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Test of hydrogeological model of infiltration in a fractured medium

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Contents

Abstract

The thesis starts with the aim of making a model capable of calculating the infiltration during a fractured medium as a operate of the quantity of fractures, their inclination, and the slope of the ground. The model was created with the Modflow software package that was believed to be the foremost appropriate for its ability to simulate the hydrogeology of the study area with larger precision. The area of the Coricancha mine in Peru was used as the study area; the goal was to use the info of atmospheric precipitation and infiltration water, which the mine has, to calibrate the model once created. Unfortunately, the model did not prove to be sturdy and was thus unable to produce the specified results, despite this, even the success of some analyzed case studies leaves open the chance of continuous this path, albeit with a distinct approach and software. Additionally, to the creation of the model, an in-depth study was carried out on the role of the mining business within the Peruvian nation and its impact on the environment; particularly, the state within which the Peruvian water resource presently pours was studied and the waters of the Rimac river adjacent to the mine that is the protagonist of this thesis. The sharp economic process of South American nation is sadly combined neither with an adequate management of the water resource nor with its opportune safeguard. In fact, the expansion in demand for water resources is combined with a powerful decrease within the latter on the one hand because of climate change conjointly related to the El niño phenomenon (also object of study), on the other hand to the serious pollution in which they pour the fewer and fewer resources available.

Introduction

The idea of this thesis starts from a bigger project than a PVA (proposal for an Environmental supervision Plan) on the Coricancha mine by Professor Alfredo Iglesias of the Madrid Polytechnic (Iglesias Lopez, 2021). Among different things, the PVA provides for a study of the geology and topography of the area to characterize the potential risk factors (with their intensity) which will afflict the area encompassing the mine, to then use the information obtained to guide the placement of the treatment plants and the positioning of waste materials created by the mine.

The Coricancha mine placed within the Rimac stream valley between 3400 and 3800 meters above sea level is situated in the the Province of Huarochirí, approximately 90 km east of Lima. The mine is an exploitation of metal ores, of that the most cultivated is gold, and has been operative for over ninety years. The area around the mine is characterized by a steep and tough topography, the rivers of the area circulate through faults and are deeply embedded in the rock, leaving no space for alluvial plains. Therefore, it is not difficult to grasp that given the encompassing topography it is difficult to search out land within the neighborhood capable of accommodating mining concentration plants moreover as accumulations of waste materials deriving from soil process and metallurgy. Exactly for this reason most of the accumulations of waste material are placed some meters from the stream bed, and though they are properly treated, coated with geo-membrane and have slopes that go with the regulations, they contain extremely polluting and dangerous substances such as arsenic and cyanides. Due to their location close to the river the chance of pollution of the Rimac increases deeply, particularly given the unstable or environmental condition events to which the area is subject (Iglesias Lopez and Minga, 2020).

The Coricancha mine operates mainly underground although all the tunnels are located above the piezometric surface. For this reason, the company has the data of the water drained from the horizontal tunnels inside the mine, the drained water tends to be acidic and for this reason it is conveyed to the treatment plants before being released into the river.

The flow of drained water has two main origins: water from infiltrations; and the water due to the injections to reduce the dust in the front of the work. Having the possibility of knowing both the total volume of drained water and that of water used for injections, it is possible to easily obtain the infiltration water values which will then be fundamental for the calibration of the model of this thesis.

From the availability, due to the presence of the mine, to know the volumes of infiltrated water and the rainfall recorded daily by the area's rain gauges, the idea was born of creating a model, using the modflow software, capable of calculating what percentage of the total rainfall in the area is infiltrates and which instead streams and reaches surface watercourses depending on various factors imposed by us. The idea was therefore to use the data of the Coricancha mine to be able to calibrate the model, and once a robust model was achieved, to be able to use its results and apply them to the entire surrounding area, so as to provide an additional tool to the risk mapping developed for PVA; and in the case of a particular interesting results, to be used globally to simulate infiltration into the fractured medium in the most varied circumstances.

In addition to the model within this thesis, the opportunity was also taken to investigate the impact of the mining industry on Peru, on the current state of Peruvian waters and the connection between the increasingly scarce water resource, pollution and one of the climatic phenomena that most characterize South America: El Niño.

Study area

Peru

Peru, capital Lima, population of 31.2 million inhabitants, official language Spanish and an area of 1.285.216 km², it is the largest country among the Andes' countries and the third on the entire continent. It is located in the north-western area of South America and is bathed in the west by the Pacific Ocean while in the east it is completely crossed by the mountain range of the Andes (see Figure 1). About half of its territory is covered by forests, also considering that beyond the Andes mountain range we find the Amazon forest; the strip of the coast, on the other hand, has a particularly cold and arid climate and is pressed by the imposing mountain ranges (Wikipedia, 2006). The mineral resources grown in the mountains make a great contribution to the country's economy.

Figure 1 *Geographic location of Peru https://img.freepik.com/vecteurs-libre/carte-du-perou_6487-148.jpg?size=664&ext=jpg*

At the administrative level, Peru is divided into 25 regions, without considering the special province which is the capital Lima (see figure 2), which hosts 33% of the total population of the country (over 8 million inhabitants) and is one of the main metropolises of the continent. In addition to Lima, the 3 other major cities of the country are Callao (885,000 inhabitants), Tryjillo

(879,000 inhabitants) and Arequipa (876,000 inhabitants); 77% of the inhabitants of Peru are concentrated in large cities (Wikipedia, 2006).

Figure 2 *Geographic location of Lima* *https://it.123rf.com/photo_147090761_stock-vector-republic-of-peru-the-capital-is-lima-flag-of-peru-map-of-the-continent-of-south-america-with-country.html*

Lima

The metropolis of Lima (see figure 3) is the capital of Peru located on the Rio Rimac basin, in fact it is in the narrow strip of the coast of Peru, on a fan-shaped river system formed by the Chillón, Rímac and Lurín rivers and their tributaries. The urbanized area is therefore located at the foot of the central Andes mountain range, which surround the former plains with moderately steep slopes, and it represents the center of economic, industrial, cultural and scientific activities of the country.

Figure 3 *Picture of Lima*
https://www.genteditalia.org/wpcontent/uploads/2018/11/Lima_Peru_Andenstaaten_Responsive_1280x520.jpg

Thanks to the development of the mining activity and the gradually growing internal trade since the mid-twentieth century, Peru has been subjected to total but uncontrolled growth, without being coupled with adequate territorial planning and appropriate legislation, especially in the field of mines. Suffice it to say that in the entire capital there are no manholes, so the metropolis' sewerage system is unable to withstand exceptional rains. These shortcomings make the entire city, but also the entire study area and the Rio Rimac basin, a highly vulnerable area subject to potentially disastrous events such as landslides, avalanches, floods etc.. (Ministero de Agricoltura, 2010); moreover, the poor protection of the territory has meant that uncontrolled open-air dumps were accumulated over time, deposits of potentially harmful completely uncontrolled mine waste. In addition to the phenomena already listed, exceptional or periodic phenomena must be added and their obvious and disastrous repercussions, for example, exceptional rainfall due to the influence of the ENSO phenomenon, that will be further explored and explained below. It must also be specified that sadly it is the poorest populations who are the most vulnerable and consequently subject to the greatest risk, especially because of the precarious material with which their homes are built. Finally, it is also necessary to add earthquakes to the list of various potentially disastrous phenomena. In fact, the entire study area (as well as the entire nation) is located in the "Pacific Ring of Fire", which is the area with the greatest seismic and volcanic activity in the world, due to the phenomenon of subduction in which the continental plate advances and overhangs (passing over) the oceanic plate of the pacific. Nowadays there have obviously been attempts by both local and national authorities to improve the living conditions of the population, attempts however significantly slowed down by the serious lack of exhaustive information on the geological, geomorphological and geodynamic environment, that only in recent years we are trying to compensate, thanks also to economic development (Ministero de Agricoltura, 2010).

Geology of Peru

Along the entire nation, the Peruvian Alps extend, which include a set of mountain ranges that divide the Pacific coast from the Amazonian plain. Several overlapping orogenic cycles and the Andean subduction (given by the collision between the South American tectonic plate and the oceanic tectonic plate) are responsible for its current stratigraphy, its magmatism structures, as well as its mineralization and seismicity (see figure 4) (Pfiffner and Gonzalez, 2013).

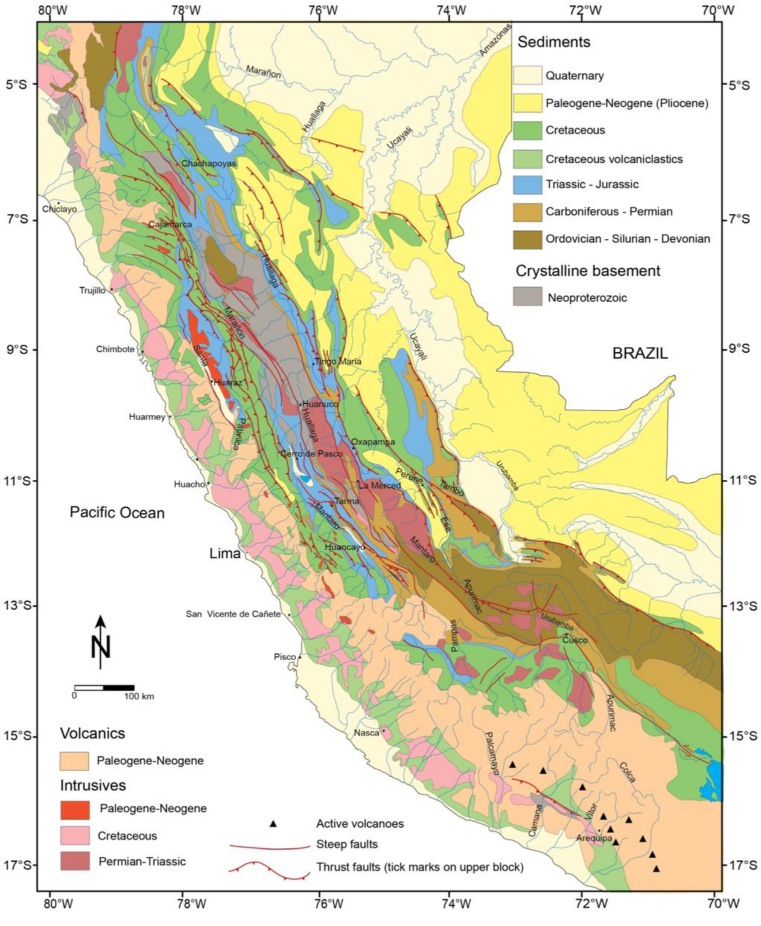

Figure 4 *Geology diagram of Peru* *https://www.mdpi.com/2076-3263/3/2/262/htm*

The entire Andes mountain range has a base of Proterozoic metamorphic rocks, on which occurred numerous sedimentations, accumulated over time and then deformed by the Paleozoic Hercynian tectonics, which were also associated with plutonic intrusions and volcanism during the Upper Paleozoic. In the Mesozoic, the cycle and formation of the Andean mountain range begins it is in this period that the structures are defined and then reach their maximum development in the tertiary sector and continue to grow to this day.

Within the history of the Andes, marine and continental sedimentation processes have occurred, also associated with deformation phases due to and accompanied by magmatic and volcanic activity. Seismic and volcanic activity is still very present today, which is why the entire Peruvian Andes are considered part of the "active seismic belt". In fact, faults and deformations in the Quaternary rock are evident throughout the entire mountain range, as well as raised erosion surfaces, volcanism and the uplift of recent marine terraces.

Given the geological context, it is not surprising that Peru is therefore a country of large and abundant mineral resources, which have been widely exploited (especially in the last century), guaranteeing the Peruvian nation a significant economic development. Within the large territory there are numerous metal deposits, which although of a different nature, can be mainly associated with the effect of intrusive sub-volcanic and extrusive magmatism, whose types of minerals and their respective volume depend on the type of rock and the origin of the mineralizing solutions from which they were generated. In particular of great economic interest are the research and their subsequent cultivation of epithermal deposits of gold and silver with high sulphation and copper porphyries with scattered gold (Ministerio de Energía y Minas, Peru, 2001).

This great mining development was mostly possible thanks to the preparation and publication of the Geological Nation Map, also integrated with the development of satellite images, thus providing a more complete base of information on the geological and mineral resources of the country.

The first real cultivation of mineral deposits, in particular gold, silver and copper, dates to the times of the ancient Incas, and then came to a first great development during the colonial era with the exploitation of gold, silver, mercury and, to a smaller extent, lead, mainly due to their silver content. However, a huge development is currently taking place in this sector. Nowadays Peru is in first place in the production of gold in Latin America (about 132 tons per year) with still potential for growth. It also produces more than 40 substances between metals and non-metals, among the best known: antimony, bismuth, cadmium, copper, tin, iron, indium, manganese, mercury, molybdenum, gold, silver, lead, selenium, thallium, tellurium, tungsten, zinc. In addition to those mentioned, other mineral deposits have also been found such as chromium, cobalt, nickel, platinum, titanium and uranium, but their potential has not yet been defined or quantified (Ministerio de Energía y Minas, Peru, 2001). On the other hand, there are numerous non-metallic minerals (whose production, unlike metals, is almost exclusively destined for the domestic market of Peru) including: barite, limestone, gypsum, kaolin, clays, refractory, talc and ornamental rocks (Pfiffner and Gonzalez, 2013).

Finally, it is also important to mention the presence of oil fields, which are mainly located in the marine sediments of the Cenozoic in the Peruvian northwest and gas fields, some of these already in the hands of private investors.

Certainly, Peru is a nation that has numerous and greater energy resources throughout its national territory, and in particular mineral resources, which could be adequately exploited with a systematic exploration of the country, based on new geological information of the territory, the knowledge of Andean metallogenies and new exploration technologies available.

Mining

Mining in Peru

As previously described, Peru is in continuous economic growth: every year there is an increase in GDP, almost doubled in the last 10 years, passing from being considered a country of medium-low income to upper middle income by World Bank standards, considering that following this growth trend, by 2029 it could even be considered a high-income country. This "economic miracle" has allowed citizens access to new resources and better consumer goods. This is confirmed by the increase in car registrations, which however lead to a consequent increase in traffic causing inconvenience to economic and social activities. In fact, it has already been pointed out that this economic growth, having occurred so rapidly, was not followed by an adequate development of infrastructures, territorial planning and above all the appropriate legislatures (Iglesias Lopez and Minga, 2020). These deficiencies are paid dearly by the poorest segment of the population who suffer the consequence. In addition to the aspects linked to natural disasters, the aspects linked to anthropogenic disasters must also be taken into consideration, the main point of which is strictly linked to environmental contamination related to mines. When growth is the goal, there is a risk (as in the case of Peru) of neglecting the services that must go along with growth to preserve resources, the environment, but above all human health. The Peruvian population wants to grow and improve their opportunities, but very often they are ignorant of what its cost is (Thomson reuters, 2021).

Much of this economic development is due to mining. In fact, it represents over 50% of foreign currency, 20% of tax collection, 11% of the gross domestic product and 65% of the annual exports of the entire nation (68% if the part concerning the extraction of oil and natural gas) (El comercio.pe, 2015) (see figure 5). This makes it a fundamental sector for the growth and development of the South American nation, due to the fact that what is exported results in a large contribution of money, useful to obtain the goods and services necessary to promote development.

