

Vitena Xhori BSc

Development of a Mine Water Management Model

Mine Water Management Practices with GoldSim

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Supervisor:

Dirk Muschalla, Univ.-Prof. Dr.-Ing.

Assisting adviser:

Salvador Jordana, MSc

Institute of Urban Water Management and Landscape Water Engineering

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Contact:
Vitena Xhori
v.xhori@student.tugraz.at

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Abstract

A practical tool has been created to allow the evaluation of mine water management. This tool can significantly influence environmental impact assessment, as it can anticipate the consequences of a given mine's operation. Additionally, it can be of significant benefit for the overall reduction of capital and operational costs. The numerical program GoldSim was instrumental in the implementation of this tool, determining not only the volume of water in the ponds and the water inflows and discharges, but also the final total emission of contaminants into receiving waters. These calculations were performed using simulations based on numerical test data.

It was discovered that the obtained results correspond to the well-known laws of mass conservation and respect the interplay within the mine and environmental compartments. Such a tool could be used in the future to model real-world mining site operations whilst using a probabilistic approach.

Kurzfassung

Ein praktisches Werkzeug wurde erstellt, um die Wasserversorgung sowie -Entsorgung im Bergbaubetrieb evaluieren zu können. Dadurch dass dieses Werkzeug die Einflüsse des Minenbetriebes prognostiziert, kann die Umweltverträglichkeitsprüfung bedeutsam erleichtert werden. Unter anderem können auch die Investitions- und Betriebskosten reduziert werden. Für die Umsetzung des Werkzeuges wird das Programm GoldSim verwendet womit die Wasservolumina in unterschiedlichen Becken des Minenbetriebes, deren Zu- und Abflüsse sowie die Schadstoffemissionen im Vorfluter ermittelt werden können. Die Berechnungen wurden anhand von Simulationen basierend auf fiktiven numerischen Daten durchgeführt.

Es wurde festgestellt, dass die erhaltenen Ergebnisse den Gesetzen der Massenerhaltung, sowie den Zusammenhängen zwischen der Mine und ihrer umgrenzenden Umwelt entsprechen. Das Werkzeug kann in Zukunft weiterverwendet werden, um tatsächliche Bergbaubetriebe zu modellieren, sowie um Systemunsicherheiten unter Verwendung probabilistischer Methoden erkennen zu können.

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List of Abbreviations

WWTP	Wastewater treatment plant
AMD	Acid mine drainage
RAPS	Reducing and Alkalinity Producing Systems

1 **Introduction**^[MR1]

In this chapter the main aspects of this project are being introduced. These include the context, objectives and perspectives of the thesis. As the topic is linked with environmental impacts, these will also be described in the following shortly.

1.1 **Context of the Project**

In the mining industry, water must be managed properly in order to generate a minimum impact on the environment. The impact can result from freshwater retrieval, from aquifers or rivers for the mining activities, or water pollution due to the spill of toxins.

Maximum performance of the whole system must be achieved with minimum cost and minimum impact on the environment. In this project, a tool will be created to calculate the quantities of water inflow and outflow between the different compartments of the water management system. The tool should help engineers to design wastewater treatment plants, basins, pipes, channels, dams and pumping equipment for the mining environment. Further, it should be able to simulate different scenarios and evaluate their results.

1.2 **Environmental Impact**

As the water used in the mining industry is mostly highly contaminated with chemical compounds that can cause health risks, it is important to know the possible impacts on the surrounding environment. These impacts display themselves through erosion, formation of sinkholes, and contamination of soil with the resulting loss of biodiversity. This project is mostly aimed at the surface and groundwater contamination, which is indicated by the contamination of aquifers. Therefore, it is important to know the quantity and quality of the infiltrated water through the soil.

The developed tool however, focuses more on the transport of material through water. Therefore, further impacts as a result of the erosion of exposed hillsides, mine dumps and tailings dams will not be considered because these impacts re-

sult from the contamination of the rivers and creeks in the surrounding area. Furthermore, these processes are linked to a large amount of input data, which is hard to obtain in the proper time from different sort of expertise.

The impacts are unique, depending on the combination of the main activity of the mine and the geologic formation of the soil. The contamination can also affect the health of the local population. Therefore, strict limits on the concentrations of substances in the effluent are in place, according to the defined norms specific to the monitored site. This way, the effects on the environment and the health risk will be minimized. Furthermore, environmental and rehabilitation codes have to be followed, ensuring that after closing the mine, the area can be returned to its original state.

The environmental impact from the mining industry depends on the location of the mine. In the wilderness, destruction and disturbance of ecosystems and habitats may occur. In rural farming areas, productive grazing and croplands can be affected negatively.

1.3 Objectives and Overview

The main objectives of this project are to check the functional stability of the different reservoirs according to their dimensions and the environment as a whole. Another important aspect is to monitor water reuse and recycling within the mining processes, to reduce runoff. These tasks will be executed using an approved environmental simulation software, which allows an estimate of the concentration of different chemical compounds in various waterways. The obtained results will be interpreted as a prediction of how a mining operation can affect the environment. This prediction can be extrapolated to two different time stages: i) during the active life of the mine and ii) after its closure. It is of significant importance to forecast the long term effects of a mine after its closure. Within this project, only the first stage will be investigated, in order to maintain objectivity, which in this case is to investigate if the created model can generally used for water management practices in mines. To that effect, only one stage of mine operations is being investigated.

According to these predictions, optimisations will be made for planning and design of the water reservoirs and the functionality of the various compartments will be checked. This way, the developed tool will help future engineers designing wastewater treatment plants, basins, pipes, channels, dams and pumping elements for the mining environment. The main goal is to maximise the performance of the whole system while minimising cost and environmental impact.

2 Literature Review

For understanding the topic of this thesis and the created model it is important to introduce some substantive definitions and coherences. These are obtained by reviewing available literature concerning both topics: i) water management in general and ii) its specific preconditions in the mining site. As mentioned before, the mining operations have an effect on the environment. This is especially true for the mine's water cycle, which is affected by the natural water cycle and vice versa.

2.1 Hydrology

2.1.1 Hydrologic monitoring

In this project, the transport of water and dissolved chemical compounds will be examined. Therefore, it is important to consider the inputs from the hydrology's side. These inputs are to be delivered from baseline hydrological monitoring. In the different phases of mine development, the hydrological data is evaluated during the later stages of the exploration phase. This affects the conceptual design and has a significant importance on the feasibility study, especially on the evaluation of the proposed mining project, to determine whether the mineral resources can be managed economically or not.

The baseline surface water monitoring provides information on both water quality and water flow. The term "baseline" is preferred to refer to current conditions of water quality and "pre-mining" to describe those conditions that likely existed during the few hundred to few thousand years before mining took place (Nordstrom, 2008). The data is obtained by continuous monitoring of the surface water and collected samples, which chemical consistency is examined. This way, the chemical loads and potential impacts on aquatic resources can be calculated. There should be monitoring installed upstream and downstream of the investigated location. Mines are often located in remote areas lacking historical precipitation and runoff data, which heightens the need for hydrological monitoring in order to estimate the missing data (EPA Region 10, 2003a).

The ground water conditions are more difficult and expensive to define, as additional data about the depth and location of the water table is needed, which can only be collected by probing the ground on various locations.

For every monitored variable, it is important to run quality control and validation checks on the data, in order to fulfil the desired regulatory and public disclosure requirements. These are mostly requirements on the representivity and allowed range of different types of error in the measurement data. A detailed information on that is found in the Guide to Climatological Practices, carried out by the World Meteorological Organization.

2.1.3 Hydrological impacts

To assess the hydrological impacts of a mine site, the first step is to identify areas that might be affected by mining activities. When the excavation in a mine intersects the water table of the area, various impacts of mining on hydrogeology of the area are immediately being felt (Pradipta, 2014). Then their significance has to be categorised according to the physical, chemical and biological resources that they affect. The impacts will be divided between surface and subsurface impacts.

Surface impacts are mostly the result of the actual construction of the mine and its facilities. Road construction, logging, mills and the construction of process facilities can reduce infiltration and increase the amount of surface runoff to streams and other surface water bodies.

Furthermore, channelization can increase the flow velocity in the streams. A higher velocity causes an increase of erosion in the upstream areas and therefore, a higher amount of sediment occurrence in the downstream areas.

The construction of stream diversions or storm water ditches induces changes on natural drainage patterns and can therefore impact vegetation resources, wetlands and wildlife habitats (EPA Region 10, 2003a).

Once the mine goes online, withdrawals from water bodies might be needed in order to regulate the water quantity and quality in several ponds that are needed

to maintain the mine. The ponds are needed in order to store and move the water in various sections of the mine. The withdrawals can affect aquatic habitats as they reduce the natural stream flow. At critical times of the year such as dry periods, a minimum flow has to be sustained. On the other hand, on high runoff periods, the operational flow should be maintained. If much water is entering the mining site, it can result in an overflow at the mine

Ground water flow regimes are primarily caused by mine dewatering activities and pumping water supply wells (EPA Region 10, 2003a). This can affect the direction of the ground water flow by shifting gradients and waterline to the mine or the well. The water drawdown can reduce spring and seep flows. The most critical impact is the actual formation of the depression cone by water pumping in order to process the ore. (EPA Region 10, 2003)

2.2 Water management in mines

2.2.2 Hydrological cycle in mine

The hydrological cycle is the continuous circulation and distribution of water through elements of the environment (EPA Region 10, 2003a). The hydrological cycle on a mine site is particularly irregular, due to the different hydrological components, as well as the natural and process water circulation. The natural water cycle consists of natural system water such as ground water and meteoric water from precipitation, snow melt, evaporation and runoff and follows the natural hydrological cycle (EPA Region 10, 2003a). In comparison to the normal natural hydrological cycle on the surface, the process of transpiration is not included, as most mining sites are located in areas with no vegetation. The complexity here lies in defining the variability of the various parameters influenced by the hydrology. Process system waters have, however, a constant and predictable flow over time.

The key issues lie in defining the interactions between the two different water systems. The quality of water entering the mine's hydrological cycle is similar to the one in nature (excluding urban wastewaters, which are channelled to a WWTP). The mine waters on the other hand have very different characteristics

but the hydrological processes are mostly the same. The natural water cycle is illustrated in Figure 1 and so is the mine water cycle in the following Figure 2.

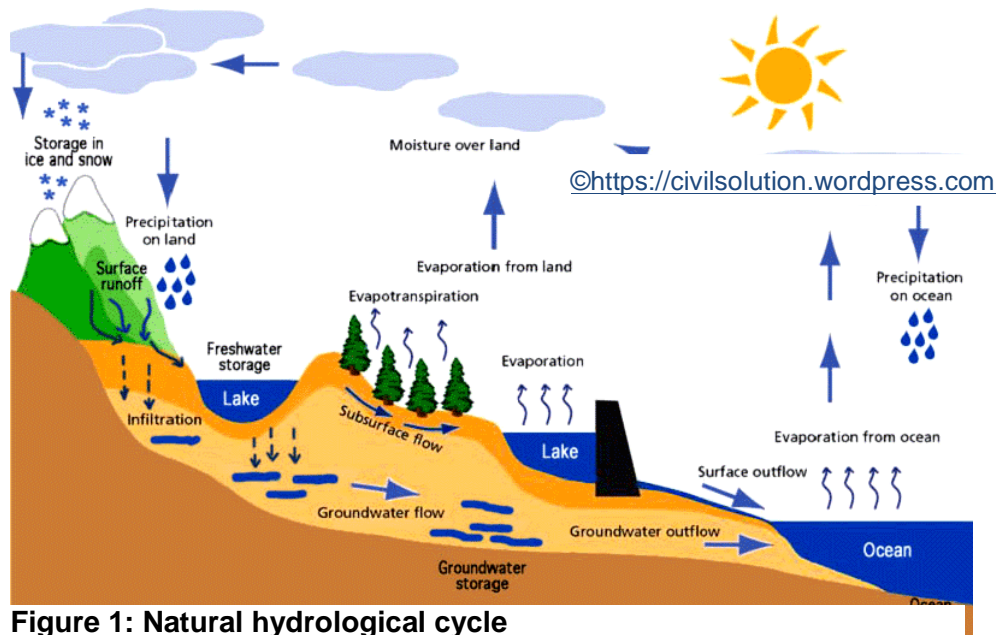


Figure 1: Natural hydrological cycle

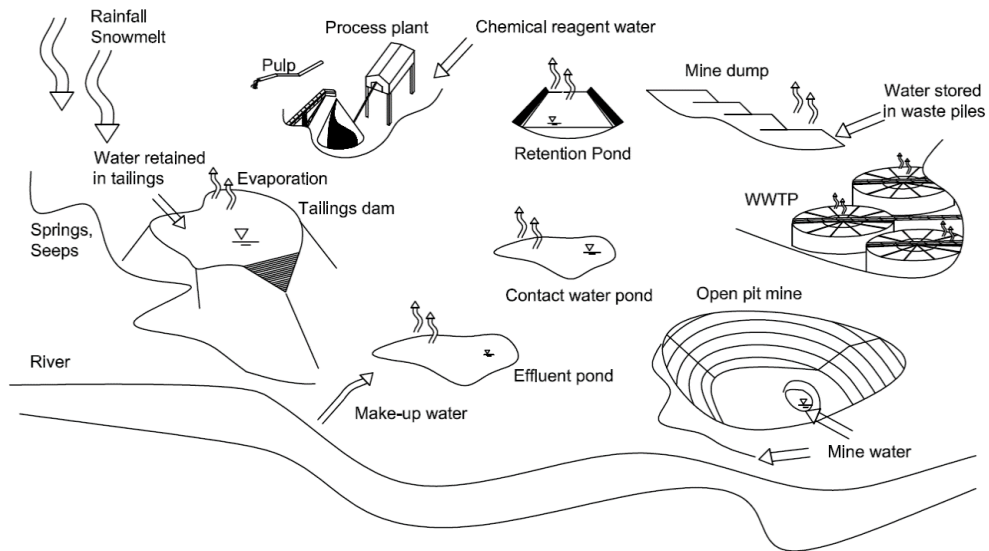


Figure 2 water systems in a mine site

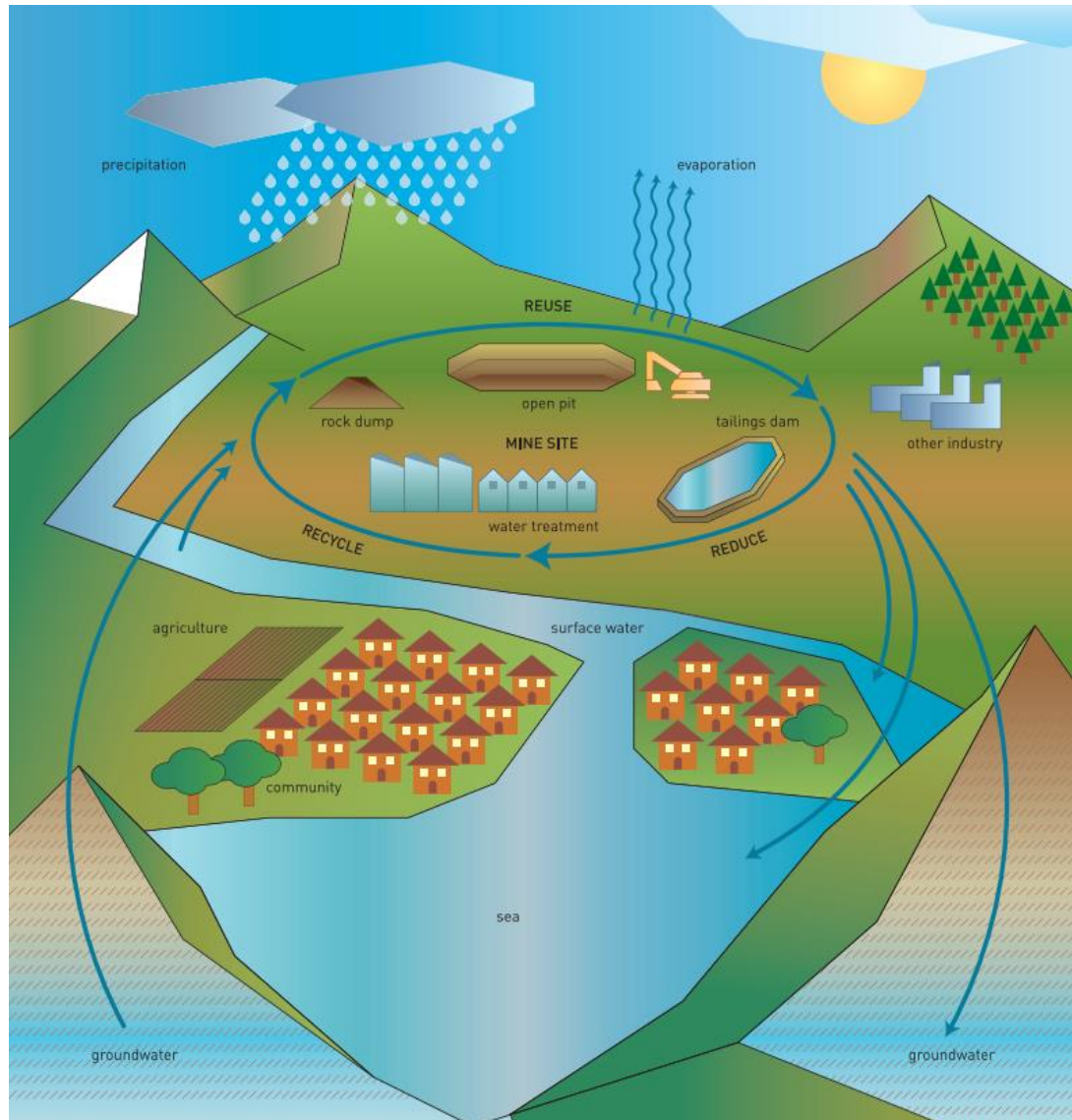


Figure 3 Hydrological Cycle in Mining (ICMM, 2012)

Within the natural hydrological water cycle, the difference between the sum of water entering the system and the sum leaving the system is equal to the mass stored in the ponds of the system as shown in Equation 1.

$$Precipitation + Inflow = Evaporation + Runoff + Change in Storage$$

Equation 1

To better understand the hydrological cycle of a mine however, definitions of new water categories (as shown in Figure 4) are needed to explain their interactions with each other. In terms of mass balance, the difference between the inflow and outflow from both natural and industrial waters in the soil as a form of infiltration or in surrounding waters is equal to the amount of water stored or reused during a later time in the artificial ponds.

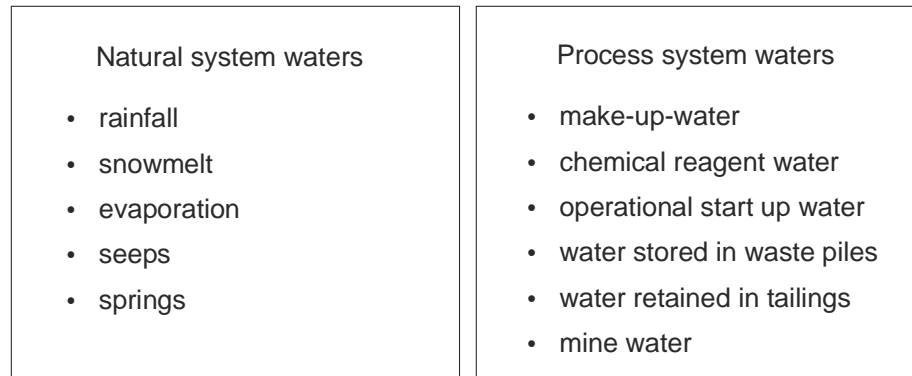


Figure 4 Natural and process system in a mine

As shown in the graphics above, natural water due to rainfall, snowmelt, seeps, springs, river retrieval and similar ways enter the mine site. These waters increase the volume of the artificial ponds and enter the system as make-up water, operational start-up water, mine water and similar. They are stored for a definite period of time in the ponds (as necessary) and used in a certain time for the continuation of mine operations. The entering waters leave the mine water system by exfiltration into the soil, evaporation or necessary discharges in the surrounding rivers or lakes. This is further discussed in Chapter 2.2 Water management in mines.

2.2.1 Receiving waters

The definition of receiving water in this context is the quantity of surface and ground water which receive treated or untreated discharges from the mine site. (EPA Region 10, 2003b)

The contaminant concentration in these waters is different depending on the quantity and quality of the waters they receive. Hence, it is important to make a classification of the receiving waters according to the mining activities they are related to. The main activity of the mine consists in crushing and milling the ore to obtain the desired mineral. This operation is similar to many other processes of a mine site and their impacts on the water supplies. This connection is shown in Figure 5, according to the time development.

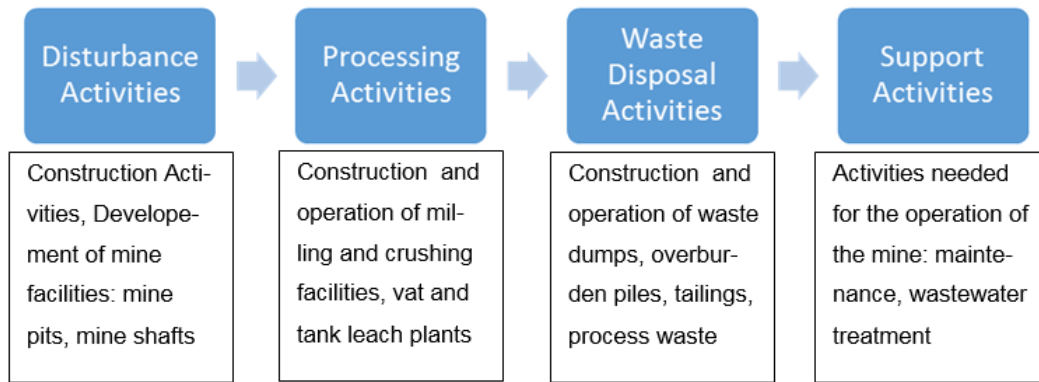


Figure 5 Mining activities influencing the receiving waters, adt. (EPA Region 10, 2003b)

The *disturbance activities* consist of preparatory activities which assist the *processing activities*. They include construction activities of developing the mine facilities. Within these, excavations, demolishing and bursting activities are needed to create the mine pits, shafts, open cuts and so on (EPA Region 10, 2003b). Since they disturb the native soil structure and vegetation, they have high impact on existing surface and groundwater by exposing the mineralized rock. On the other hand, the risk is even higher because their construction is associated with negative changes in erosion and sedimentation characteristics of the existing soil which lead directly to the increase of the watershed pollution. This happens due to the release of contaminants and their transportation through precipitation runoff and mine water. Here precipitation means all the material, dry or wet, that falls from the atmosphere to the earth surface (Gujer, 2006). The risk of pollution depends on the type of mineralization, the degree of the aquifer's disruption and the specific disturbance operation.

