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DEPARTMENT OF WATER RESOURCES AND ENVIRONMENTAL MODELLING

DIPLOMA THESIS

Flood management using the integrated 1D/2D model in InfoWorks ICM

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CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

DIPLOMA THESIS ASSIGNMENT

Maryia Babko

Environmental Modelling

Thesis title

Flood management using the integrated 1D/2D model in InfoWorks ICM

Objectives of thesis

Flood is one of the nature hazards that harms human lives and destroys their living places. This, in its turn, affect s economy and business of the whole region. The study of this thesis will use InfoWorks ICM to assess the flood impacts along the river Ölbach, Germany.
The thesis objectives are
- to estimate flood basin along the river Ölbach – North Rhine-Westphalia federal state of Germany.
- to suggest measures in order to decrease flood impacts.

Methodology

Methodology:

1. to set up a model and GIS based project
2. to calculate and sketch the flooding area with the use of InfoWorksICM software
3. to analyse and prove the results of the model
4. impact analysis: to evaluate the flood impact on urban and rural areas along Ölbach
5. risk control: to suggest protective measures in order to exclude harmful influence of floods
6. to calculate a flood area with consideration of suggested measures

The proposed extent of the thesis

60-80 pages

Keywords

Inundation area, hydraulic modelling, Ölbach, North Rhine-Westphalia (NRW), Germany, Geographical information system, flood protection, flood area estimation

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Recommended information sources

Flood risk assessment and management: how to specify hydrological loads, their consequences and uncertainties, Andreas H. Schumann , 2007

Flood risk management: hazards, vulnerability and mitigation measures Jochen Schanze [Hrsg.], 2011

Houston, D., Werritty, A., Basset, D., Geddes, A., Hoolachan, A. & McMillian, M. (2011): Pluval (rain-related) flooding in urban areas: the invisible hazard. University of Dundee, Joseph Rowntree Foundation, York, November 2011

Jha, A.K., Bloch, R. & Lamond, J. (2012): Cities and Flooding – A Guide to Integrated Urban Flood Risk Management for the 21st Century. The World Bank, Washington DC

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Declaration

I hereby confirm that this diploma thesis was written independently by myself under the supervision of Dipl.-Geogr. Stephan Bandermann and Ing. Martin Hanel. All written words and thoughts as well as images, tables and diagrams from the other authors are referred and cited in an appropriate way. This diploma thesis was not presented or published before.

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Abstract

In English

Nowadays, when speaking about flood management, flooding is one of the main concerns, in the urban areas, where flood consequences might be critical. In order to decrease the negative consequences, the flood assessment and management need to be done. Therefore, the European Commission put into force the European Directive 2007/60/EC (Protection, 2007). According to the Directive flood risk and hazard maps should be designed.

This study was based implemented upon the request of the municipality of the city of Verl, Germany. The municipality has already developed a plan for a new residential area, however the construction cannot be done as planned due to the reason that the planned residential area lays in the flooded area according to the risk map. Hence, this study was done in order to check the planned area upon the flooding and to suggest mitigation measures if the flooding occurs.

Keywords: Inundation area, hydraulic modelling, Ölbach, North Rhine-Westphalia (NRW), Germany, Geographical information system, flood protection, flood area estimation.

In Czech

Když dnes hovoříme o povodňovém řízení, povodně v městských oblastech jsou jedním z hlavních problémů, kde následky mohou být kritické. Za účelem snížení negativních důsledků je třeba provést hodnocení a řízení povodní. Evropská komise proto uvedla v platnost Evropskou směrnici 2007/60 / ES (Protection, 2007). Podle směrnice by měly být navrženy mapy povodňových rizik a nebezpečí.

Tato studie byla založena na žádost obce města Verl, Německo. Obec již vypracovala plán pro novou obytnou plochu, avšak výstavba nemůže být provedena podle plánu kvůli tomu, že plánovaná obytná oblast leží v zaplavené oblasti podle rizikové mapy. Proto byla tato studie provedena s cílem zkontrolovat plánovanou oblast při záplavách a navrhnout zmírňující opatření, pokud dojde k záplavám.

Klíčová slova: Inundační oblast, hydraulické modelování, Ölbach, Severní Porýní-Vestfálsko (NRW), Německo, Geografický informační systém, protipovodňová ochrana, odhad povodňových oblastí.

Table of Contents

List of abbreviations

1D	One Dimensional
2D	Two Dimensional
CBA	Cost-Benefit Analysis
CSO	Combined Sewer Overflow
DEM	Digital Elevation Model
DSM	Digital Surface Model
DVWK	Deutscher Verband für Wasserwirtschaft und Kulturbau
EAD	Estimated Annual Damage
EU	European Union
GIS	Geographical Information Systems
InfoWorks ICM	InfoWorks Integrated Catchment Modelling
NRW	North Rhine-Westphalia
PDM	Probability Distributed Model
RC	Runoff Coefficient
SMD	Soil Moisture Deficit
SRM	Simple Runoff Model
SUDS	Sustainable Urban Drainage Systems
SWMP	Surface Water Management Plan
SWMM	Storm Water Management Model
UK	United Kingdom
UKWIR	United Kingdom Water Industry Research

1 Introduction

Traditionally, most communities, from village to city, were built close to water. It can be explained by the fact that most human activities and basic needs depended on water resources. There are two main factors for cities to be built near a water body: - commercial and - sustainable development. The first one was economic: before the invention of such means of transportation as trains and cars, ancient civilisations had to settle closer to water in order to trade with other citizens located not only on the sea coast but also on the river banks. Thus direct access to water allowed both fast communication and convenient exchange of goods, not least due to the fact that it was easier to deliver goods by water means. The second factor was the sustainability of the community as a water body was a reliable food source. Moreover, people could get access to fresh water which was also used for agriculture, i.e. irrigation. The abovementioned improved the quality of human life, hence facilitated sustainable development of communities. Therefore, most big cities are placed near a water body.

Water use has risen significantly since the appearance of manufacturing, the invention of electricity and increasing consumption of energy. Today, in percentage correlation water consumption 10 % of all water consumption goes for domestic use, 20 % for industry demands and 70% for agricultural needs worldwide (Worldometers, 2016). According to United Nations (2013), the population of Earth will continue to grow and will reach 9.6 billion in 2050. Since water is a natural fuel, there is an increasing number of dams constructed and as the population is growing in order to increase electricity production much more dams will be constructed (Robbins, et al., 2011). Therefore, water use will increase in the next decades too. Moreover, according to United Nations (2014) 34% of the total population will live in rural area, the rest 66% of the population in the urban area by 2050. The substantial part of sustainable urban development highly relies on water supply, sewer, and stormwater drainage systems. Therefore, a sustainable water supply, sewer and stormwater drainage systems development will be required for future decades.

Once snow, rain or hail reaches the surface of the ground it starts moving. Part of it will infiltrate into the soil. The remained part of the water - from the saturated or sealed surfaces - will form a flow on the surface, which is called ‘runoff’. On the reasons that influence the increased amount of runoff is urbanisation, as the latter leads to coating surfaces with artificial materials that, in its turn, hinder infiltration. Furthermore, roads and roofs fasten runoff from the surface to the river. During the snow or rain event, runoff is continuously generated from urban and rural surfaces. However, from the rural watershed, runoff stops as soon as infiltration capacity of the soil exceeds the intensity of snow or rainfall. Runoff moves faster on artificial and sealed surfaces than on natural surfaces, therefore there is a high risk of abrupt flooding in rivers. Thus urbanisation is creating higher and more sudden peaks in river flow (Butler and Davies, 2010). Since impermeable surfaces make it difficult to infiltrate runoff, stormwater has to be moved out of the city in order to prevent flooding. Therefore, it can be seen that an extreme rainfall event is one of the major concerns and challenges of urban and rural river basins and it needs to be estimated.

Different sets of diagnostic methods and models are used to define future extreme rain events. According to Beniston, et al. (2007) heavy winter precipitation increases in central and northern Europe and heavy summer precipitation increases in north-eastern Europe, these changes in precipitations are expected to keep growing in the next years. Therefore, it is necessary to design and model how current urban and river areas will react on heavy rains in order to decrease a potential damage for cities. The main purpose of models in urban drainage engineering according to Butler and Davies (2010) "...is to represent a drainage system and its response to different conditions in order to answer questions about it, usually in the form 'What if ...? '". Modeling is used for different reasons, there are several of them mentioned below. First, modelling is used to design and build a new modern efficiently working drainage system. Second, modelling helps to analyse the existing drainage system under changing circumstances and assess if the current drainage system is capable of handling these conditions. Furthermore, it might be moderated into a design that would help to estimate mitigation measures that should be done for the existing drainage system.

Nowadays there are is a lot of different software programs developed. These programs are constructed on the basis of various physical and mathematical formulas. As mathematical and physical approaches are different per se, their models might be implemented in different fields and for different purposes. Some of them focus on sewer and stormwater, others on combined or natural drainage systems. Therefore, the choice of software depends on the type of task that engineers aim to perform or problems to solve, as well as on the availability of time and money to spend.

2 Purpose and aims

As it was mentioned before, urbanisation will grow in the next decades that will put a significant pressure on the natural water circle. Moreover, the precipitation forecast shows the increase of extreme events over central and northern Europe in the winter time and over north-eastern Europe in the summer (Beniston, et al., 2007). Therefore it is essential to design, evaluate and optimise flood measures in order to prevent any potential damages. Nowadays, there is a big amount of software programs with the tools that can give different flood mitigation measures under changed circumstances. Therefore it is necessary to choose the most appropriate software, furthermore to design, compare, and evaluate the most suitable mitigation measures.

The main purpose of my Diploma Thesis is to design an accurate model and evaluate the most appropriate flood mitigation measures for the study area. The following steps are made to achieve this purpose:

- A flood basin at the area of interest is estimated;
- Inundation measures are suggested in order to decrease flood impacts.

The goal is to make recommendations regarding the modelling of the most suitable mitigation measures within the diploma thesis.

3 Literature research

General definitions, provisions and current knowledge about flooding, its risks and management are presented in this chapter as well as approaches (procedures) of surface flow modelling. The importance of flood management is described based on the European water framework directive and scholarly literature.

3.1 Flood and flood risks

Until now, floods are one of the natural hazards that affect many regions and endanger lives and well-being of individuals worldwide. For the last decades, the number of huge floods was acquired. Table 1 shows ten most severe flood hazards and the economic damage between years 2000-2016, (EM-DAT, 2016).

Table 1. Ten most severe floods (EM-DAT, 2016)

Country	Date	Total damage
Thailand	05/08/11	$ 40,000,000,000
China	29/05/10	$ 18,000,000,000
India	00/09/14	$ 16,000,000,000
Germany	28/05/13	$ 12,900,000,000
Germany	11/08/02	$ 11,600,000,000
USA	09/06/08	$ 10,000,000,000
Pakistan	28/07/10	$ 9,500,000,000
USA	09/08/16	$ 8,733,000,000
China	21/07/12	$ 8,000,000,000
Italy	14/10/00	$ 8,000,000,000

Between 2000-2016 Europe suffered from 376 floods, and 6.6 million people were affected, 1.751 people died. The economic loss was $ 95.5 billion (EM-DAT, 2016).

According to the Protection (2007) flood is "... the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, Mediterranean ephemeral water courses, and floods from the sea in coastal areas, and may exclude floods from sewerage systems". Floods might occur due to different reasons and spread at the different range. Flood reasons constitute the base for flood differentiation and systematisation. Floods can be divided according to Klijn (2009) into the following categories with the regard to their origin, which can be seen from their names:

- excess rainfalls create inland floods;

- storms - coastal

- earthquakes - tsunamis

- man break - man-induced.

It is possible to see that all these floods are caused by natural phenomena. Flooding might be seen as natural behavior of a water body, but when natural behavior might harm to humanity the term ‘hazard’ is added. Therefore, in flood risk management only floods that pose hazard are considered (Klijn, 2009).

What is flood risk then? Flood risk is defined as a combination of probability with potential negative consequences (Protection, 2007; Klijn, 2009). The consequences are considered to be negative when people suffer or property is damaged as the result of flooding (Klijn, 2009). Thus, the combination of both factors: flood probability and possible harmful consequences define a flood risk.

The chain of causes and their effects can help to identify flood risk formation. Therefore, the Source Pathway Consequence Model (further referred to as SPCM) (Figure 1) was created by Institution of Civil Engineers in order to illustrate steps of flood risk formation.

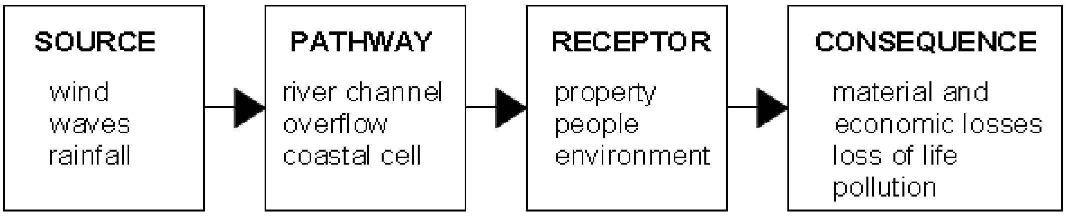

Figure 1. Source Pathway Receptor Consequence Model. Modified from (ICE, 2001)

The SPCM is an illustration of the components interaction that is based on the cause-effect chain.

The term ‘flood management’ includes analysis and assessment of all flood components in order to reduce possible damage caused by floods. According to (Schanze, et al., 2007) flood, risk management is a comprehensive analysis, assessment, and reduction of flood risk. Three main elements of flood risk management are presented in Figure 2.

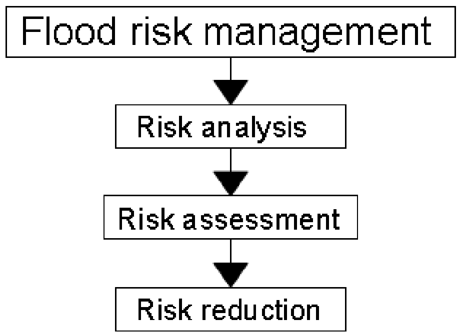

Figure 2. Structure of flood management activities. Modified from (Schanze et al., 2006)

Risk analysis aims to find flood probability distribution, water level, the velocity of the flow, sediment transportation and content of pollutants (Klijn, 2009; Schanze et al., 2006). The analysis results in creating flood risk maps and warning systems that help to prevent floods.

Risk assessment deals with risk perception and risk weighing, where risk perception takes into account risks of local people to probable adverse flood consequences and risk weight based on a decision of risk degree as a cost that might be admitted in the context of some options as benefits (Schanze et al., 2006).

Risk reduction is the final part of flood risk management. There is a range of different measures and instruments, which are implemented in different ways to decrease a flood risk. Measures can be characterised as physical actions to be taken, they are divided into two main categories: - permanent, measures that include permanent engineering construction (dams, reservoirs, retention ponds, embankments), and - temporary, measures that focus on better planning and development of better natural condition to reduce a flood risk (good planning of evacuation, land use planning and alarm waning flood) (Klijn, 2009; Schanze et al., 2006). Instruments or so called policy instruments can be characterised as non-direct actions that influence human behaviour towards flood reduction. Instruments can be divided into three main groups: communication instruments, which are supposed to increase flood awareness, financial instruments that ensure people's economic security and regulatory instruments, which are regulations that contribute to the creation of common for all society normative or standards. Instruments and measures are inter dependable, one cannot be implemented without the other, hence instruments and measures are always continuously interconnected.