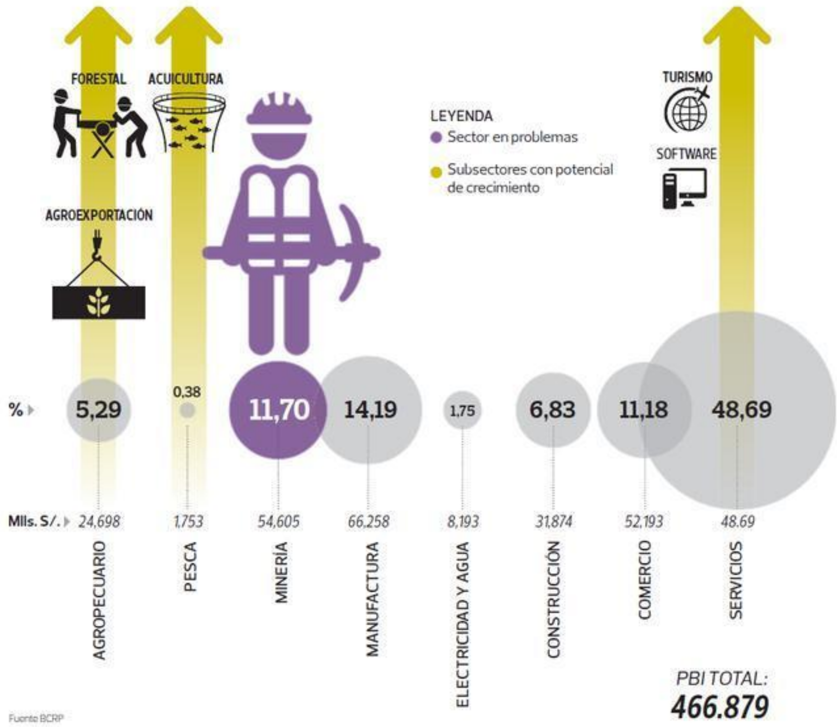

Figure 5 *Peruvian economy diagram* https://elcomercio.pe/economia/peru/importante-mineria-peru-192754-noticia/

In the case of Peru, however, there is a great obstacle in the past and still partly today: the Peruvian mining situation was decidedly "disorganized" and lacking in appropriate legislation for proper regulation of the activity. This recklessness has unfortunately led to a huge problem of environmental damage, which will be further explored later.

Therefore, it is appropriate to ask what is best to do, and how the Peruvian economy would react to the complete replacement of the mine by other resources, thus eliminating the problem of pollution and environmental impact at its root. In the long term, possible solutions were analyzed with the development of infrastructure such as the pipeline in the south, the construction of the metro in Lima or the construction of refineries. It was also analyzed current agriculture and its development and increase for export and therefore the generation of foreign currency. For the agricultural sector it has been calculated that the current 4 million hectares currently present could be doubled, with an appropriate study and investment in water resources and possible irrigation systems, reaching around 5 billion dollars in exports (El comercio.pe, 2015). Even implementing this, it could not be considered on its own completion as a substitute for the mining sector, which currently has over $ 20 billion a year in exports.

Another possible analysis was made on tourism, a fundamental part of widely developed nations such as Italy. This sector is in fact on track to be considered the second largest generator of foreign currency. Although it is promising, yet another time it still does not have such figures to be considered (at the moment it is about 7 billion a year) on a par with mines (El comercio.pe, 2015).

It is true, however, to say that there are important aspects in which mining is not in the first place and could be largely replaced, such as the tax contribution in which mining is surpassed by both production and trade; another aspect is the creation of jobs, in which once again this sector is largely replaced by production, services, commerce and construction, even if the geographical factor should not be underestimated. In fact, the figures presented here speak nationally, but it is good to keep in mind that most of the mines are located in the mountains of the Andes, and around them and because of them they have created entire towns. An example is the town of San Mateo located near the Coricancha mine, the subject of this thesis, where all, or most of the inhabitants, work for the mine itself; if the entire mining activity were to be suspended, the inhabitants of this country would find themselves unemployed and therefore forced to move to look for work elsewhere, a considerable psychological and economic discomfort for thousands of people. From the testimony collected on the spot by Alfredo Iglesias, a Spanish professor who has visited the area several times, and Julio Cesar, a Peruvian PhD student at the Madrid Polytechnic and employed at the Coricancha mine (Iglesias Lopez and Minga, 2020), it is clear how the inhabitants of San Mateo and neighboring countries, but like most mine workers, they are terrified of the possibility of mine closing and cutting their only source of income to support their families; in fact, thanks to the work of the Coricancha mine in these countries, the rate of inhabitants subject to alcoholism has significantly decreased as well as the number of suicides.

It therefore seems that the solution cannot be to look for a substitute activity for the mines, also because it would amount to losing the opportunity to exploit a rich resource, in addition to the reasons already mentioned above. However, what could and should be done is to move towards a more eco-sustainable cultivation and a pride of the Peruvian economy; in this regard, in an interview with Rubén Guevara, senior professor at Centrum Católica, he argues that instead of looking for a substitute for mining, one should work so that mining becomes a beloved sector and admired; to this end, its proposal is to work to make visible the positive impacts of mining on the national economy, to bring infrastructure and public services to the areas where mining operates, to promote alliances between companies and communities and to recognize that the mining has caused environmental damage (El comercio.pe, 2015). Obviously, this is not possible without the support of the government and therefore a strict legislature.

Pollution due to mines in Peru

The environmental impacts of mining have consequences on the atmosphere, surface waters and underground waters; these consequences in turn can affect the social, artistic, and economic environment, flora, fauna and subsequently human health. Depending on the type of mining, different impacts and levels of pollution can occur. The extraction of ornamental rocks has a strong impact on the landscape beyond smoke, noise, dust and vibrations; at the peak of contamination, the extraction of energy has the formation of acidic waters by oxidation and hydration. As for the metal mining sector, the one that is cultivated in the Coricancha mine (see figure 6), there is a decidedly complex and very diversified process, and the greatest pollution lies in the extraction of the mineral from the remaining "waste" rock, extracted from the mine, and from the dimensions in which it is necessary to grind it so that the mineral is "free", dimensions that often reach up to 100 µm; once it has been ground, subsequent procedures (which can be of chemical, physical, chemical-physical or biological origin) will take place to bring about a concentration of the mineral sought (Butler, Lall and Bonnafous, 2018). The process of releasing the material certainly has a strong environmental impact as in its grinding to such a fine size, not only the desired mineral is released, but also the other minerals present in the rock such as sulfur, arsenic, cadmium, lead, etc... (Ecologist, 2017).

Once these minerals are released, they become considerably more reactive due to the increase in its surface area of possible contact with oxygen and water (mainly); as possible examples there is the oxidation from ferrous to ferric sulfate, or the formation of sulfuric acid, both processes that contribute to the formation of acidic mineral waters. As for the concentration of the mineral, the pollution depends on the type of process involved, usually the physical processes (which are based on the difference in density or for example exploit the magnetic properties of the mineral) have a low environmental impact compared to those chemical-physical, for example flotation,

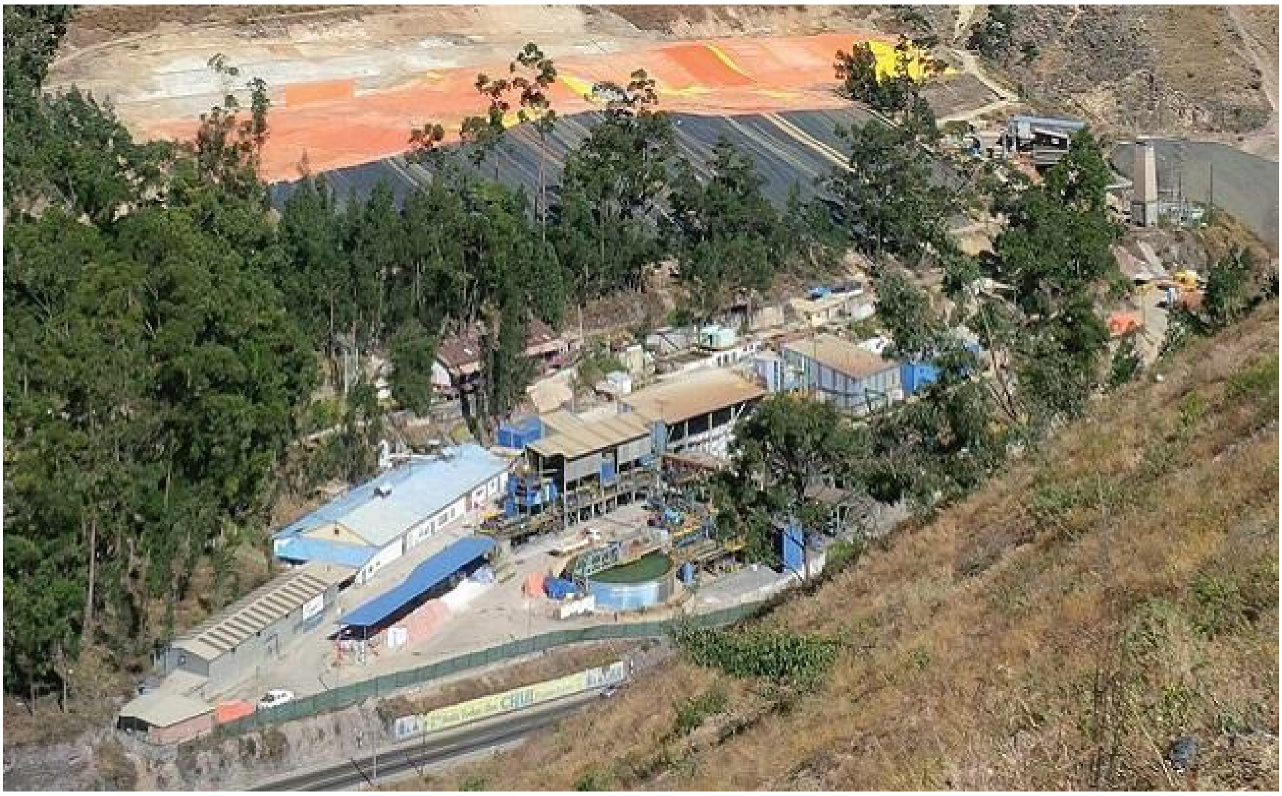

Figure 6 Picture of the Coricancha Mine https://proactivo.com.pe/great-panther-toma-una-decision-de-produccion-positiva-para-coricancha/

biological, with the use of bacteria or chemicals. In the Coricancha mine a chemical treatment is used, namely the cyanidation of gold.

Cyanidation of gold

The process of gold cyanidation, or cyanide leaching, is employed to extract gold from the raw mineral with that it is associated within the soil. The mineral is first finely ground, to facilitate the leaching process; then, cyanide is added to it, which is able to dissolve the gold within the rock, which on the contrary isn't soluble in cyanide. Once the gold has been dissolved, it will then be extracted in liquid form then treated once more to get rid of the cyanide. The cyanidation technique is one amongst the most affordable strategies in gold mining and presently nearly 90% of all gold is extracted using this technique (Netinbag, 2019). Unfortunately, despite its low price, this kind of treatment is controversial given its sturdy environmental impact and given the risk that its use poses each on the environment and on workers. within the mineralization that characterizes the Coricancha mine, alongside gold, the mineral additionally contains sulphites, that also react with cyanide. For this reason, preliminary processes are used to guarantee effective extraction. during this case, basic solutions of calcium oxide are used to neutralize potential acids, as well as extremely nephrotoxic hydrocyanic acid, and to limit the interaction between sulphides and cyanide (Golder, 2018).

Arsenic contamination effects

One of the biggest concerns regarding the pollution caused by the Coricancha mine on the Rimac River is certainly the release of arsenic, a metal that is highly harmful to human health, and the cyanide used in the gold cyanidation process. While cyanide has always been more strongly controlled and is not detected at abnormal levels of Peruvian waters, arsenic is certainly the metal with one of the most worrying concentration rates in the Rimac river.

Effects of arsenic on public health

In the WHO ranking, arsenic is considered among the 10 most dangerous chemicals for public health. Therefore, in recent years the World Health Organization has spent countless efforts in order to reduce exposure to this metal as much as possible, imposing strict guidelines, and formulating possible general recommendations on managing exposure risk, based on numerous scientific tests and data. The main guiding value was, of course, the concentration of the material itself in drinking water, so that the suggested value could be used to draw up and standardize regulatory plans around the world. Currently the suggested limit for the concentration of arsenic in drinking water is 10 mg/l, a value considered to avoid possible long-term effects from the daily intake of arsenic, for example through the consumption of contaminated water or that present in the inside food (Medina-Pizzali et al., 2018). Among the most frequent long-term effects, due to the chronic intake of the metal, there are pigmentation changes and skin lesions, such as corns and calluses, all precursors of skin cancer; in addition to skin cancer, bladder and lung cancer is "common" (Fernando et al., 2015). It is therefore obvious how arsenic is classified as a carcinogenic agent for humans. Among the other possible side effects, however, not only the possible development of cancer is found, but disorders of the nervous system, diabetes mellitus, anemia, liver disorders, cardiovascular diseases (see figure 7).

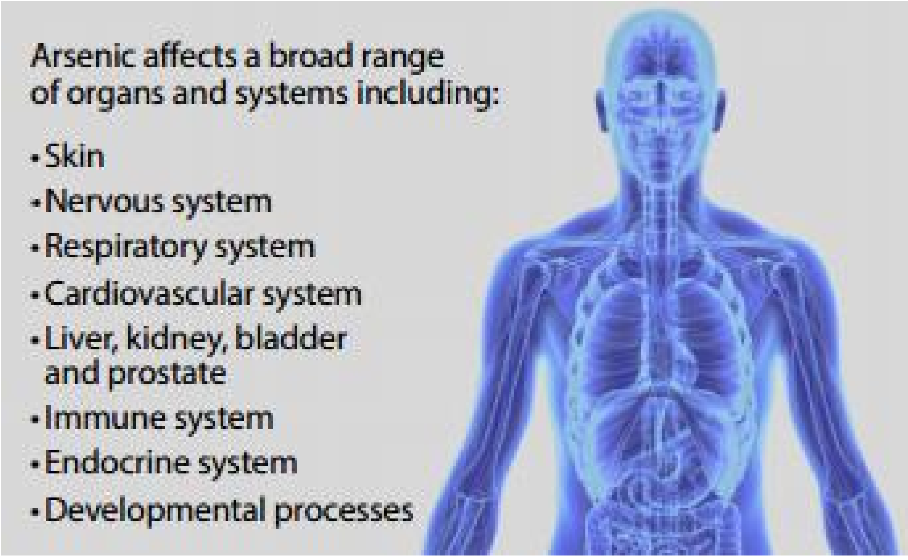

Figure 7 *summarized arsenic consequences on the body* https://www.niehs.nih.gov/health/topics/agents/arsenic/index.cfm

In addition to the concentration limits of drinking water, given the high danger of the element, it was also necessary to define other limits in order to protect the population from arsenic. An example is the limit imposed by the EPA (Protection Agency of the Environment) which establishes limits for the amount of arsenic that industries can release into the environment, as well as severely limiting the use of arsenic in pesticides (Medina-Pizzali et al., 2018). Obviously, there are also numerous standards for controlling the release of arsenic from mine wastewater and the treatment of solid processing waste, which must be suitably treated and then deposited and protected by geomembrane to avoid the formation and then release of polluting leachate in the aquifers or in the superficial courses adjacent to them.

