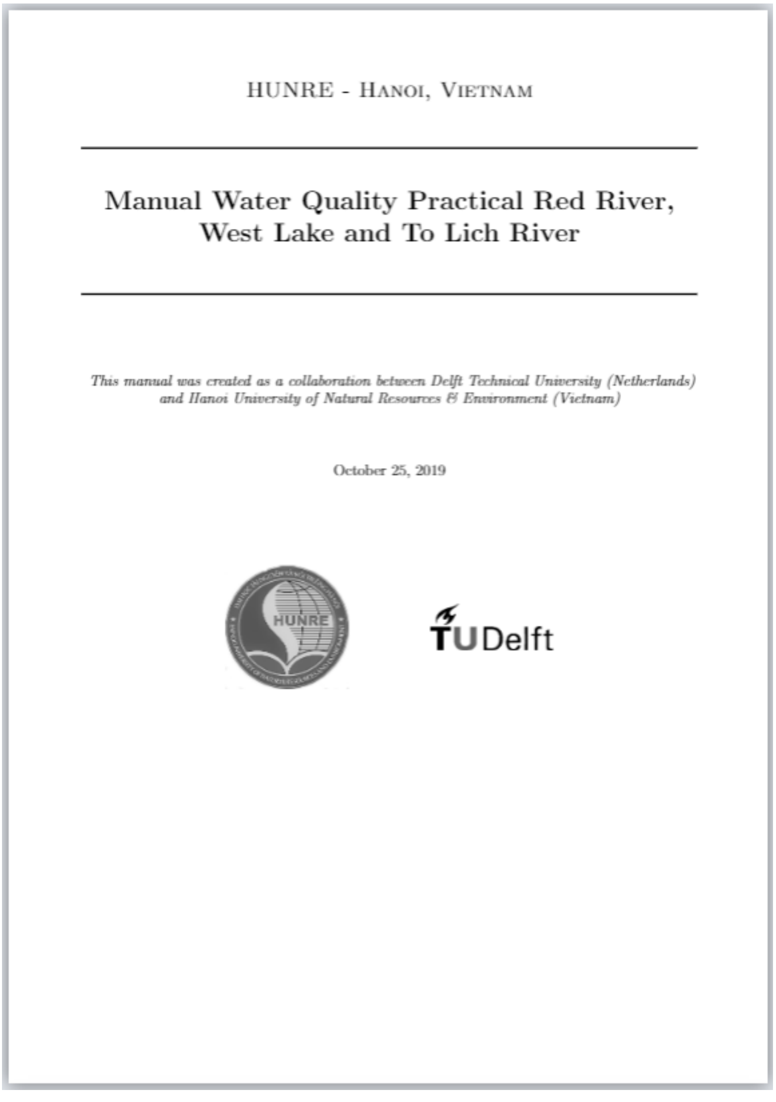
Table B.1: Parameters used in R

Argument	**Unit**	**Value**	**Description**
Len.x	[m]	3300	length of domain in x-direction
Len.y	[m]	1500	length of domain in y-direction
Nx	[m]	Len.x/10	number of grid cells in x-direction
Ny	[m]	Len.y/10	number of grid cells in y-direction
Dx	[m^2/day]	5*3600*24/100	dispersion coefficient in x-direction
Dy	[m^2/day]	5*3600*24/100	dispersion coefficient in x-direction
vgrid	[m/day]	0	Advection coefficient
Agrid	[m^2]	100	Interface area
AFDWgrid	[-]	0.5	Weight used in the finite difference scheme for advection in the x- and y- direction, defined on grid cell interfaces; backward = 1, centred = 0.5, forward = 0;
VFgrid	[-]	1	Volume fraction
r	[%/day]	Parameter dependent	Consumption rate
InitialWL	[mg/L]	Parameter dependent	Initial concentration parameter in West Lake
InitialRR	[mg/L]	Parameter dependent	Initial concentration parameter in Red River
Days	days	100	Simulation time
v.x1	[m/day]	200	Initial advective velocity in the x-direction, defined on grid cell interfaces. Can be positive (downstream flow) or negative (upstream flow). One value, a vector of length (Nx+1)

Appendix C

Manual

As the manual is a rather large document it is not available straight away in this report. It is a complementary document that is supplied along this report. The front page of the manual can be seen in figure C.1 bewow.



HUNRE - Hanoi, Vietnam

Manual Water Quality Practical Red River, West Lake and To Lich River

This manual was created as a collaboration between Delft Technical University (Netherlands) and Hanoi University of Natural Resources & Environment (Vietnam)