Schanze et al.(2006) introduced a framework for the flood risk management process where he linked all components of flood management with social influence on the decision making process. More important, his flood risk management process is mainly based on the societal conditions of decision-making, as the implementation does not have a linear structure in the real world, it always requires analysis, reconsideration, and evaluation of interim results. Thus, actions plan is tightly connected to these interim results and is being constantly updated in accordance with them. Integration of all processes is the main challenge, thus, the flood management requires constant interaction between management and decision-making (Figure 3).

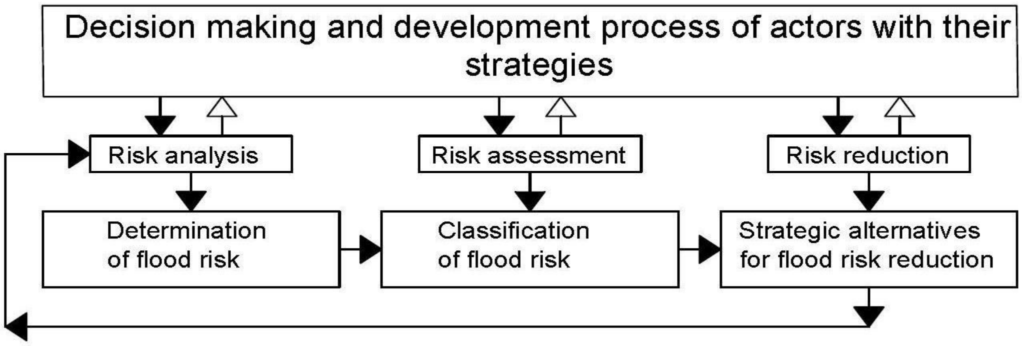

Figure 3. Full structure of flood management activities (Schanze et al., 2006)

3.2 DIRECTIVE 2007/60/EC on the assessment and management of flood risks

In the year of 2007, the Parliament and Council of the European Union agreed, adopted and put into force the European Directive 2007/60/EC on the assessment and management of flood risks. With the main goal to establish a framework for the management of inland, coastal and groundwater flood risks and aim to reduce negative consequences. The Directive contains the following parts: preliminary risk assessment, flood hazard map and flood risk maps, flood risk management plans, public information, and consultation, implementing measures and amendments and final element is reviews, reports and final provisions (Protection, 2007).

The first part allows to identify regions prone to flooding and to refuse those parts of water bodies that do not need further flood analysis. Preliminary risk assessment includes maps of river basins with the description of floods that occurred in the past and where there is a need to assess potential negative consequences concerning human health, environment, and economical losses. Second part - flood hazard and risk maps, in accordance with three scenarios: floods with a low probability, floods with a medium probability and floods with a high probability. These maps should be available online for free. Moreover, the maps should include the information on flood extent, water depths, and flow velocity as well as potential negative consequences for people. Moreover, should be given a possible number of people affected, and types of economical activities that might be damaged and environment risks (Protection, 2007).

The third part is flood risk management plans. The development of these plans is framed to reduce potential negative consequences considering permanent and temporary measures. Moreover, prevention, protection, and preparedness are the main factors to consider as measures to be taken when developing warning systems and defining characteristics of the flooding area. Public information and consultation is the fifth part, where all data on flood areas shall be in free access (Protection, 2007).

Implementing measures and amendments is the next part that requires technical formats including statistical and cartographic data to be provided. The final element is represented by reviews, reports and final provisions that contain the preliminary flood risk assessment, the flood hazard and flood risk maps, and the flood risk management plans that shall be reviewed every six years (Protection, 2007).

As at can be seen that the abovementioned steps are followed by the Directive, which in its turn corresponds to the theory and practice of the flood management that was described by (Schanze et al., 2006).

3.3 Examples of flood management methodologies within Europe

3.3.1 Flood Risk Management in Nordrhein-Westfalen, Germany

As soon as the Directive 20007/60/EC on the assessment and management of flood risks was approved within the European Union, each of 16 federal states of Germany was obliged to implement it. Thus, the Flood Risk Management department in North Rhine-Westphalia designed a plan “Hochwasserrisiko-Management. Schritte zum zukunftsfähigen Umgang mit den Risiken durch Hochwasser in Nordrhein-Westfalen” with duties and possibilities for organisations and stakeholders to cooperate and work together on flood risk problems (MKULNV, 2015). The plan follows all the stages of the Directive. Firstly, the possibility of flooding shall be evaluated, and further the results of the preliminary evaluation shall be published on an available website for free. Secondly, based on the evaluation, flood hazard and flood risk maps shall be created and remain in open access. The latter aims at helping to minimise life and property loss risks, as companies and citizens, being aware of flood risk areas, will be able to act correspondingly. In accordance with the requirements of the Directive**,** flood hazard maps should include possible extent, depth of floods and velocity of a flooding flow. The extent of flooding is calculated based on different scenarios. A ten year return period HQ 10 corresponds to floods with a high probability, HQ 100 corresponds to floods with a medium probability and HQ extreme flood that might occur statistically not more than once every 100 years. These three types of floods have significantly adverse consequences.

The flood risk maps show the land use of the areas, which might be affected by the flood. The maps also provide information on risks that require particular attention. The flood risk maps also indicate a number of residents that are considered to be vulnerable (MKULNV, 2015).

Further, the local district authorities analyse negative consequences for the main following groups of risks: human health, environment, cultural heritage and economic activity, and determine appropriate objectives for the flood management. Together with the municipalities the flood risk management group prepares the action plan. The plan is designed to minimise harm influence according to the mitigation measures and means. All the procedures described above correspond to the first step in the Flood Risk Management Planning that is called 'risk assessment with the determination of the appropriate objectives' (MKULNV, 2015).

The second step is the core for the implementation of the flood management plan - measurement planning. The municipality creates a catalog of the measurements that should be implemented in order to decrease flood risks. The catalog consists of different duties, measures, and objectives and assigns stakeholders responsible for their implementation. The municipality, in its turn, monitors the implementation of the specified measures and controls if the results lead to the achievement of the main goals. Moreover, the municipality constantly checks the existing situation so the upstream measures do not cause an adverse effect on downstream society (MKULNV, 2015).

As a final step of MKULNV (2015) the plans about the flood management activities shall be published and reported to the EU. All measurement plans are to be published together with a creation of the whole region database. The database helps to combine the measures per region and prioritise them. All measures plans are available online for free on the internet platform.

When comparing the German implementation of the Directive with the management plan introduced by Schanze et al., (2006), they both include decision-making processes as a part of action planning, where constant interaction between municipality and action group occurs.

3.3.2 UK

The flood Directive was transformed into the law for England and Wales as The Flood Risk Regulation. To fulfill this regulation a Surface Water Management Plan (further referred to as SWMP) was established. The plan was developed for local authorities with an aim to facilitate their flood risk management activities (DEFRA, 2010). Moreover, the plan aimed to increase understanding of the establishment of " ...a long-term action plan to manage surface water in an area and should influence future capital investment, drainage maintenance, public engagement and understanding, land-use planning, emergency planning and future developments (DEFRA, 2010).

The SWMP contains four main steps: preparation, risk assessment, options and implementation and review. Firstly, the preparation step identifies whether an SWMP study is required, who has to take part in planning. Moreover, the first preparation step contains aims and identifies data availability. Secondly, the risk assessment step consists of strategic (identification of the vulnerable area), intermediate (identification of hotspots within vulnerable area and establishment of possible fast mitigation measures) and detailed (aims to calculate future probabilities and consequences of flood risk) assessments. The outputs of the assessments contribute to a detailed map. Thirdly, an optional step, which identifies the most appropriate mitigation measures for the study area based on the test results of effectiveness, robustness, cost and benefits. Fourthly, the implementation and review step where a coordinated plan is developed. As soon as it is implemented**,** it should be monitored in order to assess benefits. Furthermore, SWMP should be reviewed and updated minimum once every six years (DEFRA, 2010).

The SWMP also takes into account a step of evaluation and redirection according to the results, thus, it proves the main aspect indicated by (Schanze et al., 2006) with regards to decision-making and development processes.

3.4 Surface flow modelling

All the water that flowing or is stored on the Earth is called surface water, the main form of surface water considers to be a channel flow. Thus, the main task for hydrology is to define a flow rate of the channel flow. The land area that drains into a particular stream is called catchment or watershed (Chow, et al., 1988). Rain, snow or hail, so called precipitations, contribute to the surface water either by storing or flowing on surfaces and eventually all water that falls into the catchment and does not evaporate, reaches the channel flow. Therefore, precipitation and size of the catchment are essential parameters for surface flow modelling.

Urbanisation has become the central concern for the surface flow modelling. Effects of urbanisation on surface flow are presented as an increased amount of runoff as well as a high peak in the runoff rate that is shown in Figure 4 (Chow et al., 1988).

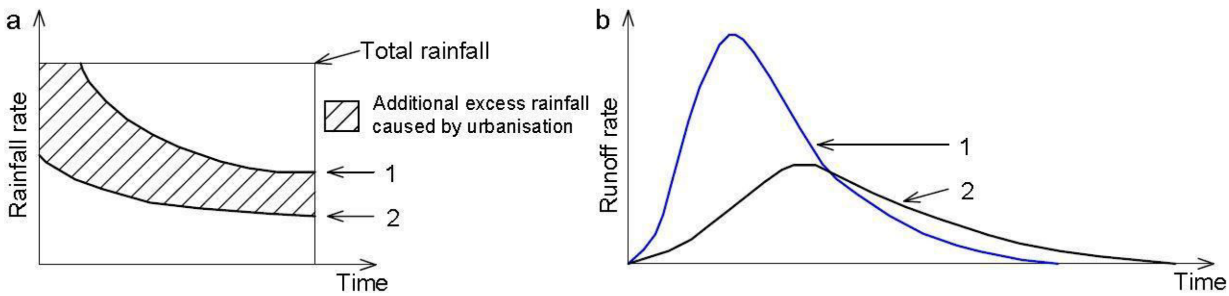

Figure 4. Urbanisation effects on (a) infiltration, where 1 infiltration before urbanisation, 2 infiltration after urbanisation; (b) runoff , where 1 runoff after urbanisation, 2 runoff before urbanisation. Modified from (Chow et al., 1988)

The precipitation excess as a result of urbanisation increases the amount of runoff due to an enhanced construction of impervious surfaces. Moreover, the impervious artificial surfaces increase flow velocity due to less friction factor, thus increased a range of runoff peaks.

Urban drainage systems have a long development history. From the beginning, wastewater and stormwater are two main concerns in urban areas. Therefore, there are two main types of urban sewerage systems in Germany: separate - where stormwater and sewer water flow in separate pipes, and - combined where storm and sewer waters are mixed and flow in the same pipe.

In the last 10-15 years, new approaches regarding the discharge of water surface- runoff regulations were implemented in Germany in order to decrease the volume of stormwater in the sewerage urban systems. The core principle is to dispose stormwater within a private property, in other words, to use a decentralised stormwater system. Disposing within a property helps to reduce a big amount of stormwater in the sewerage system, thus to reduce a runoff peak and abrupt flooding. Disposing of stormwater on a property might be done by using sustainable urban drainage systems (further referred to as SUDS). SUDS are becoming widely used in Germany due to the fact that it helps to deal with stormwater locally and in a natural way. There are some examples of SUDS measures: green roofs, rain barrels, gullies, stormwater planters, infiltration and etc. (Dunnett and Clayden, 2007).

However, nowadays, there is no federal law that regulates surface water runoff in Germany. Nevertheless, some federal states of Germany such as North Rhine-Westphalia (NRW), introduces regulation (Werker et al., 2012) on the discharge of surface water runoff where stormwater is categorised depending on the pollution concentration and treatment measures, which are suggested in order to reach a sufficient stormwater quality.

In order to present, study and design suitable stormwater systems, computational models might be used. Model is a convenient and cheaper way to present study area (real study conditions). However, it is necessary to remember that the model is a simplification of reality. Hydrological and hydraulic calculations are two main parts for urban stormwater modelling. Hydrological calculations consider the hydrological water cycle with intention of runoff estimation. A hydrological part contains an estimation of a rainfall-runoff process as soon as a runoff is generated by rainfall so it depends on rain event and watershed characteristics. In other words, the hydrological model uses input parameters (watershed parameters and rainfall characteristics) and as the output gives runoff characteristics for this particular watershed.

One of the outputs of hydrological calculation is a discharge hydrograph. The discharge hydrograph presents stormwater flow as a function of flow rate over the time at a given location. A hydrograph is a graphical representation of the river or stream flow reaction to precipitations (Figure 5).

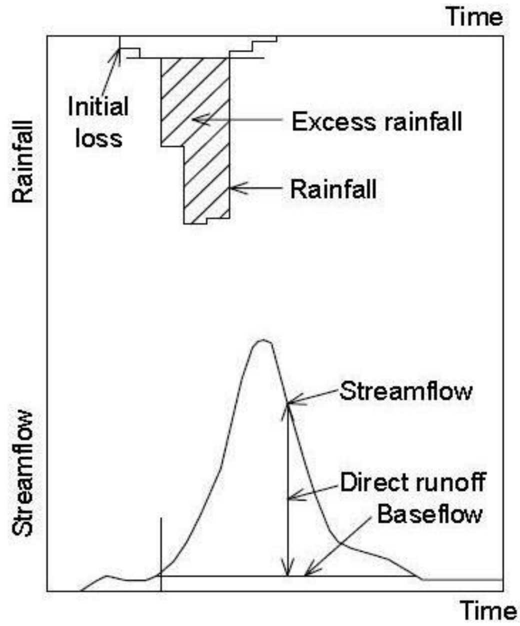

Figure 5. Discharge hydrograph form rain event. Modified from (Chow et al., 1988)

The hydrograph shows the base flow, which occurs due to the subsurface flows rather than as a result of this specific rainfall event. Moreover, this hydrograph represents direct runoff volume and the maximum flow value.

Hydraulic calculations include flow characteristics and water motion in pipes and channels that require the use of hydrodynamics. Hydrodynamic models require high resolution terrain information as an input data in order to give accurate results of hydraulic calculations. A high resolution terrain information enables to give roughness and relief of the area of interest. Moreover, general inputs for hydraulic calculations are results of hydrological calculations, topography and various parameters for numerical calculations (Schumann, 2011).

The great amount of stormwater software programs available nowadays. In Germany STORM, InfoWorks and SWMM are tools that are used widely. The InfoWorks ICM by Innovyze was chosen for my diploma thesis. The choice of InfoWorks ICM based on its integrated catchment modelling that couples hydrological and 1D/2D hydrodynamics calculations for urban and river catchments that allows to represent flow path both below and above the surfaces. Thus, InfoWorks ICM enables to assign one model for natural and manmade elements of the stormwater calculations as it in real life (Innovyze, 2017).