Processing activities are mainly summarized in the process of the main operation, which is the separation of the minerals from the surrounding material in a mine (EPA Region 10, 2003b). This can occur in different methods such as grinding or crushing. Both of them imply the use of water. Included in the processing activities are the construction and operation of the facilities in which these processes occur, such as flotation concentrators and the needed wastewater treatment plant. The water gets polluted during its first contact with the mineral, but the level of contamination depends on the type of ore being processed and the type of processing activities. Leaks in the pipeline system, storage pond overflow and other

facility failures are other reasons for contamination of the aquifers and therefore of the receiving waters.

Both, *disturbance* and *processing activities*, result in the production of wastewater and solid waste, thus *waste disposal activities* are needed. The overburden material is being deposited in overburden piles. These aim to expose the mineralized rock, excavated from the mine pit, which can contaminate the watershed by polluting the runoff by releasing sediments. In order to prevent this, the runoff water is caught and derived to the effluent water pond.

Depending on the process activities and the characteristics of the water that comes in contact with the ore, many of the tailings impoundments are toxic and should be isolated from the receiving waters. The main reasons for this include the existing soil minerals and used reagents i.e. cyanide, for subtracting the ore from compounding material, which remain in the tailings and might seep into the ground water.

Support activities are the required additional activities needed for the day-to-day operation of the mine's primary activities. More specifically, this means the equipment maintenance, fuel storage, wastewater treatment and so on.

Contamination risks are higher for the surface waters in case of failure of the essential facilities, such as spills and leakages of transport fuels and oils, and other equipment facilities (EPA Region 10, 2003b) . Further, infiltration of part of the runoff from a fuel storage leak can lead to an indirect contaminant pathway to the groundwater.

2.2.2 Wastewater

As mentioned before, many of the process or natural waters have been exposed to the mining activities and therefore need to be treated. In order to have best management practice over these waters, a categorization of the waters according to their chemical composition and consistence will be made. This way, it is easier to fulfil the predetermined restrictions for discharges, and also to maximize the reuse and recycling possibilities.

In general, there are three types of wastewater: mine drainage, process water and storm water associated with industrial activity.

Mine drainage water is understood to be any type of water that will be drained, pumped or siphoned from an active mining area. (EPA Region 10, 2003c)

These are waters that come from an open pit mine, waters drained from a subterranean mine or water that is discharged from a mine adit, which is the entrance to the mine. Usually in the field of mining industry research, this mine drainage water is referred to as AMD (acid mine drainage) due to its low pH level.

Process waters in this context are the waters used in diverse mining processes. The contamination of these waters is normally higher than that of mine drainage, as they directly get in contact with the ore and chemical reagents. The mill effluent, tailings impoundments, leach piles and ponds are typical examples of process waters. (EPA Region 10, 2003c)

Unlike drainage water, *storm water associated with industrial activity* is storm water that will not be directly discharged but used in manufacturing and raw material processing. Here, this term includes the storm water runoff that is in contact with the waste rock, overburden or tailings dams. (EPA Region 10, 2003c) This type of water, is one of the most concerning ones, as it cannot be prevented from entering the mine water system.

Under certain conditions, regulated by various legal constraints (depending on the specific country the mine is situated in), direct discharges of storm water are allowed.

2.2.3 Wastewater treatment

The main purpose of wastewater treatment is to meet the water quality standards for the effluent to receiving waters or for reuse within the mining operations. Knowing the proper wastewater treatment method is a key point in modelling the water management in mines, because treatment efficiency has to be considered in order to define the nature and grade of contamination in receiving waters. In

order to choose the best possible wastewater treatment method, in terms of treatment practices and economic efficiency, treatability testing has to be carried out.

These tests are facilitated either through laboratory tests on actual samples taken from the mine site or through pilot-scale testing. As mentioned in the EPA regulations, in EPA Region 10, 2003c: *“laboratory tests samples are taken directly from the mine site, or mining design studies and their composition tested to evaluate whether the specific regulatory and permitted limits on the samples are met or not, parameters such as metal concentrations, hardness of water, pH, TDS and trace components are to be investigated”*. This way, it can be determined if the proposed treatment method meets the regulatory restrictions on effluent quality and possible improvements.

The pilot-scale testing is similar to laboratory testing. The difference is that the samples are taken in a different way. In this case, pilot plants are used to test the treatability. Samples are taken from the mine water inflow and effluent of the pilot plant. By testing continuous effluent samples on a 24-hour/day operation, credible baseline information is developed to establish reliable design parameters for a treatment plant (SGS MINERALS SERVICES, 2015). Effluent characterization is conducted by analysing a sample of effluent to provide information on the concentrations of potential contaminants in the mine effluent (Metal Mining Technical Guidance for Environmental Effects Monitoring). Later on, a full treatment plant can be designed with the results of the treatability tests.

The design aims to meet treatment goals and reliability standards, as well as reducing investments and operating costs. In dealing with innovative technology proposals, extreme conditions on site and specific treatment goals, a more detailed and site-specific testing scheme can be devised, rather than to rely solely on the two introduced testing schemes of this chapter. These methods, however, will not be discussed further in this thesis.

For the modelling of the water management in mines, it is important to know which treatment method will be used in order to rate the WWTP's effectiveness and calculate the contaminants concentration in its outflow. There are two main categories of waste treatment: active and passive treatment. They both share similarities to the treatment methods used in treating urban wastewater, as they

rely on the same physio-chemical and bio-chemical principals. The type and dimensions of the treatment plant depend on the composition of the effluent matrix, but also on the volume of wastewater discharges.

It is therefore of interest to know the exact water flows in the system and to diminish the amount of water that needs to be treated in order to reduce costs. Furthermore, this way environmental benefits are yielded from both, reduced energy consumption and reduction of toxic waste. To achieve this, different methods such as source control, water reuse and recycling have to be considered.

Source control refers to cutting the wastewater flow directly from its source, by reducing the contact between receiving waters and pollution sources. (EPA Region 10, 2003c) This method consists of capturing uncontaminated water, and diverting it to prevent contact with possible contaminating mining activities or waste rock. By building upstream dams, the surface water such as rain and snowmelt runoff, streams and creeks can be diverted. The clearest example of this practice is the isolation of surface runoff around the tailings dam and directing it straight to the effluent. The precipitation water at the mine site can be captured through the use of liners and pipes and fed directly into the tailings dam so it does not influence the groundwater quality.

Evaporation ponds are another option to decreasing the volume of water that needs to be discharged. In general, they have the function of separating the residual ore from water by natural evaporation and at the same time, limiting the volume of water that needs to be treated. Another form of prevention practices is the reuse of water. For instance, the clean runoff captured from the mine pit will be channelled to the effluent pond and reused to supply other ponds when they hit their lower limits of their water levels. Tailings ponds also have additional groundwater monitoring facilities in order to capture runoff. The water is taken from the surface by using catching towers, surface pumps or simple siphons. These facilities are located in the tailings dam water surface. Thereafter, the water will be filtered through the dam material and recuperated from the pipe channelization. The water caught, will be channelled to the tailing's water surface again, or will be used in the water mine system. (*Construcción y operación de tranques de relaves*, 2003)

In addition to this practice, the water can also be recycled. This happens at the tailings dam, due to the precipitation of the dissolved solid matter. The clearer surface water can be collected by water intake towers, surface pumps or siphons, and reused within the facilities. The water seeped through the dam can be caught by drainage pipes, and then be diverted to the mining activities that require water. For a higher efficiency of this scheme, a water management plan has to be implemented in the planning process of the tailings dam. Due to the complexity of the process, and the uncertainty in knowing the recycled amount of water, this portion will not be considered in this project's introduced water management tool, as its prediction alone could fill another entire thesis and is better merited on a case-by-case basis.

In order to have better results on pollution prevention, a combination of the above mentioned techniques may be applied.

As mentioned before, every mine site is unique and has different operational requirements that influence the selection of the method. The hydrologic factors precipitation and evaporation rate affect the suitability of each technique the most.

2.2.1.1 Active treating of mining wastewater

The active treating of mining wastewater can occur in fixed plants or in-situ portable plants. It includes four different stages, which comprise: removal of metals, cyanide treatment, solid-liquid separation and sludge removal.

The main purposes of each of these stages will be discussed in this section. The treatment methods are principally based on the treatment of AMD and its particular features are described in the following.

As the mine drainage is naturally rich in metals, the first and most important stage of the active water treatment is their removal. This occurs via different methods using mostly physical, chemical and biological technologies. (EPA Region 10, 2003c)

Precipitation is the principle used in most of active treatment methods, wherein the pH of the wastewater is constantly adjusted in order to decrease the solubility of occurring sulphate salts that contain metals. Chemical precipitants such as

hydroxide, sulphide or combination of them both are added to back up this process. Other methods are available, though again, this is tangential to the current thesis.

Cyanide solution (NaCN) is commonly used in gold mines to separate gold from the ore as its use is a safer alternative to the previous use of mercury leaching. In some mines cyanide is also used to suppress iron. As a result, cyanide, cyanide-metal complexes or cyanide breakdown products such as ammonia, nitrates, and nitrites are present in the wastewater produced. Due to its toxicity cyanide must not reach high concentrations in receiving waters and should rather be destroyed chemically within the mine's wastewater treatment.

By using chlorine in the cyanide destruction process, extremely toxic chlorine and chloramines remain as residual waste and have to be removed before discharge in the receiving waters. (EPA Region 10, 2003c)

The third stage of the active treatment of wastewater is liquid-solid separation. After treating the metals and the destruction of cyanide compounds, the remaining solid compounds of metals, hydroxides and sulphides have to be removed. This occurs in three steps: coagulation, gravity separation and filtration.

The main purpose of coagulation is to increase the effective diameter of the metal compounds, allowing them to settle more effectively, ready them for gravity separation and the later separation from the liquid by filtration. (EPA Region 10, 2003c)

Coagulation is the process in which metal compounds absorb given chemical coagulants under certain conditions of pH, concentration, mixing time and temperature. By further mechanical mixing of the composite, the solid particles form flocs. The flocs are pumped to a clarifier, where they are permitted an appropriate amount of time for settling (EPA Region 10, 2003c). The product of this process is the sludge, which will later be removed. The third step of metal removal is filtration. It is required to extract the fine particles of metals in order to meet the effluent discharge limits.

The remaining waste of the previous process, the sludge, is in liquid form but has up to 20% solid particles. Commonly the sludge will be disposed of in a tailings pond or pit lakes, an appropriate landfill, or backfilled into mine voids.

(Zinck, 2006) The sludge management practices depend on the restrictions met at the mine site. Other treatment methods are needed than the one chosen if the sludge contains undesired amounts of chemical compounds with higher concentrations than permitted. On the other hand, sludge of coal-mines can be used for phosphorus and other metal removal from municipal waste water.

(Wei, Viadero Jr., et al., 2008)

The final step of waste water treatment is the discharge of the treated water into the receiving waters (through the effluent water pond), or its further use in the mining system.

The following table gives an overview of the most common active waste water treatment practices used in different countries.

Table 1 Active wastewater treatment (EPA Region 10, 2003c)

Treatment Stage	Treatment method	Description	Use
1. Metal removal	a	Chemical Precipitation Use of chemical reagents like: caustic soda, sulphide, ferric iron to convert soluble metals into insoluble metals and then conglomerate them into large heavy particles.	Conventional Method for Mine influenced water in the mine site
	b	Ion Exchange Adsorption of metal ions through solid porous particles with reactive surfaces and displacement of the removed metals from this created compound by adding solution of concentration ions, such as sodium chloride	For mining influenced water low in TDS (<500mg/L)
	c	Reverse Osmosis Separation of pollutants from the clean water by forcing the mining influenced water through a semi-permeable membrane using pressure	For removing metals to very low levels and will also reduce TDS up to 10-25mg/l
	d	Carbon Adsorption Use of activated carbon to adsorb organic materials, which degrade under anaerobic conditions creating sulphide that form insoluble sulfidic salts with the metals in wastewater and will be removed through filtration	Conventional Method for Mine influenced water in the mine site
	e	Biological Treatment Use of bacteria for bio sorption of toxic heavy metals and suspended solids	For mining influenced water in anaerobic conditions near neutral pH
2. Cyanide Destruction	a	Alkaline Chlorination Process Use of chlorine (Cl) under alkaline conditions to destroy cyanide through oxidation	For mining influenced water in gold mines and floatation processes aiming iron suppressing
	b	Hydrogen Peroxide Process Use of hydrogen peroxide(H ₂ O ₂) under alkaline conditions to destroy cyanide through oxidation	For mining influenced water in gold mines and floatation processes aiming iron suppressing
	c	Sulfur Dioxide/Air Process Destruction of cyanide using a mixture of sulphur dioxide, sodium sulphite, or sodium meta-bisulphite and air or use of pure sulphur dioxide while presence of air is not required	For mining influenced water in gold mines and floatation processes aiming iron suppressing
	d	Biological Treatment of Cyanide Destruction of cyanide and subsequent chemical complexation of free metals within biomass by oxidative breakdown	For mining influenced water in gold mines and floatation processes aiming iron suppressing
	e	Natural Degradation Natural degradation of cyanide through volatilization, oxidation, photodecomposition, precipitation, hydrolysis and adsorption to solids in specially designed tailing ponds that enhance the natural degradation process	For mining influenced water in gold mines and floatation processes aiming iron suppressing while the tailings pond does not discharge into natural waters
	3. Solid-Liquid Separation	Use of chemical coagulants in order to agglomerate solid metal compounds into flocs and then separate them from liquid through settling and then remove them by filtering	Conventional Method for Mine influenced water in the mine site
	4. Sludge Removal	Dewatering of the remaining liquid waste and disposal of the sludge while its disposal method depends on the characteristics and the local regulatory restrictions	Conventional Method for Mine influenced water in the mine site

2.2.1.2 Passive treating of mining wastewater

Passive treatment systems focus on preventing the metal and gypsum armouring of the water while speeding its metal precipitation. The basic principle is observed in nature in wetlands. Man-made passive treatment facilities vary in their form, but use mainly the same principles as wetlands, such as hydroxide and sulphide precipitation, or pH adjustment. Commonly organic matter is added to the system in order to decrease the soil redox potential. Most of the techniques introduced in this section are still undergoing research and are only used at pilot mining sites. (Ford, 2003)

The use of passive treatment systems on a mine site is more beneficial to the mining industry in comparison to the active ones because of their low maintenance requirements, low energy demand, and the simplicity of its back-up supply. Consequently, passive treatment systems are cost effective and can be operated over a long time period. On the other hand, the efficiency of these systems is mostly linked to certain natural boundary conditions of the influent's quality, water temperature, retention time and other reaction specific factors. (Ford, 2003) Therefore, their use is preferable during the mine's post-closing stage or for low acidity AMD. To choose the proper passive treatment method, AMD characteristics need to be quantified. This happens by quantifying the "Acidity" and "Acidity Load" which are linked with the concentration of Calcium Carbonate (CaCO_3) since the dissolution of this substance in water affects the pH change causing acidity. While the term "Acidity" describes the mass of CaCO_3 in the unit of volume of water at a certain time, the "Acidity load" refers to the transport of CaCO_3 mass for an affirmative period of time, usually given in the unit of time (per day) as it is easier to measure. (Ford, 2003)

In case of wetlands, the "Acidity Load" is given in terms of mass per area instead of time. The so-called RAPS (Reducing and Alkalinity Producing Systems) constrain all of the water to contact the compost and limestone. They are generally much more efficient in treatment terms than simple compost wetlands, and hence require far smaller land areas to provide the same level of treatment (Younger, Banwart, et al., 2002). Used in a concrete example from (Hasche and Wolkersdorfer), within a relatively small pilot plant, total iron could be reduced by about

50 %, the alkalinity increased, and the acidity decreased significantly, resulting in a slightly net alkaline mine water. An overview of this and other common used methods of passive wastewater treatment methods is given in Table 2.

Table 2 Passive wastewater treatment from K. L. Ford (2003)

Treatment method	Description	AMD Properties					
		mg CaCO ₃ /l	CaCO ₃	Flow Rate (l/s)	Oxygen Concentration	Typical pH range	Max pH attainable
1. Oxic/Open limestone Drain	Open channels containing coarse limestone aggregate constructed on existing mine drainage or on artificial drains	<500	<150 kg/d	<20	Ambient	>2	6-8
2. Anoxic Limestone Drain	Layers of coarse limestone encased with low permeability liner capped with clay to avoid air accessibility	<500	<150 kg/d	<20	<1	>2	6-8
3. Limestone Diversion Wells	Well containing crushed limestone aggregate that clarifies AMD by using attrition grinding and abrasion of the limestone gravel.	<500	1-1000 kg/d	<1000	Ambient	>2	6-8
4. Pyrolusite® Limestone Beds	Limestone beds or channels containing organic matter (algae) in order to treat AMD high in manganese or for the iron removal	<500	1-500 kg/d	Permit maximum residence time	Ambient	>2	6-8
5. Wetlands	<u>Aerobic</u> : Shallow ponds that contain vegetation planted in relatively impermeable sediments. Process of metal oxidation precipitation within the wetland occur in presence of air	<500	<1 kg/300m ²	Permit maximum residence time e.g. 1-5	Ambient	>6	n/a
	<u>Anaerobic</u> : In these wetlands, AMD treatment takes place partly into organic matter, which deprive oxygen from the water and is therefore an anaerobic process	<500	1 kg/300m ²	Permit maximum residence time e.g. 1-5	Ambient near surface <1mg/l subsurface	>2,5	6-8
6. Reducing and Alkalinity producing systems (RAPS)	AMD that needs to be treated will be ponded upon a mixture of organic matter and limestone gravel which generate alkalinity via the limestone dissolution and sulphate reducing bacteria. Improved reducing conditions and sites for metal adsorption are provided.	<300	<100kg/d	<15	<1-3 mg/l	>2,5	6-8
7. Permeable reactive barriers	In-situ treatment of AMD in order to prevent groundwater pollution by using buried layers of reactive material (organic matter, limestone, zero valent iron) in which acidity of AMD is consumed and metals precipitate.	<500	1-5 tonne/yr.	<1	Relatively reduced	>3	>6,5
8. Slag leach beds	Same treatment principle as by Oxic Limestone Drains, but instead of limestone aggregate, fine-coarse slag is used to raise pH of water to above 10 and thus boost metal precipitation	<1000	1-2 tonne/yr.	<20	Ambient	>1,5	10
9. Sulphide passivation	Passivation (decreasing activity with surrounding air or water) of mine pit walls in order to reduce interactions with AMD by using micro-capsulation technologies like: plastics, polymers, cementation or chemicals				-		
10. Electrochemical covers	Application of conduction steel mesh cathode in the upper tailings surface that are low in sulphides magnesium metal anode to generate hydroxide alkalinity by consuming oxygen. Oxygen migration is therefore prevented, which results in avoiding AMD production				-		
11. Alkalinity producing covers	Use of magnesium-based materials calcium enriched caustic magnesia MgO) as covers on waste rock piles in order to increase alkalinity to infiltrating rainwater and passivate the flow pathways				-		
12. Gas redox and displacement systems	By proving an atmosphere within underground workings the air will be displaced from mine voids with a gas mixture of carbon dioxide aiming both physical displacement and chemical consumption of oxygen				-		

3 Modelling

Modelling always starts with an abstraction process. We reduce system complexity in regard of the questions that need to be answered (Gujer, 2008). In this sense, the different stages of modelling according to the chosen methodology are described and the actual model is presented in the following chapter.

3.1 Expectations and purpose of modelling

The objective of this project remains the pursuit of an appropriate program to model the entire water management in a mine site. The result of this modelling task is to create a tool in which the necessary mine processes linked to the water management can be incorporated. For this, various programs that serve this purpose will be tested. Once the most suitable software is chosen, the model will be created, the results investigated and its applicability assessed. In other words, the following questions need to be answered:

- Does the use of this program deliver the desired outputs? (Mass of contaminants in receiving waters, flows between different ponds, etc.)
- Can the input required from the tool be obtained?
- Is the level of complexity of this program reasonable?
- Is the scale of the obtained approach adequate to the real environmental system?
- Does this program give the engineer the opportunity to adjust different dimensions of the mine facilities in order to obtain optimal conditions of mining operations?
- Is the representation of results understandable for various stakeholders?

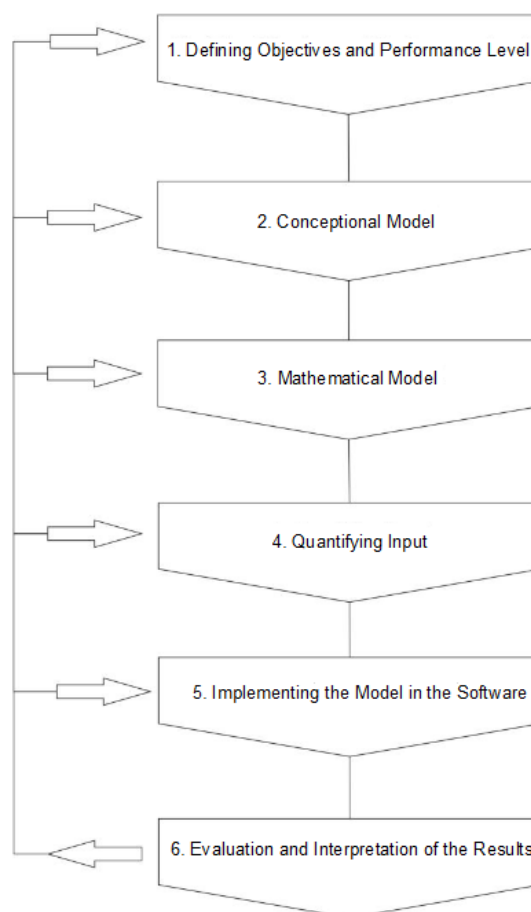
3.2 Methodology

There are two main methods for modelling an existing environmental system: top-down and bottom-up. While using the method bottom-up, high importance is given to every element of the system regardless of its position in the hierarchy of the whole system, whereas in the top-down method, the hierarchy is respected. (GoldSim Technology Group LLC, 2014) By the bottom-up method, high importance is given to every part of the model, whereby the way how this effects the total system is neglected. As the environment is a set of connected compartments, the use of a bottom-up method is completely impractical, because to heed every particular property of the compartments would lead to misdirection from the desired overall results of the system. Every subsection in the environment has its own way of functioning, related to a set of properties that are hard to obtain and has complicated impacts on the other parts of the system. The understanding of each and every characteristic of these compartments is therefore difficult. By using the top-down method higher importance is given to the whole system in comparison to each single subsection. As we are more interested in the functioning of the entire environmental scheme than the distinct parts, the correspondent modelling type to use, is the top-down one. Strictly speaking, the purpose of the model is the operation of the water cycle within the mine site. The needed inputs from each compartment will be subtracted depending on the way they affect the whole system.

In the following, the steps of the environmental modelling and the way it works will be shown and briefly described. Special importance will be given to its application in the actual task, while describing the single steps.