October 25, 2019

Figure C.1: Front page of the Water Quality Practical manual

Appendix D

Location Determination Parameter Sets

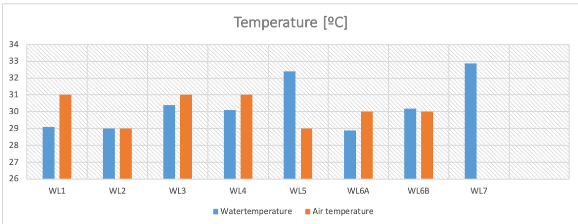


Figure D.1: temperature

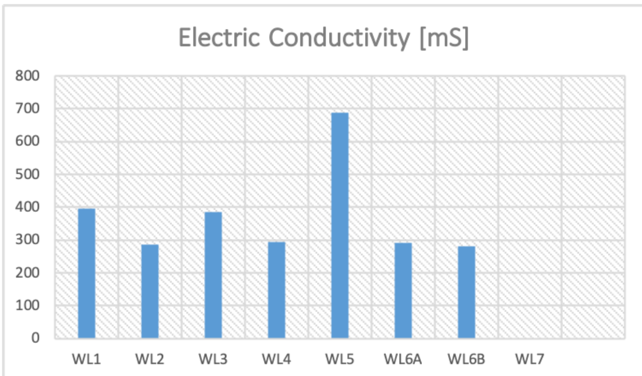


Figure D.2: Electric Conductivity

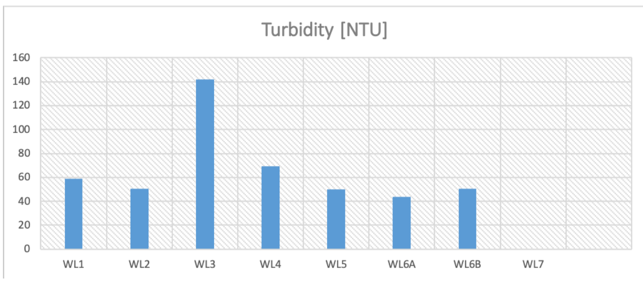


Figure D.3: Turbidity

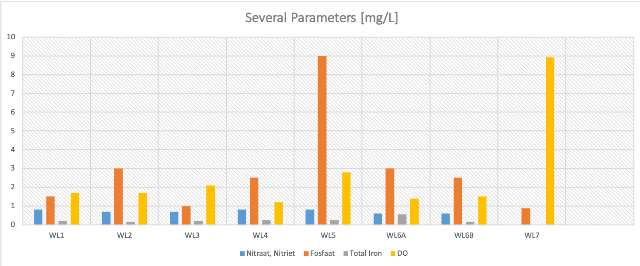


Figure D.4: Phosphate, Nitrite/Nitrate, Total Iron, Dissolved Oxygen

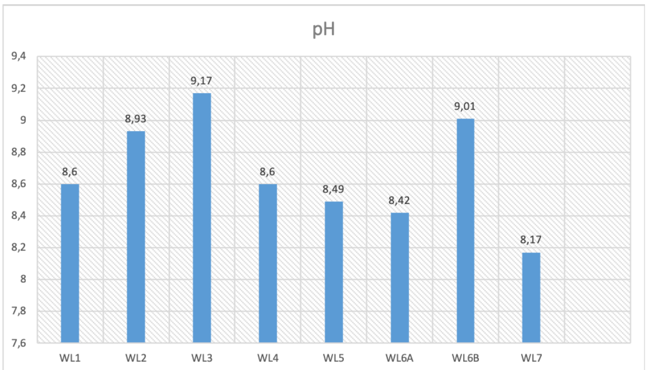


Figure D.5: pH

Appendix E

Information dams

E.1 Specifications characteristics

5.4. West Lake A Regulating Gate

Category	steel-based roller shutter
Waterway Opening + Height	3.000 x 3.000 mm
Quantity	2 gates
Designed Depth	
- Before	3.000 m
- After	0.0 m
Water Tight Sealing Form: By Gaskets	Rubber gaskets for frontal sealing
Major Material	Gate – SS400
Operation	Sectional type
Open actuator box	Electric Motor - helical warping
Opening Speed	0.3 m/minute
(maximum) opening for discharge	3.100 m

Figure E.1: Specifications West Lake Gate A[51]

5.5. West Lake B Regulating Gate

Category	steel-based roller shutter
Waterway Opening + Height	1.500 x 1.500 mm
Quantity	2 gates
Designed Depth	
- Before	1.000 m
- After	0.0 m
Water Tight Sealing Form: By Gaskets	Rubber gaskets for frontal sealing
Major Material	Gate – SS400
Operation	Sectional type
Open actuator box	Electric Motor - helical warping
Opening Speed	0.3 m/minute
(maximum) opening for discharge	1.600 m

Figure E.2: Specifications West Lake Gate B[51]

5.1. Thanh Liet Drainage Gate

Category	steel-based roller shutter
Waterway Opening + Height	12.000 x 5.350 mm
Quantity	2 gates
Designed Depth	
- Before	5.270 m
- After	2.350 m
Water Tight Sealing Form: By Gaskets	Rubber gaskets for frontal sealing
Major Material	Gate – SS400
Operation	Sectional type
Open actuator box	winching system
Opening Speed	0.3 m/minute
(maximum) opening for discharge	5.850 m

Figure E.3: Specifications Thanh Liet Dam [51]

E.1.1 Specifications regulation rules

APPENDIX I. A SYNOPSIS OF FUNDAMENTAL OPERATING RULES OF RIVER REGULATORY SYSTEM

REGULATING GATE	**FUNDAMENTAL OPERATING RULES**		
	dry season	**rainy season**	**stormy season**
1. Thanh Liet Discharge Gate	The operation is required to remain the water level of To Lich River not exceed the designed one, at EL + 4.5m	The operation is required to remain the water level of To Lich River not exceed the designed elevation, at EL + 2.8 m	The gate is required to open if whether the water level of TL is higher than that of HL, or the water level of HL ≥+4.5 m. The gate is closed if water from Nhue River flows backward and the water level of HL <+4.5 m

Figure E.4: Regulating rules Thanh Liet Dam[51]

APPENDIX I. A SYNOPSIS OF FUNDAMENTAL OPERATING RULES OF RIVER REGULATORY SYSTEM

REGULATING GATE	FUNDAMENTAL OPERATING RULES		
	dry season	rainy season	stormy season
4. West Lake A Regulating Gate	Basically, the on-off operation aims to remain West Lake's water level at the designed evaluation of + 6.0 m above sea level	The on-off operation aims to remain West Lake's water level at the designed evaluation of + 5.8 m – 6.0 m above sea level	Closed
5. West Lake B Regulating Gate	In general, the on-off operation aims to remain West Lake's water level at the designed evaluation of + 6.0 m above sea level, and to serve irrigation	Basically, the on-off operation aims to remain West Lake's water level at the designed evaluation of + 5.8 m – 6.0 m above sea level, and to serve irrigation	Closed

Legends

TL = upstream

HL = downstream

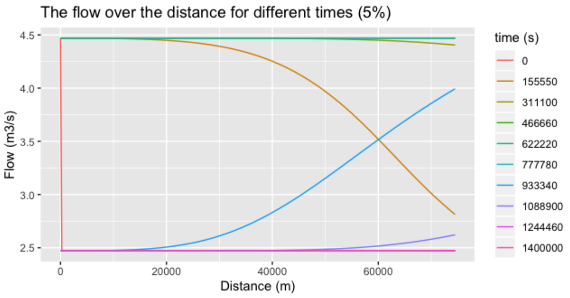
EL = elevation level

Figure E.5: Regulating Rules West Lake Dam A and B[51]

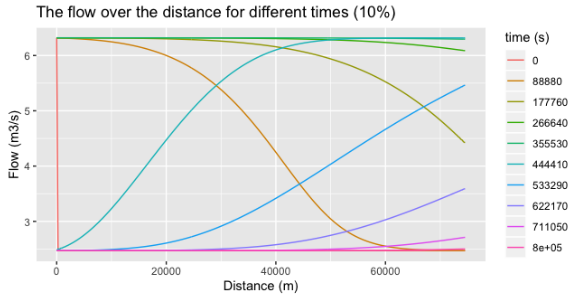
Appendix F

River flood wave models

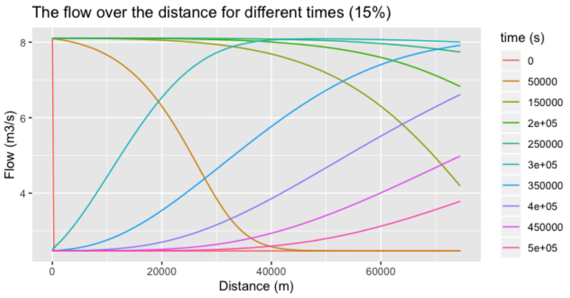
F.1 Flow against distance for different alternatives



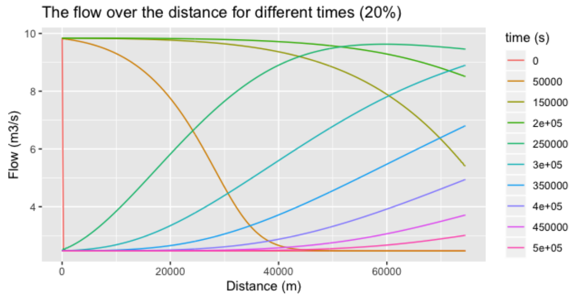
(a) Flow against distance for alternative 1 (5%)



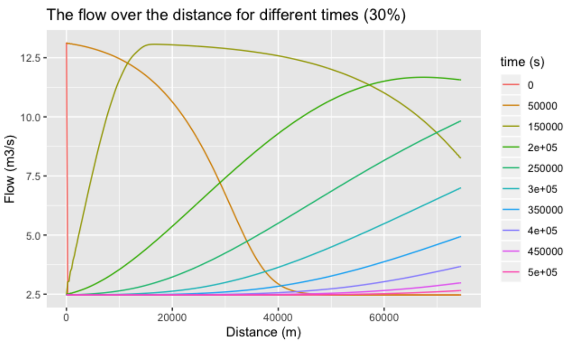
(b) Flow against distance for alternative 2 (10%)