3.5 Infoworks ICM

Infoworks Integrated Catchment Modelling (ICM) is a modelling tool from Innovyze and one of the tools from product series of InfoWorks.

3.5.1 Model layout

Infoworks ICM might be applied for studies with urban and river catchments for short and long study periods. Infoworks ICM able to do hydrological and hydraulic modelling, to model floods, to study water quality and sedimentation in the pipes and also allows to include in the model structures such as bridges, weirs, and pumps in order to create an accurate model that is the most similar to reality.

Total study area shall be divided on non-overlapping sub catchments in order to complete calculation in InfoWorks ICM. InfoWorks ICM allows assigning six different systems types for sub-catchments that are displayed as a separate layer on GeoPlan InfoWorks Window (Figure 6).

Storm	Rainfall collection
Foul	Wastewater collection
Sanitary	Wastewater collection
Combined	Both rainfall and wastewater collection
Overland	Overland floodwater collection
Other	Other system type

Figure 6. System Types that might be assigned for sub-catchments (Innovyze, 2017)

Each catchment represents an area from which water is collected. There are several ways how water might drain from sub-catchment in InfoWorks ICM:

- a single inflow node;
- a single lateral link;
- a multiple lateral link;
- another sub-catchment.

Urban area catchments include urban sewerage systems. The urban sewerage network might be built containing conduits and manholes. Moreover, the urban sewerage network might be assigned as a storm, foul and combined types depending on city sewerage systems. Rural area catchments might include channels and inflow nodes.

To describe sub-catchment area (drain area) several parameters need to be defined. Such parameters as System Type, Land Use, Soil Type, Contributing Area etc. need to be defined directly in sub-catchment window. Each sub-catchment might be assigned with only one value for each required parameter in the sub-catchment window. However, there is a separate window for Land Use in InfoWorks ICM where up to twelve Runoff Surfaces might be defined. Runoff Surface describes the runoff characteristic of a specific surface type. Each Runoff Surface, in general, might be defined as the Impervious or Pervious type and might require its own parameters to be assigned.

In order to build a model the Master Database needs to be created in Infoworks ICM. The Master Database is organised into a flexible hierarchy. On the top position in the database, the hierarchy is either Model Group or Master Group. All other database items reside within either Model Group or Master Group. Such database items as Model Network, Rainfall event, Inflow and Level Hydrographs are added to illustrate a hierarchy within the Master Database (Figure 7).

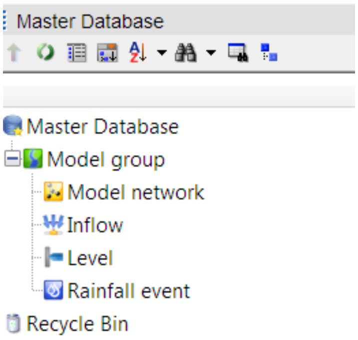

Figure 7. Master Database when building a model in Infoworks ICM

There are different input database needed to build a model in InfoWorks ICM. The necessary amount of the database items for running the model is needed. Moreover, the necessary amount parameters are needed for each database items in order to use the item in modelling.

3.5.2 Surface hydrology model

One part of the model is a surface hydrology model that is used to calculate a rainfall-runoff relation. The surface hydrology model takes into account the amount of rainfall that might be trapped by surfaces, the losses that associated with rainfall-runoff formation process, the routing process that accounts time for runoff to enter storm or combined sewerage (Figure 8).

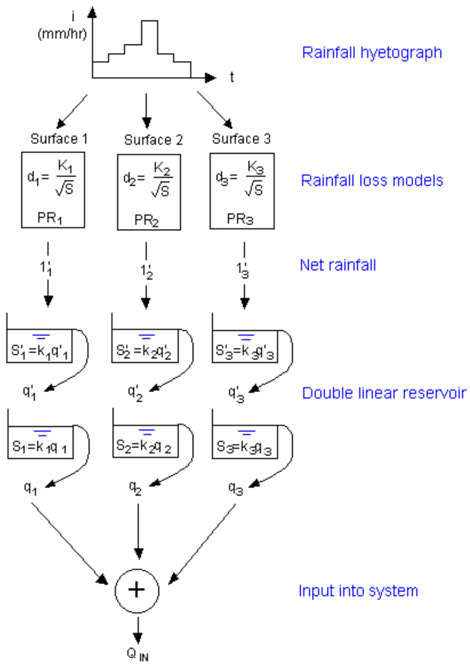

Figure 8. Principle scheme for surface hydrology model (Innovyze, 2017)

Two main processes are calculated during a rainfall-runoff modelling in InfoWorks ICM: initial and continuous losses and overland flow routing. Runoff volume model is used in InfoWorks ICM to calculate the amount of rainfall after accounting any initial losses that runs off the catchment into the drainage system (Innovyze, 2017). There are several Runoff Volume models included in Infoworks ICM: Constant Infiltration, Fixed Percentage Runoff, Deficit and Constant Loss Model, New UK, Wallingford, Horner, PDM, USA SCS Method, SRM, Green-Ampt, ReFN, Horton, Horton SWMM and UKWIR. Each of the Runoff volume model process rainfall in different ways and which Runoff Volume model to use in the model depends on the sub-catchment surface type and aims of the model.

For example, the Fixed Percentage Runoff volume model is advised for impervious areas and pervious areas where runoff does not vary significantly with antecedent conditions, as the Fixed Percentage Runoff volume model defines a fixed percentage of the net rainfall, which becomes runoff. The fixed percentage depends on a type of runoff surfaces and manually assigned for each surface by the user (Figure 9).

Surface Type	Description	Coefficient
1	High quality paved roads with gullies < 100m apart	1.00
2	High quality paved roads with gullies > 100m apart	0.90
3	Medium quality paved roads	0.85
4	Poor quality paved roads	0.80
11	High density housing	0.55
12	Medium density housing	0.45
13	Low density housing or industrial areas	0.35
14	Open areas	0.25

Figure 9. Typical values of the runoff coefficient for the Fixed Percentage Runoff volume model (Innovyze, 2017)

As soon as the Fixed Percentage Runoff volume model is not suitable for most pervious areas, as it does not account for soil decreasing infiltration capacity during a rain, another type of runoff volume model need to be used. Simple Runoff Model (further referred to as SRM) uses a soil moisture deficit time series with a constant runoff coefficient in order to get an effective rainfall. Where the soil moisture deficit is calculated with use of the Probability Distributed Model (further referred to as PDM). PDM runoff model in its turn is the only one model that calculates baseflow in InfoWorks ICM.

The runoff overland flow is calculated by routing model that is set to calculate how quickly the rainfall enters the drainage system (Innovyze, 2017). There are thirteen types of routing models in InfoWorks ICM.

3.5.3 Hydraulic equations

In order to calculate channel and pipe flows in Infoworks ICM it is assumed that one component of local velocity dominates over the two others, so two others might be neglected. Hence, to calculate 1D water flow Saint-Venant equations (one momentum and one continuity equations), which are partial differential equations, are needed to be solved.

Those formulas for continuity (conservation of mass) (Equation 1) and momentum (Equation 2) equations are applied in InfoWorks ICM.

$$\frac{\delta A}{\delta t} + \frac{\delta Q}{\delta x} = 0 \qquad (1)$$

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\delta x}\left(\frac{Q^2}{A}\right) + gA\left(cos\theta\,\frac{\delta y}{\delta x} - S_0 + \frac{Q|Q|}{K^2}\right) = 0 \qquad (2)$$

Where Q-discharge (m^3/s), A- cross-sectional area(m^2), g- acceleration due to gravity(m/s^2), θ- angle of bed to horizontal (degrees), S_0- bed slope, K- conveyance.

In order to calculate hydraulic roughness, the user might choose either a Colebrook-White or Manning equations for hydraulic roughness.

3.5.4 Result presentation

In InfoWorks ICM the results of the simulation might be presented in Geo Plan Window, Long Section Window, the 3D Manhole Window or spatial results versions of the Grid Windows (Figure 10, 11).

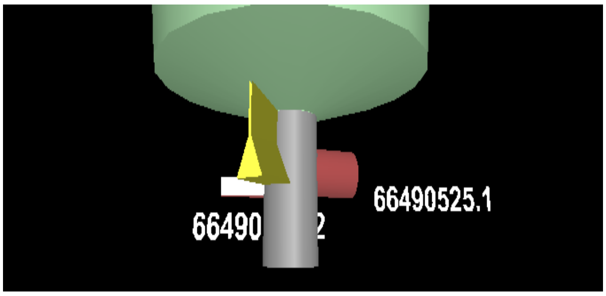

Figure 10.A screenshot of the 3D Manhole Window for result of chosen manhole

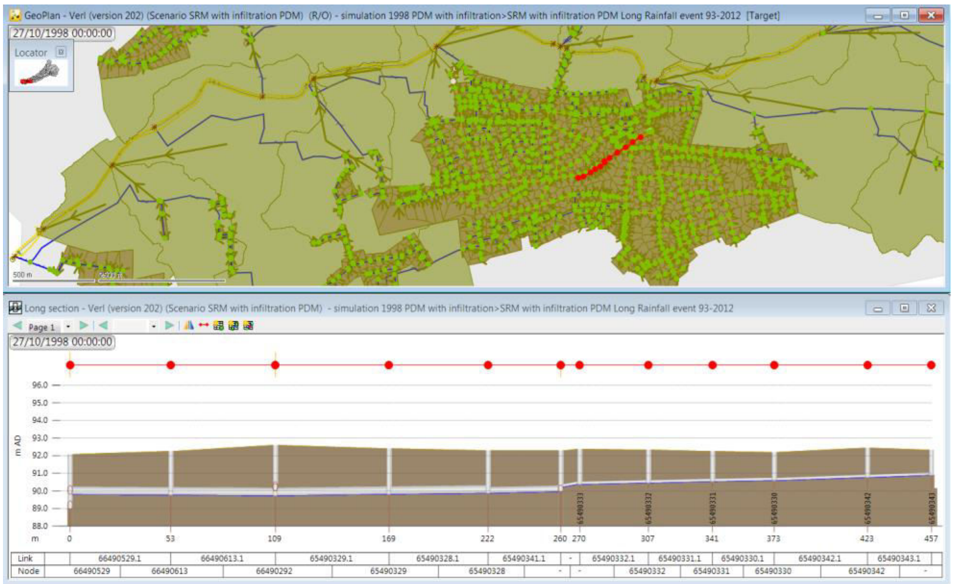

Figure 11. A screenshot of two options for displaying the results in Geo Plan Window and Long Section Window of chosen conduits.

4 Characteristics of the study area

The selected study area is the city Verl of the German state North Rhine-Westphalia and the eastern upstream catchment of the river Ölbach. Verl is located between the cities of Schloß Holte-Stukenbrock and Gütersloh, approximately 6 km to the west of Schloß Holte-Stukenbrock. The study area includes the river Ölbach, which is 29 km long, however, the area of interest covers only 3.9 km of the river. The total study area is about 6600 hectares, including urban and natural catchments (Figure 12).

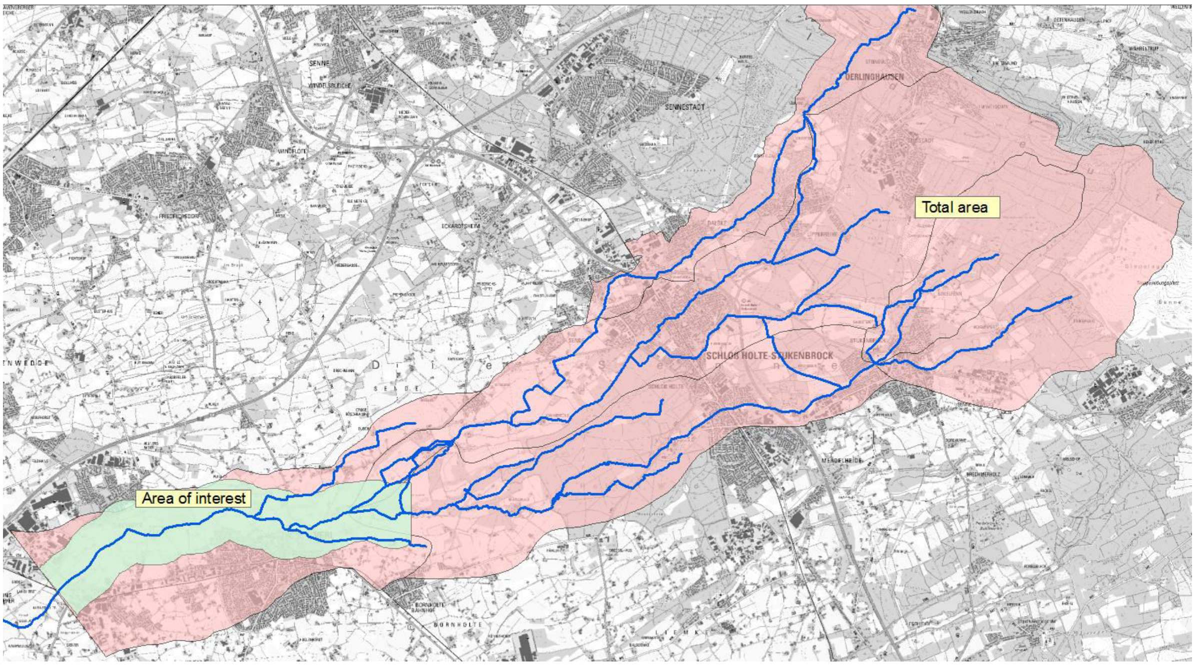

Figure 12. Map of the study area

The urban area is about 290 hectares. The urban sewerage consists of sewer, combined and separated stormwater systems. This study will focus on the combined and stormwater systems. The combined system takes both in one system, sewage and stormwater. The combined system consists of pipes with dimensions of 150 - 1200 millimeters. The combined sewer overflow (further referred to as CSO) occurs in a retention device that is constructed in order to redirect water flows above 88.145 metres, in this study case, out of the system to one of the outfalls during the heavy rain event. The principle scheme of the retention device is illustrated in Figure 13.

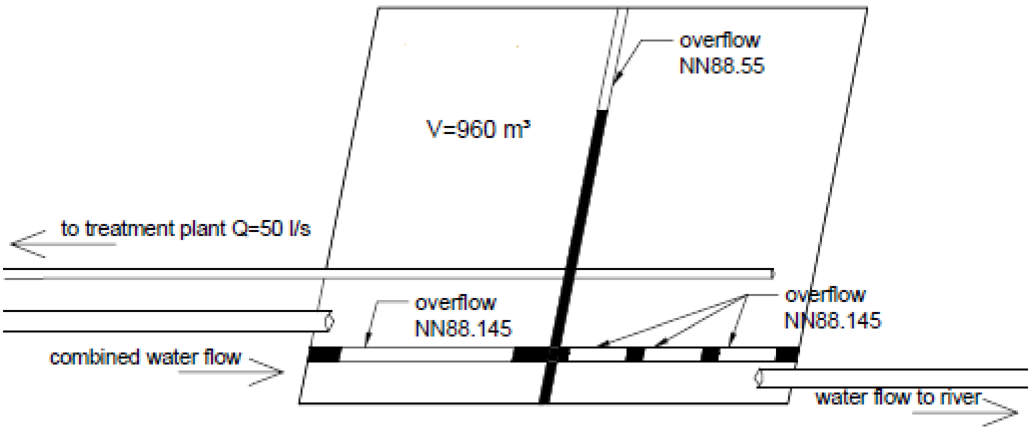

Figure 13. Principal scheme of the combined sewer retention device with overflow

As shown in Figure 14, retention volume is 960 cubic meters. The retention device stores mixed flows during the storm event. A part of the stored water continuously flows to the local treatment plant with a discharge capacity of 50 liters per second. However, as soon as device is filled, the additional mixed water overflows to the ditch that is connected to the river in this study. It is important to mention that the retention device consists of elements that enable to direct most solids to the treatment water plant rather than to allow mixed water to spill into nature. The latter is made in order to protect the nature.