Arsenic contamination in Peru

As already mentioned in the case of Peru, unfortunately, arsenic is one of the substances that has the greatest environmental and health impact. In fact, outside the capital area there are many realities in Peru where the population lives in isolated villages in semi-desert areas in which, according to (Fernando et al., 2015), most of the inhabitants find themselves drinking water directly from rivers, which they originate in the Andes and then flow into the Pacific Ocean. The problem, however, is that in most cases the rivers have arsenic concentrations far above the limit of 10 mg/l imposed by the WHO, on the one hand due to a natural zero condition thanks to the rocks that the water finds to cross in its path, on the other hand due to the mines that arise along their path that have not always faced or still face the appropriate attention to avoid releasing further concentrations of metal ions in surface water courses. Also, in the same article, it is mentioned that already in 1994, following a study of the concentration of arsenic in drinking water taken from the Rimac river, 84.5% of the samples analyzed had limits above the limits of the WHO (Fernando et al., 2015). Despite this, no actual cases of arsenic poisoning were ever recorded at the time, or perhaps there was simply no connection between the symptoms presented by the people of Lima (or even more of the rural towns along the river further upstream) and heavy metal poisoning. The same study also reported arsenic concentrations between 51 and 193 mg/l in samples taken upstream of the city, concentrations from 0 to 64 mg/l in groundwater and water courses within the capital, concentrations between 11 and 25 mg/l, all this considering that the limit concentrations imposed by the WHO are 10 mg/l (Fernando et al., 2015). Fortunately, compared to the situation 10 years ago, the latest measurements carried out by the ANA report much lower concentrations of metal ions than in the past, although not always below the limits imposed by the WHO; this improvement is certainly due to the implementation of environmental controls and regulations regarding the mining industry as well as to a strong implementation of treatments on drinking water. However, it must be reflected on the fact that these improvements have been made since it is the capital of the nation, and unfortunately there are still many countries that do not have any implementation of services and that find themselves in 2020 without access to either drinking water or an appropriate sewage system, with the obvious consequences on their health.

Case Study Coricancha mine and the Rio Rimac basin

In order to analyze the pollution caused by the Coricancha mine and the state of the capital's waters, it is first of all important to talk about the Rimac River (see figure 8).

Figure 8 *Three pictures of The Rimac River route* https://www.actualidadambiental.pe/nuevo-especial-multimedia-presenta-recorrido-interactivo-por-el-rio-rimac/

The Rimac is the main source of water supply in Lima and in the metropolitan area of Callao, although given its net decrease in flow during the non-rainy season, it is helped by a transfer from the Macapomacocha Lagoon, located in the eastern side of the Andes. The name Rimac derives from the Quechua word rimaq, which means "speaker". The river is in fact also often called "the talking river", a nickname normally attributed to the Incas, which refers to the fact that in periods of flood the strong current and the stones background make the noise of the river very intense. The river extends in the south-west north-east direction, rises on the western slopes of the Andes at a height of about 5,508 meters above sea level; it has an area of 3,503.95 km^2 for a length of 127.02 km. In its record measurements during the rainy period (1941), the Rimac achieved a flow rate of 380 cubic meters per second (Wikipedia, 2008). The mouth of the Rimac is located near the city of Lima and flows directly into the Pacific Ocean. The last part of its journey, however, is located in an almost desert area, with an almost total absence of rainfall; the upper part of its basin, on the other hand, is considered as a wet part and corresponds to 65.7% of its total length, therefore to about 2,303.1 km^2, as already mentioned it is located in the Andes at very high altitudes between 2,500 and 5,000 above sea level (Wikipedia, 2008). Among the main tributaries there are the Santa Eulalia, the San Mateo or Alto Rímac, the Río Blanco and the Surco. 191 lagoons are born along its path, some of these still never been studied in depth; moreover, in the northern part the river basin hosts numerous metal mineral exploits, including the Coricancha mine; among the most cultivated minerals we find gold which has now been mined in these areas for more than 100 years. In addition to the mines there are also numerous farms along its route, despite the high altitudes between 3000 and 5000 meters above sea level, and finally in its final part the river passes through the Peruvian capital supplying 13.5 million inhabitants with water. The entire basin, but in the northern upper part, has a very steep topography and the Rimac tributaries circulate through old faults and terrestrial accidents and are therefore embedded deep into the rock, without being there any significant floodplains.

Its strong rate of "pollution", in particular the high concentration of metal ions of the river waters, has very ancient roots. It is hypothesized that already in the times of the Incas, a community that lived between 1450 and 1532, there were serious epidemic diseases probably due to the pollution of the river; over the centuries and in part still today, the pollution of the river has seriously caused diseases in the populations of the valleys crossed, including the most famous cholera and typhus. It is true that even though the problem was already hotly present, in the last century, thanks to the great economic, demographic, industrial and mining development, the pollution rate of the river has added new peaks that are highly worrying.

Within this thesis, the causes of this strong increase in the Rimac waters are analyzed in the second chapter, but for this thesis, we focused on the correlation between pollution and the presence of the mining industry in the river basin, in particular of the Coricancha mine.

One of the main sources of pollution of the mines is given by sterile waste, or the waste of the product of soil processing and mineralogy environmental liabilities are present along the entire Rimac basin (see figures 9).

Figure 9 *Example of the mine waste on the Rimac river* https://proactivo.com.pe/relaves-mineros-amenazan-con-contaminar-al-rio-rimac/

These liabilities were inventoried by the Ministry of Energy and Mines, and in January 2019 laws were finally enacted for their preparation and maintenance. Liabilities consist of infrastructure, mining works and mine liabilities. The biggest problem is that out of a total of 349, in 192 cases the person responsible is identified and for this reason these wastes are completely devoid of any type of monitoring or coverage, thus constituting a serious source of pollution (Iglesias Lopez and Minga, 2020). In fact, many of these tailings have very high concentrations of heavy metals, in particular arsenic or cyanide given by the waste of the cyanidation processes used to obtain gold. In the remaining cases, however, 28 are attributable to the state itself, while 129 are from mining companies. The situation is aggravated by the hard topography of the terrain, in fact, given the absence of floodplains, the passives are very often placed near the riverbed, or in areas potentially affected by landslides. The Coricancha mine itself was closed for a year by the Peruvian government due to a landslide that affected the tailings treatment plant also located near the Rimac, which if it had fallen would have polluted the river waters in a manner irreparable. In fact, tailings represent a double risk at an environmental level, on the one hand the lack of care for ownerless tailings and their pollution, on the other (even in the case of an owner and their appropriate treatment) their location; it is in fact particularly difficult to find a place close enough to ensure that the transport costs are expensive but safe and large enough to be able to work safely (Iglesias Lopez and Minga, 2020).

Although the mines have significantly decreased their production, in particular the Coricancha mine suspended since 2013, they still have enough material to be able to continue to keep the inhabitants of the area rich for years. In fact, it should be remembered that the entire economy of the neighboring countries it is based on the mine itself. Furthermore, over the course of their history, these mines have undergone considerable technological as well as legislative evolution (in particular on the environment) and are continuously subjected to investigations for the control of environmental standards, which is why the environmental impact to date is considerably lower than in the past, and in some cases the presence of the mine and their water treatments is also of help to neighboring countries, for example with the use of treated water to irrigate the fields instead of raw water and polluted river.

History of the Mine

The mine is in the central Andes of Peru, in the province of Huarochiri, in the department of Lima and is part of the mining district of Viso-Aruri, in the district of San Mateo. It has been exploited almost without interruption since 1800, it is estimated that from the 1930s up to around 1996 it had a production ranging from 2,600 to 5,000 tpm (tonnes per month); in '95 Coricancha then undergoes a considerable expansion of operations from 200 tdp (tonnes per year) to about 600 tpd and a modern BIOX plant was installed, for the treatment of wastewater and washing of the mine, greatly reducing the impact environmental caused by it (Golder, 2018). In September 2000, the mine was temporarily closed due to the bankruptcy of the management company; the rights of its control, however, were purchased in 2001 by Wiese Sudameris Leasing S.A, a contract stipulated with the Peruvian contractor Larizbeascoa & Zapata, S.A.C. so as to resume the activity of the Coricancha mine in the first months of 2002. After a few months from the opening, the mine was closed again in October 2002 by the Peruvian government itself due to environmental problems connected to the storage of tailings from the mine. The mine remains closed for 5 years, until 2007, where Gold Hawk Resources Inc. (Golder, 2018) bought back the cultivation rights and implemented the water treatment plant to neutralize the acidic water from the mine, as well as promising to properly control and treat the tailings of cultivation waste, so as to strongly lower the environmental impact had up to that moment. In June 2007, under the control of Gold Hawk, operations are resumed with a much higher production rate than in the past which reached a peak of 10,000 tpm up; however, the operations were then interrupted in May 2008 due to both a movement of the soil observed on the natural hill near the tailings storage facility; this potential landslide risked in fact to end up in the river a very high quantity of tailings containing cyanide and could have caused a colossal environmental disaster making the river waters undrinkable for at least a decade, in addition to the enormous impact on the flora and fauna of the entire valley of the Rimac River. In November 2009, Nyrstar acquired an 85% stake in the mine and resumed mining operations by the end of 2010, after building a new tailings storage facility in Chinchan to remedy the problem that occurred in 2008 and thus avoid the possible environmental disaster. However, the plant and its operations at the concentrator were temporarily reduced to 30% in 2011 due to an increase in the level of moisture compaction required for dry tailings, to be then, again temporarily, completely ceased in 2012 due to concerns regarding remediation plans. For this reason, at the end of 2012, Nyrstar decided to stop extracting the material from the underground repositories of Coricancha, while continuing the relocation of Cancha 1 and 2 to the Chinchan tailings storage facility. In 2013, the entire mine was put into care and maintenance, mainly due to the constant decline in the prices of precious metals, and all operations were completely stopped. To date, after 7 years, the mine has been managed by the Great Panther Mining company, which intends to resume mining operations by 2022 (Fernandez, 2021).

As just described, the Coricancha mine has a long and tortuous history behind it, in particular the most painful part related to environmental problems and appropriate water treatment and tailings from the extraction waste. If at first the problem was completely ignored, in the last 20/30 years with the global awareness of the environment, we have begun to try to tackle the problem of pollution and to seek a solution. However, the 2008 episode is a proof of how, due to the difficult topography and other external factors, the storage and treatment of tailings is a highly current problem towards which a feasible solution is still sought both economically and environmental.

About the Coricancha mine

As already extensively described, the entire complex of the Coricancha mine is located within the Rimac river valley (see figure 10), the entire area has an important topographical relief, in fact it is located between 2,990 and 4,500 meters above sea level (Golder, 2018).

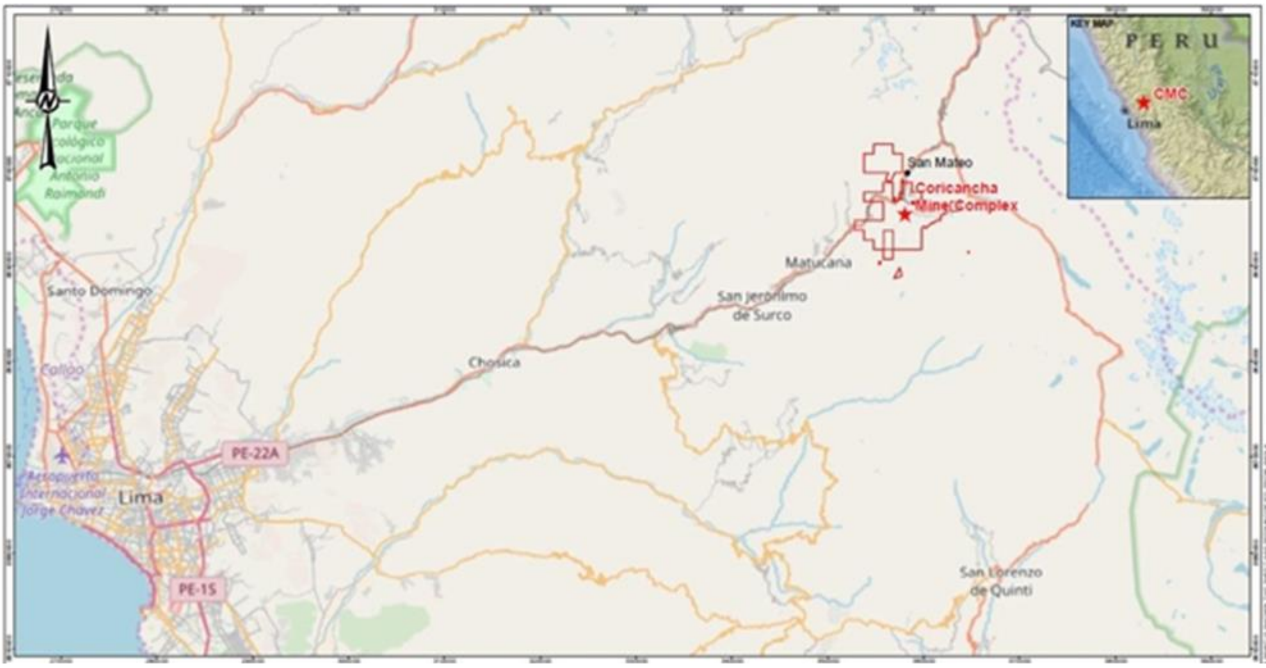

Figure 10 *geographical location Coricancha mine* https://www.greatpanther.com/_resources/pdf/coricancha-pea.pdf

The area is part of the central Andean Puna and is characterized by scarce vegetation with meadows and mountain shrubs. It is in fact the cold climate that characterizes it which means that the vegetation is limited to clusters, herbs, mosses and lichens, while in the Rimac river drainage area we can also find small bushes and the presence of some bushy trees. As for the upper mine area, all levels are mainly dominated by minor weeds and barren rock. The Rimac River in the area is flanked by the central highway and, as in the case of Lima, is the main source of water and energy for the inhabitants of the Rimac valley. Furthermore, exactly near the lower part of the mine, the Aruri River becomes a tributary of the Rimac.

Just 5 km from the Coricancha mine is the municipality of San Mateo, as the only inhabited center in the vicinity the municipality has about 4700 inhabitants, almost all workers of the mine. The entire economy of the municipality is in fact based on the Coricancha mine and on the possibility of work and therefore of support for families and citizens. Despite the economic benefits, very often in the past the citizens themselves were the first victims of environmental pollution caused by wastewater and the poor control of tailings. In fact, in the past there have been health consequences, more or less serious, attributable to heavy metal poisoning, although in recent years, thanks to the increase in controls and the new management of the mine, the cases have almost disappeared.

Local geology

Information on local geology is based on the technical report on the Coricancha mine prepared by the Golder company (Golder, 2018). The entire mining district in which the Coricancha mine is located, and therefore our study area, is made up of a set of andesitic volcanic rocks and intrusive basal sedimentary units from monzonite stocks (see Figure 11). The entire area is also characterized by tightly folded beds of gray limestone. The limestone outcrops are located along the entire Rimac river valley and are particularly concentrated near the town of San Miguel de Viso. Overlying the calcareous folds there is a Rimac geological formation, of about 1,500m, which includes the andesitic tertiary volcanic age and is characterized by alternating layers of porphyry and masses of a color ranging from greenish gray to gray. All the volcanic beds present are characterized by a thickness that varies between 10 and 40 meters and have a sub-horizontal lying, immersed towards the South-West of about 15°. The main sources of polymetallic mineralization are thought to be due to the two occurrences of intrusive rocks present in the area: the first occurrence is a small, altered, and invasive stock located near the village of Viso on the southern side of the mountain, while the mine is located on the north side; the second occurrence is represented by the sub-vertical intrusive dams tending to the North East that cut the volcanic rocks. The entire area of the mine has been exposed to considerable structural compression, which is attributed the main cause of a strong regional scale of fracture patterns, thus allowing the metallic mineralization within the sulphide and quartz fractures to fill the fractures. The hydrothermal mineralization consists of low-sulfidation and narrow veins containing zinc, lead, copper, gold and silver (Mindat, n.d.). In fact, within the study area, the cultivated gold appears as an ultrafine solid solution within the sulphide mineral structures. In particular, the most characteristic fractures are the North-West to South-East Pariachaca-Matucana fault, the trend of San Pablo and Huamuyo faults with North-South inclination and finally the NNE-SSW mineralization zones.