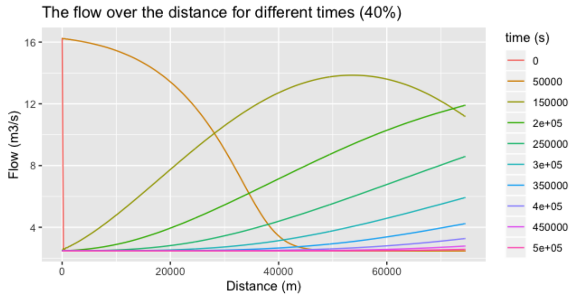
(c) Flow against distance for alternative 3 (15%)



(d) Flow against distance for alternative 4 (20%)



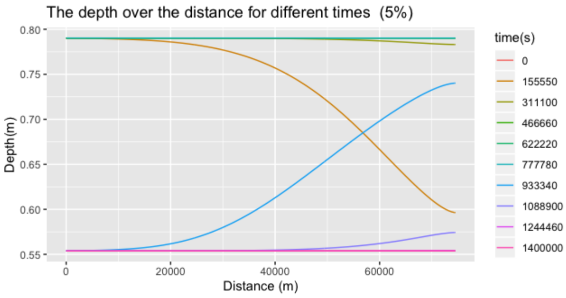
(e) Flow against distance for alternative 5 (30%)



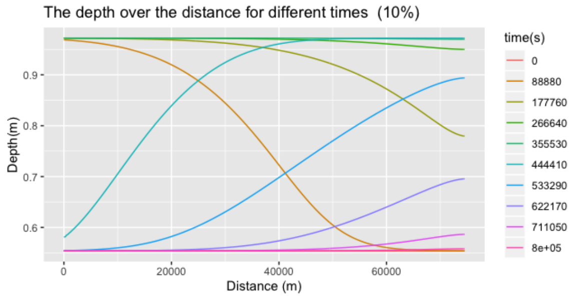
(f) Flow against distance for alternative 6 (40%)

Figure F.1: Flow against distance for different alternatives

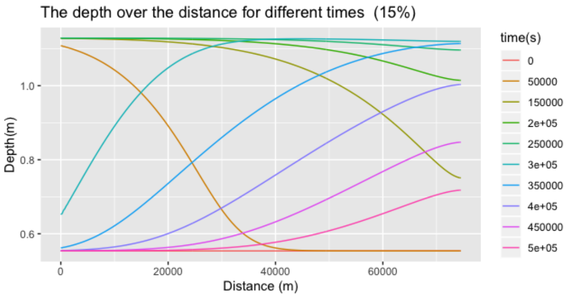
F.2 Depth against distance for different alternatives



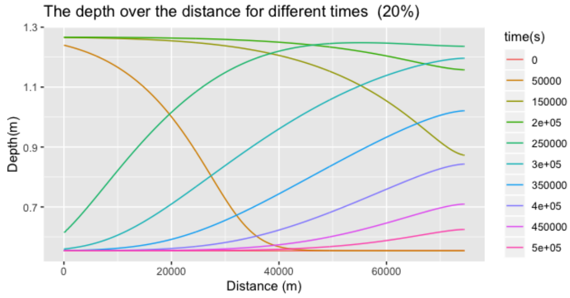
(a) Depth against distance for alternative 1 (5%)



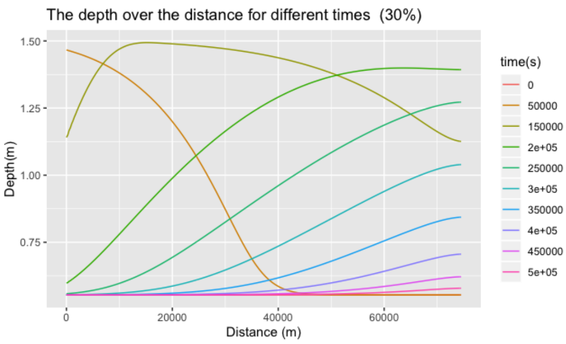
(b) Depth against distance for alternative 2 (10%)



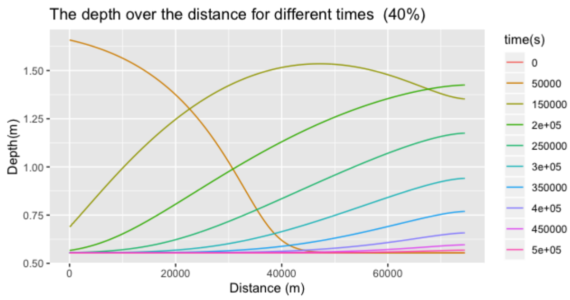
(c) Depth against distance for alternative 3 (15%)



(d) Depth against distance for alternative 4 (20%)



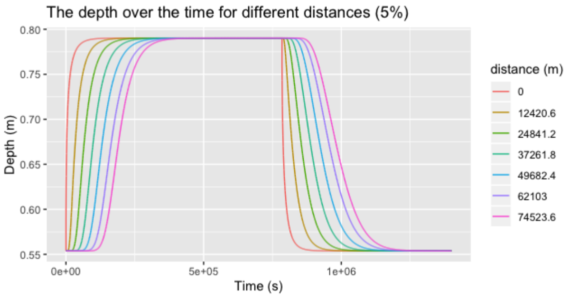
(e) Depth against distance for alternative 5 (30%)



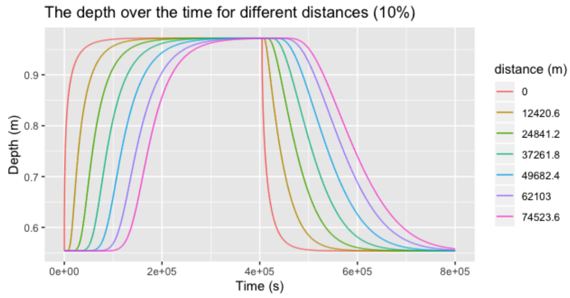
(f) Depth against distance for alternative 6 (40%)

Figure F.2: Depth against distance for different alternatives

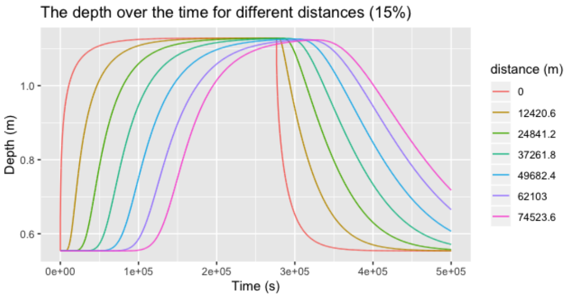
F.3 Depth against time for different alternatives



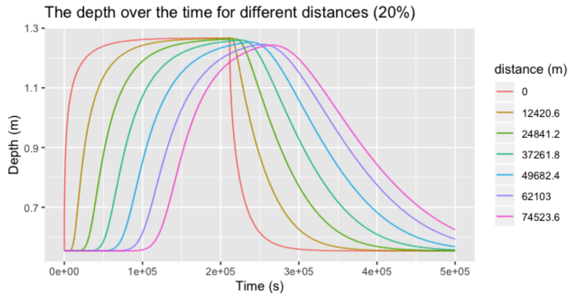
(a) Depth against time for alternative 1 (5%)