3.2.1 Stages of environmental modelling

The process of modelling an Environmental System following the top-down method is a cycle – when results are obtained, statements about the accuracy of each step can be made. This scheme is shown and described in Figure 6.



3.2.1.1 Defining

Figure 6 Schematic development of the top-down modelling method adapted (Thacker et. al, 2004). objectives and performance level

Before starting with the actual environmental modelling it is important to know why this model will be developed. In this project, the objective of the modelling is to know the flow rates in each water pond of the mine, the volume of water in each pond and the mass of contaminants released in the receiving waters. In the course of modelling, other results can be also obtained as a perk to help to better understand the interactions within the system itself. It is essential to define the performance level of the expected results, such as the scale of rigorosity of the results. As mentioned before, the objective of this project is to assure that the proposed tool for the modelling is working properly, thus it has to be proven that the correlations of the compartments with each other are correct. This can be affirmed by calibration and validation of the obtained results. The performance level of this allegation is to be shown qualitatively in form of graphs and also quantitatively while comparing the obtained results of the accumulated flows, ensuring they coincide with the law of conservation of mass.

3.2.1.2 Conceptual Model

The most important step is defining the conceptual model. It is a schematic depiction of the system in reality and the interactions within its subsystems. The correct understanding of the modelling task depends on the conceptual model, and an appropriate visualisation is essential. In other words, additional time invested on the conceptual model avoids confusion on later steps of modelling. Within this project, the conceptual model is a representation of all the elements of the mine in interaction with water (water ponds, facilities where water is used) and the boundaries to the surrounding environment (receiving waters and natural processes such precipitation, runoff, infiltration etc.). This stage of modelling is described in chapter 3.2.1.2 Conceptual Model.

3.2.1.3 Mathematical Model

The mathematical model is a further development of the conceptual model, where the linkage of the compartments is defined by mathematical expressions. Now the representation of the model is not only of a qualitative but also of a quantitative nature. Mathematical and logic expressions for the flow functions within the ponds and the surrounding environment are specified. More to this topic can be found in chapter 3.2.1.3 Mathematical Model.

3.2.1.4 Quantifying input

In the functions used for the mathematical model, usually the left side of the equations is an output and the right side of the expressions describes the inputs. Inputs are characteristics of the elements of the system or of the interactions between them. They are of different nature: constants or time-dependent functions. Before starting the actual modelling, it is important to know the importance of each input, the way it can be determined and the reliability of the obtained values. Mostly input data is linked with additional uncertainty, which leads to uncertainty in the results. In many modelling tasks, the input data is given with a probability distribution so the impacts on the results can be estimated better. The reliability of the input data is connected to many factors such as monitoring methods used, alteration over time and similar ones. Some of the inputs in the actual project are the precipitation/evaporation rate, change of pond area, infiltration rate etc. The input

data required depends also on the software used. This topic will be described further in chapter 4.2.1 Input data.

3.2.1.5 Implementing the model in the software

The next step is to transcribe the model in the chosen software. If the program to be used is not known yet, a viable program needs to be found first. In some cases, it may even be necessary to develop a new program in order to execute the desired simulation. In this project, four different programs were tested and evaluated in order to choose the most suitable one. This is all documented in chapter 4.1 Software overview.

After we defined which program is most appropriate, the mathematical model can be implemented in the way that the program requires it (“as per the manufacturer’s guidelines”). A very good understanding of the way the program works and its proper usage is therefore essential. In this stage the need of additional inputs has to be considered. More on this topic is found in the main chapter of this thesis, respectively 4.2 Simulator.

3.2.1.6 Evaluation and Interpretation of results

After running a simulation, the obtained results require proper evaluation. For that, a comparison with the expected outcomes need to be made. The main advantage of the top-down method of modelling is the fact that the overall functioning of the system is well-known, so that the results can be better evaluated.

If the results are not equivalent to the expected ones, changes have to be made starting from the first stage of this procedure: Defining objectives and performance level. If the mistake is not on this stage, then it has to be investigated on the following steps in order to make the needed changes, run the simulation again and evaluate the results. This cycle has to be repeated continuously until the error is found, and the desired results are obtained. When this occurs, the results need to be interpreted in such a way that the target audience can easily comprehend them.

For this, a good representation with the use of charts and a simple description is necessary. For example, when inputs are prioritised, the outputs will be prioritised too, and only the important ones represented.

In this project, the actual result has to confirm that the proposed tool can be used to simulate the mine water management in a real-world mine site. The grade of approximation has to be represented within different charts: flow rate between compartments, contamination level in each pond and the receiving waters, followed by a written explanation of how they correlate with each other.

The discussion about the results can be found in the final chapter, respectively chapter 0 4.2.4. Scenario and time conditions

The simulation simulates ten years, starting with the opening of the mine (without the pre-eliminatory work) and operating its operating time. This means for the inputs of volume in various ponds a value of zero. So firstly, they need to be filled with water. Because of the numerical issues of GoldSim, the Effluent Water Pond needs an initial volume at the starting time of the mine's operation, meaning the water is retrieved from the river before the defined simulation time. The time step is chosen to be a day to simplify the graph that presents the results and the precision of the numerical calculation of GoldSim.

Results.

3.3 Conceptual Model

The most time demanding process of modelling is creating the conceptual model, particularly when using the top-down way of modelling, where the most importance is given to the whole system functionality, rather than the details of its parts. In this sense it's very important that the modeller has a full understanding of the whole system, meaning the subsystems and their interactions as well. This stage of modelling focuses on the influence of the compartments on each other, but does not quantify them. Also, the boundary conditions to the outer environment are represented in some way. Once one has a stable conceptual model, where the connections and influences of the subsystems are represented, we can move forward to the next modelling stages.

In the water management system, the subsystems are the water reservoirs or water sources that also play the role of the boundaries between the actual system and the environment.

River: By river this model refers to the natural source of clean water in the system. This can also be a lake or a stream, depending on the size of the mine activities, and the water resources in that area. The water will be retrieved from the river as the primary source of fresh water.

Effluent water pond: Pond containing clean water that supplies the whole mine water system with fresh water coming from the river, tailings channel and so on. This water needs the water supply from the river, only in case that the pond hits its lower limit. In order to maintain lower costs and environmental impacts minimal amount of water taken from the river is striven.

Contact water pond: Pond containing contaminated water that comes from the mine operations, in the mine, and from the overflow of the retention pond. By overflow we mean the amount of water that moves from one pond to another, due to reaching the upper limit of the water volume in the pond. The contact water pond's overflow is channelled to the effluent water pond. As the effluent water pond is the main source of clean water in the whole mining system, this amount

of water flowing from contact water pond to effluent water pond needs to be treated first in the WTP.

Mine's water: In the mine there are two different sources of water. The definition of mine water refers to the surface water around the mine, which is captured from the mine channel before entering the mine. On the other hand, mining water is referred to the water that in any form comes in contact with the mining activities. This water is contaminated and will be sent to the contact water pond.

Process plant: Is where the separation of the water from the ore actually occurs. The water also contains process chemicals, depending on the sort of the mineral being extracted. The process water will be divided in two categories depending on its texture. The one containing the mineral in a nearly solid form, goes to the pulp. The other part, which has a higher water percentage than mineral, and therefore a fluid state, will be directed to the tailings dam.

Tailings dam: Dam containing contaminated water that comes from the process plant. Its inflow also contains minerals, which is separated by sedimentation. A certain amount of its recycled water is pumped to supply the contact water pond with water. Also in case of an overflow, the water will flow to the contact water pond.

Mine dump: The material coming from the mine that is of no further use because it is very low on minerals. It's stored on the mine site, and its volume gets bigger every year. Water coming from rainfall infiltrates through these materials and becomes contaminated. This water flows to the retention pond.

Retention pond: The amount of contaminated water that needs to be treated can be diminished by the usage of retention ponds in the mining system. This can happen by the natural process of evaporation. The infiltrated water from the mine dump will be stored in this pond. In case of overflow, the water flows to the contact pond.

WTP: Is the plant in which contaminated water will be treated according to the treatment methods described in the chapter 2.2.3 Wastewater treatment. Only if

the volume in the contact water pond reaches a certain level it will be treated in the WTP. The treated water is directed further to the effluent water pond.

The boundary conditions are defined by the processes precipitation, evapotranspiration and infiltration through the aquifers. The visual representation of this is very important, as it provides a better understanding of the environmental system. In the following, the conceptual model of the water management in a mine will be presented. This model can be applied to any mine site as it has the main parts of the water management system, but specific changes can be made, according to the number of ponds and boundary conditions.

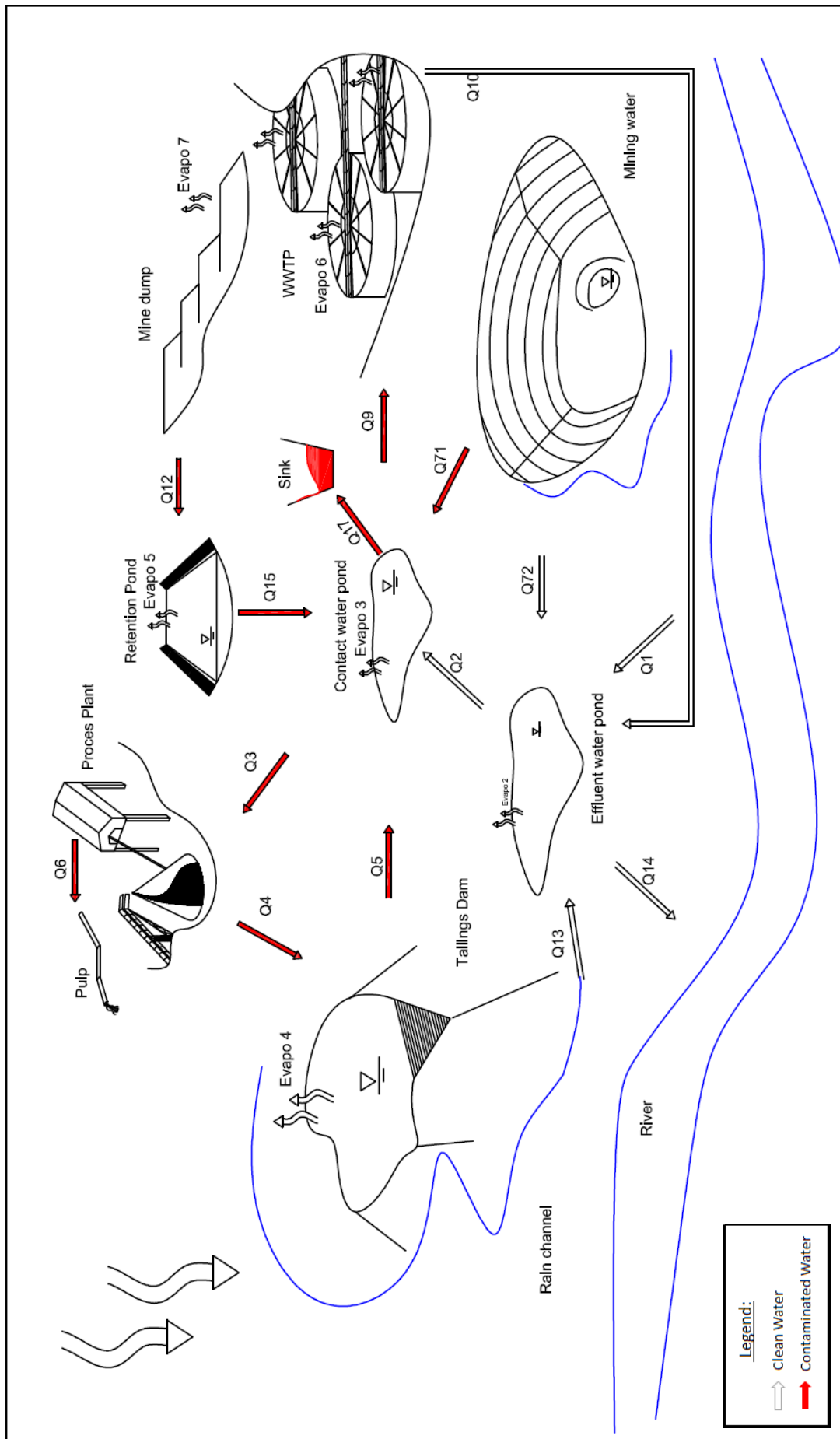


Figure 7 Conceptual model of a mine water management system

3.4 Mathematical Model

After the conceptual model is created, the next stage of modelling is creating the mathematical model. This means that the influences within the subsystems and the surrounding environment will be quantified. Mathematical as well as logical functions are also added to the definition of the interactions in the system. These functions are mass flow functions, and are mostly based on mass balance. The inputs are discussed further in this chapter. As this model follows a top-down approach, more importance is given to the whole system. In this sense, it is more accurate to focus on the way that subsystems link to each other, and later concentrate on the representation of needed inputs.

Assuming that the evaporation and precipitation rate during the whole year is given by the hydrogeological monitoring, they can be used to calculate these quantities of water with a known uncertainty.

The monthly rate per surface unit will be multiplied by the area. Or rather, using proper interpolation functions, the instantaneous value can be evaluated.

In general:

$$Precip_{(i,t)} = Precip_{(t)} * Area_{(i,t)} \quad \text{Equation 2}$$

With:

Precip_(i,t) = Precipitation in the i – Compartment in the t – timestep

Precip_(t) = Precipitation rate in the mine site in the t – timestep

Area_(i,t) = Area of the i – Compartment in the t – timestep

And likewise for the evaporation:

$$Evapo_{(i,t)} = Evapo_{(t)} * Area_{(i,t)} \quad \text{Equation 3}$$

With:

$Evapo_{(i,t)}$ = Evaporation in the i –Compartment in the t –timestep

$Evapo_{(t)}$ = Evaporation rate in the mine site in the t – timestep

$Area_{(i,t)}$ = Area of the i – Compartment in the t – timestep

In some compartments of the mine site, specific conditions need to be considered. The whole area of the Tailings is used to estimate precipitation. But, the evaporation is calculated on the lake area, which is the area of the water surface in the dam. Another condition is that the evaporation is equal to zero if there is no water in the dam. The same criteria also is added to the function of evaporation in the retention pond.

For the Tailings dam:

If: Volume of Tailings Dam $> 0m^3$;

Equation 4

then: $Evapo_{(Tailings\ Dam,t)} = Evapo_{(t)} * Area_{(Tailings\ Mirror,t)}$

otherwise: $Evapo_{(Tailings\ Dam,t)} = 0\ m^3/d$

The evaporation in the mine dump will be calculated in a different way, as there is no water surface. The amount of precipitated water that does not infiltrate to the retention pond will evaporate to the atmosphere. This assumption is reflected in the mathematical function:

$Evapo_{(Mine\ Dump,t)} = Precipitation_{(Mine\ Dump,t)} * (1 - Infiltration\ rate)$

Equation 5

The essence of this modelling stage is to define the functions of the inflows and outflows of each compartment. Many flow conditions need a comparison between the actual volume of the pond and a certain limit, minimum or maximum level of water in the pond. These constants can be defined at the beginning, or left variable to be optimized during the simulation process (especially the water quantities moving between ponds). The case of reaching the minimum level will be defined as a function of the transport pipe dimensions, in order to achieve an economic flow velocity. Overflow describes the amount of water that needs to be transported in case a pond reaches its upper boundary.

Table 3 Mathematical model

Flow Index	From	To	Description	Function
Q1	River	Effluent water pond	The quantity of water needed to refill the effluent pond if it hits its lower bound	<i>If: Volume of Effluent < Minimum;</i> <i>then: $Q_1 = \text{Constant Value } l/s$</i> <i>otherwise: $Q_1 = 0 l/s$</i>
Q2	Effluent water pond	Contact water pond	The quantity of water needed to refill the contact pond if it hits its lower bound	<i>If: Volume of Contact < Minimum;</i> <i>then: $Q_2 = \text{Constant Value } l/s$</i> <i>otherwise: $Q_2 = 0 l/s$</i>
Q3	Contact water pond	Process plant	The quantity of water needed to operate the process plant	Input data
Q4	Process plant	Tailings dam	Mixture of water and minerals	$Q_3 - Q_6$
Q5	Tailings dam	Contact water pond	Water pumped from the tailings dam	Input data
Q6	Process plant	Pulp	Mixture of water and minerals with very low percentage of water	$Q_3 * \text{Coefficient}$
Q71	Mine	Contact water pond	Contaminated water from the mine	Input data
Q72	Mine	Effluent water pond	Clean water from the mine	Input data
Q9	Contact water pond	WTPP	Amount of water that needs to be treated	<i>If: Volume of Contact > Certain Volume;</i> <i>then: $Q_9 = \text{Constant Value } l/s$</i> <i>otherwise: $Q_9 = 0 l/s$</i>
Q10	WTPP	Effluent water pond	Amount of treated water	Q_9
Q12	Mine dump	Retention pond	Water that infiltrates from the mine dump to the retention pond	$\text{Precipitation}_{(\text{Mine Dump},t)} * \text{Infiltration rate}$
Q13	Tailings dam channel	Effluent water pond	Clean water from the tailings channel	$\text{Precipitation}_{(\text{Tailings Dam},t)} * \text{Infiltration rate}$
Q14	Effluent water pond	River	The quantity of water going to the river if the effluent water pond hits its upper bound	<i>If: Volume of Effluent > Upper Bound;</i> <i>then: $Q_{14} = \text{Overflow } l/s$</i> <i>otherwise: $Q_{14} = 0 l/s$</i>
Q15	Retention pond	Contact water pond	The quantity of water going to the contact water pond if the retention pond hits its upper bound	<i>If: Volume of Retention > Upper Bound;</i> <i>then: $Q_{15} = \text{Overflow } l/s$</i> <i>otherwise: $Q_{15} = 0 l/s$</i>
Q17	Contact water pond	Sink	The quantity of water going to the sink if the contact water pond hits its upper bound	<i>If: Volume of Contact > Upper Bound;</i> <i>then: $Q_{16} = \text{Overflow } l/s$</i> <i>otherwise: $Q_{16} = 0 l/s$</i>

The input parameters vary in their dimensions. Some of them are simple scalars, while others vary with time. For example, precipitation and evaporation rates are given for a whole year, and have a one-year periodicity. Other input data such as certain areas, changes of areas, water coming from the mines, are better described in Chapter 4.2.

4 Simulation

In this chapter a simulation of the created model is described. Different software tools for creating the model are being reviewed and the proper one will be chosen in the end. Using the right program, the model can be simulated.

4.1 Software overview

4.1.1 Tested software

For the testing and further use of the software, the information written in the manuals and user`s guides were used. To make the comparison, all programs were tested to tell if their objectives appropriately matched the ones introduced in this project or not. In the following, the tested software will be described. Both the testing of water balance and water quality of the proposed water system will be modelled using the proper water management software. Several commercial and free products have been developed and used in different countries. As these programs are different in their purpose, even if they can be used to model the water management, they might solve tasks other than the defined objectives of this specific project.

In this section, four different programs and the way they work will be briefly introduced in order to make a comparison among them and to define the ideal program that will be used.

4.1.1.1 WASP 7.52, Water Quality Analysis Simulation Program

WASP 7.52 is a free water management software developed by the EPA (U.S. Environmental Protection Agency). Using this program, an investigation of the water quality and its impacts on aquatic resources due to natural phenomena or man-made pollution can be made. (EPA, 2005) The basic principle of the program is the conservation of mass, which is also linked to the conservation of momentum and energy in hydrodynamics.

The main elements of the model are nodes which represent the segments, and links, which are the segment`s interfaces. A segment is a transport section, and the links are the transport function between the segments. The hydrodynamics of the flow in this program can either be selected from the program library, or special

conditions can be written by the user and imported into the model. The program itself has two different flow options; net flow, which sums up all the flows at a segment interface in one direction, and the gross flow, which can work in both directions if opposite flows are defined. In the water management of a mine site, various flow regulations between different segments are made, in order to have a specific water quality (according to various pollutant concentrations). (EPA, 2005)

The user can specify functions for the hydrodynamics, but there is no possibility of creating “If/Then/Else” Logic Functions. This causes complications, as it forces users to write DYNHYD (hydrodynamic data) in programming language (such as C++), which would increase the complexity of the model. (EPA, 2005)

4.1.1.2 3MRA, Multi-receptor Risk Assessment

3MRA is another freeware package developed by the EPA. The main purpose of this program is to calculate the risks to the receptors, from long-term exposure to contaminants. The receptors are human (i.e. Residents, Farmers, Gardeners, and Fishermen) or ecological receptors (e.g. Mammals, Birds, Aquatic/Soil Communities, etc.). The individual on-site risks will be scaled up to a national level, and evaluated according to U.S. regulatory criteria. (EPA, 2003)

The model is created from a large selection of input data, which includes geological data taken from the site, human and ecological exposure, chemicals and even local and national meteorology. An additional implementation of regional and national databases is required. The model itself is created using several GIS-Maps which have the required information about the drainage basins, land use and ecological regions. Also, monitoring data regarding the hydrology is needed. One of the benefits of this program compared to *WASP 7.52* is that waste treatment plants, landfills and other ponds can be modelled.

But this application also has major drawbacks, as some site specific data may be missing or difficult to obtain, causing errors from empty, or estimated input figures. Also the simulations are generated for a long-term period, which induces further unpredictability as many of the variables are changing (i.e. population, age of the residents, meteorological data). These uncertainties will be examined using

a two-stage Monte-Carlo-Simulation. While the first stage of this simulation accounts the variability of data, the second stage checks the error-based uncertainty.

The program itself has a large directory of different chemical compounds, so that their transport within the whole system and chemical/biological transformation of the pollutants can be calculated.(EPA, 2003) In comparison to WASP 7.52 the aerial dispersal of contaminants can also be considered. This way, the impact on soil, ground and surface waters can be ascertained more specifically.

3MRA's purpose goes far beyond the scope of this project, making the program unusable for modelling. By using its scatter-gun results would result in sifting through an excess of moot information.

4.1.1.3 Ecolego 6.2

Ecolego is a well-known European software developed by the Swedish company *Facilia*. Using this software, dynamic models performing deterministic or probabilistic models can be simulated. The interface is a box-compartment matrix. The program gives the opportunity of defining a source (for example aquatic resources, atmosphere etc.), a sink (lower layers of aquifers ...) and other compartments in which the media flows. (Ecolego Wiki on Ecolego Website)

To create new elements is very easy, every diagonal box of the matrix can be used to create new elements or their dependencies. These elements are compartments and portray each pond in the system, as well as treatment plants. The compartments are linked using two different methods. The first option is the Transfer Coefficient (TC), which moves a certain portion of the mass in one pond to the other. Alternately, there also is the possibility to use normal transfer mode. This way the flow-rate can be determined by constants, formulas or time functions.

Various materials can be created and moved by water moving through the system. The materials we refer to are radionuclides, or chemicals of interest. Simple toxins are defined by formula and atomic number. More information is needed in the case of radionuclides and their decay daughters. The quantities of materials affect the quantities transferred between compartments.