As for the separate system, it consists of pipes with dimension of 200-1000 millimeters. These pipes serve as a connection for water to flow into ditches, which, in their turn, are connected to the river Ölbach. The stormwater outfalls from the urban area are shown in Figure 14.

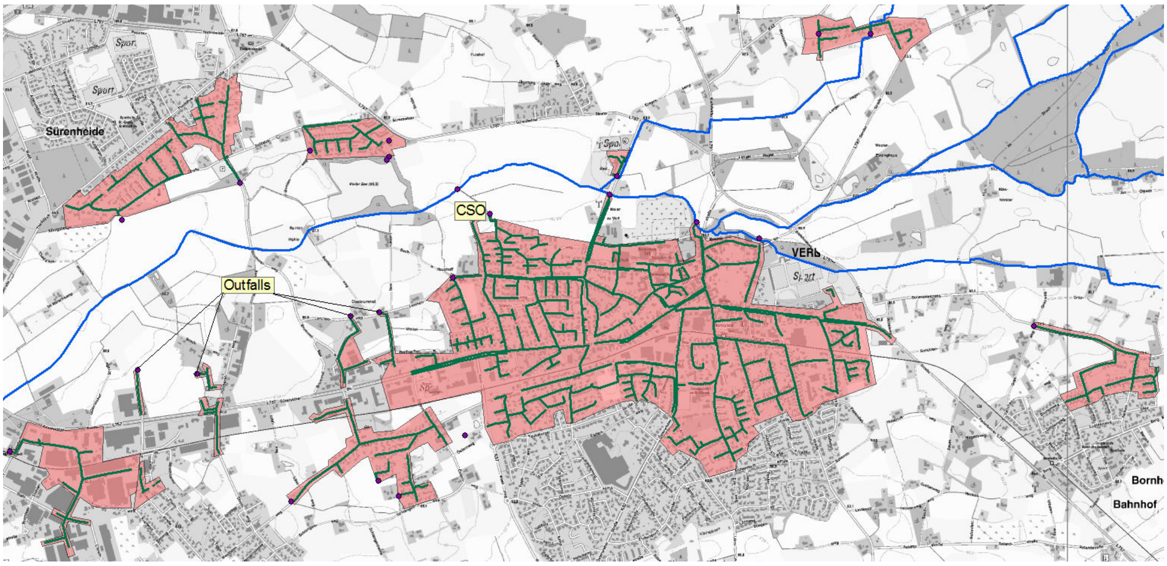

Figure 14. Map of the combined and stormwater systems for the study area of city Verl

A large area, that is about 6000 hectares, is located to the east of the study urban area. This area consists of typical landuse (mixture of forest and agriculture) for this part of the Germany. The land use for the entire study area is presented in the diagram (Figure 15).

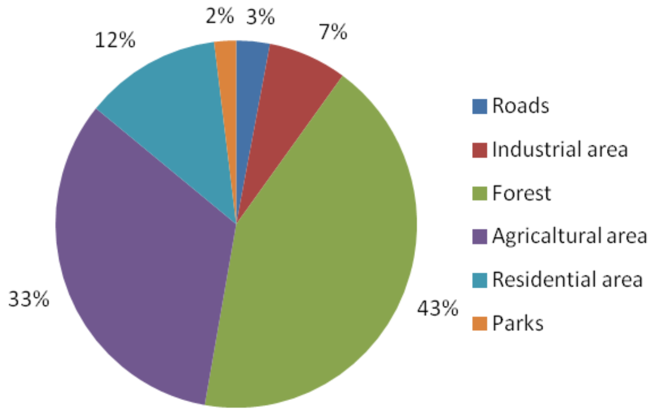

Figure 15. Percentage of each land use class for the entire study area

From the diagram below it is seen that the fully permeable area covers 80 % of the entire area. The permeable land uses are divided into several classes: parks, forests and agricultural areas. The industrial area is usually divided as 20 % of permeable and 80 % of impermeable areas. As for the residential area, it includes 60 % of the permeable and 40 % of the impermeable area.

5 Methodology

5.1 Data

Several data sets have been ordered to complete the study model.

1. Digital Elevation Model (further referred as DEM) with high resolution of 1, that means 1 pixel represents 1square meter of the ground surface. DEM is represented as a continuous raster data. DEM 1 has been used for the area of interest (Figure 13) while the DEM with the resolution of 4 for the rest of the area.
2. The map with the land use that is vector file and a vector file containing the data for buildings.
3. The meteorological data and the flow data in the river.
4. The urban sewerage system that contains a pipe network of the storm, foul and combined systems. Moreover, data have information of pipe roughness coefficients as well as ground and pipes levels.
5. The river cross sections and construction along the river were ordered.

All sets of data that are mentioned above are considered to be enough to build a model of the river Ölbach.

5.1.1 Precipitation, evaporation and flow data

Flow data were collected at the water depth gauge. In this study**,** data from 1998 to 2003 is used with a five-minute interval. Moreover, flow data with extreme events are given for the period of 1981 - 2004 (Table 2).

Table 2. Ten most severe runoff events from 1981 to 2003

Flow in m3/s	Date
6.18	30 .12.1986
6.07	19 .12.1988
5.99	**02 .01.1987**
5.9	**03 .01.2003**
5.85	**28 .10.1998**
5.71	**01 .11.1998**
5.65	30 .05.1984
5.6	29 .01.1993
5.55	30 .06.1981
5.16	12 .01.1993

Precipitation data were collected from rainfall gauge with a five-minute interval for the period from 1982 to 2012 (Figure 16).

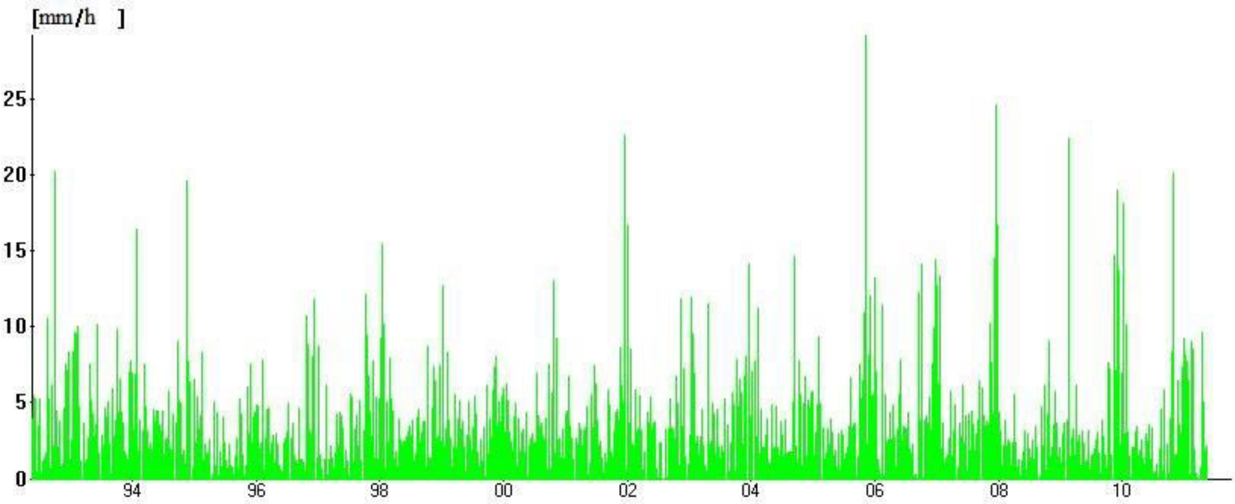

Figure 16. Long rain record for the period 1992-2012

The illustration shows that the highest rain peaks per day appear during the winter time. A long rain record from the period 1998 to 2003 is chosen for the calibration of the study model (Figure 17). It is used because of the amount of input data, which is comprehensive for this period and, furthermore, three most severe runoff peaks occurred during this chosen period (Table 2).

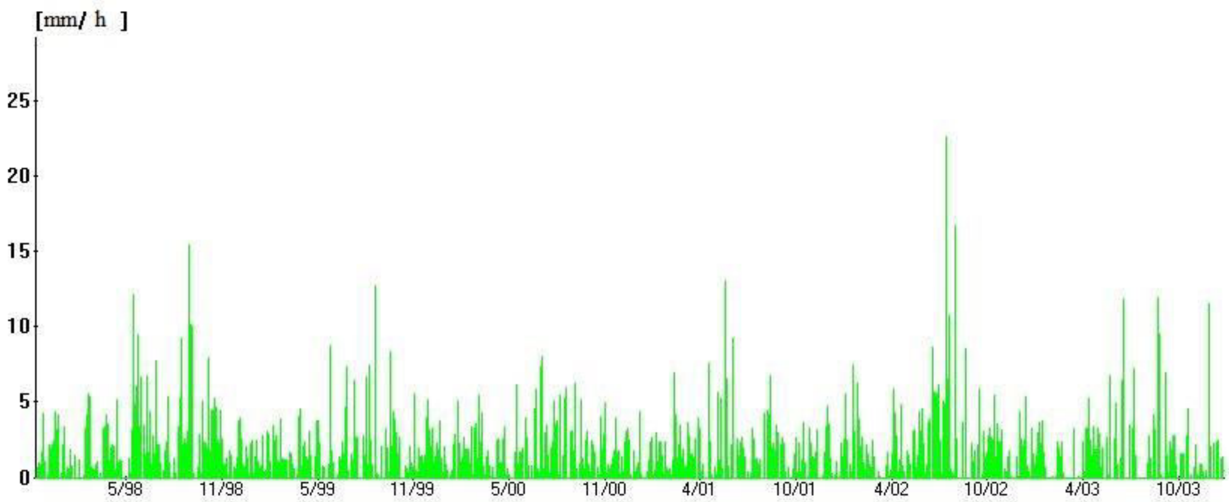

Figure 17. The chosen rain record for the period 1998-2003

Evaporation data were given with a one-day interval for the period from 1993 to 2007 (Figure 18).

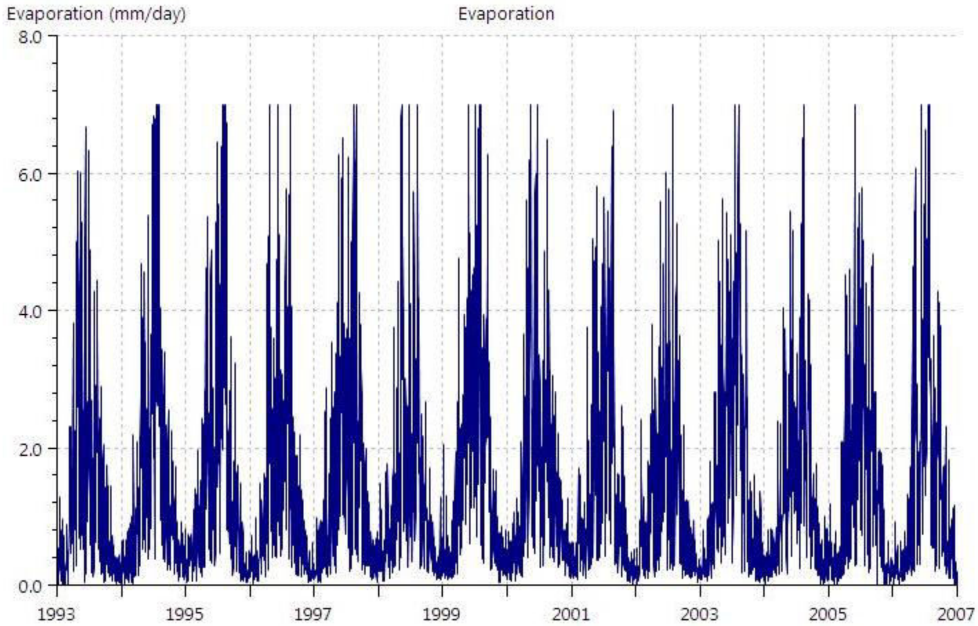

Figure 18. Evaporation record for the period 1993-2007

The data for the urban sewerage systems are given by municipality of city Verl and imported into InfoWorks ICM. Foul sewerage system is excluded from the model due to the needlessness for study case. The given sewerage model maintains such parameters as pipe material as well as pipe roughness coefficients, ground and pipe level, however an accurate information about manholes is missing. Nevertheless, given parameters are enough to assign separate and combined sewerage systems of the city Verl for this study case.

5.2 Data analysis methods

In this study, the model of the urban network and catchments was carried out with Infoworks ICM version 7.5 to simulate a coupled modelling with a one-dimensional pipe and a river model and two-dimensional surface models.

5.2.1 River model

The construction of the model was started with the building of a river. There are two main parts needed to be imported in order to build a river: the river center line and the cross sections. Firstly, cross-section data are imported. Cross section data are imported from .csv file. Once the cross sections are imported, the river center line as a .shp file is imported. To complete the river model, the banks of the river are built. Since the information about the structures along the river is not available at that stage, the construction is followed by setting a collection system model.

5.2.2 Collection system model

The collection system of the city is given in .idbf format. The sewer system is excluded from the model due to its uselessness for the study case, so the separate and combined systems remain to continue building of the model. To transport the stormwater to InfoworksICM, .csv files are used. The .csv file with all the information about manholes is imported then a .csv file with information about conduits is imported.

Once all manholes and conduits are imported their interconnections might be validated. However, some of the manholes and conduits have missing data which need to be added before the model can be used for a hydraulic simulation. There are two possibilities to fill the missing information either manually add all necessary data or use the InfoWorks ICM Inference tool. The InfoWorks ICM Inference tool estimates missing manhole cover levels, missing pipe levels, undefined pipe sizes and also to set an appropriate Head Loss Coefficients based on the angle that pipes enter/leave a manhole (Innovyze, 2017). In this study, the missing items are added manually.

Moreover, it can be seen that the ground surface gradient is assigned with the same slope as the pipes. That is actually a simplification of reality: however, in general pipes are needed to be built with the same slope as the ground. The material for all pipes is assigned as concrete. The Colebrook-White roughness coefficient is used with the value of 1.5. That is according to Hosang and Bischof (1998) is appropriate value for a used concrete pipe. The detailed information about manhole is also missing. The ground level of pipes is assigned as a floor level of the manhole as well as a roof level of the manhole is assigned as a ground level. The dimension varies for all study manholes from dimensions of 0.7 square metres to 3.7 square metres for chamber plan area and its level is assigned conforming to ground level.