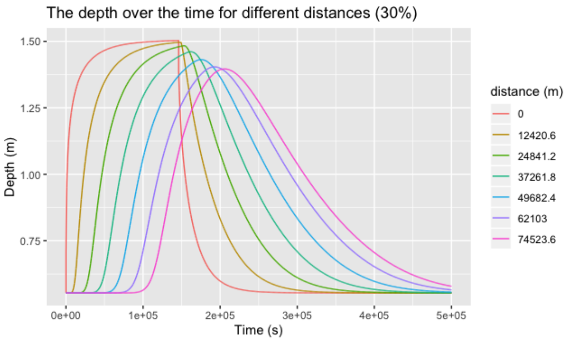
(b) Depth against time for alternative 2 (10%)



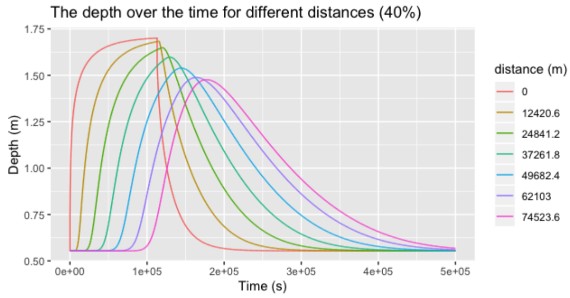
(c) Depth against time for alternative 3 (15%)



(d) Depth against time for alternative 4 (20%)



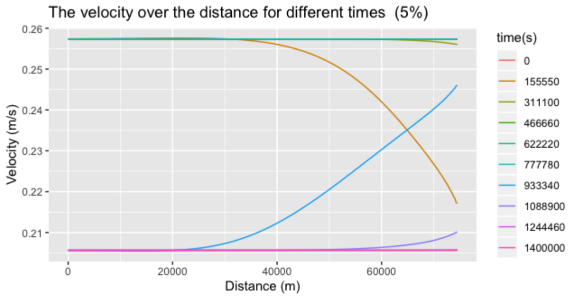
(e) Depth against time for alternative 5 (30%)



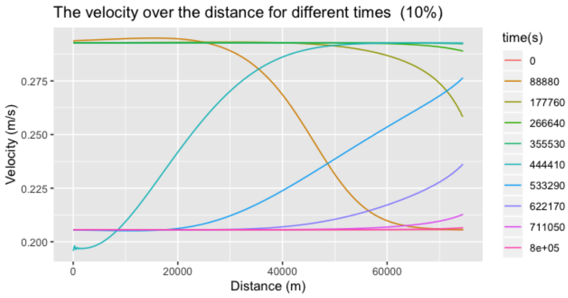
(f) Depth against time for alternative 6 (40%)

Figure F.3: Depth against time for different alternatives

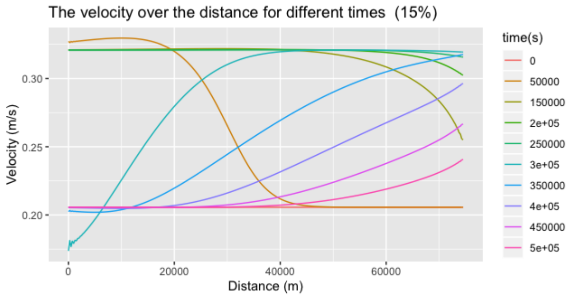
F.4 Velocity against distance for different alternatives



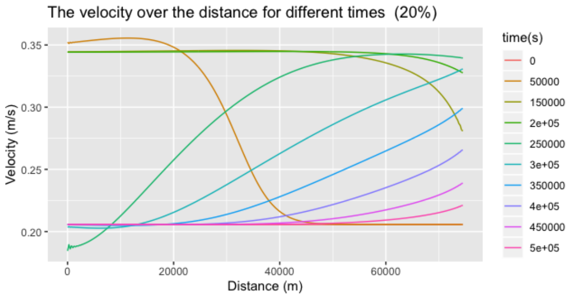
(a) Velocity against distance for alternative 1 (5%)



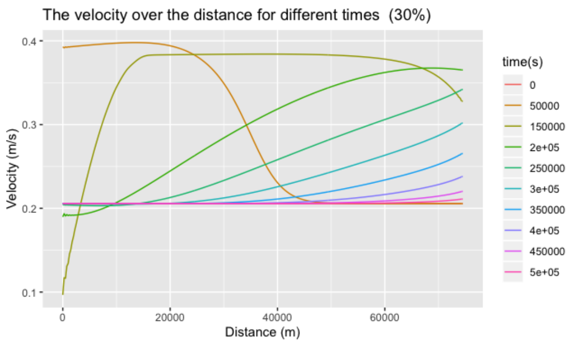
(b) Velocity against distance for alternative 2 (10%)



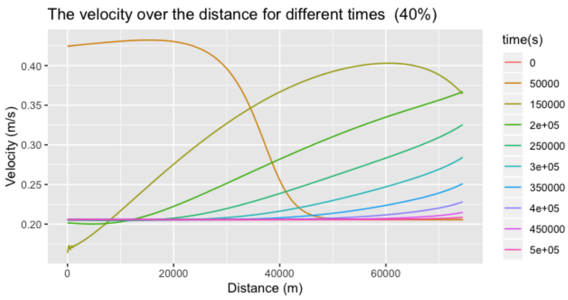
(c) Velocity against distance for alternative 3 (15%)



(d) Velocity against distance for alternative 4 (20%)



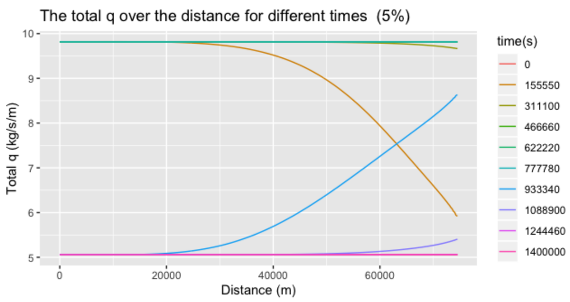
(e) Velocity against distance for alternative 5 (30%)



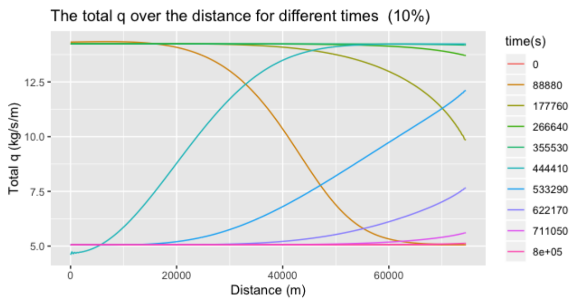
(f) Velocity against distance for alternative 6 (40%)

Figure F.4: Velocity against distance for different alternatives

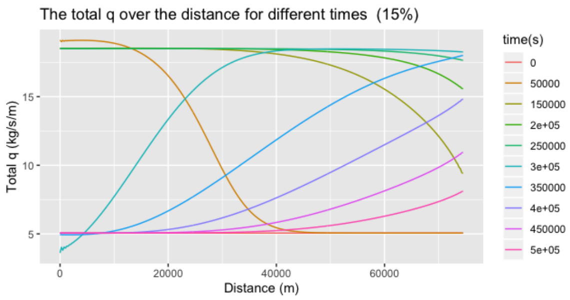
F.5 Total sediment load transport against distance for different alternatives