One limitation of this software is that users must use consistent units, as Ecolego itself cannot make the unit conversions. In other words, if a compartment is emitting water in l/s, this cannot be changed to another unit, i.e. m³/d. Also all parameters used by its flow function are required to have the same unit as the compartment itself. For example, an American flow meter giving out cubic feet of water would either be unusable, or require additional calculations, when paired with a European pump monitor which measures in litres. This missing asset of the program leads into further amount of work hours of the user and to fatal errors indicated from program while their inception is not described.

The user-unfriendly workspace using matrix-box-system means that only the operator of the software would be able to read or convey information from the model. This could cause significant issues for team members working on the same project, or when handing over the model if staff were to be leaving, without an excessive amount of documentation, a hindrance in itself for productivity. However even if the workspace is not understood from the non-users, it does produce results in diagrams and tables, which are the only way to convey its meaning.

4.1.1.4 Goldsim

Goldsim is an American software developed by the *GoldSim Technology Group LLC* that offers various options for modelling in many areas, including engineering and environmental systems. The program itself consists of different modules according to the needs of the user. The option needed for water management in mines is the *Contaminant Transport Module*. Its primary asset is a user-friendly workspace that allows to directly draw the elements of the model and also their associations with each other.

The *Contaminant Transport* is a mass transport model, which means that it simulates the transport of an unlimited number of species moving within the transport media within an environmental system. These could be either chemical constituents, bacteria, viruses or even heat. (GoldSim Technology Group LLC, 2015) The mass can be transported or stored in the transport pathways, which are the physical components of the system, such as aquifers, lakes, sediments and other soil compartments. The pathway is defined by its geometry and the media. The

transport of media through the compartments is made by multidimensional vectors (mass flux link), which have one component for each species. For example, by moving the contaminants C1, C2, C3 and C4 from a shallow aquifer to a deep aquifer, the flux link describing this movement would have four components. (GoldSim Technology Group LLC, 2015) Each of these components characterizes the transport of a specific contaminant (C1, C2, C3 or C4).

One of the advantages of Goldsim is that a WWTP can be implemented. The mass of contaminants leaving the WWTP is clearly smaller than the one entering. The treatment processes applied in the WWTP can be reproduced from the model by introducing a treatment efficiency parameter for every treated species. To estimate its value, it is important to know which treatment method will be used and what efficiency it has. This way the final mass of each contaminant in natural waters can be calculated.

Another task that can be solved is trying to compare different treatment methods in order to choose the most preferable one for guaranteeing that contamination levels are under local regulations.

4.1.2 Methodology of the comparison

In order to choose the proper program for the modelling of water management, it is important to evaluate the software tested by the same criteria. Therefore, it is significant to define these touchstones, although a distinction between the hard and soft criteria should be made. It is important to make a proper weighting of the chosen criteria's relevance. The most important hard criteria is the scope of the software and if it suits the overall purpose of creating the model. The second hard criteria is to have enough modelling elements in order to represent the various subsystems of the mine system, i.e. the WWTP which is difficult to model. The third hard criteria is the ability of creating logical functions in order to regulate the system like in real mining operations, wherein water flows are adjusted according to the pond's needs.

Other criteria like graphical representation are of second order, as the results can be organized using other software. However, the program itself delivers very good graphics and the tables can be directly formatted using GoldSim. Also, overflow functions can be written via external codes and implemented into the software. Fulfilling the soft criteria eases the overall work while using the program. The evaluation of the tested software on the defined hard and soft criteria is shown in Table 4.

Table 4 Hard and soft criteria evaluation of the tested software

Necessities		WASP 7.52	3MRA	Ecolego	GoldSim
1	Software serves the main scope of this modelling task	x	x	xx	xx
2	Various modeling elements to represent mine subsystems	-	x	x	xx
3	Mass transport functions using logic operators	-	x	x	xx
4	Graphical representiveness of the simulator itself	-	-	-	xx
5	Graphical representiveness of the desired results	x	x	xx	xx
6	Adequate results while using only essential input data	-	-	xx	xx
7	Automatical unit convention	-	-	-	xx
8	Automatic overflow functions adaption	-	-	-	xx
9	Well written manual and proper customer support	xx	xx	-	xx

The comparison made between the programs clearly shows that two of these programs, Ecolego and GoldSim, fit the criteria of this project best because of the advantages they offer. These were both used to create a model but the actual simulation happened using the most suitable software, which in this case is Gold-Sim.

A more detailed comparison is made in Table 5.

Table 5 Detailed comparison of the programs

Software	Developer	Costs	Objective	Required Input	Output	Advantages	Disadvantages
WASP 7.52	EPA	Free	<ul style="list-style-type: none"> -Defines water quality -Impacts on aquatic resources 	Depending on the type of model: <ul style="list-style-type: none"> -Time information -Parameter -Hydrodynamics 	<ul style="list-style-type: none"> -Eutrophication -Simple toxicants -Non-ionizing toxicant -Organic toxicants -Mercury -Heat 	<ul style="list-style-type: none"> -Models for specific investigation purpose -Simplifies geometry 	<ul style="list-style-type: none"> -Few Modelling elements: nodes and links -Cannot easily create logic flow options
3MRA	EPA	Free	Defines risk assessment to receptors: <ul style="list-style-type: none"> -Humans -Animals -Agriculture 	<ul style="list-style-type: none"> -Site data -Human/ecological exposure -Chemical data -Metrological data -Regional/national database -GIS maps on land use 	<ul style="list-style-type: none"> -Risk assessment index to land use -Risk assessment index to humans 	<ul style="list-style-type: none"> -Specific Outputs -Allows modelling of: <ol style="list-style-type: none"> 1. Waste treatment plants 2. Landfills 3. Aerial deposition of contaminants -Large directory of chemical compounds 	<ul style="list-style-type: none"> -Extensive uncertainty -Lots of required input cannot be provided
Ecologo	Facilia	Commercial price: €6000 Radionuclide toolbox price: €1000 Academic price: €2400	<ul style="list-style-type: none"> -Transport of contaminants -Transport of radionuclides -Water volume in the ponds -Water flows in between the ponds 	<ul style="list-style-type: none"> -Flow functions -Initial contaminant concentration -Initial volume/Max volume -Flow functions 	<ul style="list-style-type: none"> -Fluids transport quantity in time -Contaminant mass in each pond in time -Sensitivity analysis 	<ul style="list-style-type: none"> -Not much data required -Once you get used to matrix-boxes-concept, using the program is very easy 	<ul style="list-style-type: none"> -User manual is very poor -Same units should be used in every compartment -Costs -Cannot deliver monthly results
Goldsim	GoldSim Technology Group LLC	Commercial price: ~€5800 Radionuclide module price: ~€8100 Academic price: Free	<ul style="list-style-type: none"> -Transport of contaminants -Transport of radionuclides -Water volume in between the ponds -Water flows in between the ponds -Impacts on receptors 	<ul style="list-style-type: none"> -Flow Functions -Initial contaminant concentration -Initial volume/Max volume -Parameters depending on element 	<ul style="list-style-type: none"> -Fluids transport quantity in time -Contaminant mass in each pond in time -Sensitivity analysis 	<ul style="list-style-type: none"> -Overflow option -User Friendly Workspace -Allows Drawing/Writing Information -Data representativeness -Free license for Academics 	<ul style="list-style-type: none"> -Costs

4.2 Simulator

After the model setup is clear and the mathematical functions are well defined, the model can be transcribed into the language of the chosen software. The purpose of modelling in GoldSim is to simulate the contaminant transport for the period of ten years. Two different stages of modelling have to be considered. The first one is the flow model, which calculates the mass movements between the ponds, and the volume in the ponds themselves. As mentioned before, the contaminants move with the media flowing in the system, in this case water. The contaminant transport will be calculated using the volume and flow outputs from the flow model. Therefore, it is very important to have a stable and accurate flow model. Also, as the actual modelling starts with it, most of the input data is needed here.

4.2.1 Input data

Water management in the mine implies a large amount of input data. For instance, in every pond, the initial volume, addition rate, withdrawal rate, lower and upper limit should be defined. This way boundary conditions and interactions among them will be established as well. In this model artificial input data is used, as the actual purpose is to create the water management tool, not to investigate an existing project. Some of the data is provided in simple scalars, while other data has to be provided as time functions.

4.2.1.1 Precipitation rate

The precipitation rate is described as a periodic function of time and area. That means that the amount of precipitated water is given in mm per month. The precipitation rate is given for a whole year and then repeated in the next years for the whole simulation endurance. But in order to be able to investigate the simulation tool better, a scenario of twenty-two dry months from the beginning of year seven throughout to the end of October of the eighth year is used in the following diagram of precipitation rate. Later on, while presenting the results, the effect of this assumption is shown, as the inflows in the ponds are zero due to the lack of precipitation. In some the ponds the total inflow during certain times consists entirely of precipitation, i.e. retention pond. Also the evaporated amount of

water should be equal to zero if the inflow (consisting only of precipitation) is equal to zero. In reality, as stated from Jordana, this cannot occur, because even if all the water could evaporate, there would still be a minimal amount of water nearly equal to zero in the bottom of the pond creating a fine layer of moist mud containing contaminants. Such a phenomenon cannot be included in the model, where the amount of water remaining in pond due to lack of precipitation is assumed equal to zero. Is this the case, then it can be a simple clue for a proper functionality of the simulator.

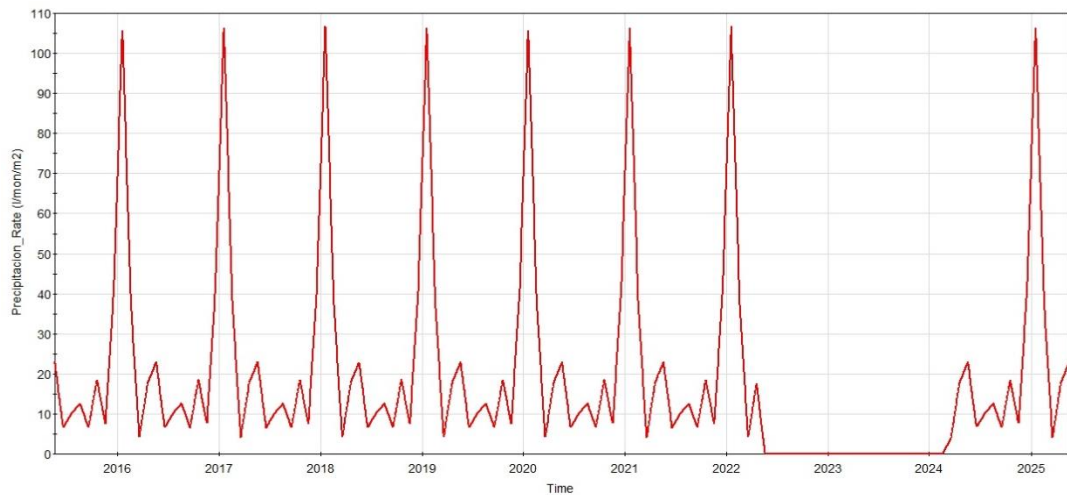


Figure 8 Precipitation rate as input

4.2.1.2 Evaporation rate

Like the precipitation rate, evaporation rate is also periodic with a periodicity of twelve months. So the input data given for the first year will be repeated every year until the end of the simulation period.

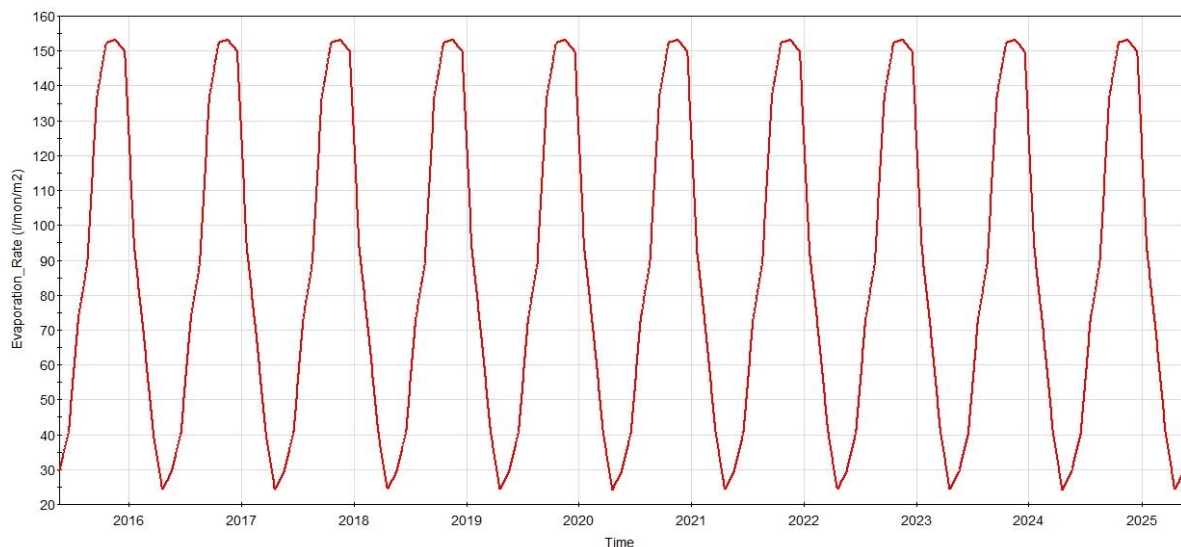


Figure 9 Evaporation rate as input

4.2.1.3 Areas

To calculate the total evaporation or precipitation in a pond, the areas are needed. To define these areas, the project of Rio Tinto in Spain was reviewed, in order to give realistic dimensions concerning the ratio between various compartments. This document can be found in the References. Some of the areas have the same value for the whole duration of the simulation and are listed below in Table 6. (EMED Tartessus, 2014)

Table 6 Constant Areas

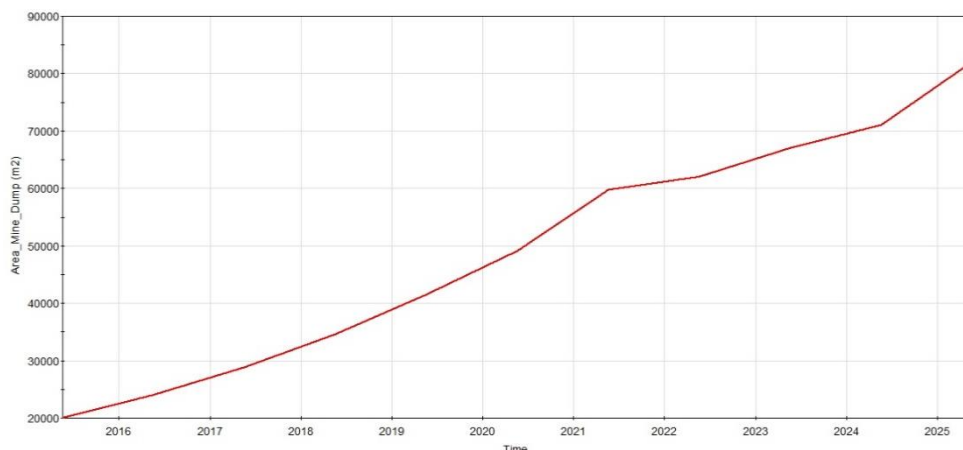
Sector	Area [m ²]
Effluent Water Pond	23000
Contact Water Pond	20000
Retention Pond	50000
Tailings Dam	2000000
Tailings Channel	5

On the other hand, some areas are changing. For instance, the Mine Dump vol-

Table 7 Mine dump area

Time [yr]	Value [m ²]
0	20000
1	24000
2	28800
3	34560
4	41472
5	49075
6	59719
7	62000
8	67000
9	71000
10	82000

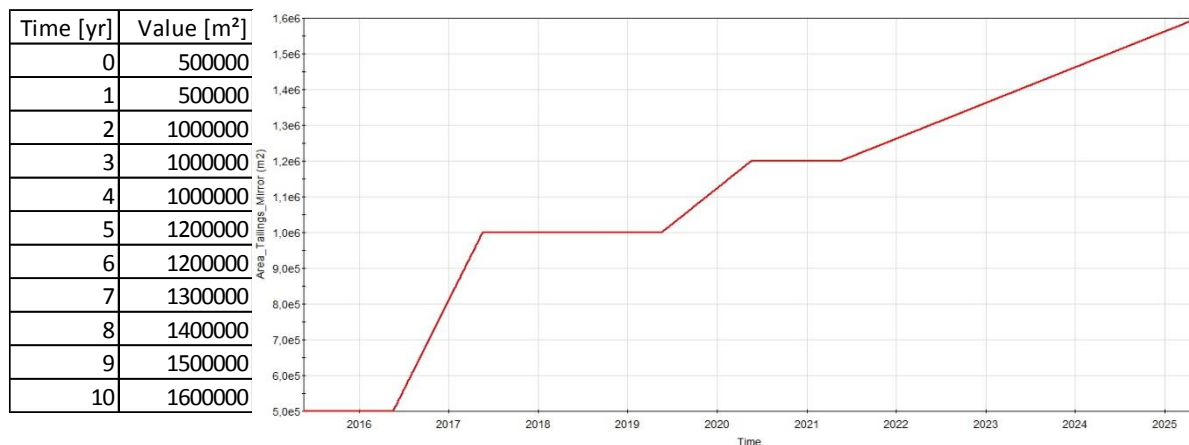
id so is its precipitation area. The change over time



of this surface is deviated from the mine operations and so it is internal input data. Fictitious areas were assumed for every year, and the program itself interpolates between them.

Also the area of the water surface of the Tailings dam changes over time along with the volume of water. A relation between the water level in the dam and the water surface area is not specified, in order to simplify the model. Fictitious values are assumed for every year and GoldSim interpolates between them.

Table 8 Tailings dam water surface area



4.2.1.4 Water inflow from the mine

Important input data in the water management system is the water inflow from the mine. Also, the given data here is fictitious and represented in the following figures. Because it is assumed that in the end of the simulation the mine is closed, an amount of 0 l/s of contaminated water will be transported during this year.

Table 9 Water inflow from the mine

Time [yr]	Q_71 [l/s]	Q_72 [l/s]
0	0	1
1	2	14
2.5	10	20
3	12	20
4	15	20
5	15	20
6	20	20
7	15	20
8	5	20
9	5	20
10	0	20

On the other hand the amount of clean water is considered to remain constant after the second year with a value of 20l/s.

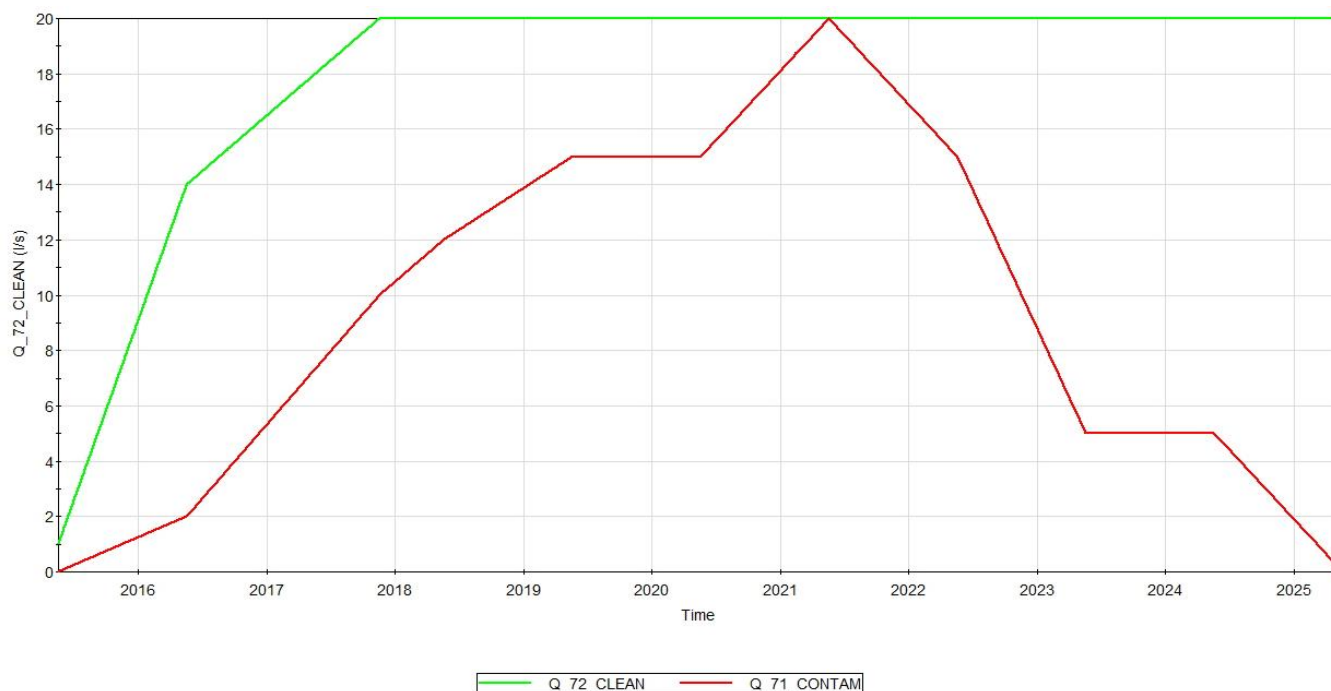


Figure 10 Mine water inflow

4.2.1.5 Pond volume thresholds

For many of the ponds certain conditions regarding their volume need to be considered in order to regulate the overflows and withdrawals in the whole system. The lower limit is the minimal operational water level that the pond can reach. Every time this level is reached by the contact and effluent pond, water has to be retrieved from the river. As the lower limit must not reach zero, it is defined as 10 m³.

Nevertheless, the lower limit of the retention pond is 0 m³, so that all the water in it can evaporate. At the start of the simulation it is empty. Later on it will be filled with water from the mine dump infiltration. This reflects the purpose on building a retention pond in the first place. The upper limit on the other hand is the maximal capacity of the pond. If this volume is reached, the overflow of the pond is going to flow towards the defined destinations. These two parameters are very important for the dimensioning of the ponds and dams.

To support the engineering work, the input data can be varied, creating different scenarios to choose the most suitable one. Many of these parameters are created

Table 10 Pond parameters

as explicit variables in the software, linked to the pond. This way they can be changed very easily. An initial volume can also be defined among the input parameters of every pond. It is suitable to define this value higher than the lower limit of the pond. As many of the ponds retrieve water from other sources, ponds can create errors in the models logic. Also, the River is modelled as a pond, meaning a reservoir element in GoldSim. It should have an initial volume, so that it does not run empty at the start of the simulation, even though the volume of a river cannot be calculated. The following Table 10 shows the values of these parameters for certain ponds.