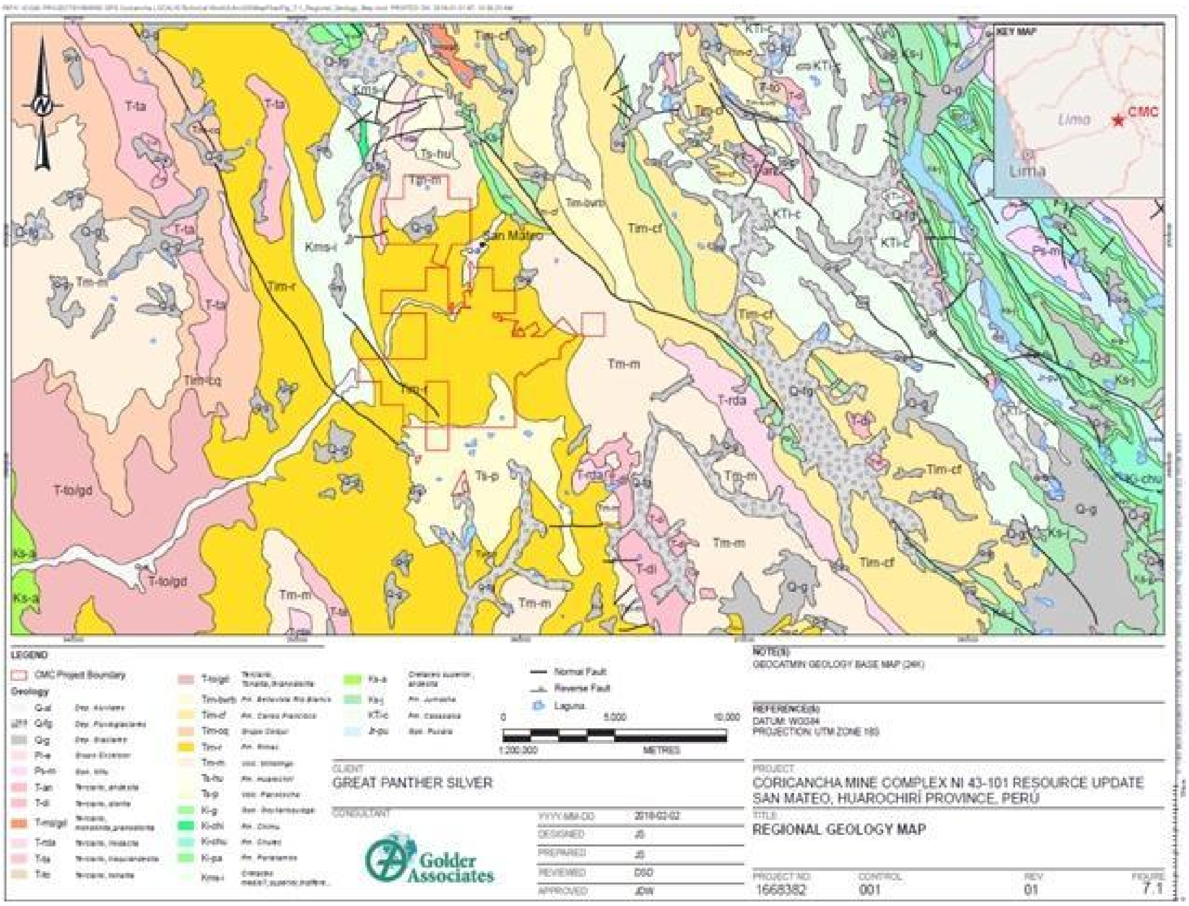

Figure 11 Local geology of the mine https://www.greatpanther.com/_resources/pdf/coricancha-pea.pdf

Climate

The Coricancha mine is located in the central Andean mountains and the local climate is strongly influenced by the altitude (we are around 3000 meters above sea level) and by the mountainous topography. There is an average annual temperature of about 8°C, with the presence of intense rainfall in the period from December to April, contrasted instead by a dry season in the period from May to September, in which there is minimal or no rainfall (Golder, 2018). This type of climate is classified as a semi-arid cold type of climate and short or bushy vegetation, therefore without the presence of large shrubs. Speaking of climate, we cannot fail to mention how this is influenced and upset by the periodic phenomenon of El Nino, which leads to a substantial increase in rainfall, as well as by the diametrically opposite phenomenon of La Nina, which instead involves drought.

Water management of Peru

Peru is one of the 20 richest countries in the world in water and, despite this, between 7 and 8 million Peruvians (out of a total population of about 26 million), do not have access to drinking water. Part of this problem is certainly to be attributed to the fact that the water resources are not homogeneously distributed throughout the national territory, indeed the distribution is rather heterogeneous and is not necessarily located in the places of greatest demand, in the case of Peru in the capital Lima; in fact, more than 70% of the Peruvian population resides on the coast, with an arid climate in which only 1.8% of the nation's total water resides. Due to this geographical reason, but above all to a poor management of the entire water cycle by the government, the United Nations classified Peru in a situation of water scarcity, with less than 1700 m^3 of $water/inhabitant/year$ (Fernando et al., 2015). In particular, the most vulnerable situation is found in Lima; it is in fact located in an almost desert area with a rainwater supply of about 9 $mm/year$; the capital is fed by the Rimac River, which is the main supplier of electricity as well as water. The problem of the capital lies in the river itself, which, although it is the main source of water, also holds the record for the river with the highest rate of pollution in South America.

To aggravate an already unpromising situation there is also the fact that, also thanks to the strong economic development mentioned in the introductory chapter, the city of Lima is continuously expanding on a democratic and urban level, without however being properly followed by an appropriate development of water and sewerage network. Currently in Lima, about 1.5 million inhabitants have no access to either drinking water or an appropriate sewage system. Citizens are supplied with drinking water through the use of tankers (see figure 12), which however exploit the fundamental demand to sell the resource at a price, on average, 2 times higher than those who have access to a "normal" domestic connection, aggravating even more the gap between the poor and resourceless population and the rich population. This system also ensures that the poorest populations without access to the domestic connection must be very diligent about the water used by limiting personal hygiene, cleaning the house and clothing, as well as the consumption of the same; thus, sometimes worsening the already extremely precarious health and hygiene conditions. Furthermore, the lack of an adequate sewage system means that, even for the part of the population that has running water available, there is no adequate wastewater treatment system. In Peru, 70% of wastewater is not treated at all, and is released directly into surface water courses, which strongly contributes to pollution that is already very present (Fernando et al., 2015).

Figure 12 *Use of water tanks in Peru* https://www.americasquarterly.org/article/how-countries-manage-water-peru/

In fact, the water system is closely linked to the sanitation system and how above all the efficiency of a good water system is closely linked to the health of those who have turned it on. Water is a source of life and access to drinking water is closely related to human health.

However, the problem of the lack of drinking water is not only reflected in the water and sewage system of the city of Lima but also on the demand for water for agriculture or livestock, which often are reduced to using the untreated water available to them and therefore highly polluted, further affecting human health.

The pollution of Peruvian water is therefore almost uncontrolled in both the primary, secondary, and tertiary sectors, from the lack of treatment of mine wastewater to domestic wastewater. The polluting substances in the water are therefore varied, both of organic and inorganic origin, and regardless of their origin, the contaminated waters pose a serious risk to the entire Peruvian population, and to that part of the population that does not have direct access to sources of drinking water, both to the entire population that benefits from agricultural products that have been illegally irrigated and fed (i.e. most of them) with contaminated water or of dubious origin. In the particular case of Peru and the Rimac River, the greatest rates of pollution, and those of greatest concern, are the high concentration of arsenic, lead, cadmium; the consequences of the chronic intake of these types of substances are varied, among which the best known are cancer, diabetes mellitus and cardiovascular diseases. To understand the pollution rate of the Rimac River, just think that the maximum limit recommended by the WHO (World Health Organization) for arsenic is 10 mg/l while for surface and underground water levels near the capital Lima it varies between 13 and peaks of 193 mg/l (Ccoillo, 2018).

Between 2006 and 2015 the national urban and rural water sanitation plan was launched, which provided that 30% of the Peruvian public investment was invested for the treatment of national water. This investment led to the implementation of a new water management and agricultural production monitoring system, which is still anything but sufficient. For this reason, and also given the serious problem that it entails, the investor and the study behind the possible solution of the problem requires an even greater investment. Surely among the possible solutions it would be efficient to reconcile the population in areas where it is easier and more sensible to implement a water and sewage system, for example by moving families living in more isolated areas, mountain and rural, to more accessible areas (a solution obviously unthinkable from various points of view, also already mentioned in the previous chapter) (Water(on)line, 2013). However, there are more concrete alternatives, even if some of these perhaps not so easy to implement, for example the construction of three dams on the three main rivers: the Rimac, Chillón and Lurín rivers to be able to store water in the periods with greater rainfall. Easier and of semi-immediate realization is the creation of a master plan for the building expansion currently underway, to preserve the environment and avoid construction in already highly overpopulated areas, as well as a strong implementation of pre- and post-consumer water treatment systems.

It should be borne in mind that such a big problem requires huge funds to be tackled, and that even if you have unlimited money, the complete reclamation of the Rimac River basin remains a complete utopia, and that even a considerable improvement requires not only money, a lot of time. Surely an awareness of the population, as well as the stricter regulations for industries, in particular the mining industry, would ensure that the situation may not worsen further; later in this chapter some proposals for the "solution" to the water problem in Peru will also be listed.

Water quality in the Rímac river basin, San Mateo district, affected by mining activities

It has already been underlined that due to geographical, climatic, and political factors, Peru, and in particular the capital Lima, have a highly unequal distribution of water resources, in which 38% of citizens have 98% of the total resource, while the remaining 62% have only 1.8% of the nation's water (Americas quarterly, 2019). An inequality that is destined to be even heavier and difficult to manage considering a phenomenon such as global warming, which involves a faster melting of glaciers and the supply of fresh water currently available. The big underlying problem is, in fact, that while the demand for water in the capital is destined to increase considerably, given the demographic increase and the massive building expansion affecting the Peruvian capital in the last decade, the availability of the resource is increasingly scarce. For example, one of the most worrying consequences of water shortages would concern the Peruvian food industry, which would find itself without enough water to cultivate the fields, without considering the very quality of the water it would use. In fact, the already bad situation is aggravated by the massive state of pollution in the Rimac river, the main source of water for the capital and therefore its 10 million inhabitants. In fact, since the beginning of the 1930s a strong mining activity began to develop, with the exploitation and cultivation of polymetallic deposits, the uncontrolled activity although it has enriched the country itself, however, has led to the degradation of water quality of the river, just think of the amount of potentially toxic and completely uncontrolled mine waste. In fact, stringent environmental regulations have only begun to be applied in recent decades, all waste from past mines is still today completely abandoned alongside the river without any type of control or protective geomembrane that prevents it from spilling into surface waters or the pollution of the aquifers.

Contamination of the Rimac River

It has already been widely stressed that water quality is of vital importance for human health, but what is often not considered is how all economic and social activities are based on the availability and quantity of water. The quality of a water resource contributes in a fundamental way to the economic productivity and social well-being of a population. The 3 rivers that feed Lima, in particular the Rimac river, are affected by discharges from industrial, mining and agricultural sources as well as by discharges of domestic wastewater, presenting, as already mentioned, very high levels of contamination (Agua fondo, 2019). In Figure 13 below it can be seen that the Rimac River alone receives hundreds of discharges of domestic, industrial, and agricultural wastewater in its entire length.

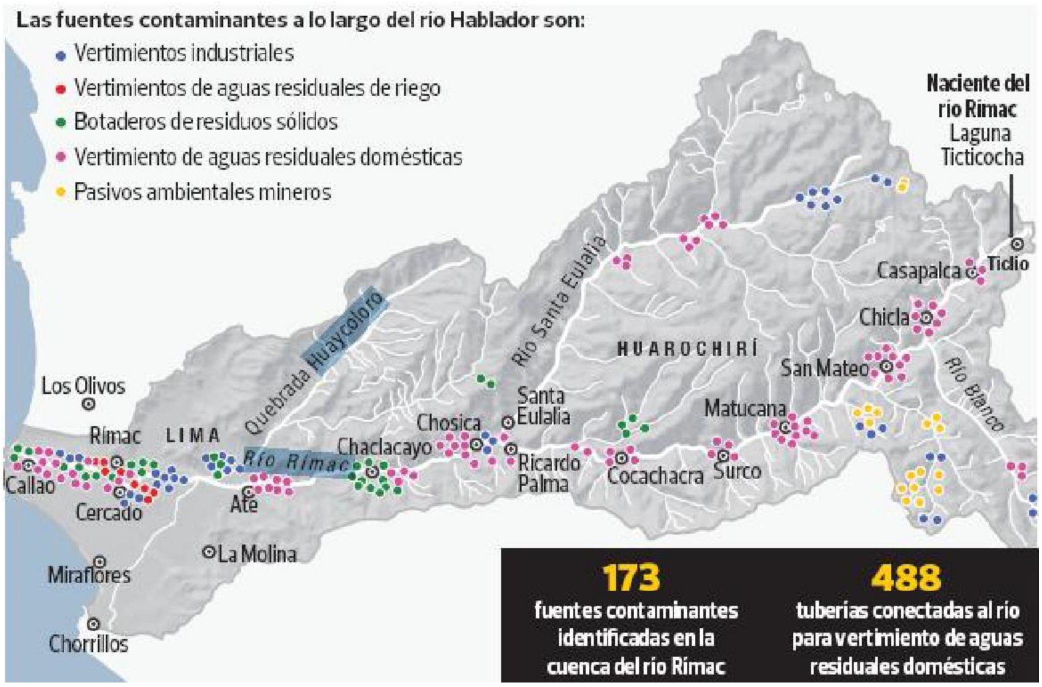

Figure 13 diagram of the different sources of pollution along the Rimac River https://aquafondo.org.pe/wp-content/uploads/2015/11/4._La_contaminacion_de_los_rios_de_Lima.pdf

Main sources of contamination

It has already been anticipated that the mine is one of the main sources of pollution of Peruvian waters. The main problem lies in the fact that the tailings and waste from these activities were in the past, and in part still now, discharged into the river or open landfill without any kind of treatment or remediation. In addition to the pollution due to the mining activity, a large part of the pollution is also due to untreated wastewater, due to the fact that most of the municipalities (as well as most of Lima itself) do not have an appropriate sewage service as well as effective water treatment plants. To this, we must then add the numerous open and uncontrolled solid waste dumps present along the entire length of the three rivers of Lima. Finally, especially in the case of the Rimac river, there is pollution due to industries, that has reached levels such as to cause the color of the river itself to be affected, taking blue/gray colors given by the dyes used by textile companies or laundries. Compounding the situation is the fact that it is particularly difficult to access or have the opportunity to carry out recent studies of the situation of the waters of the Rimac River.