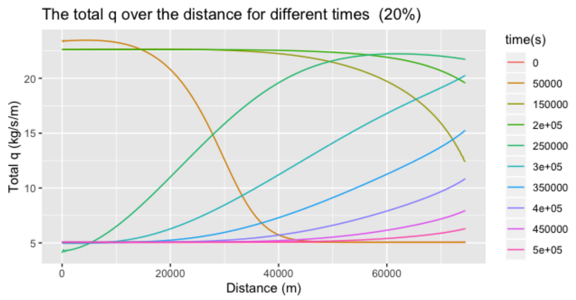
(a) Total sediment load transport against distance for alternative 1 (5%)



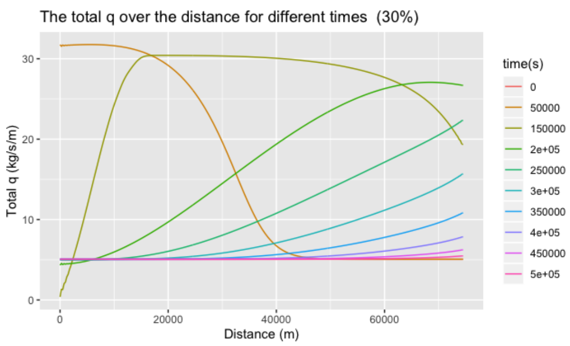
(b) Total sediment load transport against distance for alternative 2 (10%)



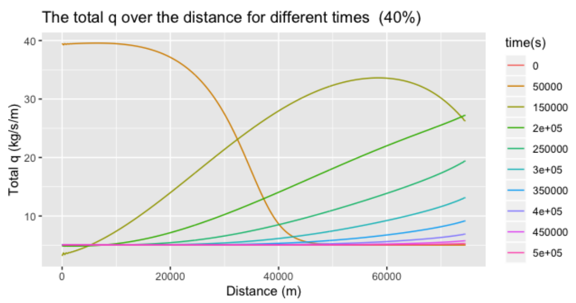
(c) Total sediment load transport against distance for alternative 3 (15%)



(d) Total sediment load transport against distance for alternative 4 (20%)



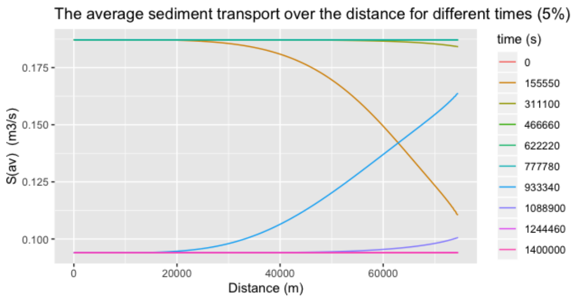
(e) Total sediment load transport against distance for alternative 5 (30%)



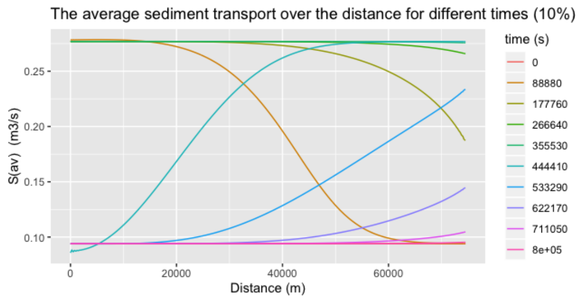
(f) Total sediment load transport against distance for alternative 6 (40%)

Figure F.5: Total sediment load transport against distance for different alternatives

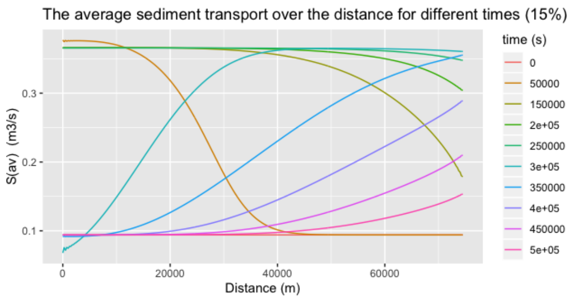
F.6 Sediment transport against distance for different alternatives



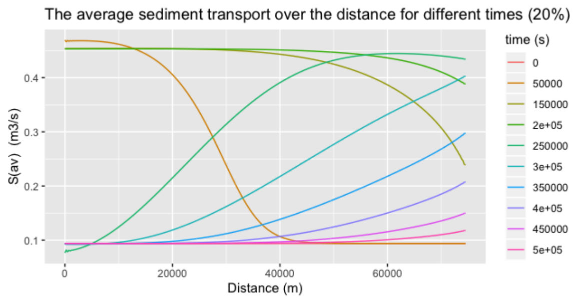
(a) Sediment transport against distance for alternative 1 (5%)



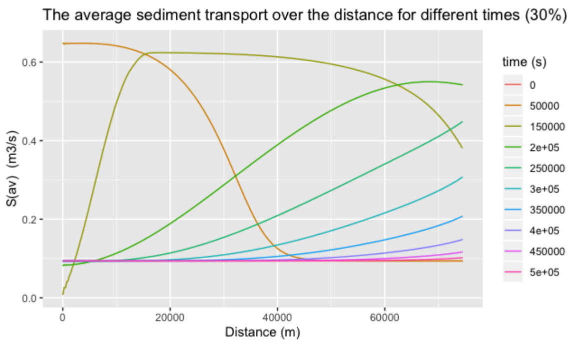
(b) Sediment transport against distance for alternative 2 (10%)



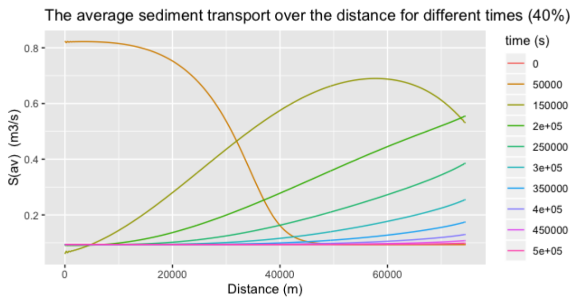
(c) Sediment transport against distance for alternative 3 (15%)



(d) Sediment transport against distance for alternative 4 (20%)



(e) Sediment transport against distance for alternative 5 (30%)



(f) Sediment transport against distance for alternative 6 (40%)

Figure F.6: Sediment transport against distance for different alternatives

Appendix G

Wave and Sediment Model in R

```r
#Clear workspace
dev.off()
rm(list=ls())

#Loading packages for use code
library("rivr")
library("dplyr")
library("ggplot2")

#DYNAMIC FLOOD WAVE MODEL

#input parameters
baseflow = Qin / 0.02831685 #initial flow converted to $ft^3$/s
flow = Qnew / 0.02831685 #new incoming flow converted to $ft^3$/s
flushing time = tflush # time needed for flushing (s)
Cm = 1.486 #unit conversion coefficient for Mannings equation
gr = 32.2 #gravity acceleration in ft/$s^2$
mannings = 0.025 #manning coefficient
sideslope = 1.24 #side slope
slope = 6.2e-5 #bed slope
width = 21 * 3.2808399 #bottom width converted to feet

numnodes = 301 #number of nodes
dt = 10 #temporal resolution
dx = 815 #spatial resolution
times = seq(0,500000, by = dt) #timeseries

mt = c(5001, 15001,20001, 25001, 30001, 35001, 40001, 45001, 50001) #monitoring nodes in time
mn = c(1, 51, 101, 151, 201, 251, 301) #monitoring nodes in space

#BOUNDARY CONDITIONS
wave = ifelse(times >= tflush, baseflow, baseflow + flow) #upstream boundary
downstream = rep(-1, length(wave)) #downstream boundary

#RUN MODEL
run = route_wave(slope, mannings, Cm, gr, width, sideslope, baseflow, wave, downstream, dt dx, numnodes, mn, mt, "Dynamic", "MacCormack", "Qy") #function to run the model