Water sources	Type of water	Cu [mg/l]
Contaminated Water Q71	contaminated	1
Clean Water Q72	non-contaminated	0
Tailings Runoff	non-contaminated	0
Mine Dump Infiltration	contaminated	1

Pond	Initial Volume [m ³]	Lower Bound [m ³]	Upper Bound [m ³]
Effluent Water Pond	30000	10	100000
Contact Water Pond	30000	10	80000
Retention Pond	0	0	5000
Tailings Dam	30000	10	200000

4.2.1.6 Contaminants

To keep the system simple, only one species (Cu-Copper) will be investigated. In the contaminant transport module, Cu will therefore be defined as the only species being moved with water through the compartments. The modelling of its transport begins with defining the sources containing Cu. In general, there are two different water sources: those which bring clean water in the system and the other ones which are causing contamination.

The sources are important, because the contamination can be defined as a boundary condition (in this context as input data). In other pathways, the contamination is estimated by a result of the simulation from an output. For further simplification of the system, the concentration of Cu in clean waters is 0 mg/L and in those contaminated 1 mg/L. In the actual mine site, the water entering from different sources has various concentrations of the contaminants and for an actual approach, these values have to be measured and provided as input data. The sources of water in the model are in the following Table 11:

Table 11 Water sources

Another source of water is the river. Due to pumping water from it to the effluent pond and also due to discharging water from that pond, the concentration of Cu in the river, changes. One of the most important points in this project is to know the mass of Cu being discharged into the river. At the beginning of the simulation the water in the river is non-contaminated; therefore the initial mass of Cu in it 0 g and so the concentration 0mg/L.

4.2.2 Flow model

The mathematical model will be adapted to the software. The first step in the flow model is to model the ponds which are:

- Effluent water pond
- Contact water pond
- Retention pond
- Tailings dam
- Sink

But also the *River* and *Pulp* are parts of the Flow Model even though they are not ponds. They both are needed to represent the complete system.

The river is a source of mass that means that it feeds the whole system through the effluent pond. One of the end results is the amount of water retrieved from it, as well as the discharge from the effluent water pond. On the other hand, the Pulp can be seen as a sink, not to be mistaken for the contact water sink. By its definition, a Sink, in this case the Pulp, serves as a fictitious pond to calculate the solid mass that is going out of the system.

The main element used in the flow model is the reservoir. This element is an integrator element, and keeps track of the media moving into and out of the reservoir. The reservoir is used to model the ponds, as it also informs about the volume of the media stored in it. Other than that, different elements are used to regulate the connections between the ponds. Figure 11 shows the flow model. Its essential features are described in detail below.

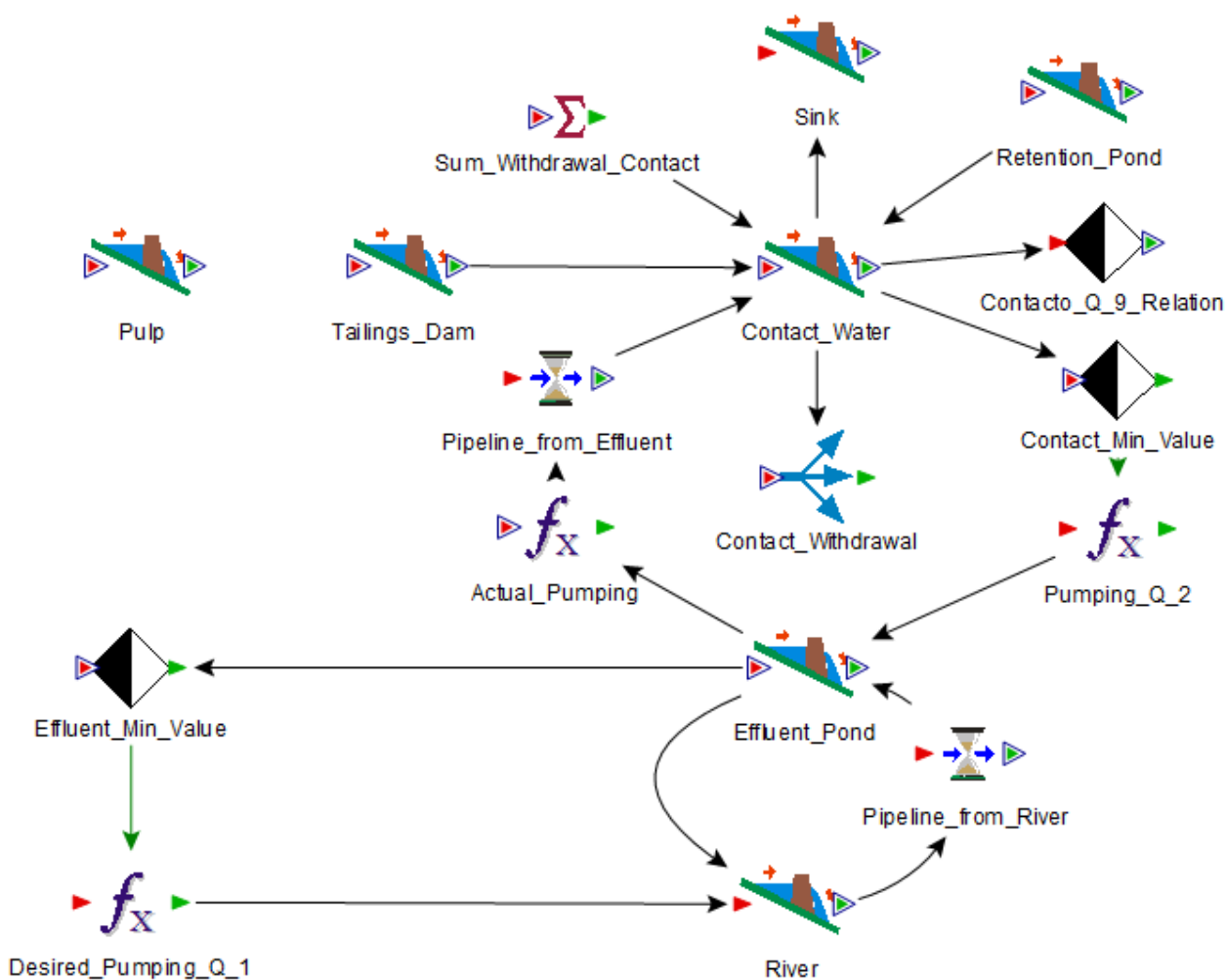


Figure 11 Flow Model in GoldSim

The most important conditions of defining the performance of the system are the logic functions used for reaching...

- ... the minimal level of water volume in the *Contact Water Pond*
- ... minimal level of water volume in the *Effluent Water Pond*

- ... the level of water volume in the *Contact Water Pond* to send water in the *Wastewater Treatment Plant* using the Q_9 function

For reaching the condition of maximum level of water in the ponds, a status element is not needed. GoldSim does this automatically, once the upper limit of the pond and the destination for its overflow are defined. The amount of water moved with the overflow does not need to be defined.

The use of the *Status Element* allows checking if the system is working properly. The status of a logic condition can be tracked and showed. If its status is true, then an expression of flow is activated.

For the status element, two conditions have to be defined. The first one is on true state. That means that if the condition: $Effluent_Pond \leq Effluent_Min$ is met, then the state of the Status Element is on „True“. At the same time the condition for the „False“ state is defined. By definition it is the contrary of the „True“ trigger. Anyway a buffer is needed. The condition is: $Effluent_Pond > Effluent_Min + 10$ m³. The volume of 10 m³ is needed as a buffer to make the system stable. Otherwise the state of this status element would change very quickly from a state to the other one and the system would not be accurate.

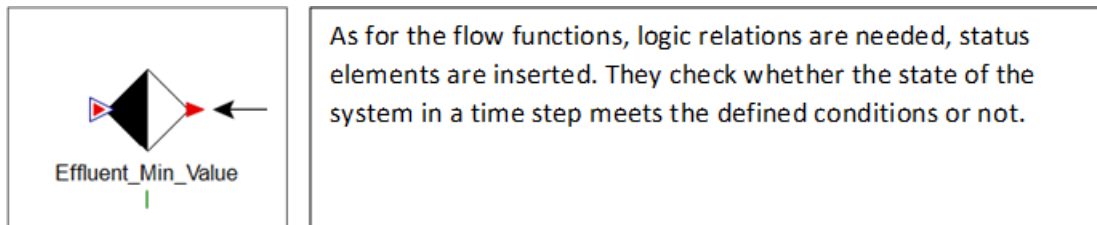


Figure 12 Status Element

The state element will be used in the definition of the function that regulates the flow. In the handled example of the „Minimal Level of Effluent Pond“ a function element is used to take the desired amount of water from the river to supply the effluent pond. The state of the status element is part of the function that regulates this mass movement.

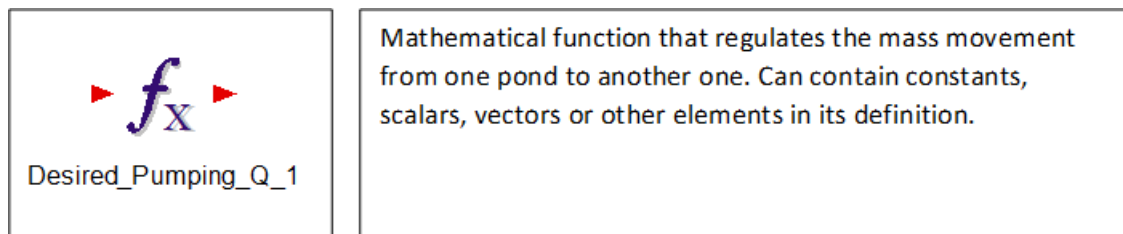


Figure 13 Function element

In this example, the expression is named „Desired Pumping Q1“. This means that the function has a theoretical value that is different to the actual value of pumping. Ponds cannot deliver water to one another if their lower limit is reached. In this sense the amount of water delivered is lower than desired. The same principle applies for the transfer function between the effluent and contact water ponds. The function here is triggered by the event of reaching the minimal value in the effluent pond. This is why the state of „Effluent_Min_Value“ is inserted in its definition. The desired amount of pumped water from the river is 200 l/s. In case the water volume in the effluent pond is higher than its minimum value, no water will be pumped. In this example, it can also be shown that the use of different units does not obstruct its function. The only thing that matters is that the unit should be volume/time, as it represents a water flow rate.

Between the effluent water pond and the river there is another transfer to be considered. The overflow of effluent is going into the river. Introducing two different directions of water movement between these compartments implies a recursive loop. A special element named „Material Delay“ is used to regulate this matter. The delay can be defined by the user, and in this example has the duration of one day, which also is the length of a time step. It can be optimized according to the pump’s parameter in order of achieving the most sustainable solution.

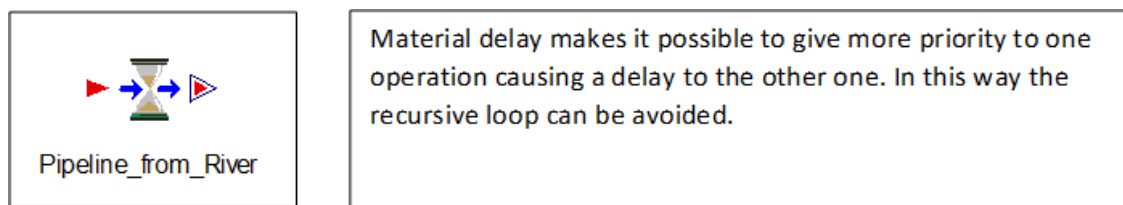


Figure 14 Material delay element

4.2.3 Contaminant transport

In GoldSim the contaminant transport is modelled using the contaminant transport module based on the flow model. The main elements used are the Transport Pathways. GoldSim Transport Pathways represent physical components through which contaminant species can move (and/or be stored) such as aquifers, lakes, sediments, surface soil compartments, and the atmosphere (GoldSim Technology Group LLC, 2014) . There are different types of pathways according to the approach of the actual water management system in mines as shown in Table 12:

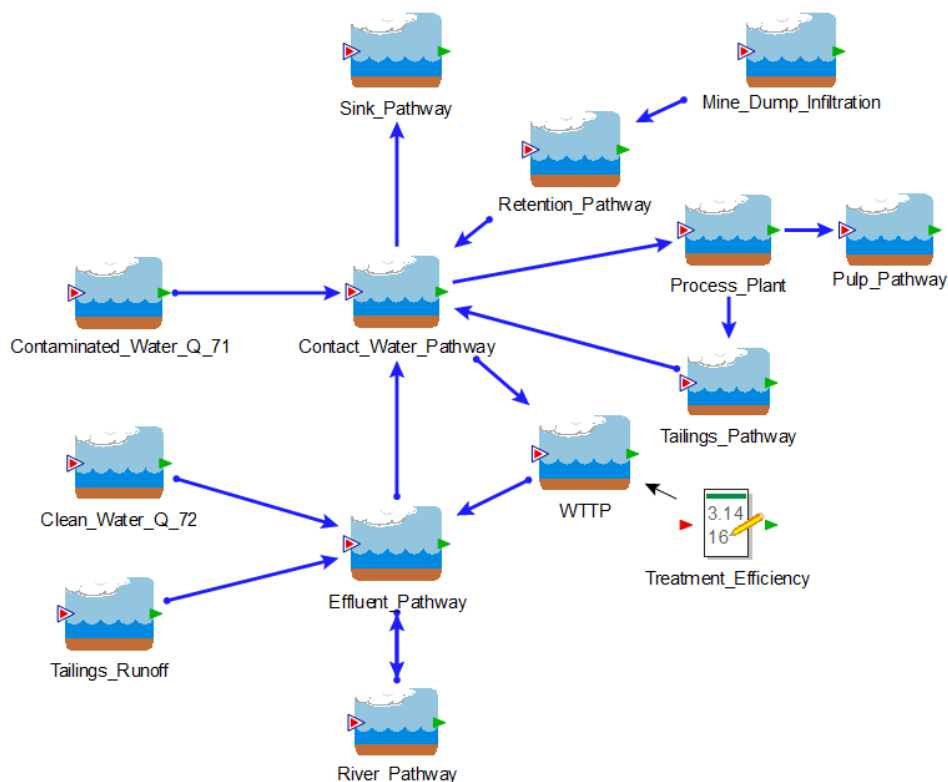
Table 12 Different types of pathways in GoldSim

Model	Purpose of use
Cell pathway	Ponds lakes shallow soil compartments atmosphere
Aquifer pathway	vertical transport through un-saturated zone hori- zontal transport in aquifers, riv- ers, channels, pipelines
Pipe pathway	vertical transport through un-saturated zone hori- zontal transport in aquifers, riv- ers, channels, pipelines and through fractured rock masses
Network pathway	multiple pipes
External pathway	pathways with an external de- fined transport operation by us- ing external program modules (analytical, finite element, finite difference transport models)

As mentioned earlier, the transport of media through the aquifers will not be considered as a result of the lack of input data on certain geological characteristics of the soil and flow processes. This leads to a simplification of the model by using only Cell pathways.

For every pond in which the volume changes, GoldSim will create a pathway in the contamination transport model in order to represent it. Furthermore, for every pond modelled in the flow model, there will be a corresponding cell pathway. The volume of media that enters the pathway is the same as in the respective pond in the flow model.

Additional pathways are introduced for the water sources such as the mine drainage waters, divided into Contaminated_Water_Q_71 and Clean_Water_Q_72. Furthermore, other pathways such as Tailings_Perimetral_Runoff and Mine_Dump_Infiltration were also not of interest in the flow model as their volume does not change in value.



They only represent a pathway of the media and are only important to provide
Figure 15 Contaminant transport model in GoldSim

the initial mass of contaminants entering the system. On the other hand, a WWTP

is implemented in this system in order to maintain a treatment efficiency for the contaminated water.

The transport of media through the pathways is defined by Inflows and Outflows from every pathway to another. They represent the same quantities as in the flow model but within the contaminant transport module, the linkage of the pathways is easier to represent. While in the flow model the direction of arrow elements implies the dependencies of the features to one another, the contaminant transport shows the direction of the flows in between pathways. This aspect of GoldSim allows the user to have a better understanding of the model.

There are different ways of mass transport between Cell Pathways. Between most of them advective transports are characterised by a flow rate. This rate is already defined in the flow model by using the mathematical model expressions mentioned in chapter 3.4, and is given upon the characteristics of the pathways. In the WWTP pathway, the water is being treated, therefore the mass being transported through its outflow needs to be reduced. This is not anymore a simple advective flux, but is fractioned by a treatment efficiency coefficient which depends on the chosen water treatment method. This element is a vector, containing a specific fraction of mass for every species; in this case, a scalar of value 0.5 since the simulation is made only for Cu.

4.2.4. Scenario and time conditions

The simulation simulates ten years, starting with the opening of the mine (without the pre-eliminatory work) and operating its operating time. This means for the inputs of volume in various ponds a value of zero. So firstly, they need to be filled with water. Because of the numerical issues of GoldSim, the Effluent Water Pond needs an initial volume at the starting time of the mine's operation, meaning the water is retrieved from the river before the defined simulation time. The time step is chosen to be a day to simplify the graph that presents the results and the precision of the numerical calculation of GoldSim.

5 Results

This is the final chapter of the thesis in which the obtained results of the simulation are being represented, discussed and summarized. It is important to tell if the tool works properly and whether it can be used in the future for modelling real-world mines. As the created model can be used for more specific purposes in the future, it is important to give some new perspectives and outlook over the optimizations of it.

5.1 Discussion of Results

In this chapter the results obtained from the flow simulator and the contaminant transport simulator are looked at separately, even though the second ones are depending on the first ones. That is because it makes no sense building a proper working contaminant transport model over a non-working flow simulator.

5.1.1 Pre-evaluation of the results (Law of Mass Conservation)

Before the final simulator was created, the generated model was tested for its ability to respect the laws of physics. The law tested in particular is the Law of Mass Conservation. The results were promising because of the small error between the results delivered by the program, and the one calculated manually by knowing the monthly accumulated water volume for the period of one year.

This investigation succeeded before the flow and contaminants transport model were optimized, therefore the results are different from the final ones. Every pond will be checked to see if the change in the contained water follows this law for a given period of time as shown in Equation 6.

$$Volume_{Pond} = \sum Inflows_{Pond} - \sum Outflows_{Pond} \quad \text{Equation 6}$$

In other words, for every pond the outflows (pond's withdrawal rate) and inflows will be presented in the form of a table for the interval of one year. These values are given as a cumulative value for a month and therefore have the same unit as the volume. Primarily the theoretical volume change is the difference between inflows and outflows, and will be calculated for every month, and then compared to the one delivered from GoldSim. As a final step, these values will be checked for the whole year with the error given as a percentage. The ponds of interest are mainly the effluent and contact water pond. For a higher accuracy of the results, the scenario simulated is linked with an overflow of the contact to the effluent water pond in September of 2015 and checked how this affects the system. The overall maximal error is in the contact water pond results, with a value of 0.63 m³. Compared to the volumes involved, this error is about 2% of the amount of water in the contact pond, and acceptable considering the fact that this is a numerical simulation.

Table 13 Mass conservation in Effluent Water Pond

Water Balance Effluent Pond										
Time	Volume [m ³]	Cumulative Precipitation [m ³]	Cumulative Infiltration from Tailings Channel [m ³]	Cumulative Pipeline from River [m ³]	Cumulative Clean Mine Water [m ³]	Cumulative Process Plant Water [m ³]	Cumulative Withdrawal Rate [m ³]	Cumulative Overflow Rate [m ³]	Volume from Water Balance [m ³]	Difference to Goldsim Volume [m ³]
Initial	30000.00									
2015 may	35047.00	179.30	3897.00	0.00	1258.00	0.00	287.90	0.00	35046.40	-0.60
2015 jun	0.00	224.80	4887.00	0.00	5083.00	0.00	45241.00	0.00	0.80	0.80
2015 jul	100000.00	227.40	4943.00	389352.00	8160.00	0.00	65222.00	237460.00	100000.40	0.40
2015 ago	7487.00	273.20	5939.00	119573.00	11115.00	3747.00	170242.00	62918.00	7487.20	0.20
2015 sep	100000.00	195.40	4249.00	111999.00	13570.00	69960.00	2939.00	104527.00	99994.40	-5.60
2015 oct	0.00	363.60	7904.00	0.00	16930.00	0.00	117488.00	7710.00	-0.40	-0.40
2015 nov	100000.00	275.60	5990.00	104536.00	19197.00	25814.00	11670.00	44143.00	99999.60	-0.40
2015 dic	0.00	967.80	21040.00	236706.00	22745.00	0.00	128281.00	253178.00	-0.20	-0.20
2016 ene	100000.00	2098.00	45598.00	47493.00	25700.00	24747.00	34483.00	11153.00	100000.00	0.00
2016 feb	57172.00	1016.00	22098.00	251986.00	26717.00	7746.00	52582.00	299809.00	57172.00	0.00
2016 mar	7106.00	263.60	5729.00	0.00	31420.00	0.00	87479.00	0.00	7105.60	-0.40
2016 abr	70539.00	358.70	7798.00	313841.00	33220.00	24403.00	36093.00	280095.00	70538.70	-0.30
Sum [m ³]		6443.40	140072.00	1575486.00	215115.00	156417.00	752007.90	1300993.00		

Volume Difference [m ³]	40539.00
Total OUT [m ³]	2053000.90
Total IN [m ³]	2093533.40
Total IN - OUT [m ³]	40532.50
Error [m ³]	6.50
Error [%]	0.02%

Table 14 Water balance in contact water pond

Water balance contact water pond

Time	Volume [m ³]	Cumulative Precipitation [m ³]	Cumulative from Effluent [m ³]	Cumulative Contaminated Mine Water [m ³]	Cumulative Retention Pond Overflow [m ³]	Cumulative Tailings dam Overflow [m ³]	Cumulative Withdrawal Rate [m ³]	Cumulative Overflow Rate [m ³]	Volume from Water Balance [m ³]	Difference to GoldSim Volume [m ³]
Initial Volume	30000									
2015 may	8797.0	155.9	0.0	34.0	0.0	0.0	21393.0	0.0	8796.9	0,06
2015 jun	0.0	195.5	0.0	383.2	0.0	0.0	9375.0	0.0	0.7	-07
2015 jul	0.0	197.7	44487.0	843.2	0.0	0.0	45528.0	0.0	-0.1	0.1
2015 aug	45383.0	237.5	68313.0	1298.0	0.0	0.0	24466.0	0.0	45382.5	0.5
2015 sep	32427.0	169.9	163269.0	1689.0	0.0	0.0	144549.0	33534.0	32427.9	-0.9
2015 oct	0.0	316.2	0.0	2193.0	0.0	0.0	34936.0	0.0	0.2	-0.2
2015 nov	36141.0	239.6	113669.0	2555.0	0.0	0.0	80322.0	0.0	36141.6	-0.6
2015 dic	0.0	841.6	8521.0	3087.0	0.0	0.0	48591.0	0.0	-0.4	0.4
2016 jan	51059.0	1824.0	125935.0	3542.0	0.0	0.0	80242.0	0.0	51059.0	0.0
2016 feb	0.0	883.9	31068.0	3725.0	0.0	0.0	86736.0	0.0	-0.1	0.1
2016 mar	34059.0	229.2	55894.0	4422.0	0.0	0.0	26486.0	0.0	34059.2	-0.2
2016 apr	0.0	311.9	81571.0	4712.0	0.0	0.0	120653.0	0.0	0.9	-0.9
Sum [m ³]		5602.9	692727.0	28483.4	0.0	0.0	723277.0	33534.0		