In April 2012, an ANA (Autoridad National del Agua) monitoring was carried out, which found that in the waters there were high levels of metals and highly toxic heavy substances, as well as a high level of fecal coliforms, thus far exceeding international environmental quality standards. This high pollution costs the nation millions of dollars a year to treat and purify this water to a drinkable level, in order to distribute it to the capital, and despite the money spent, there are still many Peruvians who do not have access to this service and find themselves having to buy water in tanks from individuals. In addition, most of the water used for irrigation and breeding is not even pre-treated, resulting in environmental and health problems.

Water pollution due to the Coricancha mine

We have already spoken in general terms about the pollution of Peruvian surface waters and its causes, but it is appropriate to investigate the conditions of the study area around the Coricancha mine, in the San Mateo district, and its participation in water pollution of the Rimac River. From a geological point of view, much of the bed of the Rimac River in the San Mateo district is made up of minerals with a high percentage of iron and magnesium, witness the purple color of the rocks that compose it. Obviously, the presence of these minerals in the ground also reflects on the waters of the river itself, which for this reason have a strong presence of metal ions in concentration. Another predominant presence is that of pyrite, due to the massive volcanogenic sulphides of lead, zinc, copper belonging to the Paleocene of the Upper Cretaceous that make up the province of Huarochirí, which is evidence of the presence of andesitic lavas and gaps of gray color bluish to greenish, due to the oxidation of pyrite. The interaction between pyrite and water, resulting in oxygen and the action of biological agents, conditions the formation of acidic water which leads to the leaching of metals. As proven by the ANA laboratory analysis in 2008 (Utero.pe, 2017), leaching then leads to the high concentration of lead, zinc, and copper ions in the river waters.

It should therefore be emphasized that the presence of metal ions within the waters of the Rimac river is not exclusively due to industrial activities or mining activities, in our case especially from the San Mateo district mine, but also from the geological context in the which passes the riverbed.

Human activity in this area is therefore not to be considered exclusively harmful, but rather always from the analysis of the waters carried out by the ANA company it is evident that in the last decade the presence of metal ions has significantly decreased in the waters of the Rimac river, thanks to the increasingly constant and efficient treatment techniques used. However, these techniques, although they are significantly improving the quality of the water, are still not enough and in recent years the presence of metals such as lead, cadmium, arsenic, manganese, and iron is still above the requirements established by the national environmental quality standards of water for irrigation use. The waters therefore require more targeted treatments by the competent authorities, implementing and improving the treatment systems of mineral effluents and greater control and monitoring, in particular by DIGESA (Directorate General of Environmental Health), which is the main body responsible for monitoring Peruvian water resources.

Paying greater attention to the pollution due to the Coricancha mine, based on the analysis of the waters over the years it is clear that the main problems are 2: on the one hand, the existence of passive waste material due to uncontrolled past mining with the consequent generation of leachate, on the other hand the current activity of the mine with the consequent mining discharges and acid drainage of the mine. This pollution, in particular the total abandonment and carelessness of waste with its consequent highly contaminating leachate, affects the health of the residents of the municipality of San Mateo, who have high concentrations of lead, arsenic and cadmium in the port, finding themselves living too much close to the sterilization facilities. In addition, some inhabitants have also presented other harmful effects on health, such as dermatological diseases, damage to the body, etc.

Despite this, although it is clear that there are still significant consequences on the health of the inhabitants of San Mateo, the current technologies used in the San Mateo district mine, such as the HDS (High Density Sludge) ensure that the effluents meet the current environmental regulatory requirements.

Therefore, the current management of the mine has definitely improved and seems to comply with all the increasingly restrictive environmental regulations imposed in recent years. In fact, in addition to the appropriate treatment of the acidic drainage waters of the mine, the treatment of the passives has also significantly improved. If in the past, unfortunately not so remote, the management of passives was completely uncontrolled and they were simply discharged in the open without any kind of control, now all passives (the most dangerous ones such as those present arsenic and cyanide) are suitably protected by reinforced geomembranes and with suitable systems for the flow of constant monitored leachate. (see figure 14)

Figure 14 *photo of a huge accumulation of mine waste material* https://grufides.org/blog/peligro-latente-para-el-r-mac

The only problem, however, remains in their location, which very often is found to be a few meters from the river and in areas with landslide danger, from which the very idea of the thesis of the creation of a model that can help the choice of the location of these waste materials is born, so as to avoid a possible environmental disaster. The example of 2008 concerning the Coricancha mine has already been previously, and how the wrong location of a passive treatment plant and the mine's waste has put the entire health of the Rimac river at risk, due to a landslide which risked releasing into the river a considerable concentration of cyanide deposited in the mine's waste liabilities.

Wastewater problem in Peru

Very often it tends to attribute the blame almost exclusively to the mining industry for the state in which Peruvian waters flow, and if on the one hand, especially in the past, these arguments can be understood, often one of the true and most devastating environmental impacts of Peruvian waters is the lack of wastewater treatment.

In fact, until 2014 the city of Lima had 41 domestic residual water treatment plants (considering only the municipal treatment plants and not the private industrial ones that you have no way of knowing). These 41 plants had a total flow rate corresponding to 3.178 l/s, or only 17% of the effective 18.850 l/s collected by the company Sedapal, which manages the drinking water service in Lima (Moscoso Cavallini, 2011). This situation involved a very high pollution of surface waters, higher and certainly much less controlled than the wastewater of current mines which are forced to follow stringent environmental regulations. To counter this strong shortcoming, in 2013 two mega-PTRAs (planta de tratamiento de agua residuales) were inaugurated in Taboada and La Chira. These two megalithic plants have made it possible to achieve 100% coverage of the residual waters of Lima and Callao, thus treating a total capacity of the city of 20 m^3/s (Ministero de Agricoltura, Peru, 2010).

The implementation of the water treatment plants was managed by the Ministry of Housing, Construction and Sanitation (MVCS), and thanks to the new plants it was finally possible to treat all the wastewater and eliminate its polluting elements, through physical, chemical, and biological processes in order to be able to subsequently unload them at the bottom of the sea without having a huge environmental impact.

The first of the two mega purification plants is that of Taboada (see figure 15), operational since 2013 and located in Callao, it required an investment by the American government of 148 million US dollars and decontaminates the waste water of 4,300,000 inhabitants in the capital and Callao, with an average flow rate of 14 m^3 per second. It still appears to be the largest wastewater treatment plant in South America (Lagua, 2016).

Figure 15 *photo of Taboada treatment plant* *https://www.iagua.es/noticias/peru/14/07/16/%C2%BFconoces-la-mayor-planta-de-tratamiento-de-aguas-residuales-de-sudamerica-52165*

The second plant is instead that of La Chira (see figure 16), located in the district of Chorrillos; this plant came into operation two years later than that of Taboada, in 2016 and reclaims the sewers of 2,600,000 inhabitants of Lima. Also, this work required a massive investment of about 80 million US dollars and thanks to its 6.3 m³ per second, it completed the aim of being able to treat all the wastewater of the capital (Accionada, 2016).

Figure 16 *photo of the La Chira treatment plant*
https://www.acciona.ca/projects/water/wastewater-treatment-plants/la-chira-wwtp/

However, despite the enormous economic effort by the Peruvian government to be able to cover the water treatment of the entire capital, the environmental impact of wastewater for Peru is still a major source of concern and needs even more sacrifices: on the one hand for try (as far as possible) to repair the damage that already exists, just think of the disastrous conditions in which the capital and its sewage system suffered up to less than 10 years ago, with plants that in addition to treating less than 20% of the total water worked with concentrations of BOD5 (biochemical oxygen demand) 42% higher than the design values with an unimaginable environmental impact; on the other hand to bring this water treatment regime to the whole of Peru and not to limit it exclusively to the capital (Ministero de Agricoltura Peru, 2010).

As already mentioned, the Peruvian state still has a long way to go as regards the state of fresh water. Of the approximately 31 million inhabitants in 2019, however, a project "INICIATIVAS

PRIVADAS COFINANCIADAS DEL SECTOR SANEAMIENTO 2019" was finally presented by the government itself (Ministerio de Vivienda, construccion y saneamiento, 2019). With this 2019 project (currently slowed down due to the global pandemic), the Peruvian state proposed by 2021 to have a total coverage of drinking water and wastewater management for the main Peruvian cities (where 77% of the population resides) to an investment of approximately 50 million US dollars, and to cover the entire nation including rural areas by 2030.

Possible solutions

Since the problems are numerous, it is impossible to propose a single definitive solution for the management of the waters of Peru and in the specific case of those of the Rimac river valley; however, there are certainly some main aspects that if implemented could most likely lead to an improvement in current conditions.

First, it should be noted that the Peruvian water problem is strongly linked to the political and socio-economic climate, there are in fact big problems of various quality and origin, some related to the different management of the water system at urban and rural level. In order to achieve true optimization in resource management, this gap in the management of policies and resources between the urban and rural world must be bridged.

In fact, in the Peruvian rural world, which has already mentioned comprises 22% of the population, in 2021 there are not yet adequate structures for the management of drinking and wastewater. This gap at the level of hydraulic technology only further reinforces an economic gap between the "rich" and the "poor" and will seriously harm the human health of the latter. The main solution, already partially implemented by the Peruvian government, would certainly be to have a massive implementation on the entire Peruvian hydraulic system without neglecting the often-forgotten rural component. Furthermore, it is sufficient to consider that if even the smallest Peruvian municipalities, very often located at high altitudes in the Andes and therefore among the first anthropogenic sources of river pollution, had access to an adequate water treatment system, excessive pollution could already be avoided upstream, thus not going to overload the water treatment plants already present in the cities. A more fitting example is the Rimac river with its anomalous levels of polluting organic matter in concentration in its waters. It is true that since 2019 there has been a turning point from this point of view and a plan has been initiated by the Peruvian government to have by 2030 a total coverage of water treatment in the entire nation, and not only in the main cities, through the " INICIATIVAS PRIVADAS COFINANCIADAS DEL SECTOR SANEAMIENTO 2019 " (Ministerio de Vivienda, construccion y saneamiento, 2019).

In addition to the gap between rural and urban and therefore the problems of water supply, its heavy pollution must also be considered. It has already been analyzed how the pollution factor of Peruvian waters, and in particular of the Rimac, is due to multiple aspects: a natural factor due to the strong metallic mineralization that characterizes the riverbed; an industrial factor given by the improper and controlled discharge of washing water; the wastewater released into the river without any type of treatment and finally the strong mine activity that occupies the upper part of the Rimac basin.

In some respects, it has already been mentioned which are thought to be the best solutions to the heavy pollution of Peruvian waters, also in this case we always refer to political factors and to the implementation of appropriate monitoring systems, as well as control of anthropic activity in the river basin.

Very often we tend to attribute the cause of the pollution of the waters of the Rimac river, or in general of Peru, such as exclusively to the mining industry. It is important to remember, however, that although the latter (especially in the past it had a sadly important role) this is not true. Industrial activity, but above all, the lack of wastewater treatment is often an issue that is heavily neglected on which resources and legislatures should be implemented. All washing water released by industries or mining structures, as well as wastewater must be compulsorily treated before being released into the river; without strict laws and controls, you can never hope for an improvement in current conditions.

In the case of the mining industry, as regards past mining, the great problem of uncontrolled mine liabilities must also be addressed. All the inert waste from the mine must be suitably cataloged and if they are not treated, suitably re-located in protected areas, protected by special materials, and monitored to be sure that their leachate cannot be a source of pollution for ground and surface waters. Unfortunately, since many of these liabilities cannot be attributed to any source, it is the government itself that must take on this burden, especially from an economic point of view. With regard to future mining, however, each mine management company must ensure the utmost care in not contaminating the lower parts of the basins, using the necessary technology (which albeit expensive are necessary) which must be known to state professionals who are responsible for supervising the activities of the companies, in order to avoid and control any accidents; all this by appropriately remunerating the managers and employees to maintain economic control and prevent them from succumbing to any corruption.

Finally, in conjunction with each potential initiative, whether small or large, a significant awareness campaign should be meted out for the population. From the manager of a vital trade to the individual who uses water just for non-public purposes, the importance of water, the scarceness of the resource, the sturdy impact that every inhabitant has on the overall pollution of the latter, and so on must be understood. it is of course extremely important that the modification in technology is additionally combined with a change of mentality on a part of the entire population, each for the health of the inhabitants and for the preservation of such a vital resource; as a result of while not the 2 things along it's not possible to get a satisfactory result, and without a satisfactory result the Peruvian nation risks falling into an awfully sturdy crisis.

El Niño and climate change

The ENSO acronym of El Niño-Southern Oscillation is a climatic phenomenon that develops on the Pacific Ocean, at the height of the equator (between the coasts of Ecuador and the islands of Malaysia), which causes a strong warming of the waters of the Central-Southern and Eastern Pacific Ocean in the months of December and January, and which statistically occurs between three and seven years (see figure 17).

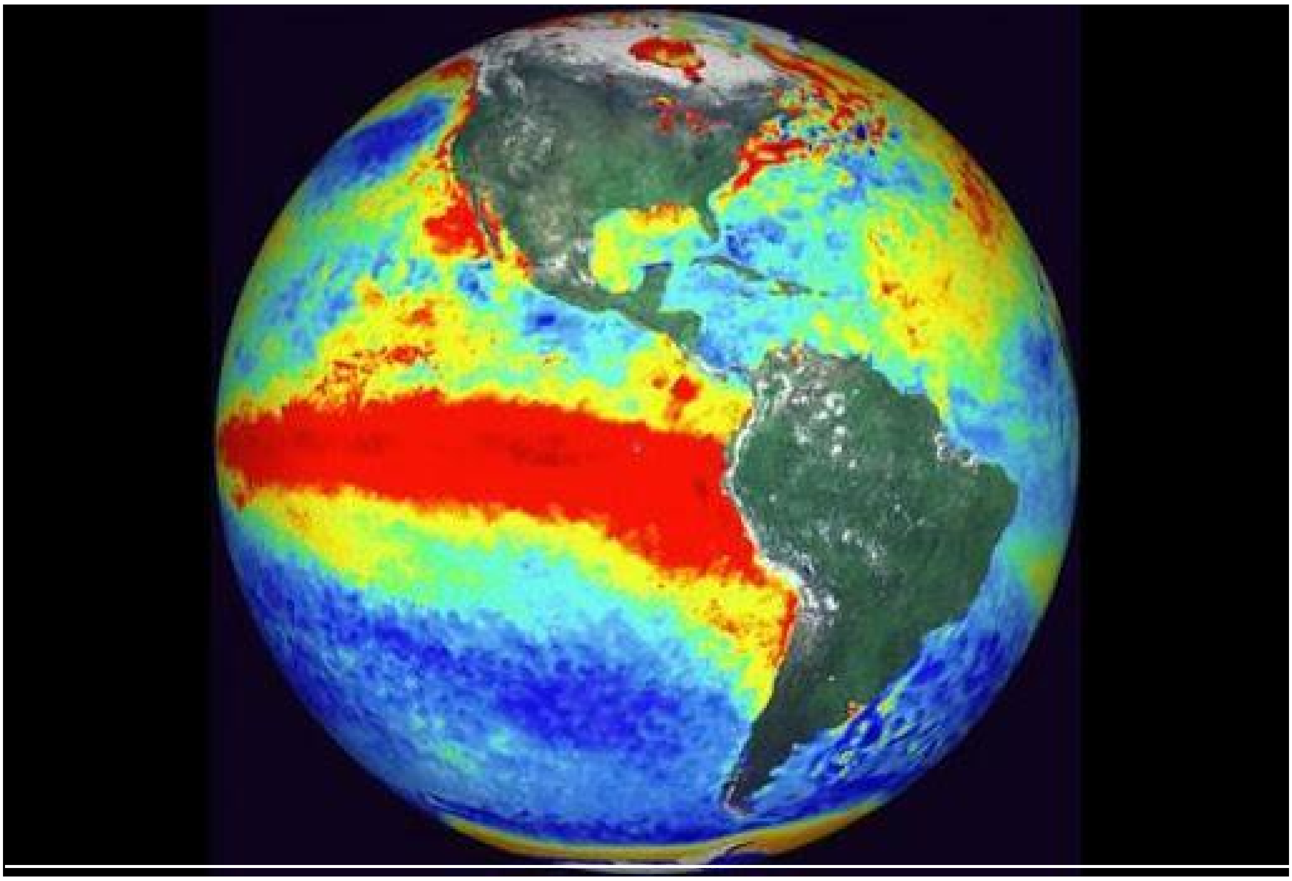

Figure 17 *Global view of El Niño* https://www.ilmeteo.it/notizie/clima-come-influisce-el-nino-nella-diffusione-delle-epidemie

This anomalous warming of the waters causes floods on the coasts of Central and South America, including Peru, which is the subject of this thesis, and the opposite phenomenon, namely drought on the Asian and Australian coasts. Although the countries bordering the Pacific are consequently the most affected, it is believed that this phenomenon has effects on a global scale through modifications of the atmospheric circulation of the whole planet.