```

```
#convert feet back to meter
run$distance <- run$distance * 0.3048 #m
run$flow <- run$flow * 0.02831685 #$m^3$/s
run$depth <- run$depth * 0.3048 #m
run$velocity <- run$velocity * 0.3048 #m/s
run$area <- run$area * 0.09290304 #$m^2$
run[is.na(run)] <- 0 #give NaN values the value zero

#filter results
run.times = filter(run, monitor.type == "timestep") #filter data set to data set with monitor nodes in time
run.nodes = filter(run, monitor.type == "node") #filter data set to data set with monitor nodes in space

#PLOT

flowdistance = ggplot(run.times, aes(x=distance, y=flow, color=factor(time))) + geom_line() +labs(title="The flow over the distance for different times (alt)",="Distance (m)", y = "Flow (m3/s)", color = "time (s)")

depthdistance = ggplot(run.times, aes(x=distance, y=depth, color=factor(time))) + geom_line() +labs(title="The depth over the distance for different times  (alt)",x ="Distance (m)", y = "Depth(m)" ,color = "time(s)")

velocitydistance = ggplot(run, aes(x=distance, y=velocity, color=factor(time))) + geom_line() +labs(title="The velocity over the distance for different times  (alt)", x ="Distance (m)", y = "velocity(m/s)" ,color = "time(s)")

depthtime = ggplot(run.nodes, aes(x=time, y=depth, color=factor(distance))) + geom_line() +labs(title="The depth over the time for different distances (alt)", ="Time (s)", y = "Depth (m)", color = "distance (m)")

#SEDIMENT TRANSPORT MODEL

#input parameters
hpart = run$depth #depth
upart = run$velocity #velocity
kinv = 1e-6 #kinematic viscosity in $m^2$/s
s = 1.212 #(density sediment - density water) / density water
d50 = 2e-5 #median diameter of the medium value of the particle size
g = 9.81 #gravity acceleration in m/$s^2$
mu = 1.5 #coeffient related to bed load transport
alfab = 0.015 #coefficient related to bed load transport
rhos = 1212.82 #density sediment kg/$m^3$

#calculations
Dstar = d50 * (((s-1)*g)/(kinv^2))^(1/3)
thetc = (0.3/(1+1.2*Dstar)) + 0.055*(1-exp(-0.02*Dstar)) #critical theta for bed load transport
ucr = 5.75*log10((12*hpart)/(6*d50))*sqrt(thetc*(s-1)*g*d50) #critical velocity for bed load transport
run$ucr <- ucr #add parameter to data set

thcrsus = (0.3/(1+Dstar)) + 0.1 * (1-exp(-0.05*Dstar)) #critical thetha for suspended load transport
ucrsus = 5.75*(log10((12*hpart)/(6*d50)))*(thcrsus*(s-1)*g*d50)^(0.5) # critical velocity for suspended load transport
run$ucrsus <- ucrsus #add parameter to data set
```

```r

Me = ((upart - ucr)/((s-1)*g*d50))^(1/2)
qb = alfab * rhos * upart * hpart * ((d50/hpart)^(1/2)) *(Me)^(mu) #bed load transport
run$qb <- qb #add parameter to data set

Me2 = (upart - ucrsus)/((s-1)*g*d50)^(0.5)
qs = 0.03 * rhos * upart * d50 * ((Me2)^2) * ((Dstar)^(-0.6))#suspended load transport
run$qs <-qs #add parameter to data set

totalq = qs + qb #total sediment transport
run$totq <- totalq #add parameter to data set

Bav = 21.15 + hpart * 1.25 * 2 #average width
run$Bav <- Bav #add parameter to data set
Stot = (totalq / rhos) * Bav #Total sediment transport in $m^3$/s
run$Sav <- Sav

#filter results
run[is.na(run)] <- 0 #give NaN values the value zero
run.times = filter(run, monitor.type == "timestep") #filter data set to data set with monitor nodes in time

#PLOT

qtotdistance = ggplot(run.times, aes(x=distance, y=totq, color=factor(time))) + geom_line() +labs(title="The total q over the distance for different times (alt)",x ="Distance (m)", y = "Total q (kg/s/m)",color = "time(s)")

sedimentdistance = ggplot(run.times, aes(x=distance, y=Stot, color=factor(time))) + geom_line() +labs(title="The average sediment transport over the distance for different times (alt)", ="Distance (m)", y = "S(av)  (m3/s)", color = "time (s)")
```

Listing G.1: Convection-Diffusion in R

Table G.1: Parameters used in R

Argument	**Unit**	**Value**	**Description**
Qin	[m/s]	2.47	initial flow in TLR
Qnew	[m/s]	depends on alternative	new flow into the TLR
tflush	[s]	depends on alternative	time gate is open for every scenario
Cm	[-]	1.486	unit conversion coefficient for Mannings equation
gr	[$ft/s2$]	32.2	gravitational acceleration
g	[m/s^2]	9.81	gravitational acceleration
mannings	[-]	0.025	mannings coefficient
sideslope	[-]	1.24	average side slope of the cross section of the TLR
slope	[-]	6.2E-5	average bed slope of the longitudinal section of the TLR
width	[m]	21	average bottom width of the TLR
numnodes	[-]	301	number of nodes in the model
dt	[s]	10	temporal resolution
dx	[ft]	815	spatial resolution
kinv	[m^2/s]	1e-6	kinematic viscosity of water
s	[-]	1.212	specific density
d50	[m]	2e-5	median diameter of the medium value of the particle size
mu	[-]	1.5	coefficient related to bed load transport
alfab	[-]	0.015	coefficient related to bed load transport
rhos	[kg/m^3]	1212.82	average density sediment

Appendix H

Extensive Water Quality Parameter Explanation

The selection of water quality parameters is based on previous studies of the water bodies and ultimately choosing the parameters which are most significant for to the water quality. In this project, all measurements are done using a standardized fieldwork procedure. All procedures are documented and shown in appendix C

Dissolved Oxygen

Dissolved oxygen (DO) is the concentration of free oxygen (O_2) in the water in mg/L. This parameter is very important for the water quality. When the DO level is below a certain level this has a negative impact on the aquatic life. Fish and crustaceans need a certain amount of free oxygen in the water for respiration, which differs per organism. This value ranges from 1-6 mg/L for oysters and crabs while shallow fish may need up to 15 mg/L. ([33]) This also applies to plants and phytoplankton in case there is not enough light available for photosynthesis. Free oxygen is also used for the decomposition of organic material, coming from dead algae and other dead organisms. Decomposition is done by bacteria and fungi at the bottom of the water body but also occurs in the water column itself. An excess of this organic material, e.g. from human waste, can quickly lead to oxygen starvation. On the other hand, when the DO level exceeds a certain level, it has a negative impact on the water quality as well. For some aquatic life it can cause the gas bubble disease, which leads to high mortality rates [33]. Concentrations in fresh waters vary form 1 mg/L to more than 15 mg/L. The concentration differs per season, location and water depth. These large fluctuations are explained in the following paragraphs.