Volume Difference [m ³]	-30000.00
Total OUT [m ³]	756811.00
Total IN [m ³]	726813.34
Total IN - OUT[m ³]	-29997.66
Error [m ³]	-2.34
Error [%]	0.01%

Table 15 Mass conservation in retention pond

Water Balance Retention Pond						
Time	Volume [m ³]	Cumulative Precipitation [m ³]	Cumulative Mine Dump Infiltration [m ³]	Cumulative Withdrawal Rate [m ³]	Volume from Water Balance [m ³]	Difference to Goldsim Volume [m ³]
Initial	0					
2015 may	0,1064	389.7	140.7	530.3	0.1000	0.0064
2015 jun	0.0997	488.7	178.3	667.1	0.0064	0.0933
2015 jul	0.1480	494.3	183.6	677.9	0.0997	0.0483
2015 aug	0.1721	593.9	224.1	818	0.1480	0.0241
2015 sep	0.2071	424.9	162.9	587.7	0.2721	-0.0065
2015 oct	0.2399	790.4	307.9	1098	0.5071	-0.2672
2015 nov	0.2842	599	237	836	0.2399	0.0443
2015 dic	0.4413	2104	846	2950	0.2842	0.1571
2016 jan	1444	4560	1859	4975	1444	-0.4413
2016 feb	1200	2210	912.6	3367	1199.6	0.4
2016 mar	0.1092	572.9	239.9	2013	-0.2	0.3092
2016 apr	33.23	779.8	332	1079	32.9	0,3208
Sum [m ³]		14007.6	5624	19599		

Volume Difference [m ³]	33.23
Total OUT [m ³]	19599
Total IN [m ³]	19631.6
Total IN - OUT[m ³]	32.6
Error [m ³]	0.63
Error [%]	1.90%

Table 16 Water balance in tailings dam

Water balance in tailings dam

Time	Volume [m ³]	Cumulative Precipitation [m ³]	Cumulative Process Plant Water [m ³]	Cumulative Withdrawal Rate [m ³]	Volume from Water Balance [m ³]	Difference to Goldsim Volume [m ³]
Initial	50000					
2015 <u>may</u>	74130	15588	14800	6258	74130	0
2015 <u>jun</u>	112945	19550	39495	20230	112945	0
2015 <u>jul</u>	142657	19773	44555	34616	142657	0
2015 <u>ago</u>	168836	23755	48360	45936	168836	0
2015 <u>sep</u>	172361	16994	50423	63893	172360	1
2015 <u>oct</u>	183622	31618	55848	76205	183622	0
2015 <u>nov</u>	189972	23961	57670	75281	189972	0
2015 <u>dic</u>	263401	84160	63336	74066	263402	-1
2016 <u>ene</u>	461779	182392	67141	51155	461779	0
2016 <u>feb</u>	582756	88390	66254	33667	582756	0
2016 <u>mar</u>	657402	22918	74506	22778	657402	0
2016 <u>abr</u>	750718	31193	75726	13603	750718	0
<u>Sum [m³]</u>		560292	658114	517688		

Volume Difference [m ³]	700718
Total OUT [m ³]	517688
Total IN [m ³]	1218406
Total IN - OUT [m ³]	700718
Error [m ³]	0
Error [%]	0,00%

5.1.2 Flow model results

The main purpose of the flow model simulation is to determine the water flow from one pond to another. Another important point is to estimate the volume of water in the pond, in order to dimension them economically while considering the boundary conditions for the minimum and maximum water levels. The ponds will therefore be engineered in a certain way that guarantees the safety and stability of the whole system. Attention is also given to the volume of water taken from the river, as this negatively influences the environment. Furthermore, we must also monitor discharges from the Effluent Pond as this will have effects too, both in volume and composition.

The simulation period is 10 years with a time step of one day. Only the operation time of the mine is considered. The other two stages: pre-operation and post-closure are not investigated in this project. Although the input and output from a mine water management system is linked with a lot of uncertainties and reliant to the time factor, a deterministic simulation is run. As the results are going to be analysed on their plausibility, within the deterministic concept they can be checked using the mass balance principle. On the other hand, knowing the dependencies of ponds between each other, the credibility of the outputs is easier to review. The accumulated volume in the ponds is also of merit due to planning objectives. In the following, the result will be presented. For a broad spectrum of results on the flow model, a larger amount of data is introduced in the attachments.

5.1.1.1 Tailings dam

From the beginning of the simulation, the amount of water coming from the process plant (Q4 in Table 3) increases linearly with time, until it reaches a constant value in the 48th month of the simulation. As a result of the increased volume of water in the Tailings' upstream, and therefore its evaporation surface, the Tailings pond does not yet reach its upper limit in this month but later in the 56th. At the time steps when the evaporation reaches its minimum value, in the months of December (according to the input data), an overflow rate will be directed gradually to the contact pond, thus the volume of the tailings pond decreases.

Table 17 Inflows and outflows of the tailings dam

Tailings dam			
Inflows	from	Outflows	To
Precipitation	Environment	Evaporation	Environment
Q_4	Process Plant	Overflow rate	Contact

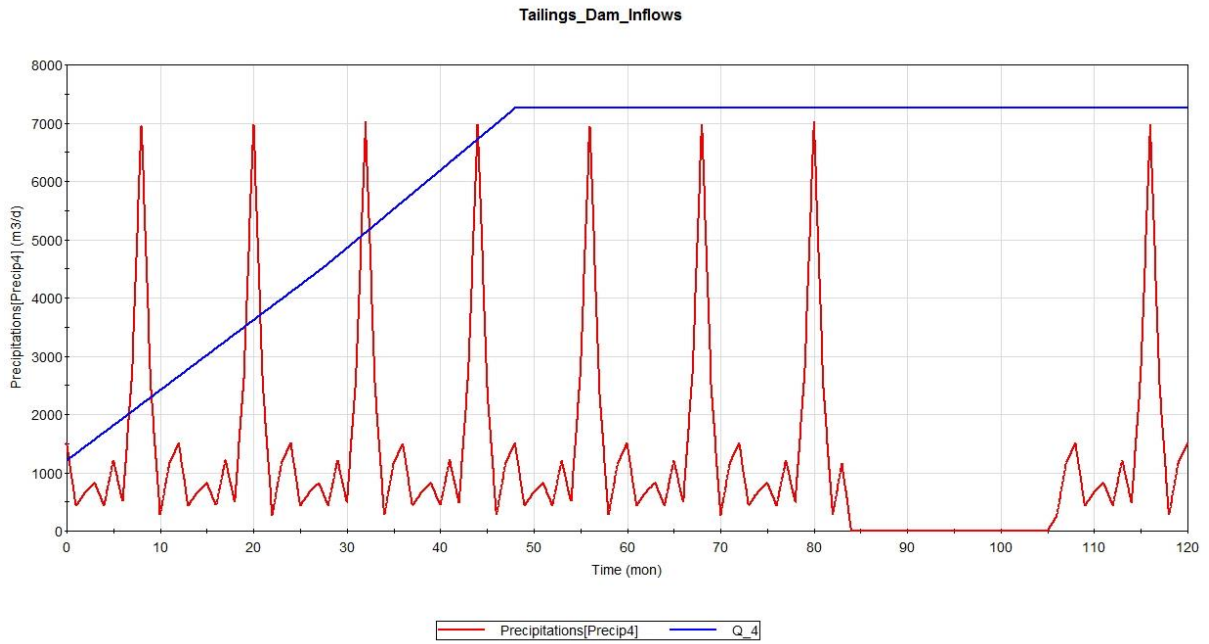


Figure 16 Tailings dam inflows

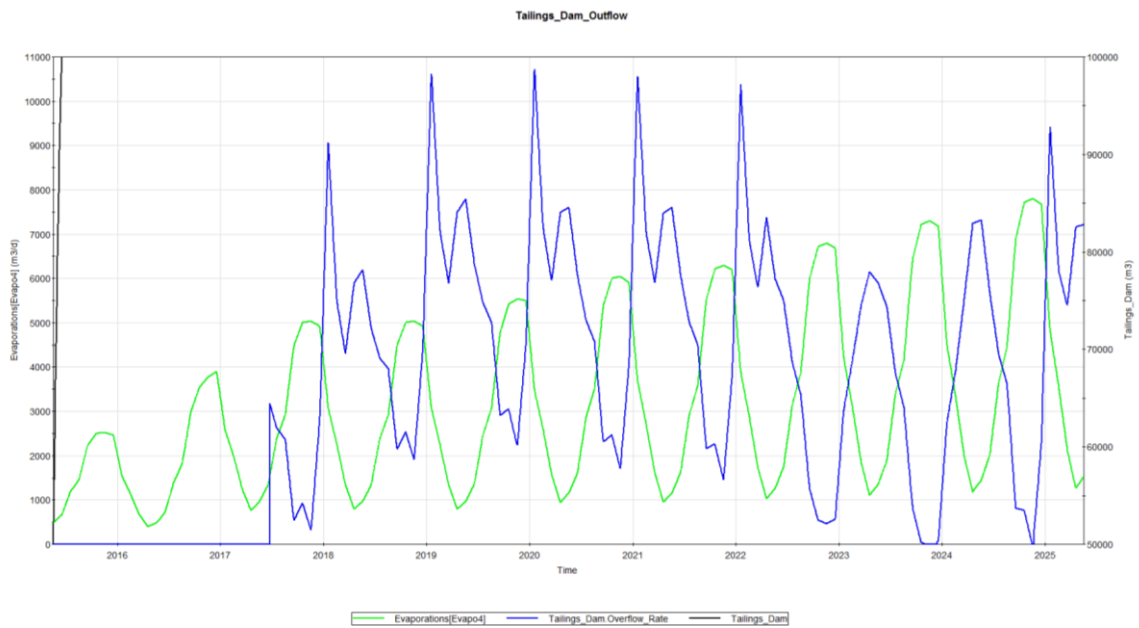


Figure 17 Tailings dam outflow

In all the time steps when the pond overflows happens, the volume in it decreases. It is the choice of the engineer to enlarge the pond in its dimensions or to operate with this frequency of overflows. These results can be checked with the change of volume in the pond, shown in Figure 18.

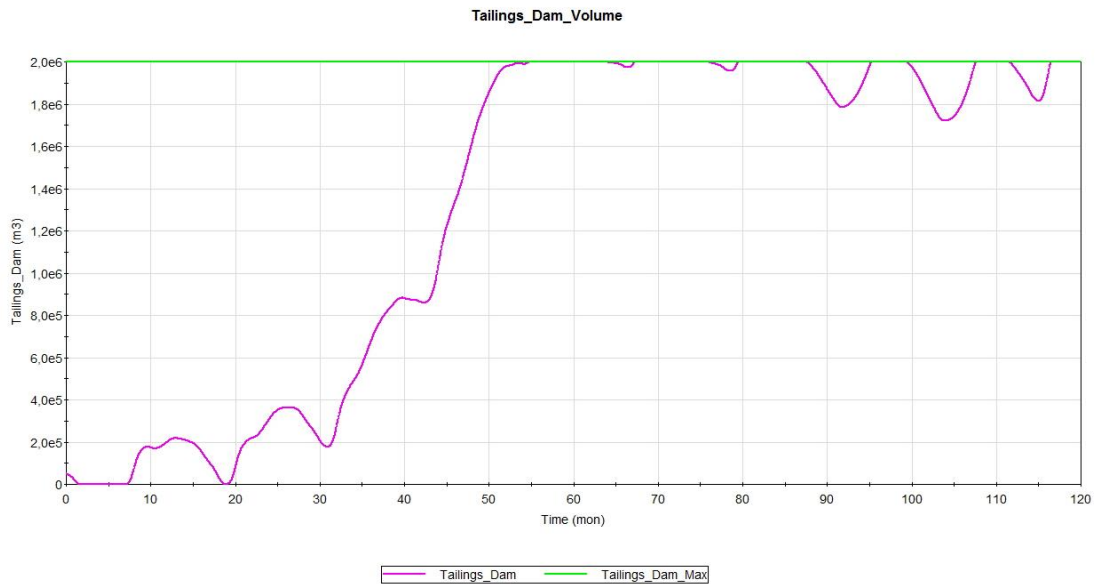


Figure 18 Volume in tailings pond

5.1.1.2 Retention pond

The next pond to be checked is the retention pond. As its purpose is the evaporation of the collected water, **Table 18 Inflows and outflows of the retention**

this is the main outflow exiting the pond. The other outflow is the one of infiltration into the ground. In case of reaching the upper bound, the overflow rate will be directed to the contact pond.

Retention Pond			
Inflows	from	Outflows	to
Precipitation_6	Environment	Evaporation_5	Environment
Q_12	Environment	Overflow rate	Contact

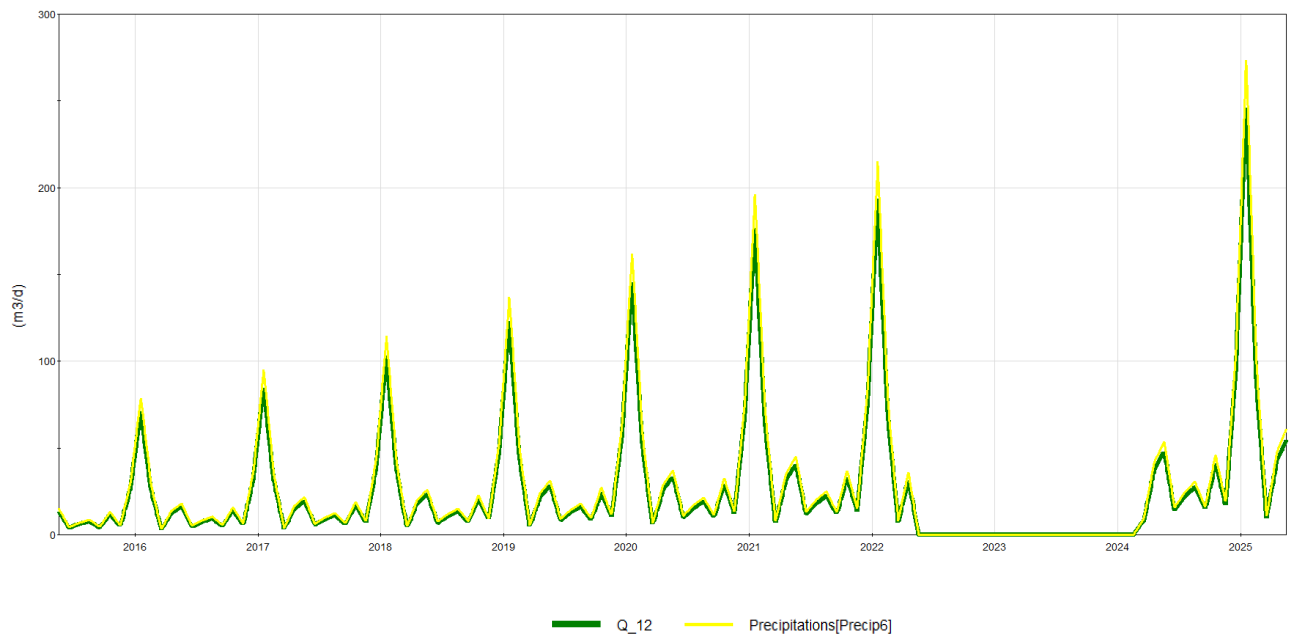


Figure 19 Retention Pond Inflows

As shown in the chart above, respectively Figure 19 Retention Pond Inflows the inflows in the retention pond are caused by precipitation on the pond itself, and the infiltration from the surrounding watershed (Q_12). Thus, these two inflows are proportional to each other, but Q_12 has higher values as a result of the bigger area. With time, the area is getting bigger therefore the inflows are too.



Figure 17 Retention Pond Outflows

The dry period between year 2023 and 2024 affects the retention pond's volume, as its only inflow is the precipitation. During this period, the inflow rate is , therefore its volume also is 0 m³.. In the beginning of the years 2021, 2022 and 2025, the retention pond reaches its upper bound, hence in the outflow chart, the corresponding overflow can be seen at the same times.

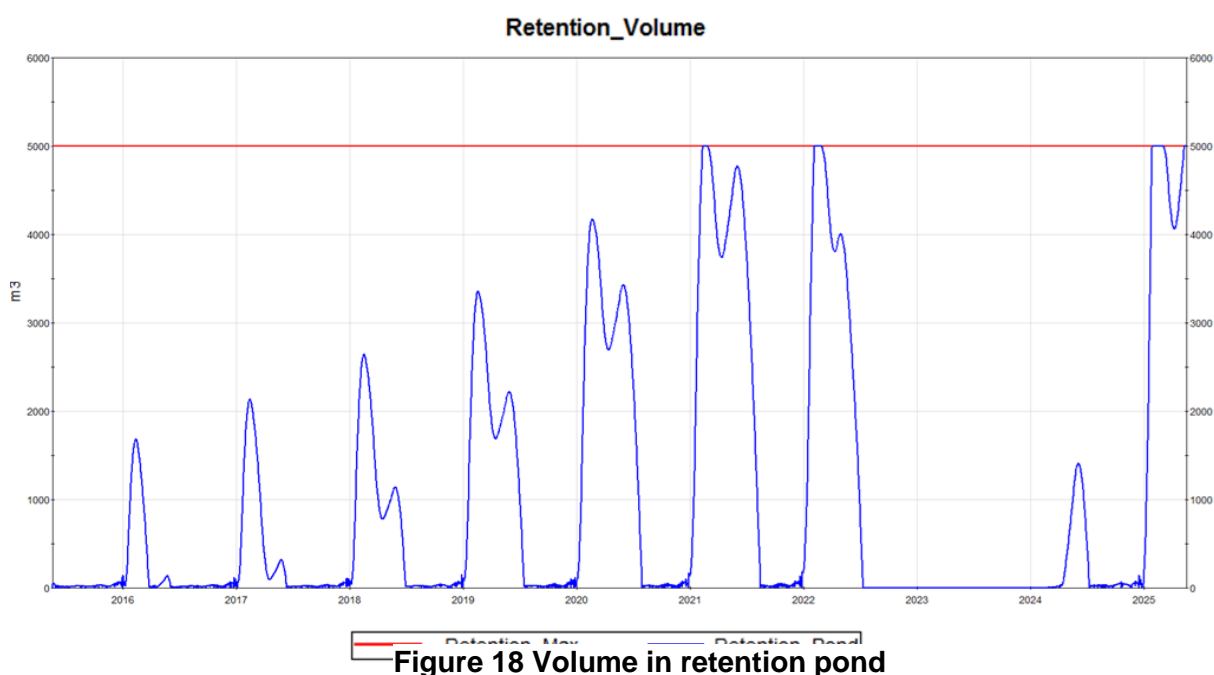


Figure 18 Volume in retention pond

5.1.1.3 Contact water pond

This water pond is more complex, as it has more inflows and outflows and at the same time is involved in a recursive loop. It is the main operator of the mine, as it regulates all the processes that occur on the site. In case of reaching the upper limit of its volume, the overflow of the contact water pond will be directed to the WWTP and to the sink. The water sent to the WWTP is channelled to the effluent water pond after it has been treated. The flow rate of this path is constant, as the WWTP can only treat a certain amount of water at a time. The rest of the overflow is redirected to the sink. We strive for an outflow of 0 m³/d to the sink, as the acidity of this water is high. In the results of the simulation this is achieved, thus a new dimensioning of the contact water pond would not be necessary.

As the results of the contact water pond oscillate with time, due to the dynamic operation of the mine, another form of representing them is needed. Therefore cumulative flow rates are shown in a smaller time scala, that is within a year also among the results.

Table 19 Inflows and outflows of the contact water

Contact Water Pond			
Inflows	from	Outflows	to
Precipitation_2	Environment	Evaporation_2	Environment
Overflow_Retention	Retention Pond	Q_3	Process
Overflow_Tailings	Tailings Dam	Q_9	Treatment
Q_71_Contaminated	Mine	Rest of Overflow	Sink
Pipeline_from_Effluent	Effluent		

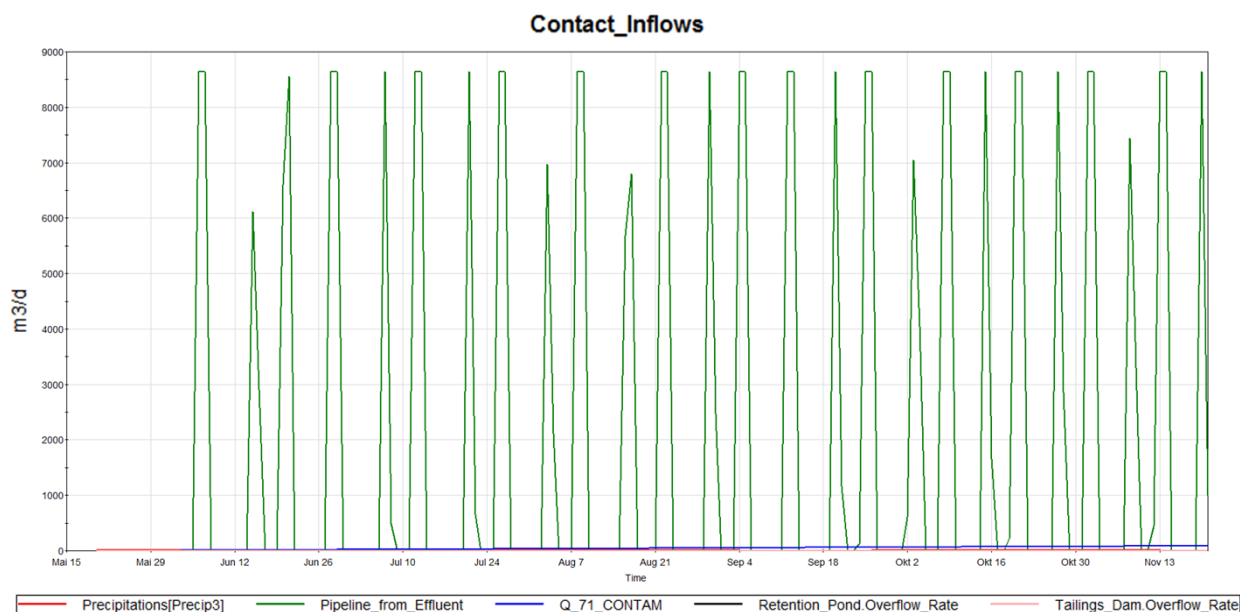


Figure 19 Contact water pond inflows within one year (Time-Series-Result)

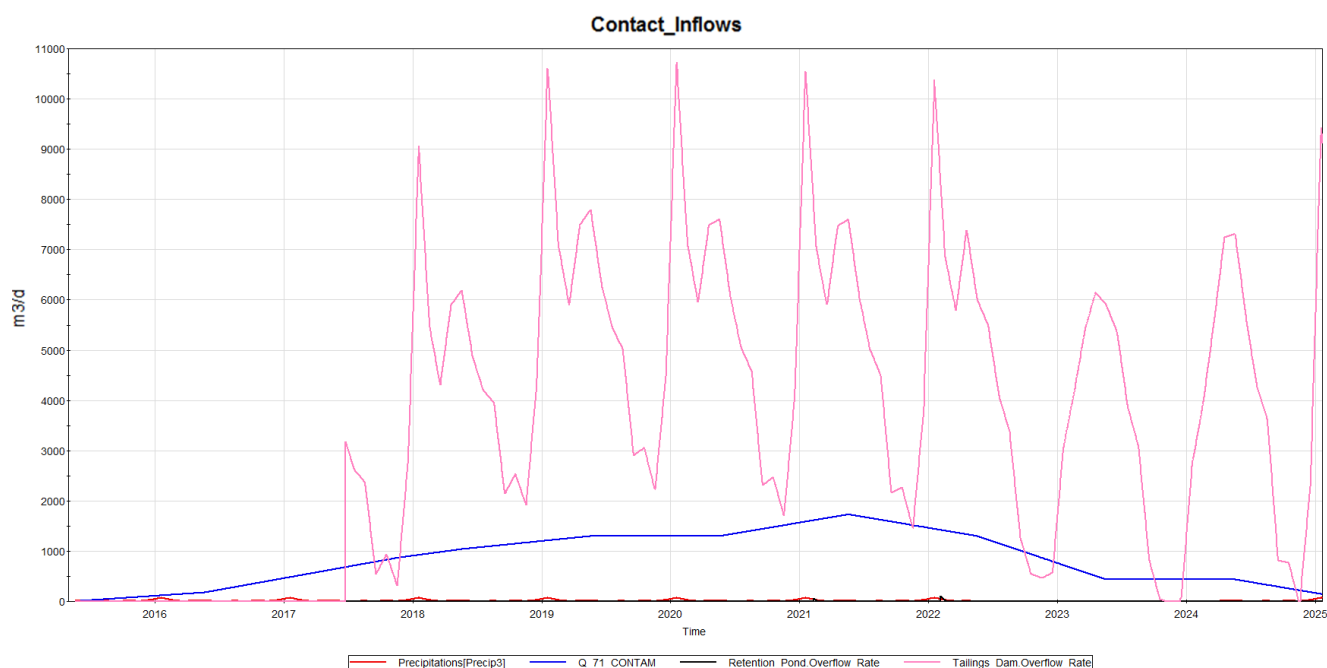


Figure 20 Inflows of contact water pond excluding the inflow from effluent water pond (Time-Series)

So far, it can be seen in the chart of the first year's inflows, that the main inflow in the contact water pond is the one coming from the effluent pond at times where the Contact Water Pond's volume reaches its lower limit. In order to have a clear understanding of the other inflows, another chart is shown in Figure 20 for the duration of the whole simulation (10 years), where the amount of water coming from the effluent pond is not included.