In this thesis we tried to understand the phenomenon on a global and local scale, with its consequences on the study area of the province of Lima in Peru. Moreover, it was also studied the possible relationship between ENSO and global warming, induced by man, and what the effects may be at a meteorological, environmental, social and economic level on the Peruvian nation.

What's EL Niño

History

El niño, translated from Spanish as "the baby", owes its name to the Peruvian fishermen. In fact, in the 19th century they noticed that every few years the water of the eastern Pacific Ocean became abnormally warmer (the warming of the waters in the months of December and January is normal, but in the El Niño season this warming is over the charts) causing a decline in the fish population of the area. They also noticed that this particular phenomenon did not happen every year, but always took place in the months of December/January and therefore in conjunction with Christmas, hence the choice of the name and the reference to the Child Jesus (Climatecentral, 2016).

However, the first real knowledge of the ENSO phenomenon can be attributed to the scientist G. Walker (see figure 18), who was the first to introduce the idea of Southern Oscillation and to carry out the first real studies on it in 1924 (Wikipedia, 2020a).

Figure 18 *Picture of scientist G. Walker*
https://it.wikipedia.org/wiki/Gilbert_Walker

He, in fact, discovered that the air pressure at sea level fluctuates periodically in the region between Australia and South America. He also noticed that when the pressure was higher than normal in the Australian regions and more generally in the western Pacific and lower than normal in the opposite coasts of the Pacific, Central and South America, there were abundant rains in the central equatorial Pacific, drought in India, as well as what mild winters in Western Canada. Walker, however, also noted periodically every few years the pressure anomalies were reversed with respect to what was previously described and that even with these anomalies there were climatic oddities (see figure 19). It was precisely because of this alternating movement of the pressure field on the Pacific that Walker first introduced the term Southern Oscillation (SO), second and last part of the acronym ENSO under discussion (Climatecentral, 2016).

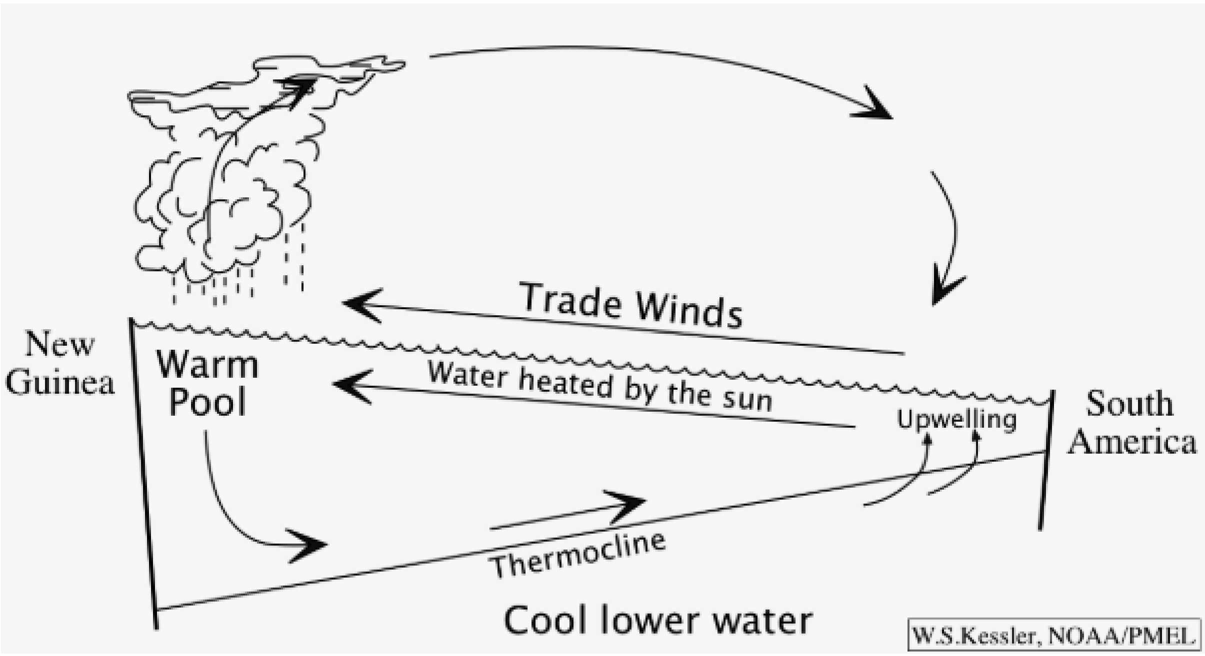

Figure 19 *Trade winds scheme* https://faculty.washington.edu/kessler/ENSO/Virginia-lecture-slides.html

Despite his great intuition and the studies, he carried out over the course of 30 years, Walker did not understand, especially due to the lack of adequate means of observation, the connection between the SO and the El Niño phenomenon and therefore the close correlation between the ocean and the atmosphere; in fact, it took 36 years and a development of the means of observation of the Pacific to arrive at a true understanding of the phenomenon. As a matter of fact, it must be understood that until the mid-1950s the Pacific area, being so vast and devoid of population, had been "neglected" in the observations, which is why studies on this area are very recent and why today many phenomena including ENSO itself still remain to be fully understood.

It was in fact only in the 1960s that Jacob Bjerknes discovered that the rise in temperatures on the west coast of South America was not a local phenomenon, but that this warming extended thousands of kilometers towards the center of the Pacific Ocean, and that this increase was always accompanied by all the climatic changes associated with the Southern Oscillation described by Walker. Bjerknes was also the discoverer of the Walker cell, a convective cell generated by the temperature and atmospheric pressure gradients between the Eastern and Western Pacific. It was therefore Bjerknes, following his discoveries, who coined the term ENSO still used today.

We must also attribute to Bjerknes the discovery of the phenomenon of La niña, closely related to El niño, indeed he noticed that following each ENSO the waters of the Eastern Pacific did not return to the previous temperature conditions, but became unusually cold, thus inducing a serious of characteristic climatic repercussions.

From then to the present day there have been numerous studies that have led to a greater understanding of the phenomenon, nevertheless there are still many questions that are waiting for an answer, in particular the focus of this thesis is to try to understand how this phenomenon can be related to climate change that the earth is undergoing at the hands of man and how the concomitance of these two phenomena may have affected and how it will affect our Study Area in Peru, its meteorology and hydrology.

Phenomenon explanation

In order to have a better understanding of the phenomenon it is necessary to break it into 3 distinct cases or, if desired, the 3 most characteristic oscillations: the neutral condition, el niño and la niña.

Neutral condition

Thanks to the rotation of the earth and the Coriolis force, trade winds are generated near the equator, which blow from east to west and because of these winds the sea level in the Asian coasts is usually about half a meter higher than at the level on the coasts of South America; in addition to the higher sea level, trade winds cause warmer surface water, warmed by the sun, to be pushed towards the west coasts of Indonesia, Australia and New Zealand and consequently deep water in the eastern Pacific coasts colder rises to the surface to replace that westward thrust thus creating a temperature gradient from one coast of the ocean to the other. This difference in temperatures also influences the climate of the areas concerned; in fact, above the western Pacific area, characterized by the warmest water and also for this reason called "Warm Pool", the air above is much warmer and humid. This warm air is therefore found to rise and thus contributes to the creation of clouds full of humidity and consequently abundant rains throughout the area between Indonesia and Australia (Sengupta, 2017).

The hot currents, once they reach the upper atmosphere and discharges of humidity after the rains, then travel eastwards over the regions of central and south America, in particular the nations of Ecuador and Peru.

Therefore, summing up the warm and humid air located above the Warm Pool of the western coasts of the Pacific rises, causing a low pressure zone on the ground, once at high altitude and now discharged of humidity following the rains between Indonesia and Australia, it moves from west to east and then descends, like cold air and discharged of humidity, on the Pacific coasts of South America and thus generating a high pressure zone, and then moves back to low altitude from east to west, where they will acquire again heat and humidity, in the form of the previously mentioned trade winds. This cycle just described is called Walker's Circulation (or cell), which is the phenomenon discovered by Bjerknes previously mentioned (see figure 20).

Understanding the Walker circulation is in fact fundamental when speaking of ENSO; in fact, it is precisely the (even substantial) modifications of the cell itself that characterize the phenomena of niño and niña explained below.

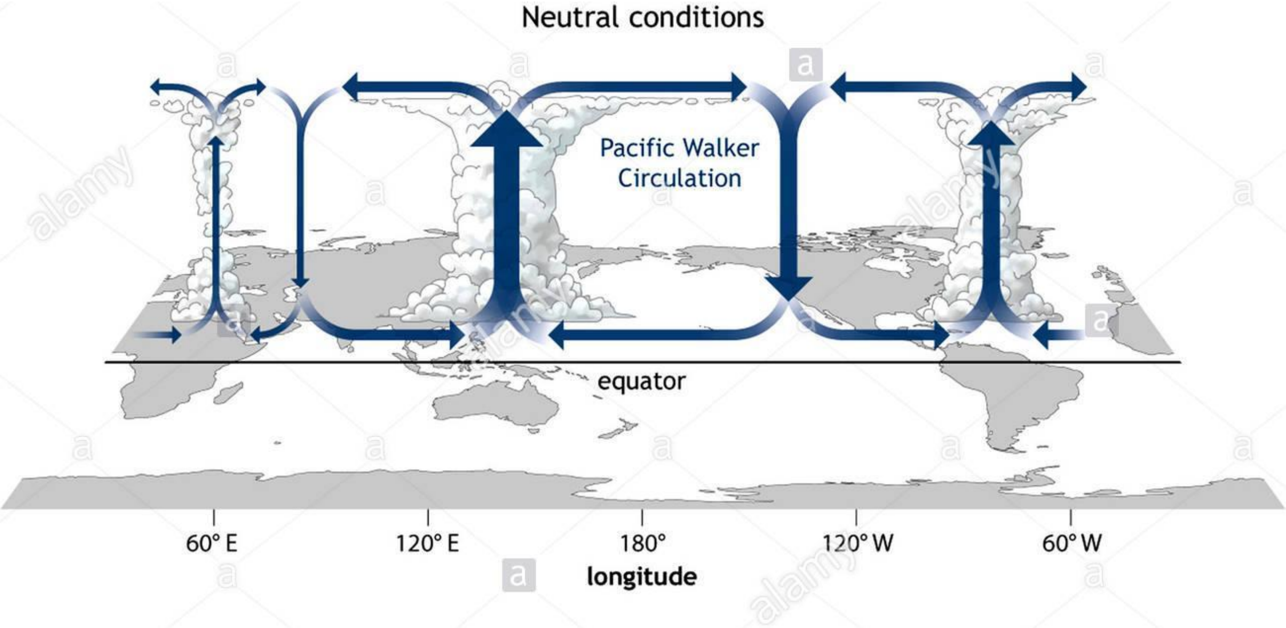

Figure 20 *Neutral conditions diagram* *https://earthobservatory.nasa.gov/features/ElNino*

El niño

It has already been said that a warming of the waters on the eastern Pacific coasts is normal in the months of December/January, but periodically the phenomenon called El niño occurs in which the warming of the waters is more intense and this warming lasts for a period that can vary from 12 to 18 months and which reappears periodically between 2 and 6 years (Sengupta, 2017).

In the "phase" of El niño, the winds that previously pushed the warm surface water towards the coasts of Asia are much weaker than normal, so the hot water is no longer displaced to the west, but rather slowly moves towards the central-eastern Pacific Ocean; doing so in such a way that the deep cold water rises in this case on the coasts of Asia and no longer on the South American ones as in the neutral condition. During the El Niño phenomenon you can understand that temperatures locally rise even 3-5°C above the norm (Sengupta, 2017). Even today it has not been fully explained what the reasons behind this phenomenon may be, the most accredited hypothesis states that the trigger lies in the fact that the ocean struggles to dispose of an excess of accumulated heat, and that this goes influencing the strength of the trade winds thus triggering a chain reaction resulting in ENSO. In fact, year after year, the Warm Pool mentioned in normal conditions grows in volume, thus favoring the formation of storm clouds increasingly eastwards, towards the central Pacific, thus upsetting Walker's circulation and triggering the suppression of the trade winds. The apex of the phenomenon, or el niño, therefore leads to the disruption of the equatorial atmospheric circulation of the Pacific, making Walker's cell practically disappear. In fact, when the warm surface waters extend along the coasts from Indonesia to Peru, together with the warm waters, the genesis of clouds and rains also shifts, leaving in drought, usually and now sadly combined with large forest fires, the western coasts of the Atlantic and causing torrential rains and devastating floods to the eastern coasts. In addition to the atmospheric consequences there are various other phenomena associated with ENSO, among these it is interesting to mention the phenomenon "guilty" of the first discovery of El niño: as the warm surface water finds itself abnormally covering the ocean surface almost homogeneously, there is no longer the rise of cold water currents towards the surface and together with it the rise of nutrient-rich substances along the coasts of Peru, reducing and changing the fish fauna and bringing serious consequences to the Peruvian fish market. (see figure 21)