Day/night fluctuations

Free oxygen in water is produced during photosynthesis and is used for respiration and decomposition. Photosynthesis needs daylight, whereas respiration and decomposition can continue during nighttime. Therefore, the DO concentration declines during the night and is be lowest just before dawn [73].

Temperature fluctuations

Cold water can hold oxygen than warmer water. Therefore, when the water temperature is high it is 'fully saturated with oxygen' with a relatively low DO level compared to colder water bodies [33]. This limits especially the DO level at the surface of a water body in summer. Furthermore, in summer the photosynthesis and decomposition accelerates. At the end of the summer, when the plants die, their decomposition causes a decline in the DO level. In very cold winters, when there is an ice-layer on top of a lake, the oxygen molecules from the air can not be absorbed in the water.

Depth fluctuations

Water depth can vary a lot over the seasons. In a shallow water body that gets mixed due to surface winds, the DO variations over depth are very little. These kind of water bodies are called polymictic. However, for deep, stratifying water bodies the fluctuations in DO concentrations can be problematic [33]. Stratification divides a water body into horizontal layers with different properties. In this section further lake stratification and the effect on the DO-concentration are discussed.

The top layer of a lake is called the Epilimnion [33]. This layer is exposed to sunlight, which enables photosynthesis that consequently gives dissolved oxygen as a by-product. Furthermore, oxygen molecules dissolve from the atmosphere into the Epilimnion. This happens due to the difference in oxygen saturation between air and water. This effect can be enhanced by the wind, because the wind-induced waves create a larger contact area. The DO-level in the Epilimnion therefore stays around 100%, in equilibrium with the atmosphere [33].

The bottom of the Epilimnion is determined when the temperature steadily starts to drop, this boundary is called the Thermocline. From there on downwards it is called the 'Metalimniom'. The thickness of this layer fluctuates throughout the day and it can be explained as a 'transition' layer. The oxygen level here can be either higher or lower than in the Epilimnion. It depends on the balance between the respiration demand of the aquatic life in the water body and the released oxygen from photosynthesis if the sunlight gets through the Thermocline [23].

The bottom boundary of the Metalimniom is called the Chemocline and it indicates where the water gets anoxic. From there on we speak about the 'Hypolimnium'. Even though the circumstances here (higher pressure and cooler temperatures) would suggest that the water can hold more oxygen, the oxygen levels are nihil. This is due to the decomposition of organic material which uses oxygen. Also, the fact that there is no oxygen supply from the air or photosynthesis contributes to the extremely low oxygen level. Most lakes naturally mix one or two times per year, which restores the oxygen in this layer. When this is not the case, the Hypolimnium is called the Monimolimnion.

Dissolved oxygen is measured with a calibrated dissolved oxygen sensor in a water sample. For this study the Greisinger G1610 device is used, which gives the concentration DO in mg/L. This is equivalent to parts per million (ppm). DO can also be expressed as the percent % DO of air saturation. Hundred per cent corresponds to the equilibrium situation, where the water holds the same percentage of each gas molecule as the percentage of that gas is in the atmosphere [23].

Chemical Oxygen Demand

The Chemical Oxygen Demand (COD) is a measure of the amount of oxygen that could get depleted in a water volume by adding an oxidizing agent. The SI-unit for COD is mg/L. It is commonly a measure for the depletion of oxygen by a chemical reaction. When the COD value of a waste water is known it gives an indication for the oxygen-depletion effect that occurs when mixed with another source. Therefore, the higher the COD value, the more polluted the water is. Thus the COD is indicated as the rate or status of the effluent affecting the water body.

The oxidizing agent that is most often used in experiments is the chemical reagent $K_2Cr_2O_7$, which supplies the oxygen demand. This agent is used in this research as well. After the chemical reactions took place (i.e. after 1.5-3 hours), the experiment is done. With the result, the amount of oxygen required for both biodegradable and non-biodegradable substances is determined. However, it is not possible to differentiate these substances solely from the obtained COD-value. As discussed in the DO section, low oxygen levels effect the aquatic life negatively.

Biological Oxygen Demand (5 days)

The Biological Oxygen Demand (BOD) determines the oxygen required for the depletion of the waste in water by adding micro-organisms and is therefore biologically. The SI-Unit for BOD5 is mg/L, which is usually measured after the water sample has been in a incubator at 20 ° C during a period of 5 days (BOD5), as the oxygen demand is supplied by the DO in the water. There are also testing methods that take three or seven days, the names of these tests are called BOD3 and BOD7, respectively.

With this test, only the oxygen required for depletion of biodegradable substances in the water is calculated [7]. Hence, the BOD5 value obtained from a water sample is always be lower than the COD value obtained from the same water sample. Normal values of the COD/BOD5 ratio are between 1.3-1.5. If this value doubles, it indicates that a lot of non-biodegradable organic material is present, i.e. not biodegradable by ordinary micro-organisms. This information is very useful when the water quality needs to be improved, hence the COD and BOD5 tests are often used in conjunction with each other. Both COD and BOD5 give a measure of the oxygen demand in water [34].

Turbidity

Turbidity is a measure of the rate to which the transparency of water drops due to suspended particles being present. These particles can have a natural source or come from human intervention. The turbidity is determined by the Total Suspended Solids (TSS) in the water sample. The effect of turbidity on aquatic life is difficult to deduce [47], because it depends on the level and duration of exposure and differs over the type of animal. The unit in which the turbidity is often expressed is the Nephelometric Turbidity Unit (NTU). When measuring turbidity it is important to make sure that there are no large non-biological particles floating in the sample that could disturb the results.

The most accurate way to measure turbidity to date is to filter, dry and weigh a water sample. This is a relatively simple method, however, it is rather time consuming. Another test to measure turbidity is a turbidity tube test, this is a very easy and low cost test. It consists of a tube with a vertical scale on the side and a secchi disk on the bottom. The water sample must be slowly poured into the tube, until the secchi mark on the bottom disappears. The transparency of the water determines moment of disappearance. The vertical scale can be read and the height [cm] can be converted to NTU. How to use this tube and the relationship between NTU and water column height in centimeters is described in the manual in appendix C. A disadvantage of this test is that the accuracy of this test is dependent on the precision with which the tube is made and calibrated, as well as the eyesight and interpretation of the performer of the test. In addition, large pieces of plastic or other garbage could deliver less accurate results.

Another possible measurement is a nephelo meter, this device measures the turbidity by employing a light beam through the water sample and measuring the light on the other side of the sample. A downside of such a turbidity measurement is that, when using sensors, most data is not inter-comparable. Turbidity units such as FNU or NTU have no intrinsic biological, chemical or physical significance. On the other hand, this type of measuring generates more accurate results. The measurements in this study have been done with a nephelo meter (2100Q HACH Turbidity meter) with a accuracy of approximately 2%.

pH

The pH of a fluid is the negative log of the H^+-concentration in water. A fluid with a pH of 7 is considered to be 'neutral'. Acid fluids have a pH below 7, where alkaline fluids have a pH above 7. It is seen as a chemical property of a substance. pH is changed by OH^- and H^+ ions in water. The water equilibrium can be written as $K_w = OH^- + H^+$. A specific pH can be caused or induced by several origins or processes. Several species are dependent on a steady pH level that does not alter too much from its average value of 7. For example, shellfish and clams need an pH of about 7 to be able to extract calcium for their shell growth [62].