The combined system contains a retention device that is mentioned in “Characteristics of the study area” part. To implement the retention device in Infoworks ICM, additional structures are assigned, such as weirs and an outflow rule (regulator) for the pipe from the retention device to the Water Treatment Plant, where max flow is 50 liters per second (Figure 19).

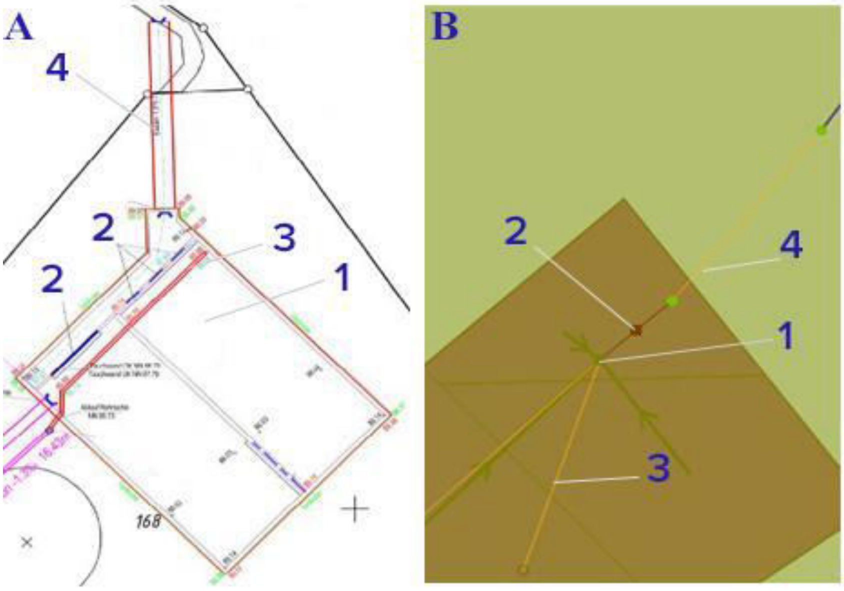

Figure 19. (A) Sketch of the retention device (B) model in InfoWorks ICM where 1, reservoirs; 2, weirs; 3, pipe to the treatment plant with the max flow 50 l/s; 4, pipe to the river.

Moreover, the combined sewer system of the city of Verl includes the temporary reservoir-pipe with the D= 2000 millimeters in order to store water during a high rate rain event. During a long intense rain event, the temporary reservoir-pipe might be filled with water. When it occurs and water rises to the level of the weir in the manhole 2, water overflow to stormwater system. This temporary reservoir-pipe and its connections to the manhole are shown below (Figure 20).

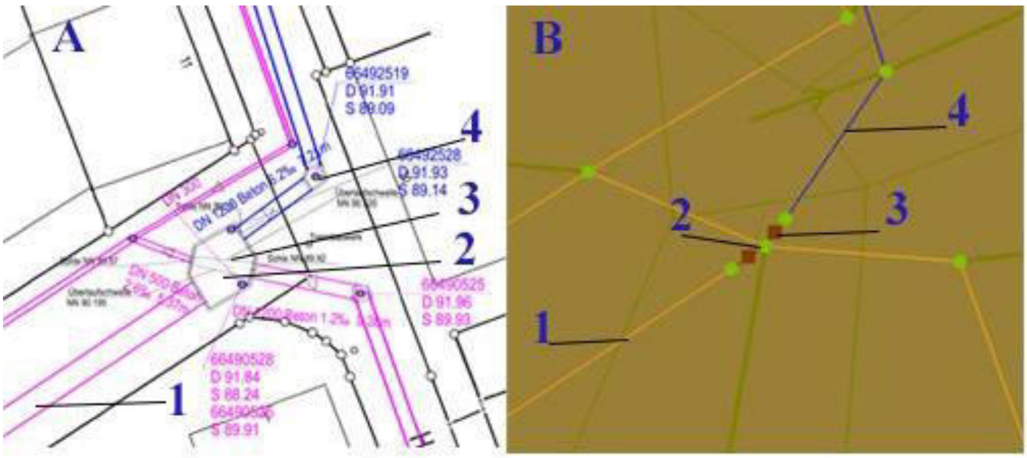

Figure 20. (A) Sketch of pipes network with the temporary reservoir and (B) the same pipes network in InfoWorks ICM where 1, temporary reservoir-pipe; 2, manhole; 3, weir; 4, pipe to the stormwater system

The underground sewer network is now complete. In order to provide flow inputs into the underground sewer system and complete the rural area model, delineation of the catchments is necessary. Flow inputs will come from rainfall as a runoff from the impervious areas and in dry periods by the wastewater produced by local population, which is living within the catchment. The first step in the delineation is to import main catchment boundaries. The second step is to subdivide the catchment to create individual sub-catchments within the catchment boundaries. The catchment polygon can be automatically subdivided using the "Create within selected polygon" tool within InfoWorks ICM. InfoWorks ICM divides the catchment considering the fact that each sub-catchment will drain to a specific manhole.

Since the study model consist of a combine sewer system, a wastewater profile is required during the model simulation in InfoWorks ICM. Population density, the water discharge norm per person in day and a day distribution curve are set in the study model.

At this point, the urban part of the model might be considered as an assigned (complete) one.

5.2.3 Sub-catchments

To process a hydrological modelling, the area needs to be divided into sub-catchments. However, there is no tool for sub-catchments delineation in InfoWorks ICM. Thus, the whole study area is divided into sub-catchments that are delineated in GIS with the use of ArcHydro tool (Maidment, 2002). DEM1 is used to delineate sub-catchment in the area of interest (the city of Verl) and DEM4 for the rest study area. Then catchments as a .shp file are loaded to InfoWorks ICM to proceed a modelling. DEM shows that study catchments are mostly flat except for the upper catchments. The downstream catchments have a hilled area at their east part. That is also proved while visiting the study area.

5.2.4 Runoff volume models

At the beginning the GreenAmpt model that is developed by Mein and Larson (1973) was planned to be used as this model is used for rural and pervious surfaces and takes into account initial soil deficit. However, it is proved that the interflow and the baseflow in the sub-catchments cannot be calculated with Green Ampt model in InfoWorks ICM. The user requires to assign the baseflow value for this model manually. The baseflow and interflow can be calculated only with the use of PDM model (Moore, 2007). Since the interflow and the baseflow calculations are essential for the river modelling, the PDM model is chosen for the underground calculation. The Simple Runoff Model (further referred to as SRM) is chosen to calculate the effective rainfall from the runoff surfaces. The Equation 3for the effective rainfall calculation is presented below.

$$\textbf{Effective Rainfall = Catchment rainfall *RC * (1- SMD)} \quad (3)$$

Where, RC-constant runoff coefficient, SMD- Soil moisture deficit factor

The soil moisture deficit (SMD) is calculated by using PDM in this study. Constant runoff coefficient (further referred to as RC) can be estimated from land use and soil types GIS files for each sub-catchment. Once effective rainfall is estimated, it is applied to a simplified PDM model to calculate the baseflow.

5.2.5 Implementation of constant runoff coefficients

InfoWorks ICM allows setting of the RC for a sub-catchment from GIS data. To do this, the GIS file with information about land use (surface type) and soil types is required. Moreover, a table .csv format file with a runoff appropriate to a pair land use-soil type needs to be added. InfoWorks overlaps GIS files and assign the corresponding value of runoff coefficient from the table to the sub-catchment data grid.

The vector data of land use is given. The study area is divided into 11 main surfaces and for each surface type abbreviation is given in Table 3.

Table 3. The land use surfaces for the study catchments

Surface types	Area (ha)	Abbreviation
Roads: gravel	4	F
Paved parking lots, roofs etc	178	G
Industrial area	549	H
Open spaces, parks, cemetries	153	J
Woods and Scrub	2782	K
Agricaltural area	2151	N
Irrigated Pasture	3	O
Range and Pasture	22	U
Vegetation free area	8	V
Water bodies	52	S
Residentia area	752	X

The distribution of the land use is represented in Figure 21.

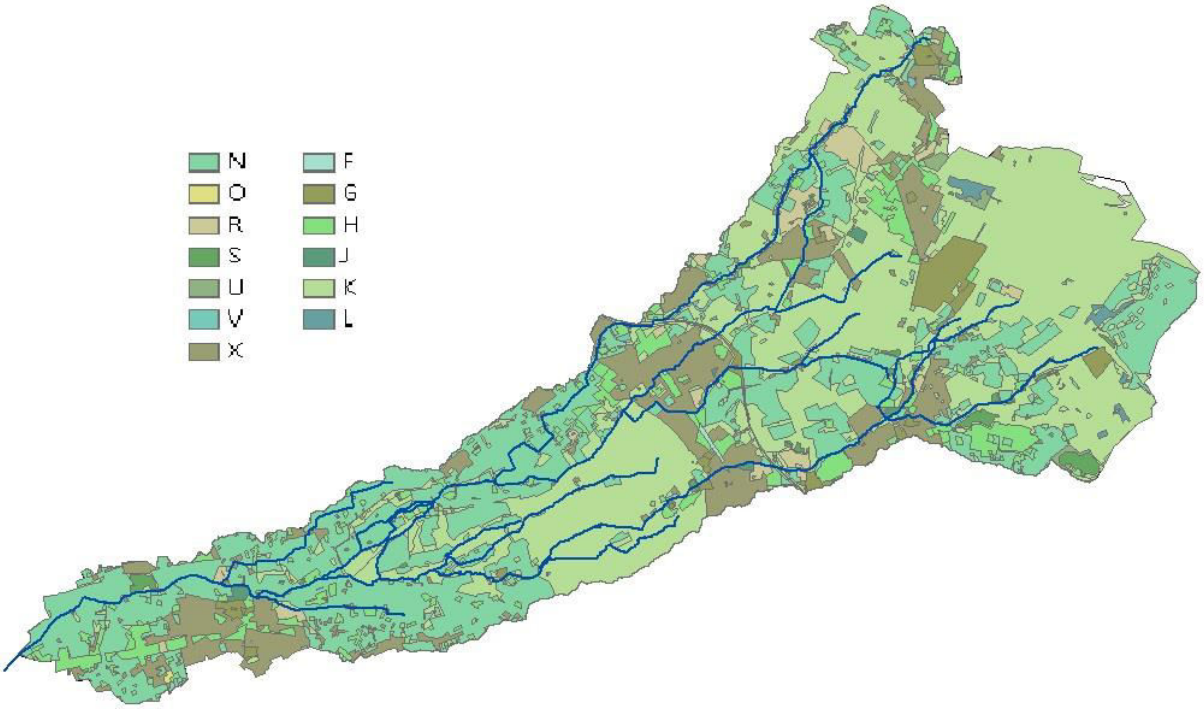

Figure 21. The distribution of the land use in the study area

Concerning the soil data, four main soil types are represented in the study area: sandy soil, sandy loam, clay and silt loam. InfoWorks ICM uses British soil classification that contains four soil types. British soil classification is shown in Figure 22 and is based on the following characteristics:

Soil Type	Definition
A	(Low runoff potential) High infiltration rates even when thoroughly wetted. Chiefly deep, well/excessively drained sands or gravels. High rate of water transmission.
B	Moderate infiltration rates when thoroughly wetted. Chiefly moderately deep/deep, moderately well/well drained soils with moderately fine/moderately coarse textures. Moderate rate of water transmission.
C	Slow infiltration rates when thoroughly wetted. Chiefly soils with a layer that impedes downward movement of water, or soils with a moderately fine/fine texture. Slow rate of water transmission.
D	(High runoff potential) Very slow infiltration rates when thoroughly wetted Chiefly: • clay soils with a high swelling potential • soils with a permanent high water table • soils with a clay pan or clay layer at or near the surface • shallow soils over nearly impervious material Very slow rate of water transmission.

Figure 22. The soil types classification (Innovyze, 2017)

Hence, the study soil types are classified according to the table from InfoWorks and abbreviated as A,B,C,D. The soil type distribution is represented in Figure 23.

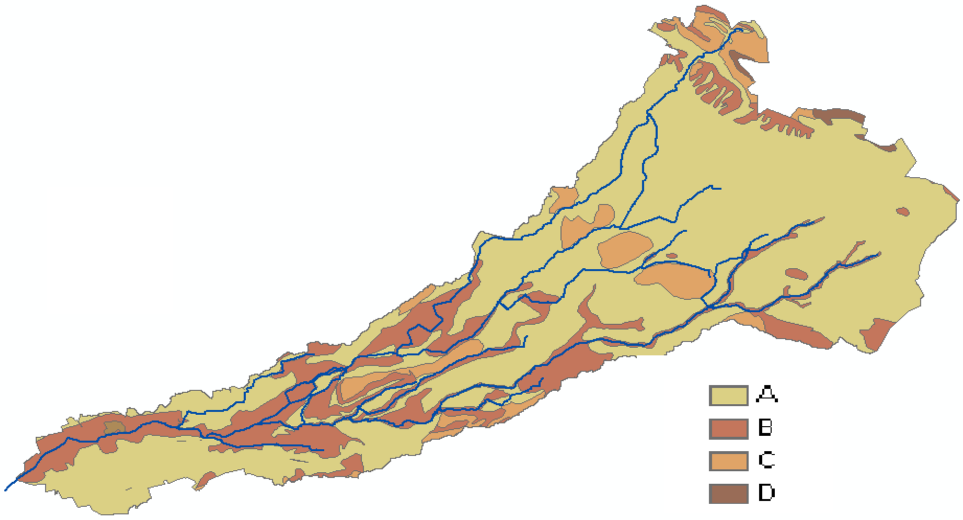

Figure 23. Distribution of the soil types in the study area

The land use surface determination and soil reclassification are done in order to assign runoff coefficients according with the pair soil type-land use. The values for RC are suggested within a model description in InfoWorks ICM. The table below represents the assigned RC (Table 4).

Table 4. Runoff coefficient that appropriate to a specific pair land use-soil type

Land Use/Soil type	A	B	C	D
F	76	85	89	91
G	98	98	98	98
H	81	88	91	93
J	39	61	74	80
K	36	60	73	79
N	49	69	79	84
O	35	48	65	70
U	25	59	75	83
V	37	60	71	77
X	61	75	83	87

5.2.6 PDM Descriptor

One of the important objects within the PDM calculation is the PDM Descriptor. The PDM Descriptor consists of all parameters for underground calculations, for example, minimum and maximum storage capacities, baseflow and interflow time constants, interflow rate etc.

InfoWorks allows calibrating automatically values that are used by Descriptor in a sub-catchment. The process of calibration uses the observed rainfall, evaporation, flow and temperature to optimise set of parameter values used by the PDM Descriptor. However, the calibration can be done just for one sub-catchment, in other words Infoworks does not consider the connection of the catchments. Hence, the observed data need to be available for each study sub-catchment in order to optimise the PDM Descriptor parameters. For this study, the flow data are only available at one gauge which is located in the urban part of the river Ölbach (Figure 24).

Figure 24. Location of the gauge

In order to use PDM model and the PDM calibration options in InfoWorks, the following procedures are cogitated.