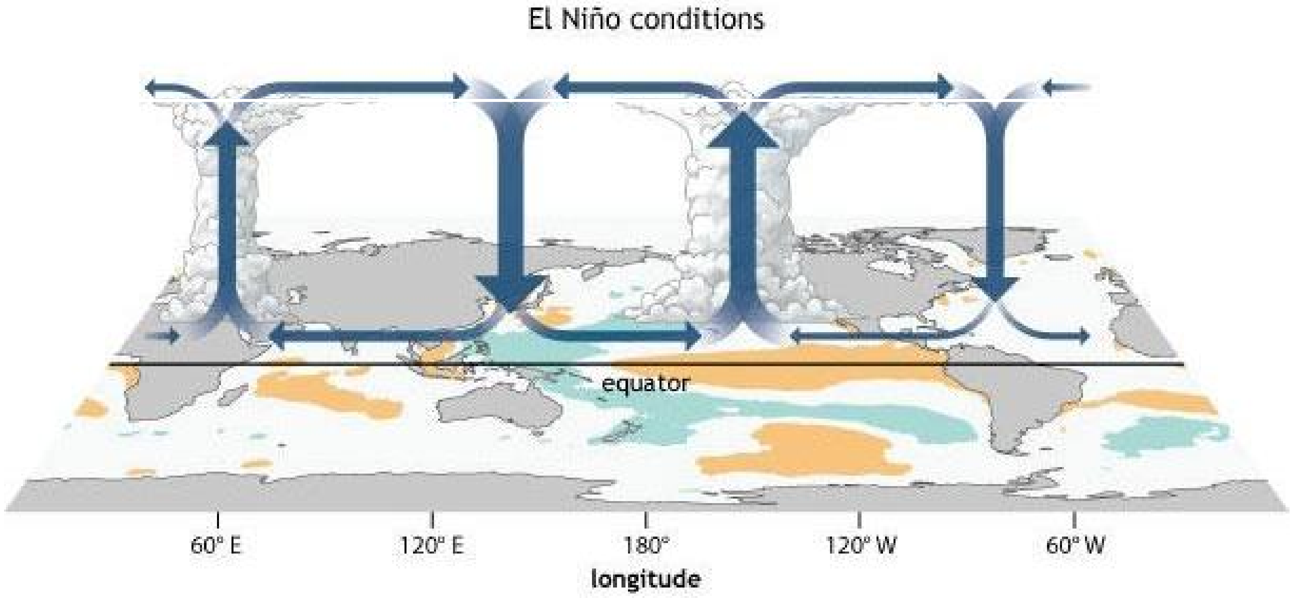

Figure 21 *El niño diagram* https://earthobservatory.nasa.gov/features/ElNino

La niña

The niña or also called ENSO cold is a phenomenon that can occur following a phenomenon of El niño, in which instead of returning to neutral conditions the waters of the eastern tropical pacific undergo a significant drop in temperature. During the la niña phenomenon we have the weather conditions and, consequently, also the diametrically opposed effects of the "hot" ENSO phenomenon. The trade winds are more intense than normal, thus bringing the surface waters from east to west with more grandeur and greatly strengthening Walker's cell. The atmospheric consequences, as already mentioned, are opposite to those of El niño, drastically reducing the rainfall in the central Pacific, and strongly accentuated with significant flooding in the Western coasts. (see figure 22)

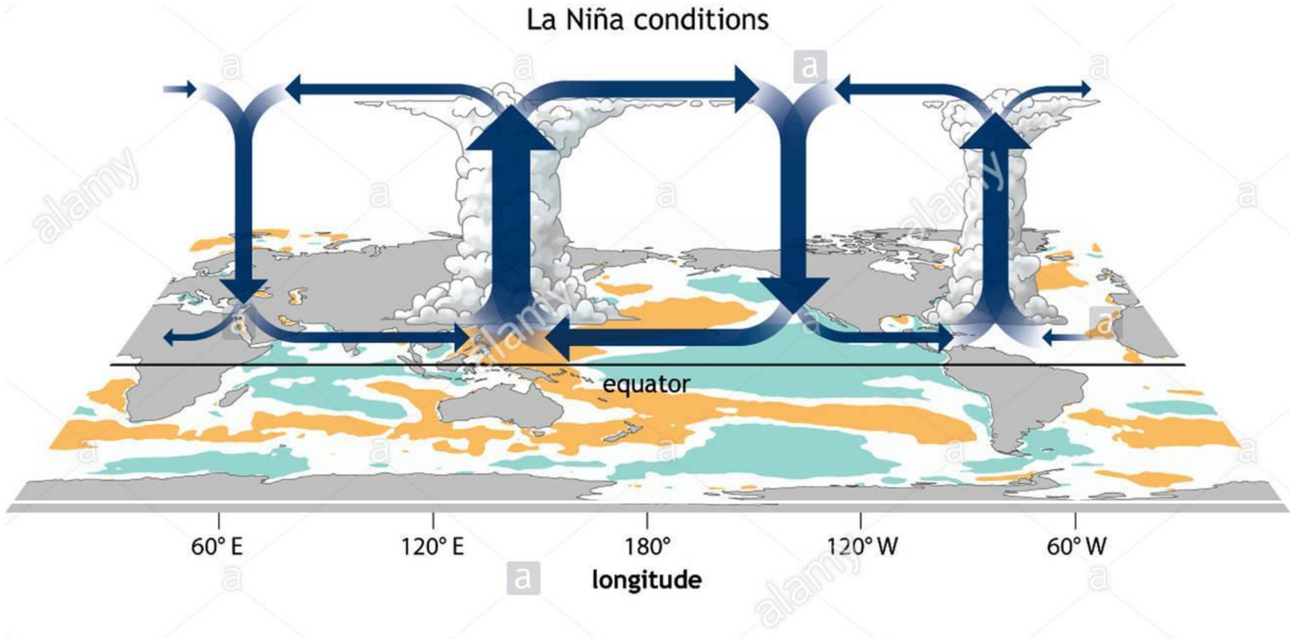

Figure 22 *La niña diagram* *https://earthobservatory.nasa.gov/features/ElNino*

The effects of ENSO on a global level

The changes in ENSO on the Pacific coasts have been named, but in reality, the anomalies of the ocean surface temperature have global consequences (atmospheric teleconnection) (see figure

23), leading to drought or particularly intense floods in various parts of the globe or by affecting the temperature global average (particularly hot years of El niño and vice versa for la niña).

To understand why and to have an example of what the atmospheric teleconnection implies, an example taken from the Webinair "El niño and Climate Change" conducted by the meteorologist

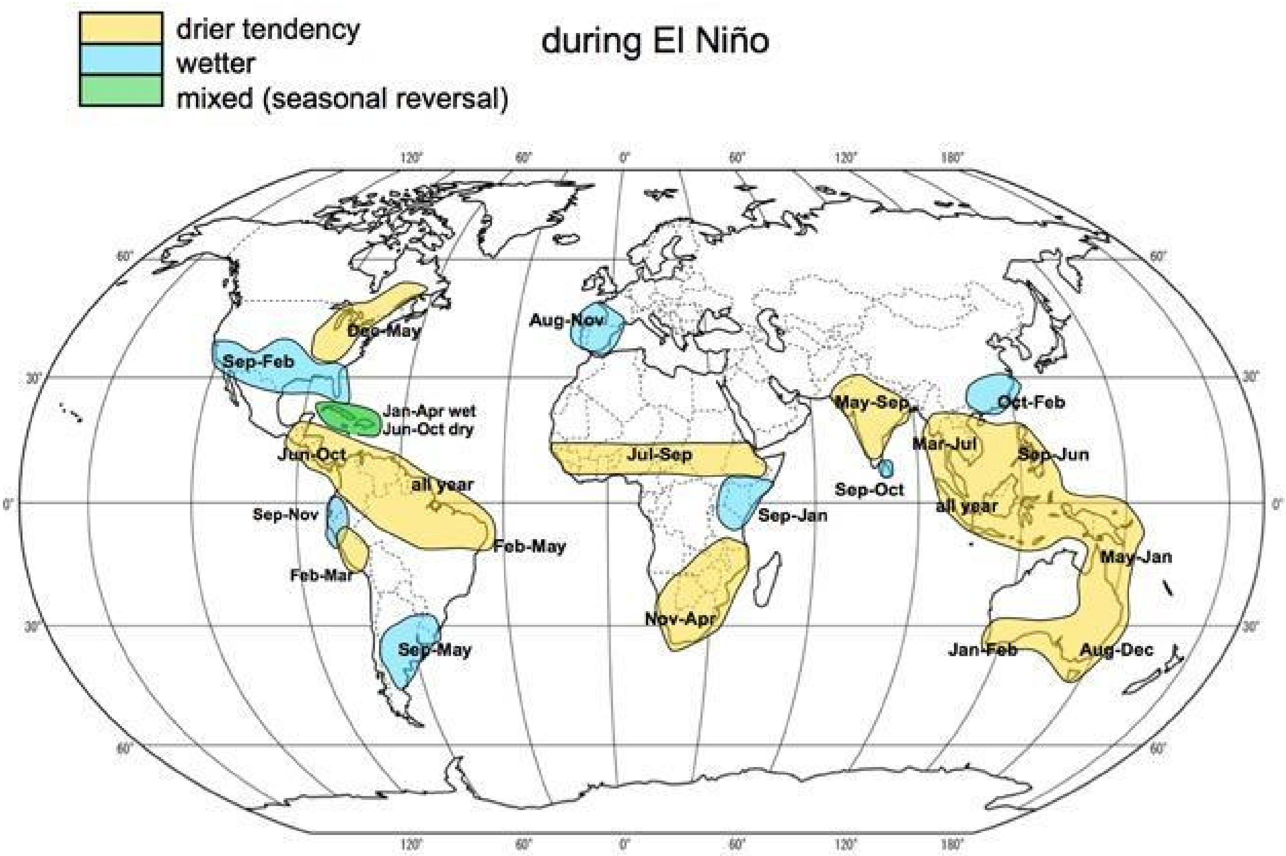

Figure 23 *Atmosferic teleconnection of El nino diagram*
https://www.researchgate.net/publication/282354112_Big_Changes_Underway_in_the_Climate_System

Tom Di Liberto in January 2016 can be used (Climatecentral, 2016). He advises to imagine having something on a large road with average traffic, but secondary to a large main road; whenever the main road is diverted due to work in progress on the road leading to one's home, which obviously significantly increases the traffic (and possible accidents) on the second road. Imagining the machines as potential thunderstorms on the Pacific and the works in progress as the phenomenon of El niño, which is the cause why the machines are diverted towards the hypothetical road home. This should make us understand that El niño is not classifiable as a storm and it is not itself causing potential storms in the rest of the globe but causes these storms to deviate from their main course and end up abnormally in other areas, thus affecting the rest of the globe.

Global Warming

Global warming is a rise in the planet's surface temperatures. Although the earth's temperatures have been scientifically proven to fluctuate, just think of the various ice ages over the millennia, and therefore part of the warming can be attributed to natural causes, nowadays an additional factor must be added: the anthropic one. The use of fossil fuels, deforestation, intensive farming, and agriculture are causing an anomalous global warming. Furthermore, not only are there problems related to global warming, but the more serious problem is also the speed at which this warming is occurring. The United Nations Intergovernmental Panel on Climate Change (IPCC) has recorded an increase in global average temperatures over the past 100 years of 0.74°C (Research gate, 2015).

One of the most predominant factors of this increase is scientifically supported to be correlated with the increase in CO_2 emissions into the atmosphere. There is a striking example in the figure 24 below where it clearly shows how the trend in CO_2 values of temperatures over the last millennium is correlated.

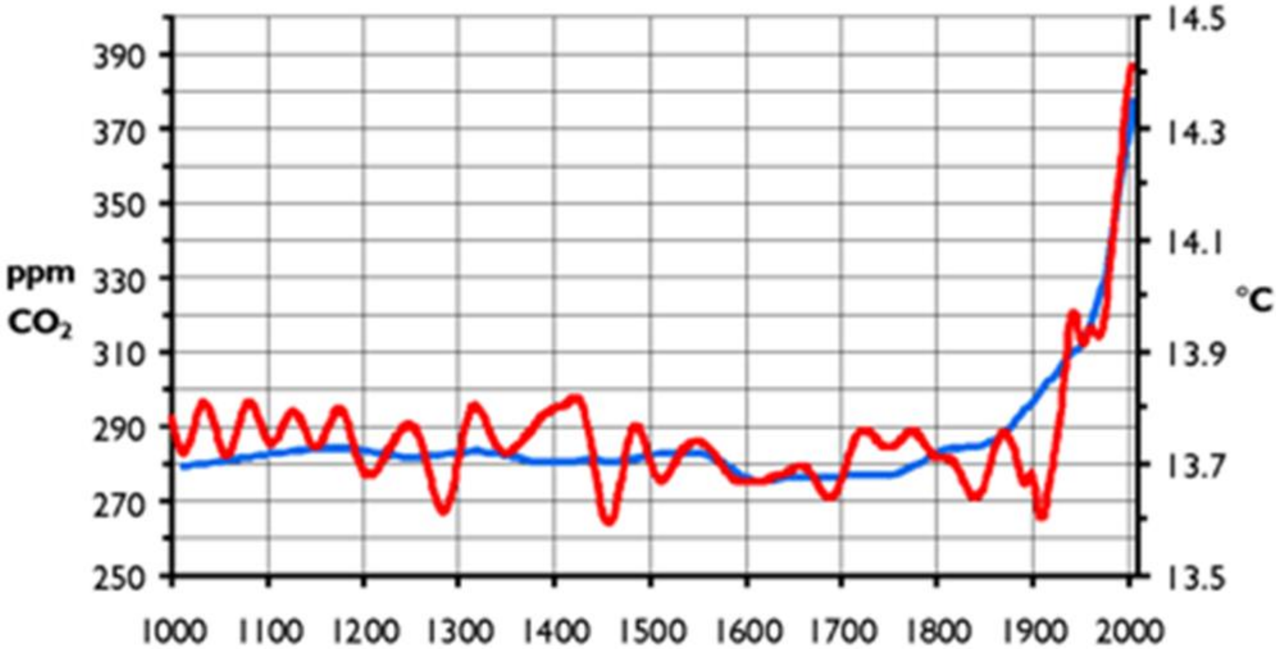

Figure 24 *Trend of CO2 emissions and the average temperature of the planet over the last millennium scienze-naturali.com/clima-e-eventi-meteo-estremi/12763*

In fact, there are more than thirty international scientific associations that support the thesis of climate warming attributable to human activity, but there are multiple theories on its repercussions globally. In this thesis project, as already expressed above, one of the objectives is exactly that of trying to analyze and understand the correlation between global warming and the El Niño phenomenon, and consequently its hypothetical consequences at a global level, but above all on the study area of this project, Peru, and the Rio Rimac basin.

The correlation between El niño and climate change

It has already been pointed out that El Niño is the best-known oscillation cycle in the Pacific and how this phenomenon greatly affects the ocean surface temperatures and atmospheric events (including extreme ones); therefore, it is not surprising to think that many scientists have wondered how climate change affects and will affect ENSO in the future. It is in fact known that the climate and consequently also the ENSO phenomenon, is considerably influenced by internal influences both natural (for example volcanic eruptions or solar radiation) and anthropogenic (deforestation and increase in greenhouse gases); the real question in question, however, is not whether there is a correlation and an answer between climate change and ENSO, but what kind of answer we are talking about:

1. Frequency - Should we expect a higher and more frequent number of ENSOs in the future or are we going towards a decrease in the phenomenon?

2. Intensity - Will there be more extreme conditions, or will they be milder?

3. The consequences - Even if a certain frequency and intensity have been established, what are the consequences of atmospheric events (especially extreme ones) caused by it on a planet subject to global warming?

In recent decades there have been countless statistical analyzes and different modeling studies that have been applied to the phenomenon (Climatecentral, 2016). The problem is that a type of phenomenon of frightening complexity is being analyzed. Nowadays it is still not completely able to predict whether the El Niño phenomenon can occur with a difference greater than two years, in climate models even a difference of a tenth of a degree in the initial conditions can lead to the long term to a series of responses of the model diametrically opposed to each other. It is therefore not difficult to imagine how various models exist which prove completely opposite theses on the influences of our influences on the frequency and intensity of El Niño episodes. Despite this, it is interesting to talk about a recent study by Wenju Cai, from the University of Qingdao in China, and collaborators, published in Nature, which seems to have radically changed the stalemate of recent years. The hypothesis takes into account the fact that the difference in future projections of El Nino events by the real models depends on the fact that each model differently simulates the localization of warming in the Pacific waters, each model being a representation (albeit simplified) of reality, thus making mistakes of different magnitudes in an attempt to reconstruct actual reality. Thanks to a mathematical formula coined by them, the Chinese researchers were able to take into account these differences in the study of the influence of global warming on the El Nino phenomenon, discovering that by doing so most of the models, unlike before, highlighted both an increase in frequency and an increase in intensity of El Nino and La niña. A connection of this kind would therefore imply a greater amplification of global warming, with the El niño years even warmer than current predictions, further exacerbating the impacts given by exceptional atmospheric events connected to the phenomenon (floods or fires).