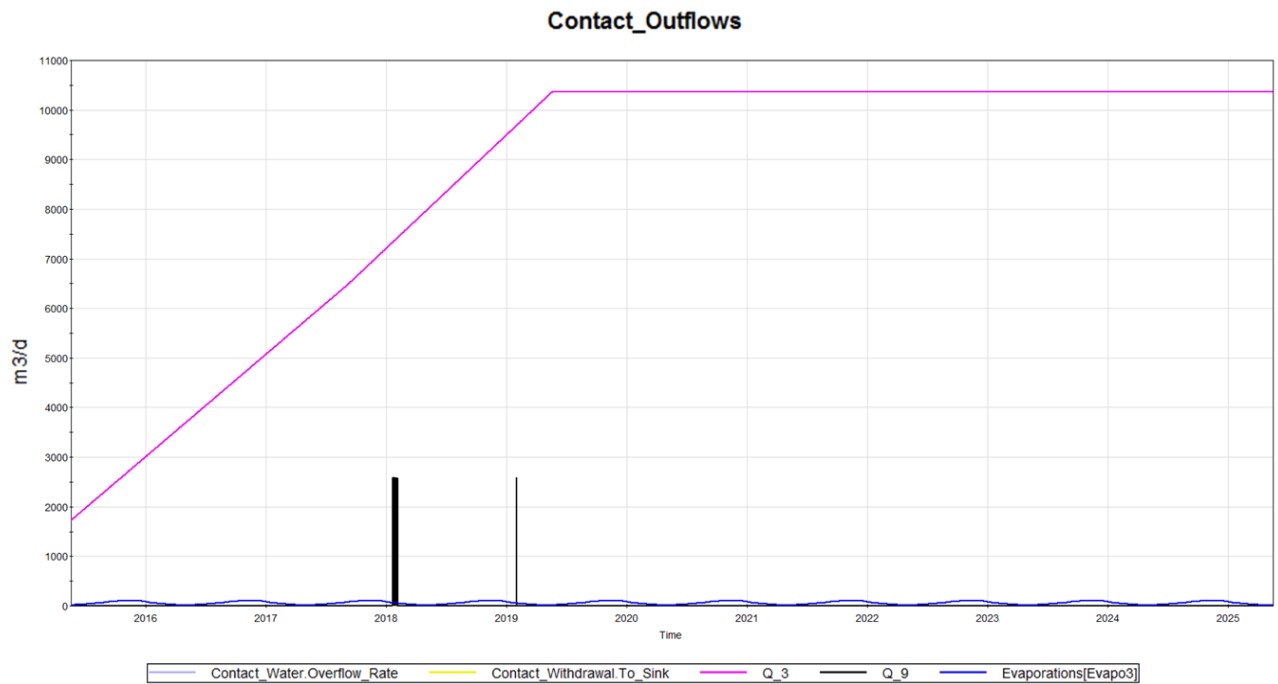


Figure 20 Outflows in contact water pond

In the beginning of the simulation, the processing of ore requires a low amount of water and also the volume of contact water pond is low, hence the outflow rate is inferior to later ones when the mineworks increase.

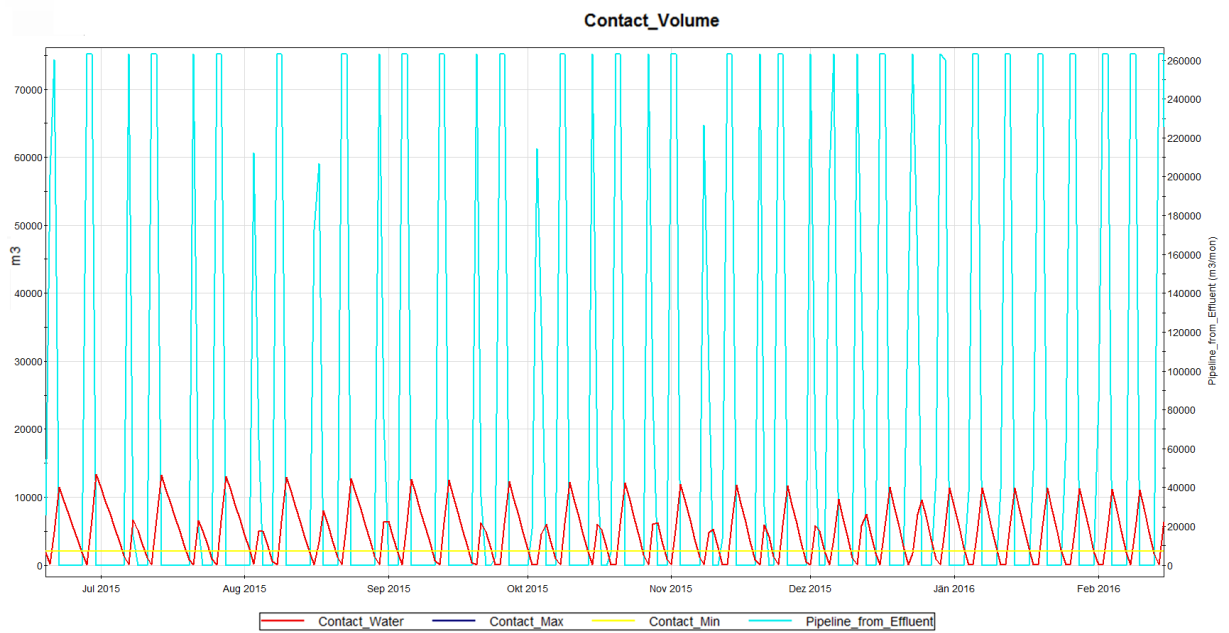


Figure 21 Volume changes in the Contact water pond for the duration of a year

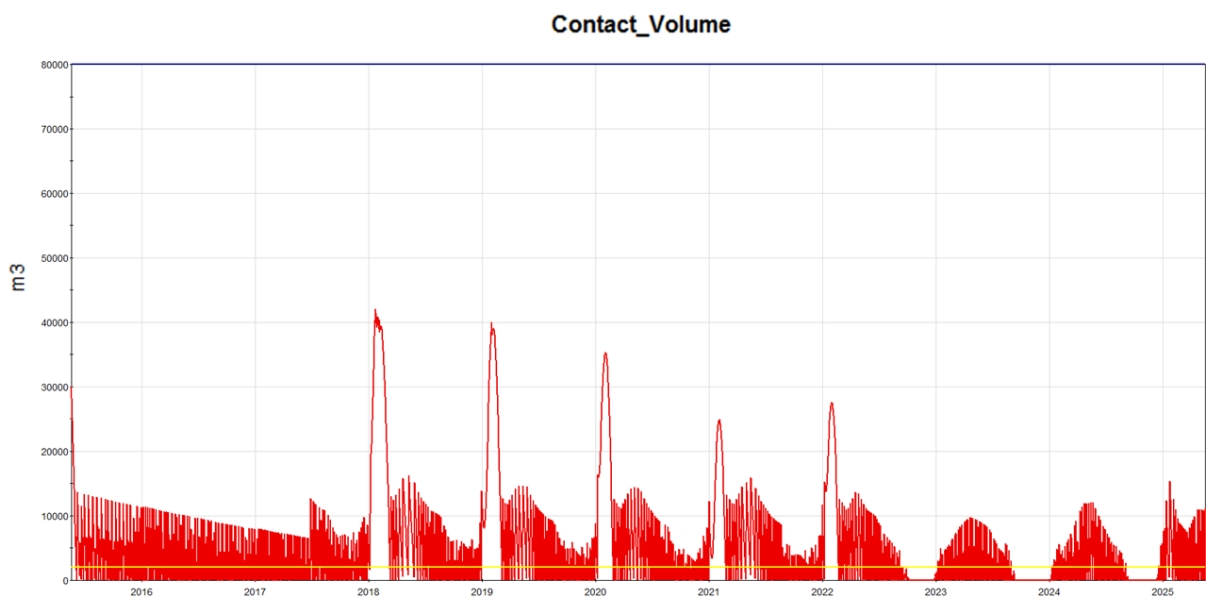


Figure 22 Volume changes in the Contact water pond for the duration of the whole simulation

The volume in the contact water pond does not reach its upper limit for the whole simulation period, hence there is no outflow to the sink. Therefore, the point of dimensioning this pond is achieved, but from an economist's point of view, smaller dimensions should be considered in order to decrease the overall costs of the pond. The lower limit is constantly reached whereas water from this pond should continuously be sent to the process plant. In the beginning of the years 2018-2022 the volume in the contact pond reaches higher values, due to the

overflow of the Tailings dam. The maximum volume is reached at the beginning of the year 2018 when water is directed to the WWTP for several times. Due to the oscillations of the water flow coming from the effluent, the volume development also tends to have a wave-like form. In order to show this connection better graphically, a short period of the simulation is shown in the subsequent figure. As shown in the chart above on Figure 22, when the contact water pond hits its lower limit of 10 m³, the inflow from the Effluent Water Pond is activated. This occurs within a timestep of a day, as it can not happen at the same time. This would result in instability of the system.

5.1.1.4 Effluent water pond

In the chosen hierarchy of the system, the Effluent Water Pond stands above the Contact Water, as it supplies it with fresh water and makes the connection to the receiving waters (River). This is the reason why the results of this pond are being analysed last.

Table 20 Inflows and outflows in effluent pond

Effluent Water Pond			
Inflows	from	Outflows	to
Precipitation_1	Environment	Evaporation_2	Environment
Q_10	Treatment	Pumping_Q2	Contact
Pipeline_from_River	River	Overflow Rate	River
Q_72_Clean	Mine		
Infiltration_Retention	Retention		

The results of the inflows and outflows of the effluent water pond are shown respectively in Figure 23 and Figure 24 for the whole duration of the simulation.

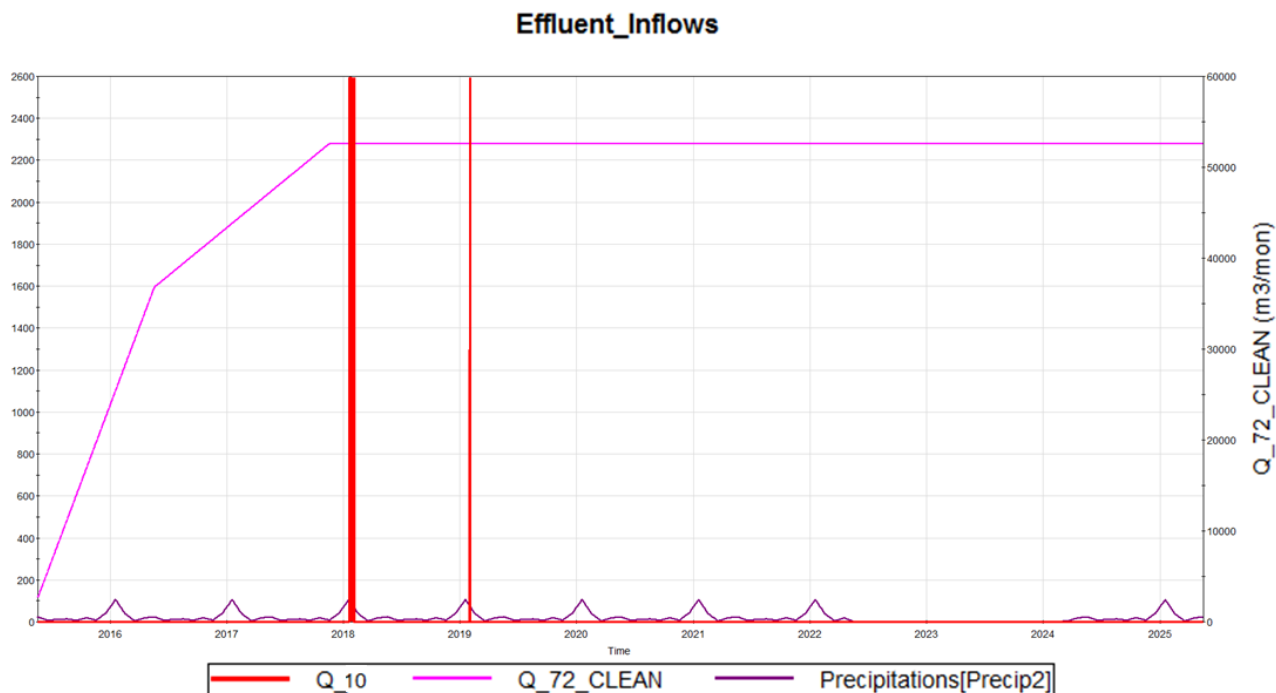


Figure 24 Inflows of the Effluent water pond

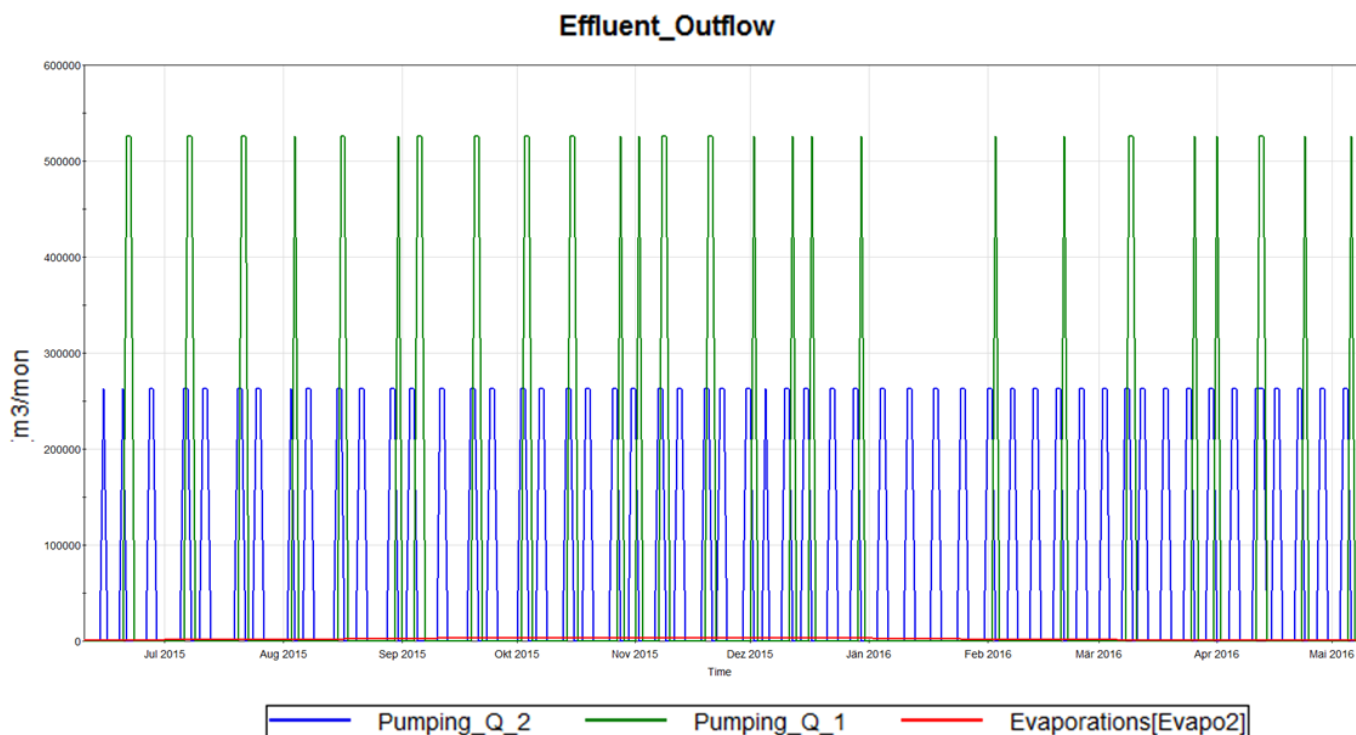


Figure 23 Outflows of the Effluent water pond

Once the amount of water coming from the contact water pond reaches the WWTP, it will be treated. The treatment process lasts one time step (1 day) and can be optimized when the used treatment method is known to provide a material delay within the model for a better approximation to reality.

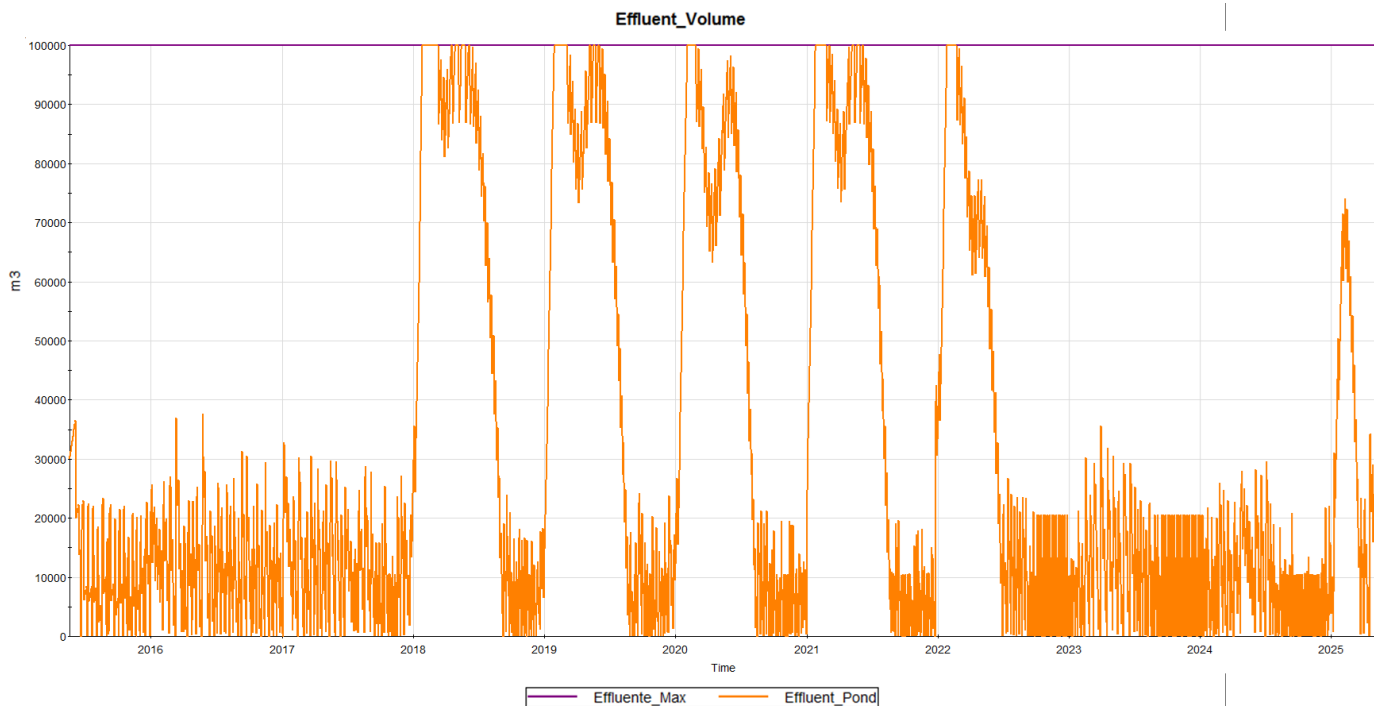


Figure 26 Effluent water pond volume during first year of simulation

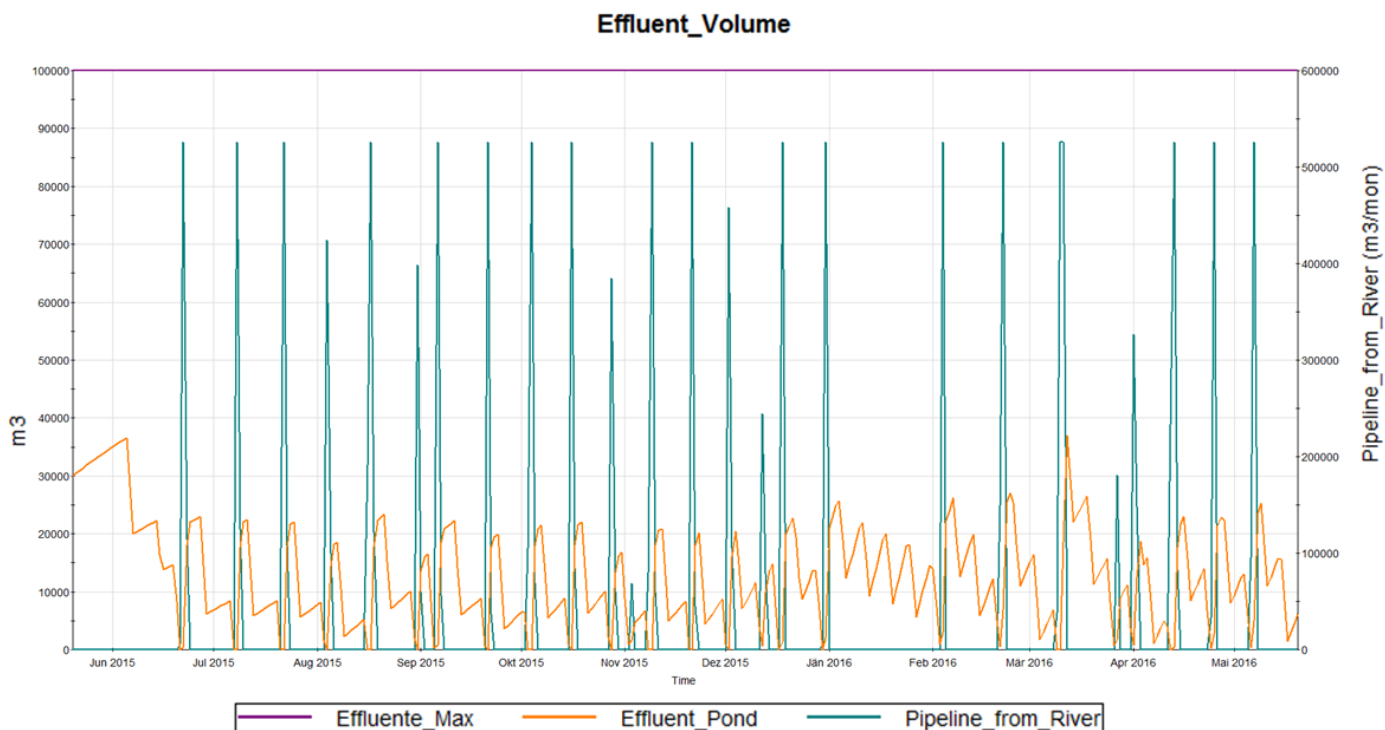


Figure 25 Effluent water pond volume (Time-Series-Values)

The water volume of the Effluent Water Pond is shown for the first year of the simulation with the correlation to the inflow from the river in Figure 26. Again, this is due to the oscillations, which prevent a good overview for the whole duration of the simulation. In times where the pond reaches its lower limit, water will be subtracted from the river within one time step (1 day).