As a first step, the entire model is divided between two models. One model consists of all catchments above the gauge and the second - below the gauge.

As a second step, it is decided to simulate only the urban part within the second model in order to see the runoff peak flow in the river from the city. The runoff volume model for this simulation is assigned as the Fixed Percentage Runoff since this model is recommended for sealed surfaces and defines a fixed percentage of the net rainfall. Three Percentage runoff coefficients are set for three main urban runoff surfaces: roofs, roads and urban green area. Values for the RC are: roofs - 1.00, roads - 0.95, urban green area - 0.05. Hence, it is assumed that 100 % of the rainfall from roofs, 95% from roads and 5% from urban green area goes directly as a runoff.

As for the third step, the difference between the observed flow in the gauge and flow that comes from the city is calculated. This manipulation is done in order to prevent any loss of the runoff peak from the urban area in the river during the following calibration. The resulting flow values are used as observed data for the following step.

The fourth step is to merge all delineated catchments in one big catchment for the entire area above the gauge, in order to automatically calibrate the parameters used by the Descriptor in the sub-catchment. Once, the Descriptor parameters are calibrated, they are set for the simulation of the first model with a design rain event with 100 year return period. As a result of the simulation flow, an input flow for the second model occurs, later this model is simulated with the inflow from the first model and design rain event.

5.2.7 Design rain event

Design rain event represents statistical characteristics of rainfall. It is derived from the analysis of the data with many years of rainfall records. Design rain is usually used to cover future rain events. In this study design rain events with 100 year return and duration of 60, 90, 120, 180, 240, 300, 360, 720, 1080, 1440, 2160, 2880, 4320 minutes are created based on Pecher and DVWK distributions (LANUV, 2004). The model with the catchments above gauge is simulated with all design rains in order to choose a rain event that gives the highest runoff (Figure 25).

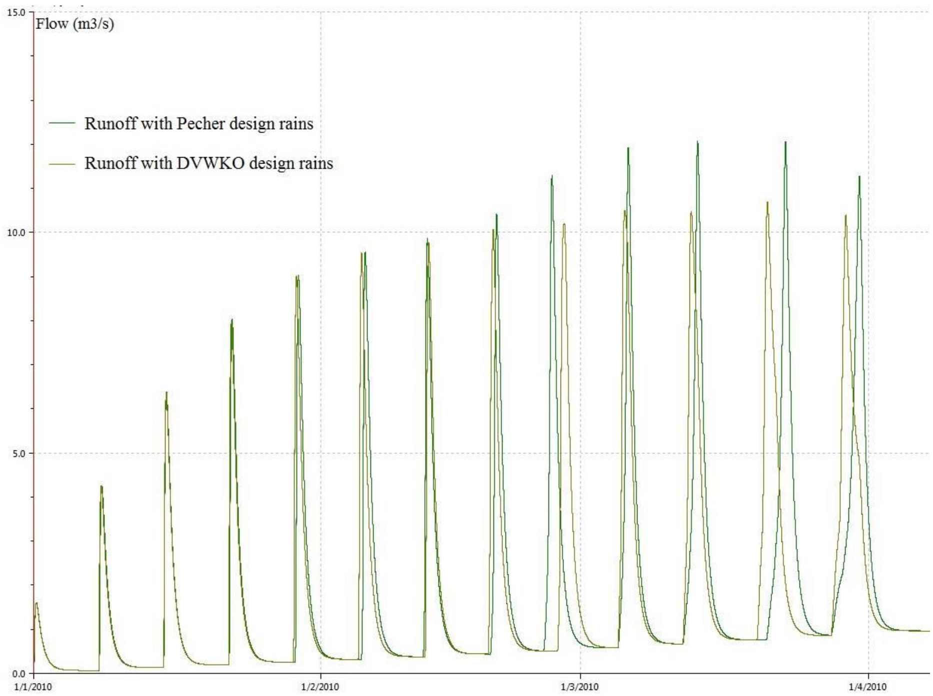

Figure 25. Design rain events HQ100 with duration of 60, 90, 120, 180, 240, 300, 360, 720, 1080, 1440, 2160, 2880, 4320 minutes

A line chart depicts flow over a period of time, showing upward moving till the next-to-last (2880 minutes) peak, where flows reach the highest values and moderately stop rising and start falling. That means that the Pecher design rain for two days gives the biggest runoff at the study considered river spot. This rain event is chosen for the flood modelling.

5.2.8 Baseflow

The model above the gauge calculates the baseflow within the calibration of PDM Descriptor. The mean average value of the baseflow is estimated and assigned as a constant value for the model below the gauge. The mean average baseflow is calculated to 0.4 cubic metres per second.

5.2.9 Coupled 1D-2D model

To complete model, the 1D network model is connected to the created 2D mesh. In order to calculate exchange flows between 1D and 2D zones, each manhole in the 1D network model needs to be assigned with the flood type. InfoWorks ICM allows to assign a manhole with one of the presented further flood types: “2D”, “gully 2D” or “inlet 2D”. By choosing “2D” type, the exchange water is calculated with use of weir equation. With “gully 2D” type, water is calculated using a Head Discharge relationship. And “inlet 2D” type uses user-defined inlet parameters. “2D” flood type is chosen for the study manholes.

6 Current state of the problem

According to the European Directive 2007/60/EC (2007), the authority of the German state North Rhine-Westphalia identified regions that might be flooded. Moreover, flood hazard maps and flood risk maps are prepared for the flood event with the probability of 10, 100, 500 year return period (Figure 26 and 27).

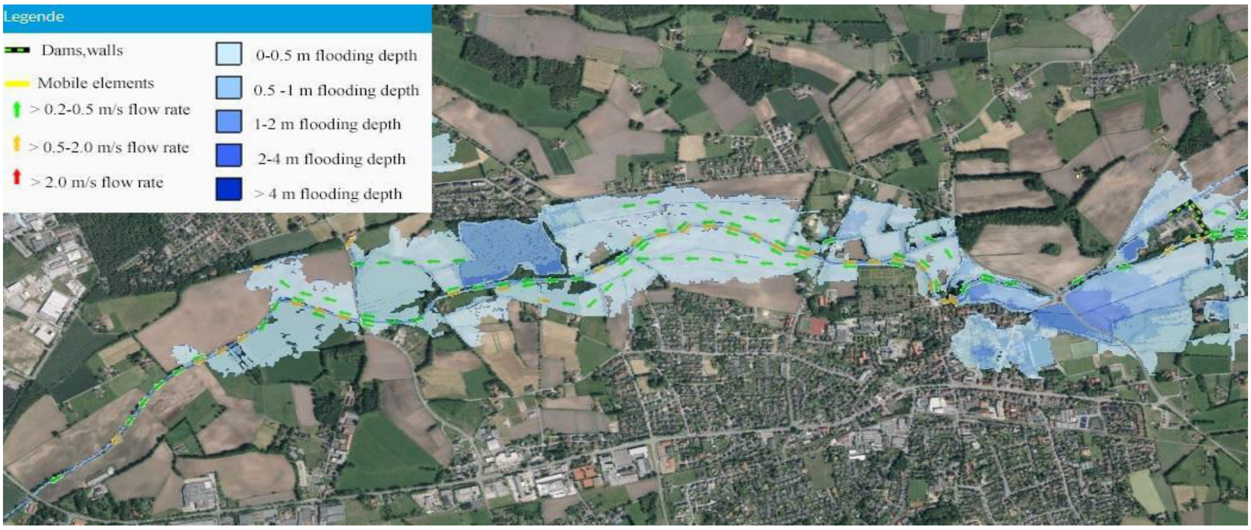

Figure 26. The flood hazard map for the study area with HQ100 (ELWAS Karte, 2016)

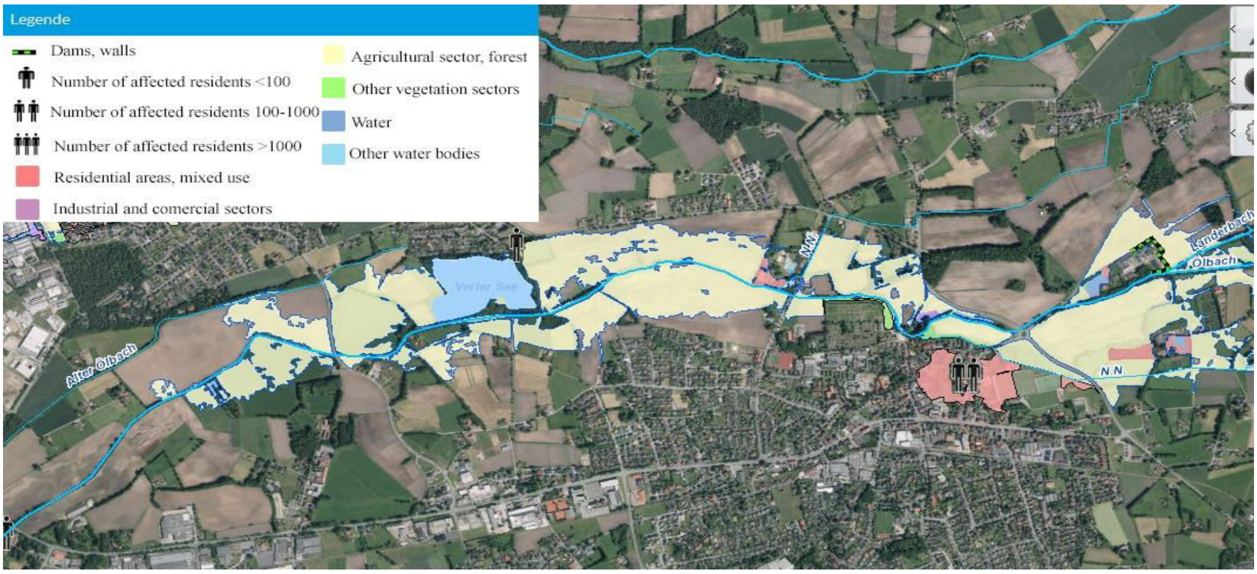

Figure 27. The flood risk map for the study area with HQ100 (ELWAS Karte, 2016)

The municipality of the city of Verl developed a construction plan in the new residential areas. However, planned constructions lie within the hazard and risk areas. Thus, the municipality is not allowed to begin building any structures within areas located in flood risk areas. However, the municipality doubts that this part of the city reside in flooding area due to the reason that none flooding occurred before in Verl. Therefore, the municipality is interested to make analysis and careful calculation for the river Ölbach.

My Diploma Thesis is implemented upon the request of the municipality order to assign accurate computational model and to provide accurate results from the model in accordance with the flood area of the river Ölbach in the territory of the planned constructions (Figure 28).

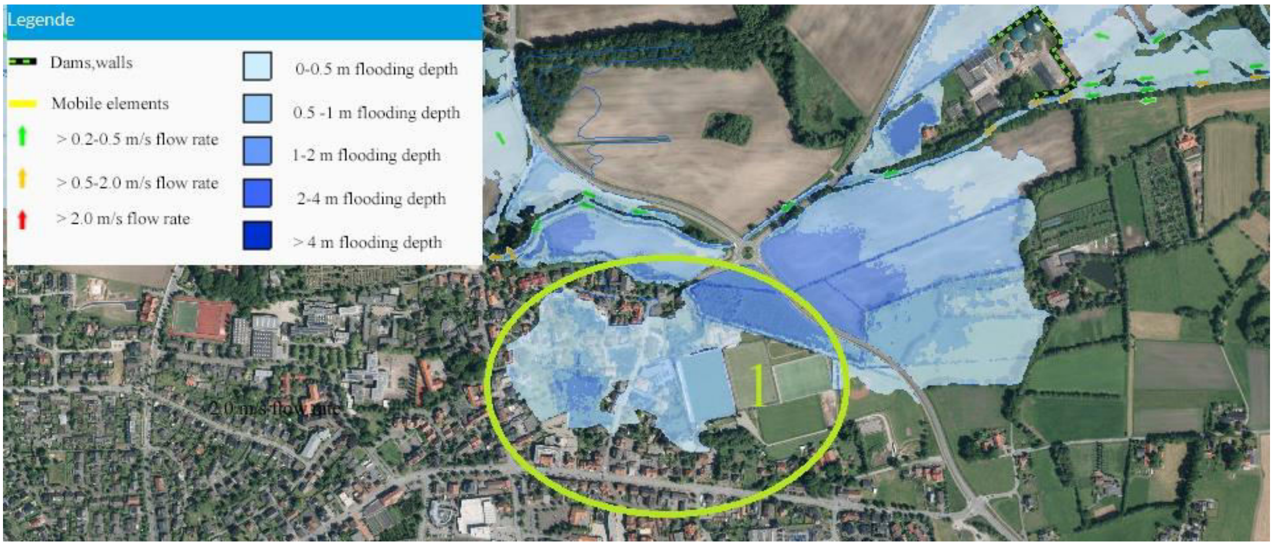

Figure 28. The flood hazard map for the study area with HQ100, where 1, the area of the planned constructions (ELWAS Karte, 2016).

7 Results and Discussions

7.1 Field trip and usage of the observed data

In this study a field trip takes place before the study model is assigned. The field trip is focused on the collection of the data relating to the area of the planned residential areas. Furthermore, the past and current condition of the catchments along Ölbach, appearance of high rain events, all unknown data regarding to the separate and combined systems and related problems are discussed with the authority during the field trip.

The following observed data are considered during the study modelling.

1. Location of the area of interest
2. Location and dimension of culverts around the area

The Figure 29 shows the most important points for the flood modelling in this study case.

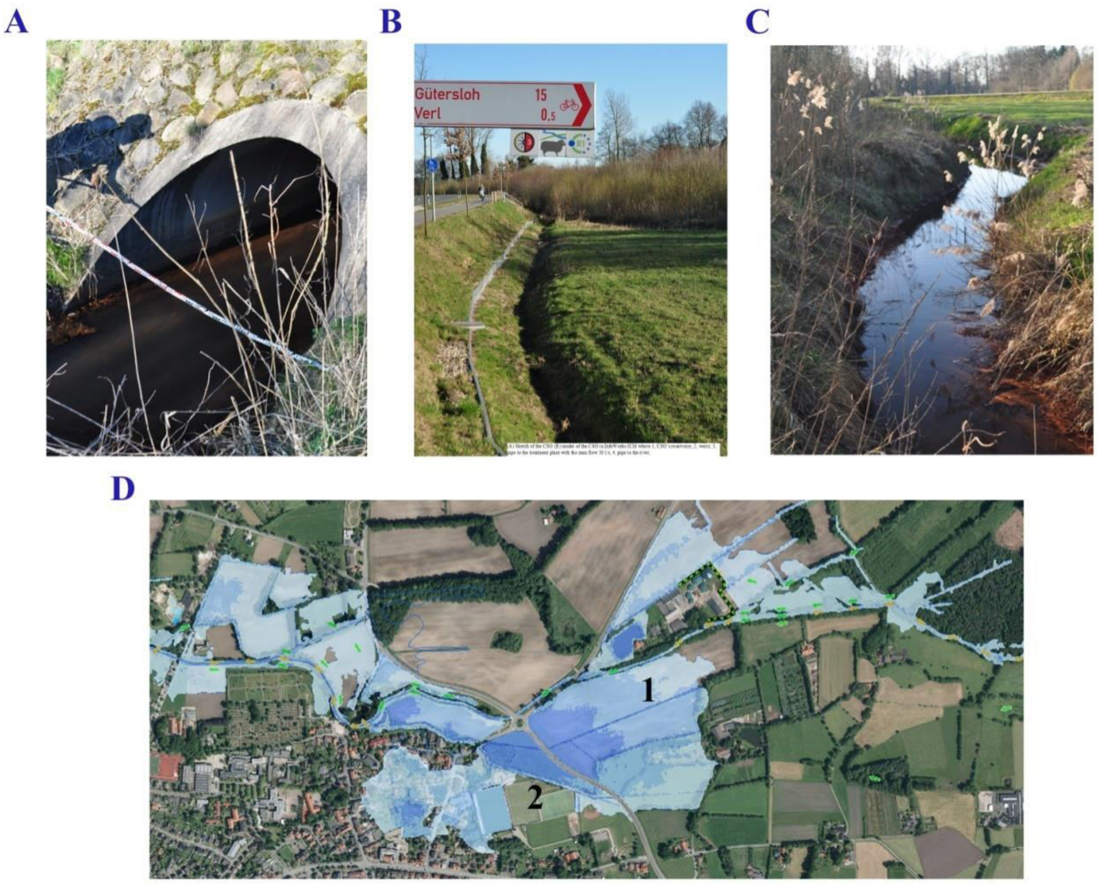

Figure 29. (A) the culvert that connects area 1 and 2 (photo D), (B) the trench along the road at the area 2 , (C) the channel of the stormwater system, that connects area 1 and 2.