Measurements on pH in this research are done with a Greisinger pH measurement tool. The difficulty in measuring pH values is to make sure that the concentration of the sample is representative for the water body that is being investigated. If one, by coincidence, measures the pH of a certain sample that has a significant higher concentration, the pH value could be much higher or lower than the value that initially was expected. In appendix C, a manual is presented which gives a detailed explanation of our measurement method. This manual is focused on minimizing errors while measuring.

Electric Conductivity

The Electric Conductivity is simply the ability of an electric current to flow through a material, which in this case is water. This parameter is helpful to determine the total dissolved solids (TDS), because concentration of ionic species primarily determine the conductivity of a current through an electrolyte solution. It is expected that the EC in the polluted water bodies are higher than in the RR as there are more ions present. Furthermore, the EC has a linear relation with temperature, the higher the temperature, the higher the EC value [30]. Also, during the rainy season the EC values are generally higher than in the dry season. This has to do with surface runoff. Due to heavy rainfall, surrounding areas might bring ionic substances into the runoff water [4]. The EC is measured by applying an electrical field with the EC meter. The electrical current that results from motion of electrically charged particles caused by the forces of this field is measured with the EC device. The higher EC value, the more electrical charged particles are present.

Nitrite & Nitrate

Nitrites (NO_2^-) are chemical compounds containing nitrogen and oxygen, which occur in natural circumstances. They are formed from nitrate (NO_3^-) reduction or ammonium (NH_4^+) oxidation [60]. The presence of solely nitrites in water is no indication for pollution although in combination with nitrate or ammonium, it is. Nitrite itself can also signify the use of corrosion inhibitors in industrial process water. Nitrite in drinking water can harm the health of life stock, humans and especially babies.

Nitrates (NO_3^-) are commonly present in much higher concentrations than nitrites, because nitrate is more stable with regard to acidity and temperature variations [60]. Nitrates are the by-product of the demolition of animal and/or human waste seen that nitrogen is a key component of all living organisms. It can also come from the runoff of fertilized land.

Nitrogen and Phosphorus are the most common nutrients for algae and other aquatic plants in freshwater. They are involved in a process called eutrophication, explained in section 3.2.1. The SI-unit in which the concentrations of nitrite and nitrate are measured is mg/L. During this study, Hach strips are used and the outcomes are calibrated with a Lovibond-meter (spectrometer). How the HACH strips are used is explained in the manual supporting this report.

Phosphate

In nature, phosphorous is mostly present in the form of phosphate. Phosphate is the chemical composition of the mineral phosphorous and oxygen, PO_4^{3-}. Phosphorous is an important element for all living beings at the planet, as it is a part of the material of which their cells consist. But not only animals need phosphorous, the growth of plants is made possible by phosphorous as well [57]. Even though phosphate contains the essential element phosphorous, the concentration phosphate in water should be limited. A large amount of phosphate in water causes eutrophication in the same way nitrogen does, with all its consequences [43]. For further information about eutrophication see section 3.2.1.

In natural water bodies, the concentration of phosphate is usually low. Large concentrations can be caused by humans, for instance due to the runoff of fertilizers used in agriculture and the deposit of ill treated wastewater. In addition, a high nitrate concentration can cause an increase in the concentration of phosphate [43]. The SI-unit in which the concentration of phosphate is measured is mg/L. During this study, Hach strips are used and the outcomes are calibrated with a Lovibond-meter (spectrometer).

Total Coliforms and E. coli

When human feces end up in the water it results in the presence of pathogens. Pathogens are organisms that cause diseases to human beings and are therefore an important factor in assessing the water quality. However, testing on pathogens in not useful, this is because there are a lot of types of pathogens, of which some occur in very small concentrations. Instead, it is convenient to test on the coliform bacteria, which can work as an indicator for pathogens as they are caused by the same pollution sources. Total coliforms are bacteria that can be present in soil, in animal or human waste and in water that has been influenced by surface water. Assessing total coliforms is done more easily than pathogenic bacteria, because they are present in much larger numbers than pathogens and they respond similarly to environmental influences and water treatment. These factors make total coliform a good indicator of pathogens and therefore of the sanitary condition of the water [16].

Within total coliforms, fecal coliforms can be separated as a different group. This group of bacteria is present in the guts and feces of warm-blooded animals. Fecal coliform is therefore even a better indicator for human waste than total coliforms. The bacterium that covers most of the fecal bacterial group is Escherichia coli, commonly known as E. Coli. Out of the five groups of total coliforms that can be distinguished, E. Coli is the only bacterium that usually is not present nor reproducing itself in the environment. This property makes E. Coli a good indicator for human, fecal contamination and hence the possibility of having pathogenic bacteria in water [16]. The level of E. Coli is influenced by the amount of carbon resources present, the temperature and the temperature regime, the pH and the water availability. All factors are not constant in our study case. It has been proved that E. Coli can survive in open environment conditions and can be harmful for humans (depending on the type) [74].

The detection of total coliforms and E. Coli are both carried out by the Aquagenx TC+EC MPN. This unit MPN indicates the Most Probable Number of viable cells per 100 ml. The test kit for TC and EC are rather expensive, that is why they are not used for every test location but shall be used at some specific measurements to give an insight in EC and TC values.

Ammonium

Nitrogen can be present in water in several forms. One of the forms that can be distinguished, is ammonia. Ammonia is the only form in which nitrogen can directly cause toxic harm to aquatic life. In water with pH lower than 7, ammonia takes the form of the ammonium ion (NH_4). In water having a pH above 7, ammonium takes the form of ammonia (NH_3). In nature, ammonia is not commonly present in water, as it is converted to nitrates by bacteria in soil [3].

Ammonia can enter water from a natural resource or from human contamination. Via wastewater disposal and nitrogenous fecal waste of animals, ammonia enters water directly. The aquatic environment can indirectly receive ammonia through atmospheric gas exchange with air, nitrogen fixation and agricultural water runoff. The latter is common, as ammonia is used in fertiliser, but also in the fabrication of multiple materials such as plastics and paper. In this project, ammonia is measured using Hach test strips which has the unit $[mg/L]$.

Total Iron

Iron is naturally occurring in many types of rocks, soil, ground water and in some types of sediment. In an aquatic environment, it can occur in two forms; as soluble ferrous iron Fe^{2+} or as insoluble ferric iron Fe^{3+}. A transition between the two types of iron is made when water with ferrous iron gets exposed to air. The iron precipitates and ferric iron occurs.

As mentioned above, iron is present in natural organic material, it can therefore be found in surface water in which the natural material is in contact with the water. However, the total iron content of a water body can also be changed by human interferences. Factory waste or domestic household waste can contain high iron concentrations, increasing the total iron concentration of a water body [13]. Furthermore, iron is a common molecule found in different types of soil. Total iron concentrations can change when a different kind of sediment is added to the water body.

Iron is essential for human beings. However, it can be very harmful in large concentrations and can even lead to death [61]. Aquatic life is effected directly and indirectly. Their metabolism and osmotic capability can be directly destroyed by high iron concentrations in water. Simultaneously it also induces a higher turbidity. Indirectly the structure of the habitat and food resource is affected. Combining the direct and indirect consequences lowers the bio-availability of aquatic life (depending on the type of animal) [82]. Iron is measured using the Akvo app and the test strips from Hach company. The unit used is $[mg/L]$.