5.1.1.5 River

The final investigation made on the Flow Model Results is comparing the River Inflows and Outflows. Once these two are known, the negative aspects of the mine to the surrounding environment can be assessed. In the graphs above, it is shown that on every time step in which the volume of the effluent water pond reaches its lower bound, water from the River is needed and therefore taken. On the other hand, when the upper limits reached, over the years 2018-2022, water will be discharged into the river. Considering the previous results seen for the Contact Water Pond, these are actually the same time periods in which the contact water pond overflow to the effluent occurs.

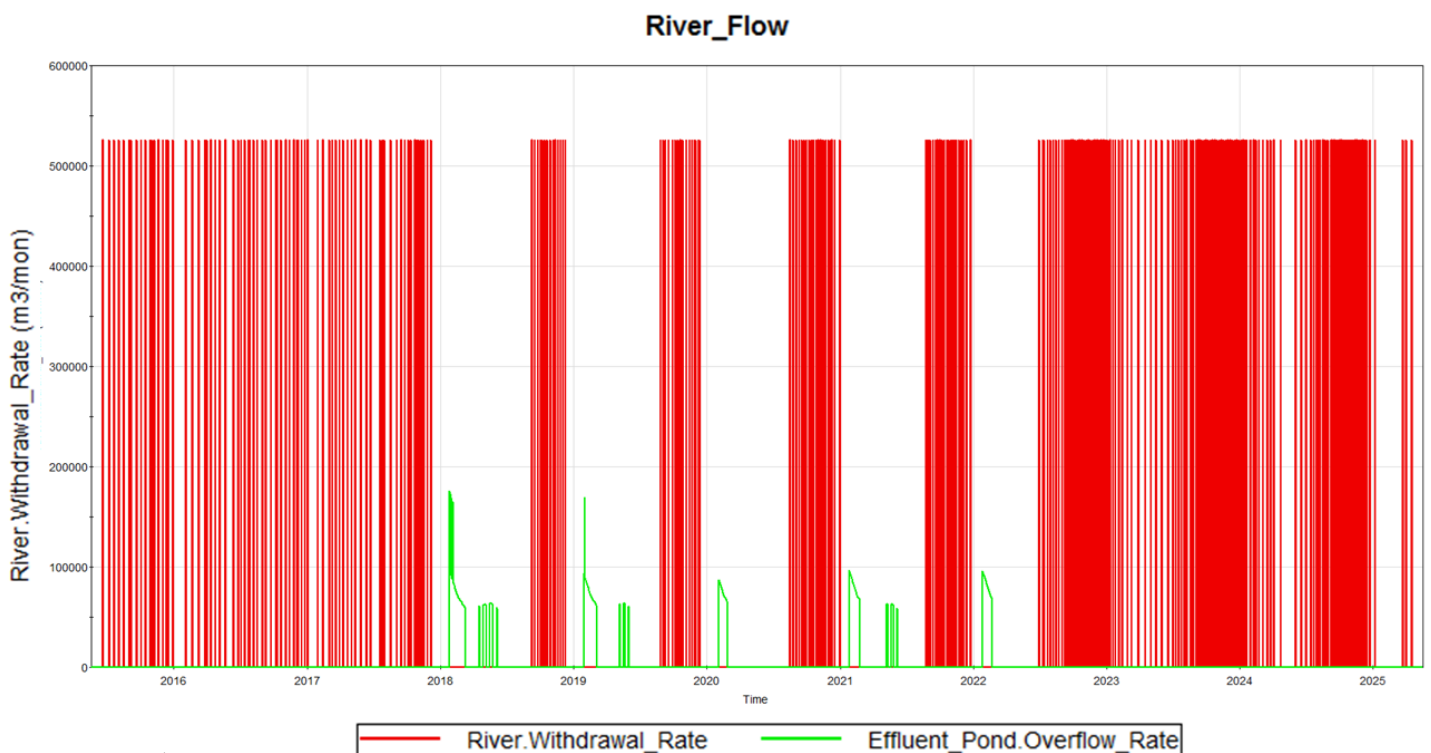


Figure 27 River flows

From the analysis done in this chapter it can be concluded that the results obtained from the simulation are respecting the laws of physics and have perfect correlations with each other. In respect thereof, it can be stated that the flow model in GoldSim can be used for further simulation and therefore as a base for the contaminant transport simulation, which results are presented in the following.

5.1.3 Contaminant transport results

Other than the flow model, the results in this module are not that simple to analyse due to the complexity of the flow itself. A possible way to validate them is to compare the mass of contaminants with the volume changes in the pond. In cases where the volume of a pond is decreasing because of evaporation or the lack of precipitation, then the mass of water changes, while that of Cu does not. This is why a 10-month long dry period was assumed to begin with. The dry period works as a test to proof the proper function of the contaminant transport model. On the other hand, when the volume reaches the value of 0 m³ there is no water in the pond, so the concentration of Cu in the water will be 0 g/m³, therefore a comparison between concentration and mass should be made.

5.1.1.1 Retention pond

As the only source of water in the retention pond comes as a result of natural processes such as precipitation and infiltration, this pond is chosen to examine the results of contaminant transport.

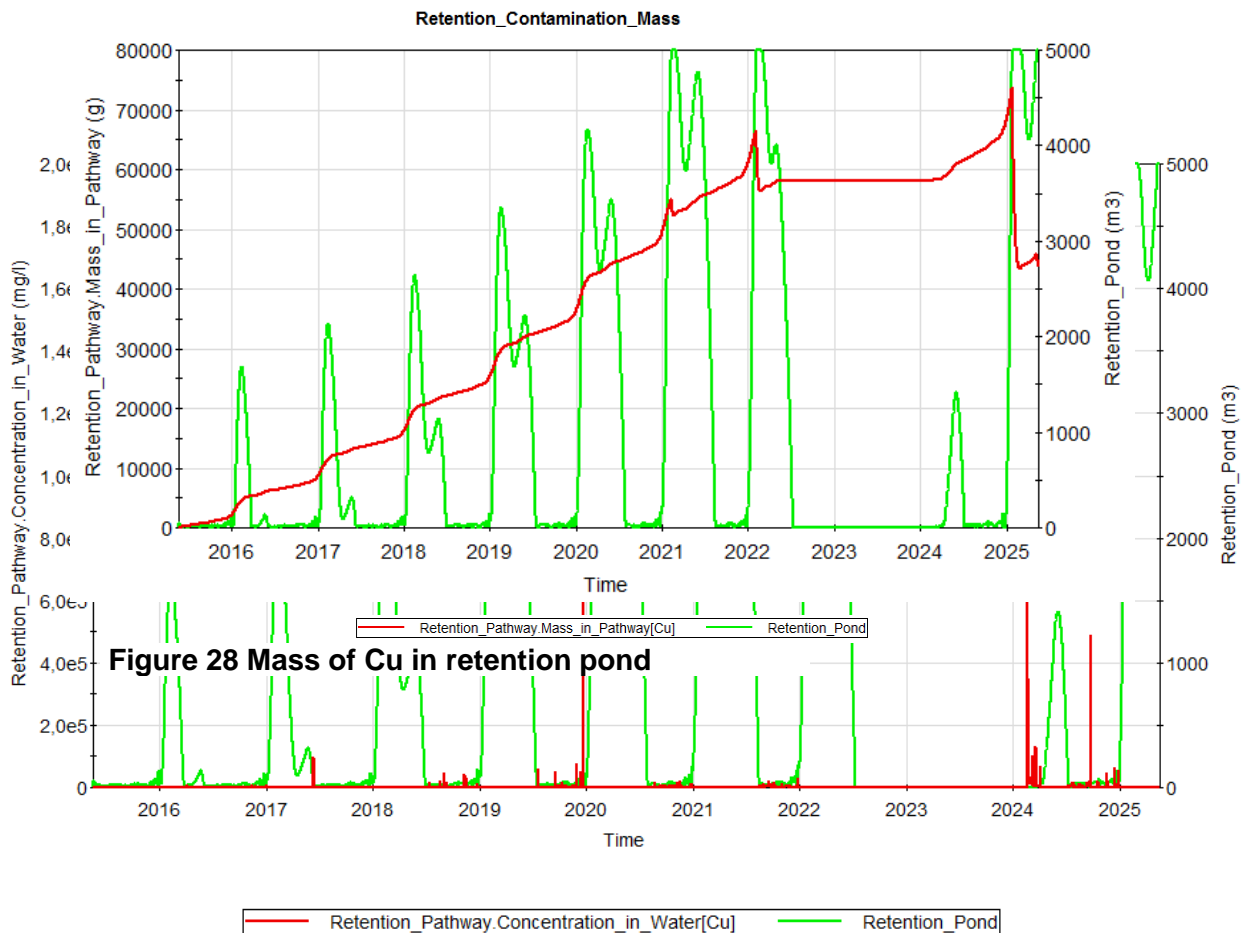
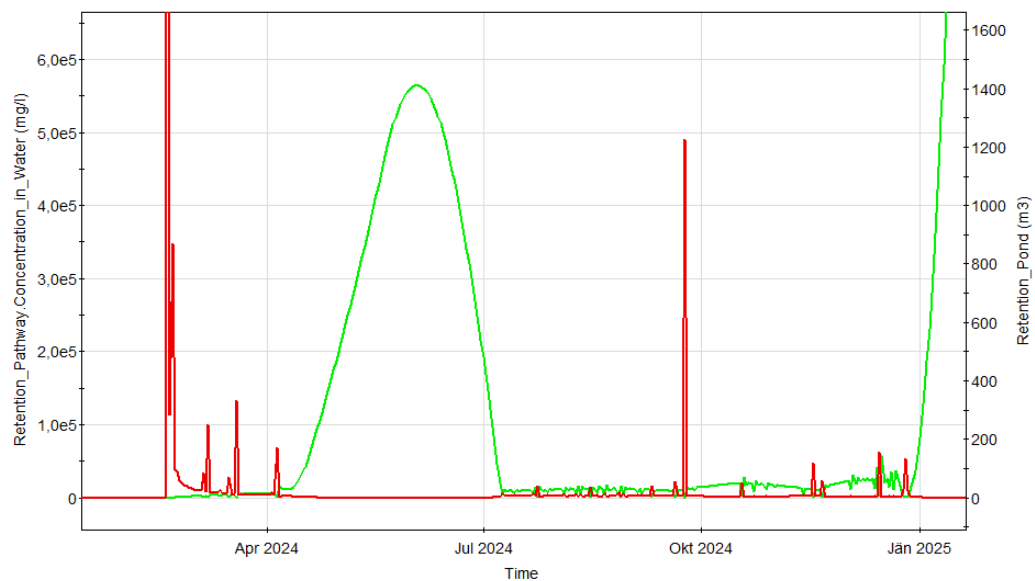


Figure 29 Concentration of Cu in retention pond

As mentioned before, in the dry period, no contaminant is being transported, as water only evaporates. Hence, the mass of contaminants remains constant, as shown in Figure 28. In time steps where the pond's volume reaches its upper bound, overflow occurs to the contact water pond. A part of the mass will be transported, therefore a decrease in mass occurs (i.e. Year 2022). On the other hand, inspecting the concentration of the contaminant, it can be observed that during time steps in which the volume converges to 0 m³, the concentration of Cu increases. Exactly after the dry period, where the concentration changes from 0 to 1,8 kg/l. This unrealistic value is very high considering that the mass of 1 L of

water has is 1 kg. This result can be interpreted that the pond only contains Cu due to its lack of water.

Right after water enters the system in year 2024 after the dry period, the concentration of Cu decreases rapidly, while the change in mass is not considerable. To support this statement, the following picture shows a closer look of a section of the previous graph that was shown in Figure 30.



5.1.1.2 Contact water pond

Another condition that should be fulfilled by the contaminant transport model is that while the contaminated water enters the WWTP from the Contact Water Pond, it will be treated, thus the water directed to the Effluent Water Pond after treatment is not contaminated.

As shown in Figure 31 in green, the Mass of Cu in the contact water pathway is changing with time. So does its concentration, shown in red change. This correlates with the fact that the contact water pathway has, over time, a various number of inflows and outflows containing contaminated and clean water. The inflow to the WWTP occurs only when the contact water pond reaches a certain volume, as mentioned before in the boundary conditions of the simulation in Table 10. In this case, contaminant mass will be transported to the WWTP. With a delay of

one time step (1 day) the same amount of water will be sent to the effluent water, but the water is treated beforehand, therefore no mass of contaminant will be transported with it. Indeed, the mass of contaminant in Effluent Water Pond remains 0 mg/l. It can therefore be proclaimed that the created tool is working properly.

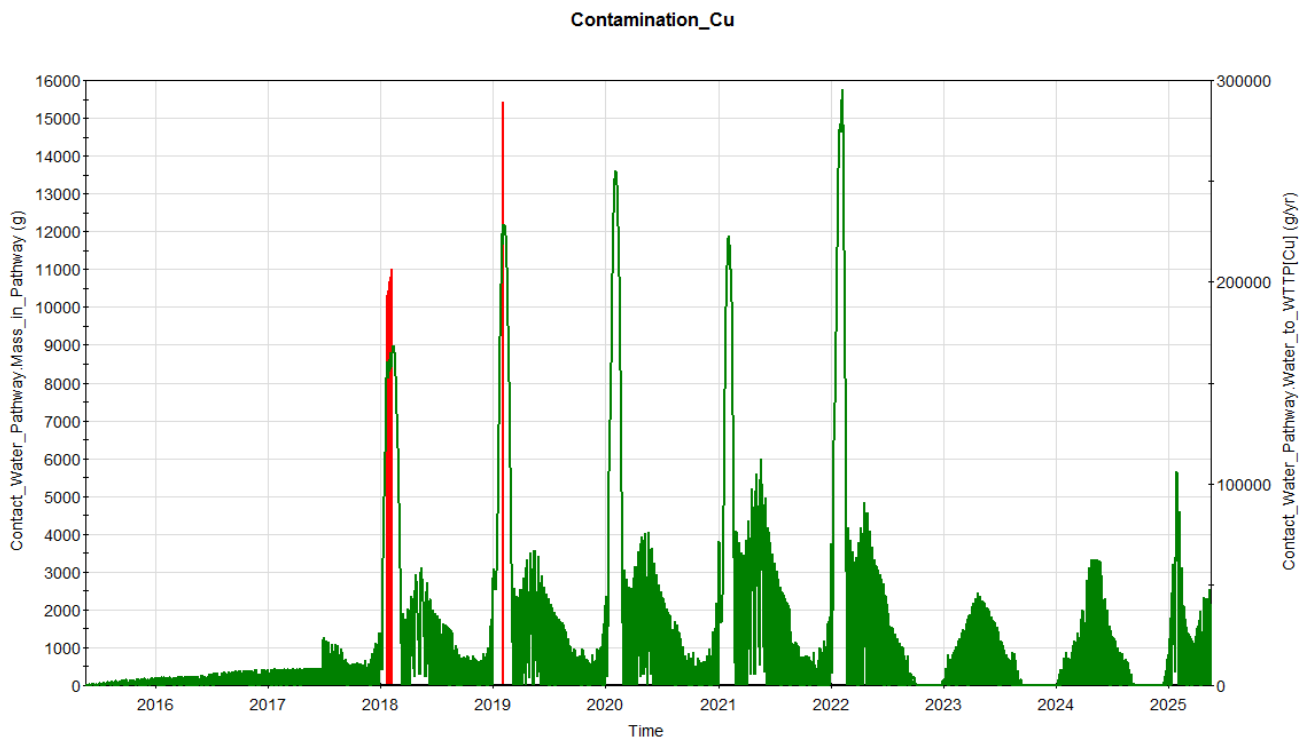


Figure 31 Contamination Cu in contact water pond

5.1.1.3 WWTP

To support the statement made in chapter 5.1.1.2, the mass in the WWTP Pathway is also being investigated and its development represented graphically in Figure 32.

In the beginning of the simulation, there is no inflow to the WWTP until the year 2018, in which mass from the Contact Water Pond is being directed towards the WWTP. Therefore the mass of Cu in the WWTP reaches the value of 523 g on 21st of January 2018. More mass will be brought by the repeated inflows from the Contact Water Pond.

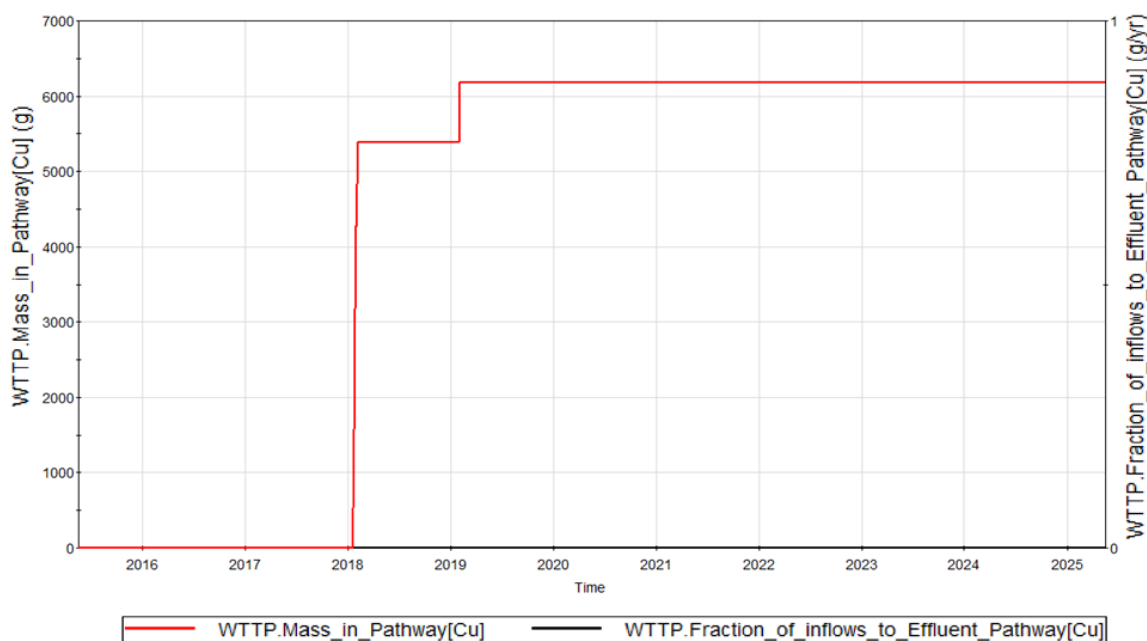


Figure 32 Mass of Cu in WWTP

As no mass will be transported within the Outflow to the Effluent Pond, the mass in WWTP only increases with every inflow, until it reaches the value of 5389 g on the 2nd of February 2018. The mass remains constant until the next Inflow on the 2nd of February 2019, where it reaches the value of 6181 g. After this instance the mass remains constant in WWTP as no more Inflows occur.

As a conclusion, the created tool can be used to simulate the contaminant transport on a mine site. It is important to choose the correct lower boundaries of volumes in various ponds, as reaching a 0 value leads to numerical errors.

6 Conclusion and outlook

- The designed tool using the program GoldSim could be further utilised to optimise the water management practices on a mine site, delivering the desired outputs: water flows within the compartments, volume of water in the ponds, contaminant mass in the receiving waters discharge, and intake from the receiving water, etc.
- The maximal deterministic error on water volume according to the water balance within a year is 0,06 m³ in the effluent water pond, which equals a total error of 2%.
- Difficult mine processes such as wastewater treatment can be successfully modelled and its characteristics can be described as well.
- Optimization of the system can easily be made through changes to the ponds' characteristics, such as their dimensions, initial volume, upper and lower limit of volume, area etc.
- The representation of the results is optimal and can be adapted for different purposes and stakeholders.

For the purpose of this project, a simple deterministic system with fictitious input data was created. In the future other tasks are to be implemented and designed.

These include:

- Applying the model with real input data from an actual mine site and comparing the results of the model (contamination mass, water volume flow, pond volumes), with the real data obtained from the operating mine site. The simulation of various scenarios is also desired.
- Run of a probabilistic simulation, wherein the uncertainties can be inherently applied and accounted for.

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