7.2 Calibration

As it is mentioned in the Methodology part the parameters for the study model are automatically calibrated using the PDM Descriptor. In order to use calibration the following observed data are used: flow, rain and evaporation records from 01/07/1998 to 01/03/2003. Calibration results are presented in Figure 30.

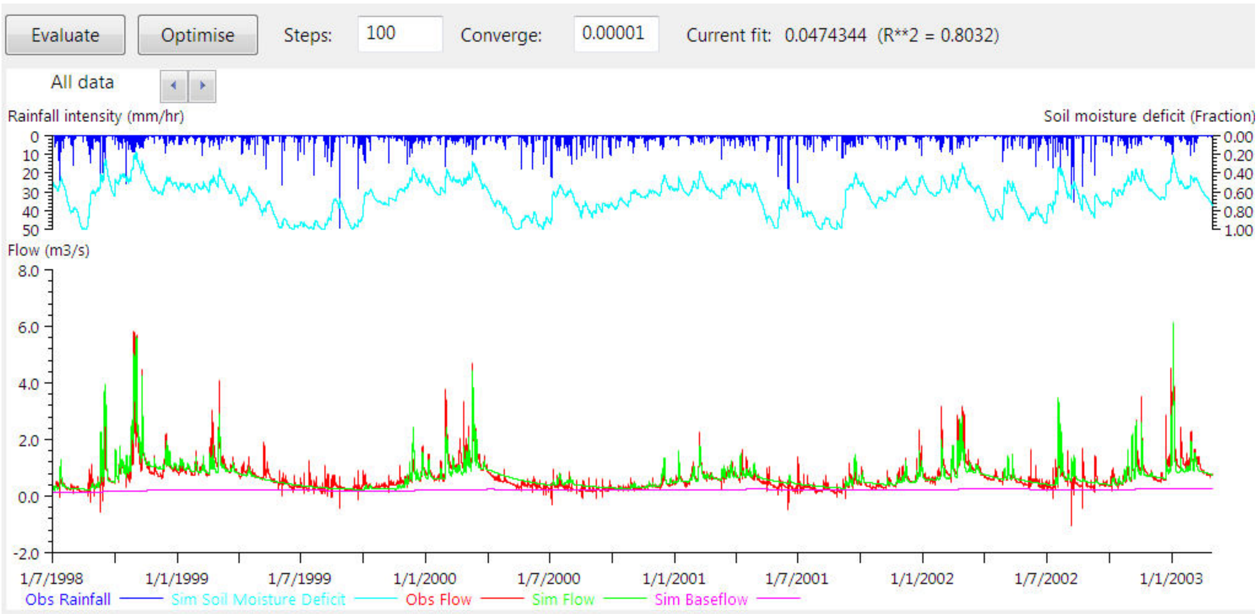

Figure 30. Calibration results

The mean of the squares of the differences at each time step are used as function for the comparison of simulated and observed flows. The Figure 32 shows that the study model is calibrated for the period from 1998 to 2003 with the R^2= 0.8032 value of the coefficient of determination or goodness of fit.

Further, the goodness of fit is checked for three most severe rain events within the indicated before period (Figure 31 and 32).

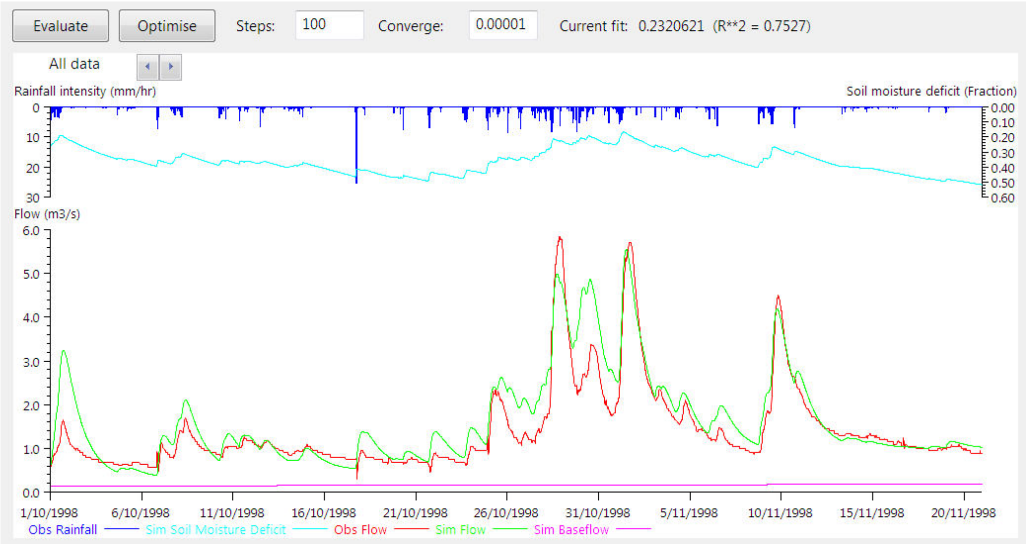

Figure 31. The calibration result for period 1/10/1998- 30/11/1998

During the period 1/10/1998-30/11/1998 two most severe rain events appeared, the coefficient of determination for entire period is R^2= 0.7527.

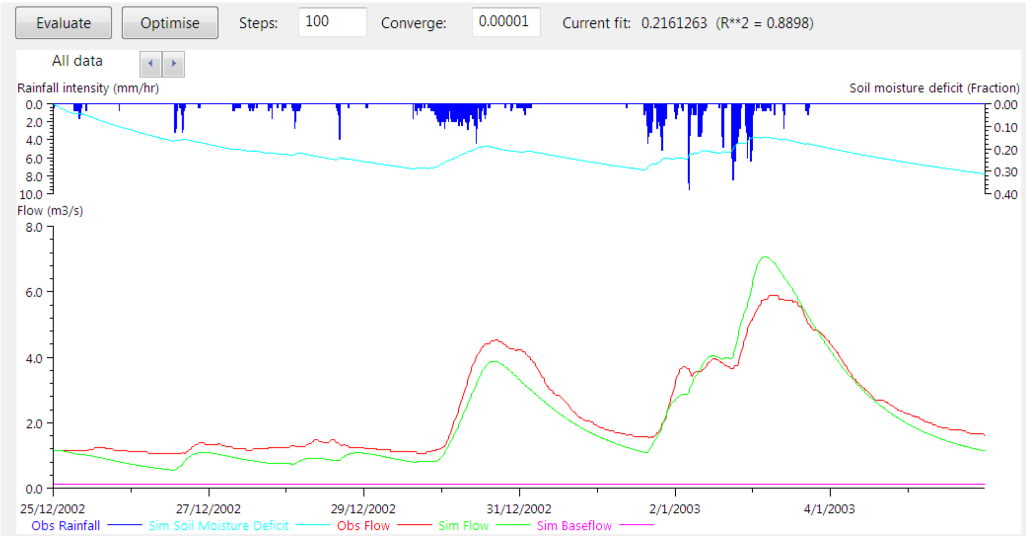

Figure 32. The calibration result for the rain events 25/12/2002-05/01/2003

The coefficient of determination for the period 25/12/2002-05/01/2003 is R^2 = 0.8898.

The model is validated due to the time limits and because of unexpected issues, and, furthermore, the calibration of the model is considered to be enough for this study.

7.3 Flood hazard assessment

The maximum flood extent for the design rain event of 100 year return period is calculated and shown in Figure 33.

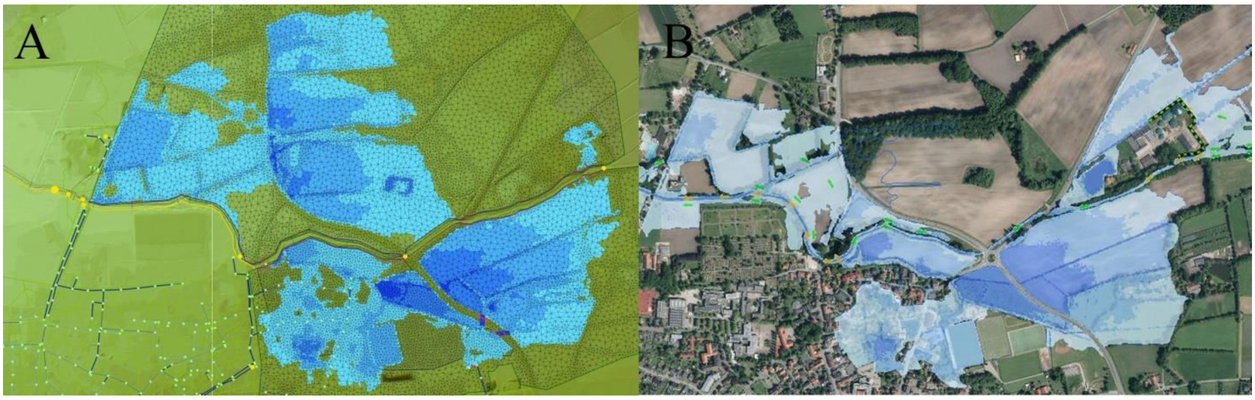

Figure 33. Flood extent for the HQ100 (A) calculated in this study (B) taken from ELWAS Karte (2016)

The Figure 33 illustrates the calculated flood extent by the study model and the one presented in the ELWAS Karte (2016). As it can be seen, the study model has proved that the planned constructions lie within the flood hazard area. However, the north part has a difference in the extension of the flooding. This might be explained by the difference in Digital Elevation Models.

In order to prevent the flooding in the area of interest, the model is modified. The network modifications are chosen with the consideration of the modeled flood areas, the local topology and the future expenses. InfoWorks ICM allows to view the replay of the results throughout the study simulation. Hence, this tool allows to view where the water, that flooded the area of interest, comes from. When viewing replays of the study simulation, it is captured that the water flows from the eastern field through culverts. Therefore, following changes in the network are done.

1. Since there is only one small spot with few buildings in the eastern field and the rest area is used for agriculture, it is decided to accumulate all water in the eastern field. As it is mentioned above, two culverts that connect the eastern area with the area of interest are found and their dimensions are measured during the field trip. Moreover, it is has been found that one of the channels is filled with mixed water but the second channel is dry and the reason for its existence is incomprehensible. Hence, it is decided to block the dry culvert.
2. In order to prevent the flooding flow from spilling into the channel the wall along the second channel has been set in the study model.
3. Since few buildings are located on the east field, the second wall has been set

around buildings to avoid their flooding.

All these modifications intended to prevent the area of interest from the flooding.

7.4 Flood hazard assessment with the implemented modifications

The maximum flood extent with the implemented modifications for the design rain event with 100 year return period is calculated and shown in Figure 34.

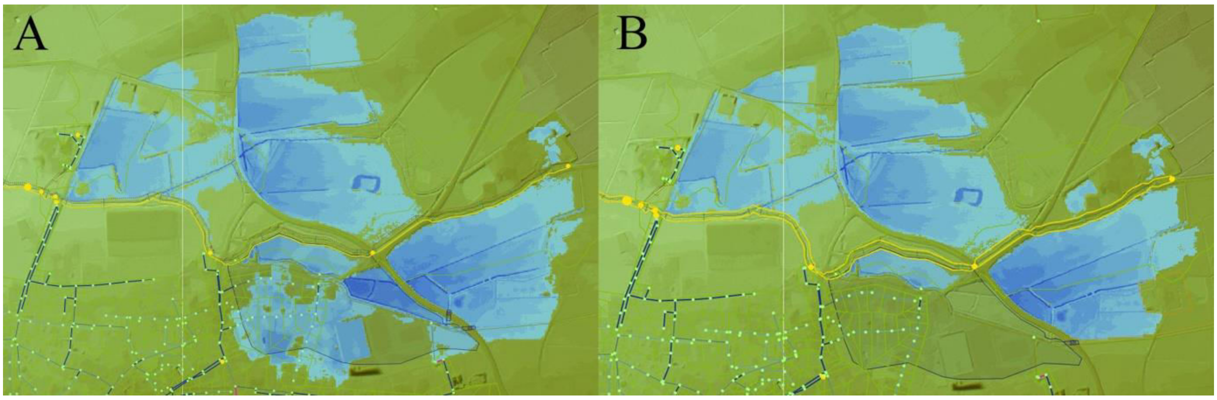

Figure 34. Flood extent for the HQ100 (A) without modifications (B) with modifications

Figure 34 illustrates that there is no flooding acquired in the area of interest with the use of network modifications. However, it is important to check that network modifications do not cause bigger flooding downstream. Therefore, the cross-section that is located downstream of the simulated part of the river has been chosen to compare the water level, velocity and flow for both simulations. The results in graphs are presented in Figure 35.

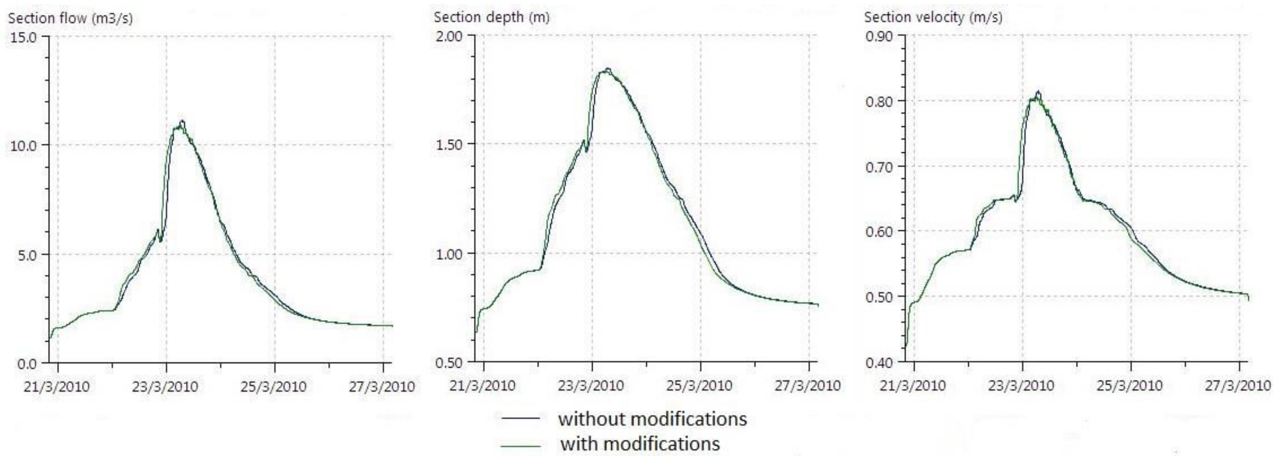

Figure 35. Comparison of two simulation results at the downstream cross section

As seen in Figure 35, the simulation results state that all the above mentioned parameters are not significantly varied, slightly higher values correspond to the first simulation, where scenario with no measures has been simulated. According these graphs it might be concluded that the mitigation measures do not cause an adverse effect on downstream areas. The eastern field (area of accumulation) is analysed further for following characteristics: 1- highest depth and 2- accumulative volume. Results are presented below (Figure 36 and 37).

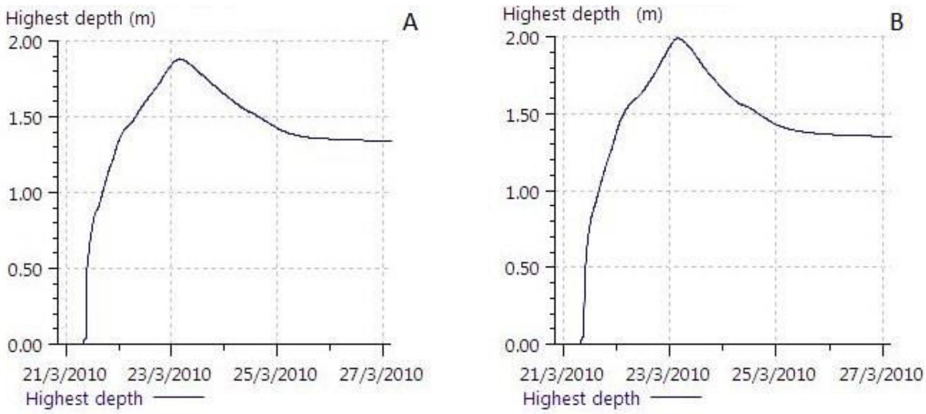

Figure 36. Highest depth for (A) the simulation without modifications (B) the simulation with modifications

As seen from graphs above the highest flood depth is appeared for the simulation with applied measures.

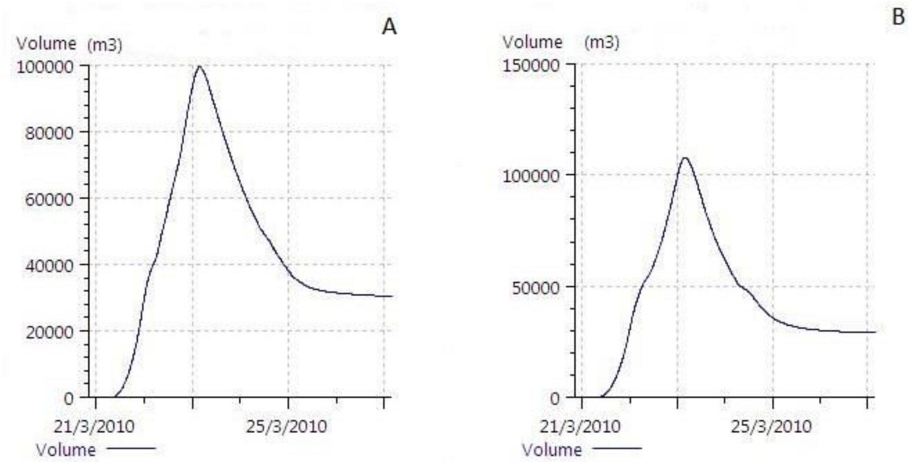

Figure 37. Accumulative volume for (A) the simulation without modifications (B) the simulation with modifications

Both results (Figure 36 and 37) are reasonable as the approach was to handle as much as possible water within the agriculture area (eastern field) for the simulation with modifications.

In order to completely evaluate the differences in the simulated scenarios the water balance has been checked for both simulations, results are presented in Table 5.

Table 5. 2D results with the calculation of mass balance error

	North Mesh Zone		South Mesh Zone	
	Without modifications	With modifications	Without modifications	With modifications
Initial volume (m3)	0.00	0.00	0.00	0.00
Final volume (m3)	63,820.44	68,281.64	56,456.27	30,892.19
Inflow (m3)	880,695.43	985,897.54	2,690,499.78	2,520,385.85
Total outflow (m3) :	868,420.02	964,954.11	2,647,652.63	2,498,082.97
1. ouflow to river banks	816,552.88	905,244.06	2,647,652.63	2,498,082.97
2. boundaries	51,867.14	59,710.06		
Water balance error (%)	**5.85**	**4.80**	**0.51**	**0.34**

As seen, the mass balance of the North Mesh is higher than of the South one. It might be explained by the following causes:

1. A high timestep for the simulation, a timestep of 60 seconds has been used in this study, although the recommended value for a 1D-2D calculation is 10 seconds or less (Innovyze, 2017).
2. Instabilities in 1D model due to oscillations between the 1D and 2D and poor convergence are considered as the second appropriate cause of mass balance error in this study case (Innovyze, 2017).

Furthermore, regarding to Table 5, by closing the culvert between two fields more water has been flowing at the North Mesh zone. However, as it is seen from the study, the simulation has a different area of flooding than the estimated by the state. The latter is assumed due to the accuracy of the Digital Elevation Model. The high resolution DEM is used in this study case, however, it is not clear if the study DEM has a better quality than DEM that is used at calculations by the federal state. According to Alrajhi, et al. (2016) and Peckham, et al. (2007) DEM has a crucial role in the flood modelling. Hence, it is important to check its quality and accuracy for the project results.

Moreover, the Digital Surface Model (further referred as DSM) is not available for this study, so it cannot be concluded that during this study the real impact of the flooding is estimated. According to Aktaruzzaman (2011) and Nalbantis, et al. (2017) in order to assess the adequate impact of the flooding on the urban area and to take appropriate measures for flood mitigation the high resolution surface data are required. Therefore, the use of high resolution DSM would be beneficial for our study case and it is strongly recommended for studies similar to this case.

In order to find the best measures for the flood inundation in the area of interest, alternative scenarios are needed. Due to time limits, the only one scenario has been applied. Chosen measures are considered to be beneficial as the study results are successful. However, alternative scenarios are needed to be implemented for the final results in order to find measures with lower society and environmental costs and higher efficiency. There are several tools that help to rank mitigation measures. One of the tools that might be used and become an essential tool for the flood management in Netherland according to Jonkman, et al. (2017) is cost-benefit analysis (further referred as CBA). The main principle of CBA is to assess all benefits that are generated by measures implementation over the cost of the measures (Jha, et al., 2012; Jonkman et al., 2017). CBA is considered to be time consuming and does not have a standard framework to apply in order to estimate all cost and benefits. Nevertheless, CBA provides rational information to the decision maker and gives her power to decide which options to use (Jha, et al., 2012; Jonkman et al., 2017).

The other tool and an alternative way to assess the mitigation measures is key figure assessment. According to DEFRA (2010) with the key figure assessment it is easier and quicker to make a decision about appropriate mitigation measures for a modeller. The key figure assessment helps to estimate effectiveness of mitigation measure by determining the main assessment indicators, more specifically: area of roads in square metres, number of flooded properties etc. (Ahlman, 2011; Larsson, 2012).

If to compare the both methods, CBA is more complicated and time consuming method however more reliable and strong tool (DEFRA, 2010). Moreover according to Larsson(2012) in small flood areas, as my case study, to use the key figure method is recommended as it is more beneficial and easier method than CBA.

8 Conclusion

In this study, InfoWorks ICM software has been used in order to create a coupled 1D/2D model and to estimate a flood extend along the river Ölbach in North Rhine-Westphalia federal state of Germany. At the beginning all geographical data are set in GIS, later all prepared data are imported to InfoWorks ICM. The model has been calibrated and flood area has been estimated. The impact analysis could not be done as the man-made terrain data were not available. However, the mitigation measures are suggested and flood area with consideration of suggested measures was estimated. The study model has shown that one of the culvert needs to be closed. Furthermore, it is required to build two walls in order to prevent the area of interest from flooding and to have permission to build new residential area in this area. During this study all established goals have been met.

The suggestions for future studies are formulated below:

1. According to Innovyze (2017) InfoWorks ICM has the ICM RiskMaster tool with the option to estimate the economic impact of floods relative to an estimated annual damage (EAD) value. Hence, it is recommended to use ICM RiskMaster for further analysis and projects similar this study case.
2. According to (DEFRA, 2010; Jha et al., 2012) the cost-benefit analysis as well as key figure methods are becoming a standard tool for the flood management and help to estimate the most beneficial mitigation measures. To make cost-benefit or key figure analysis of suggested measures seems to be reasonable in this project as well and can be recommended for projects similar to this study.

References

Ahlman, S. (2011). Plan B–hantering av översvämningar i tätorter vid extrema regn. SVU Rapport, 3. (Plan B -planning of urban floods caused by extreme rainfall) Svenskt Vatten AB, SVU Rapport 2011-03, Stockholm.

Aktaruzzaman, M., 2011. High Resolution Digital Surface Model (DSM) to Support Modelling of Urban Flooding.

Alrajhi, M., Khan, M.A. and Alobeid, A., 2016. INFLUENCE OF DEM IN WATERSHED MANAGEMENT AS FLOOD ZONATION MAPPING. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 41.

Beniston, M., Stephenson, D.B., Christensen, O.B., Ferro, C.A., Frei, C., Goyette, S., Halsnaes, K., Holt, T., Jylhä, K., Koffi, B. and Palutikof, J., 2007. Future extreme events in European climate: an exploration of regional climate model projections. Climatic change, 81(1), pp.71-95.

Butler, D., & Davies, J. (2010). Urban Drainage, Third Edition (3 edition). London ; New York: CRC Press.

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). Applied Hydrology. McGraw-Hill Series in Water Resources and Environmental Engineering.

DEFRA. (2010). Surface Water Management Plan Technical Guidance. Department for Environment, Food and Rural Affairs, Flood Management Division, London, March 2010.

Dunnett, N., & Clayden, A. (2007). Rain Gardens: Managing Water Sustainably in the Garden and Designed Landscape (1st edition). Portland, Or: Timber Press, Incorporated.

ELWAS Karte. (2016). ELWAS Karte. Viewed 31 February 7, 2017, <http://www.elwasweb.nrw.de/elwas-web/index.jsf#>

EM-DAT. (2016, December 19). Disaster Profiles. Viewed January 28, 2017, from <http://www.emdat.be/disaster_profiles/index.html>

Protection, C., 2007. Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the assessment and management of flood risks. Hosang, W., & Bischof, W. (1998). Abwassertechnik (11 edition). Stuttgart: Teubner Verlag.

ICE. (2001). Learning to live with Rivers. Final Report of the ICE's Presidential Commision the Review the Technical Aspects of Flood Risk Management in England and Wales. The Institution of Civil Engineers, London. [Institution of Civil Engineers].

Innovyze. (2017). Innovyze - InfoWorks ICM - Integrated Catchment Modeling. User Manual.

Jha, A. K., Bloch, R., & Lamond, J. (2012). Cities and Flooding: A Guide to Integrated Urban Flood Risk Management for the 21st Century. World Bank Publications.

Jonkman, S.N., Brinkhuis-Jak, M. and Kok, M., 2017. Cost benefit analysis and flood damage mitigation in the Netherlands. Heron, 49 (1).

Klijn, F., De Bruijn, K., Ölfert, A., Penning-Rowsell, E., Simm, J. and Wallis, M., 2009. Flood risk assessment and flood risk management; an introduction and guidance based on experiences and findings of FLOODsite (an EU-funded integrated project). Deltares.

LANUV. (2004). LANUV: Ermittlung von Bemessungsabflüssen nach DIN 19700 in Nordrhein-Westfalenar. (Determination of flow outlets according to DIN 19700 in North Rhine-Westphalia in German).

Larsson, J., 2012. Assessment of flood mitigation measures-Further development of a proactive methodology applied in a suburban area in Gothenburg.

Maidment, D.R., 2002. Arc Hydro: GIS for water resources (Vol. 1). ESRI, Inc..

Mein, R.G. and Larson, C.L., 1973. Modeling infiltration during a steady rain. Water resources research, 9(2), pp.384-394.

MKULNV. (2015). Hochwasserrisiko-Management Schritte zum zukunftsfähigen Umgang mit den Risiken durch Hochwasser in Nordrhein-Westfalen.(Flood risk management Steps for the future-oriented handling of the risks caused by floods in North Rhine-Westphalia in German).

Moore, R.J., 2007. The PDM rainfall-runoff model. Hydrology and Earth System Sciences Discussions, 11(1), pp.483-499.

Nalbantis, I., Papageorgaki, I., Sioras, P. and Ioannidis, C., 2017. Effect of uncertainty in Digital Surface Models on the extent of inundated areas. Hydrological Processes.

Peckham, R. J., & Jordan, G. (2007). Digital Terrain Modelling: Development and Applications in a Policy Support Environment. Springer Science & Business Media.

Robbins, P., Hintz, J., & Moore, S. A. (2011). Environment and Society: A Critical Introduction (1 edition). Wiley-Blackwell.

Schanze, J., Zeman, E., & Marsalek, J. (2007). Flood Risk Management: Hazards, Vulnerability and Mitigation Measures. Springer Science & Business Media.

Schumann, A. H. (2011). Flood Risk Assessment and Management: How to Specify Hydrological Loads, Their Consequences and Uncertainties. Springer Science & Business Media.

Unated Nations. (2013). World population projected to reach 9.6 billion by 2050 | UN DESA | United Nations Department of Economic and Social Affairs. June 13, 2013.

United Nations. (2014). World's population increasingly urban with more than half living in urban areas | UN DESA | United Nations Department of Economic and Social Affairs. October 7, 2014.

Werker, H., Schmitt, T.G., Alt, K., Hofmann, J. and Treunert, E., Chr. Bennerscheidt, S. Ellerhorst, A. Kaste und A. Schmidt (2012), Dezentrale Niederschlagswasserbehandlung in Trennsystemen-Umsetzung des Trennerlasses NRW. Teil 2: Vergleichbarkeit von dezentralen und zentralen Behandlungen. Korrespondenz Abwasser, Abfall, 59(5), pp.426-436.

Worldometers. (2016). Water consumption Statistics - Worldometers. Viewed January 12, 2017, <http://www.worldometers.info/water/>.