The model results show how, under global warming conditions, warming of the surface layer of Pacific waters occurs faster than before, creating a larger vertical temperature gradient in ocean waters. Increasing the gradient improves the dynamic coupling existing between the atmosphere and the ocean, thus making the conversion between the stochastic fluctuations of winds with a potential El Niño event more efficient, consequently increasing its frequency and intensity.

To further support the thesis there are also the historical data of ENSO. In particular, the Climate Change Research Center of the University of New South Wales in Sydney, Australia, has been involved in analyzing paleoclimatic indicators to reconstruct the behavior of El Niño and La Niña over the last 600 years. Historical data has led researchers to state that ENSO's 1979 and 2009 historical events were the most intense in the last 600 years. The study was also confirmed by further research by a US group, which expanded the research to the last 7,000 years, also confirming that the magnitude of the El Niño and La Niña phenomena was extraordinarily higher in the twentieth century compared to the past. In addition to the amplitude, it was also studied how the frequency of ENSO has increased by 60% in the last 50 years (although here it is stated that the frequency of La Niña phenomena has instead decreased) (Climate.gov, 2017).

Therefore, based on the previously cited articles, El Nino phenomena are likely to become more frequent and intense as global warming intensifies. Such an increase would consequently also affect the extreme events connected to it, such as extreme floods, persistent droughts, and dangerous Australian fire seasons with consequent devastating economic, environmental and social consequences.

El niño in Peru

The Peruvian nation is certainly among the countries most affected by ENSO. During an El niño event, depending on its intensity, the weather conditions above the national territory change significantly, causing anomalies in the behavior of rain, air temperature and ocean surface water. Along the Peruvian coasts, the surface temperature of the sea increases, thus decreasing the outcrop of the cold water and the nutrients it brings with it, the salinity of the coastal water and the content of dissolved oxygen also change and an increase in the sea level occurs. As for the atmosphere, however, there is a decrease in winds, an increase in air temperature in the coastal area due to the heating of the sea surface, a consequent increase in air humidity and a decrease in atmospheric pressure.

A clear example of the fact that climate change in the Peruvian region is such and so profound is that the Multisectoral Committee in charge of the National Study of the El Niño phenomenon had to determine an index to define the occurrence and magnitude of the phenomenon in the coastal regions of Peru, calling it ICEN (Índice Costero El Niño) (see figure 25). This index is based on an average of three consecutive months with monthly sea surface temperature anomalies. The period in which ICEN indicates "abnormally hot conditions" for at least 3 consecutive months is therefore called El Nino in the coastal region of Peru (Ministero del Ambiente, Peru, 2014).

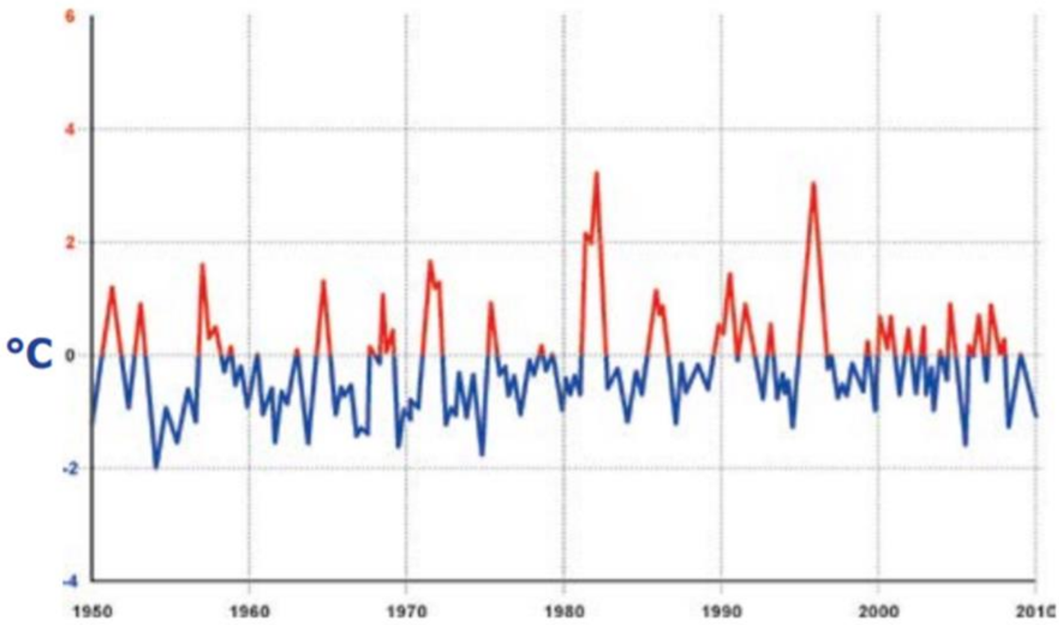

Figure 25 *El Niño Coastal Index (ICEN). Coastal El Niño and La Niña events indicated in red and blue, respectively.* http://www.bom.gov.au/research/projects/El-Nino-Indices/

It is also thanks to this index that the intensity of the single phenomenon over the years is determined, and this index is also taken as an indicator of the extent of the consequences and exceptional atmospheric phenomena affecting the nation.

The El Nino phenomena, even the not exceptional ones, have various consequences, positive but mostly negative, on Peru.

First of all, it is good to start with the main and numerous negative effects related to ENSO; it has already been stressed several times that the presence of the El niño phenomenon leads to floods and heavy rains, therefore among the main consequences there are the destruction of infrastructures (especially those of a productive type, such as irrigation canals, dams, gates etc ..), also associated with a loss of agricultural land due to both flooding and salinization of the soil (which involves consequences not only at crop level) and a possible and probable clogging of the tanks. Another very expensive problem is related to the destruction of communication routes (mainly roads and bridges) as well as the destruction of basic sanitary facilities, such as sewers, with a consequent increase in diseases such as cholera, malaria, or various infections (Bom.gov.au, 2016). Two other major impacts, especially at the economic level, concern on the one hand the production of farming, in fact the high temperatures reduce the production of meat and milk; on the other hand, the entire economy of Peruvian fishing, in fact warmer water also implies fewer nutrients, which is why many fish species find themselves migrating or descending to shallower depths; in particular we are talking about the anchovy banks which are a predominant part of the fish market in Peru. Finally, with respect to the environmental impact, the increase in temperatures and heavy rains also cause an acceleration of glacial retreat, the death or migration of some animal or plant species, a high probability of occurrence of forest fires (more linked to high temperatures).

As for the possible positive impacts, we start by talking about fish fauna; in fact, the presence of abnormally warm waters on the coasts of the nation leads to the appearance of new pelagic species; moreover, this increases in the surface temperature of the sea, especially in autumn and winter, helps reduce the frost in the central and northern sierras. In addition to this, an increase in rain and temperatures favors the cultivation of rice plantations along the coast, otherwise with a relatively arid climate. In addition, these large precipitations also favor the regeneration of wild flora, as well as cultivation, an example of which are the forests in the north of the nation or temporary meadows which can be exploited for livestock farming. Not to mention that an increase in rainfall also favors a recharge of the aquifers.

It was then explained that there are also positive environmental effects concerning ENSO, this probably due to the fact that the planet earth has a complex and wonderful mechanism to keep itself in balance, and it can be understood how El Nino helps to periodically compensate aridity that normally characterizes the coasts of South America. However, it is not negligible that the human footprint is now preponderant and that although nature can withstand or need this phenomenon, the infrastructures and the presence of man are mostly negatively affected by the repercussions of ENSO; proof of this is the economic losses following events such as El Niño 1982/83 (losses of US $ 3,283 million) and El Niño 1997/98 (caused damage estimated at USD 3,500 million), losses equal to 11.6% and 6.2% of annual GDP for 1983 and 1998 respectively (www.bom.gov.au, 2016). These huge losses are also because Peru, although as already described above is experiencing a very rapid development, is still a developing country and consequently presents a very high vulnerability, especially regarding drastic climatic variations. It will therefore be important for the future of the nation a large investment of both time and money to try to reduce vulnerability as much as possible, given how highly probable it is according to scientists that in the future it will face much stronger and more frequent events.

Model

ModFlow

For this thesis it was determined to work with the ModFlow program. Modflow is a U.S. geologic Survey modular three-dimensional ground-water flow model with finite differences. Modflow is thus a modular hydrological model and is currently considered a world standard for the simulation and prediction of groundwater conditions as well as for the interactions between surface and groundwater.

The program was born in 1984 solely as a groundwater flow simulation code (USGS, 2019), however because of its smart and solid structure for the integration of further simulation capabilities, its functions have considerably enhanced over time. In fact, currently the real packages that can be associated with ModFlow include functionality to simulate systems of coupled surface water and groundwater, substance transport, to be able to impose variable flow and density (to also include the choice of salt water and more fresh water), compaction of the aquifer system furthermore as land subsidence and at last the estimation of parameters and management of groundwater. Moreover, because of the modflow computer code it is possible to reconstruct the hydrogeological characteristics of the study area with virtually extreme precision, furthermore, as having the ability to introduce, in any quantity, external elements both anthropogenic equivalent to wells, drainage trenches, waterproof barriers, drains and natural ones such as, for example, a stream or a lake.

In addition to the hydrogeological characterization of the territory, thanks to modflow it is also possible to simulate the effect of rain or evapotranspiration, and it is possible to introduce the presence of control piezometers to be able to calibrate the models with real data measured in the field.

Exactly for its properties and its versatility it was considered that modflow was the most suitable software on which to develop the infiltration model in the fractured medium. In the case of this thesis, the software was used to simulate not the flow of groundwater or the movement of a pollutant in an aquifer (idea from which Modflow itself was born), but to exploit the ability of high precision in the characterization of the hydrogeology of the study area to simulate one of the most complex aspects of this field: the fractured medium.

Goal of the model

The goal of this model was the creation of a numerical model that would represent as reliably as possible a true physical model of the infiltration in a fractured medium; the creation of the model was based on obtainable information from the Coricancha mine area in Peru. it's obvious to mention that the important physical medium is very complex and that in reality the fractures are often of various origin and depth, to not mention the actual fact that it is virtually not possible to be able to effectively dispose of their actual number and their position or inclination in reality; nevertheless, the concept of this thesis was to be ready to attempt to produce a tool, during this case a model, able to correlate completely different scenarios regarding the fracture (explained below which are the various scenarios analyzed in this project) to their respective infiltration.

Within the model, the effective rainfall data measured by the mine's rain gauges are used as input. Effective rainfall data is used as it is intended to simulate how the precipitation water once it reaches the ground or infiltrates through fractures to reach the underlying aquifer or small stream on the surface and then join the nearest watercourse. As a simplification to start, it was decided to neglect the effect of evapotranspiration that could always have been added later once the model was completed; furthermore, considering the study area, the evapotranspiration would still be negligible compared to the precipitation and disposition data. In the real physical medium, the water once infiltrated can either go to feed an underground aquifer or exit further downstream from other fractures in connection with the one from which it has infiltrated; for the purpose of our model, it was decided to simulate an underground aquifer capable of accumulating (and thanks to the zonebudget) count the volume of infiltrated water. Hence the idea of being able to create a model capable of determining what percentage of water infiltrates and when instead it streams depending on the number of fractures, their inclination, and the slope of the land.

Obviously, although the idea of the model started from a real physical place with well-defined characteristics such as the Rio Rimac basin, the real aim was to obtain a model that could represent any real physical model of infiltration in a fractured medium. The starting data obtained from the Coricancha mine should have served as a tool to calibrate the parameters of the model and to verify its actual feasibility and functionality. In fact, it should be emphasized that the data used in this project may not always be available in an area; in fact, while it is very common to have precipitation data available, it is not so common to be able to have water infiltration data available in a certain area and it is also due to the availability of these data that the idea of developing model.

As previously highlighted, they are in a particular geological and topographical conditions; in order to be able to model, however, some simplifications had to be made. First of all, the entire rock and soil of our study area was classified as waterproof, regardless of its geology; whereby waterproof we mean a rock that cannot be crossed by water. In the study area in the impermeable soil various fractures have formed, of varied nature and origin, within which a hydrodynamic infiltration behavior is triggered, which is exactly what we are trying to simulate. As has already been pointed out, for this model, it was decided to neglect the possible effects of evapotranspiration, this choice was also dictated by the fact that the study area, due to the type of climate and topography of the area, reports evapotranspiration data practically negligible which can allow us to use the recorded precipitation data as if they were effective rainfall; however, it remains important to specify that if the model is used the inputs to be used would be those of effective rain. Within the model, the quantity (not the percentage but easily convertible) of infiltrated water will be calculated, which in the case of the model and the physical medium is considered as if it were to feed the aquifer, and the quantity of water that would remain as superficial and then run off and end up feeding the nearest watercourse, the Rimac river in the case of the study area. It is not difficult to imagine how this model can have important and vital uses within the field of hydrogeology, however it's important to stress that it had been exactly the chance to possess access to the amount of infiltrated water in the study space that made its construction doable. In fact, it's already been explained previously, how the info of this thesis are obtained from a doctoral thesis to determine an environmental surveillance plan in the Coricancha mine, and the way it could be possible to have an idea of the flow of the various areas of the Rio Rimac would be a very important tool for classifying the hydrogeology of the area and also the attainable areas wherever it's possible to treat and deposit the waste from the mine; as an example by seeing what are the characteristics of the ground so that more runoff is formed that may probably damage the accumulations of waste material present within the area.

Different case studies

For the model in question, it had been determined to start out initially from simplified case studies, that might then be enlarged once a primary sturdy case study of the model was developed. it had been therefore decided to start by analyzing the various infiltration behaviors during a fractured medium as a function of three variables:

1. The slope of the ground
2. The number of fractures
3. The inclination of the fractures

Starting from the primary variable, it was determined to investigate the infiltration of the case of three potential slopes: 10%, 20% and 30%; these slopes were conjointly chosen based on the analysis of the study area and are those (albeit simplified) that most characterize the surroundings of the Coricancha mine and the Rio Rimac basin.

For the number of fractures, also in this case, three series were chosen: a pair of fractures of one km; five fractures of two hundred meters; and finally, ten fractures of one hundred meters; the concept is that the full fracture surface is always constant in all 3 cases, and that what changes is solely the number of fractures within the same area. clearly this case may be an important simplification of reality, except for the start of the model it was considered effective to create the initial scenario as manageable as possible. All the fractures extend linearly in depth till they reach the first layer (starting from the bottom) that represents the aquifer.

Finally, the third and last case is the variable concerning the inclination of the fractures, at first it was decided to work with all the fractures parallel to each other and varying their inclination with respect to the slope of the ground; of considerable interest for the model would also have been the study of fractures inclined differently from each other, which would have been the first step integrated into the model if it were possible to make it work. In this case, the three inclinations with respect to the slope of the ground were therefore: parallel fractures, perpendicular fractures and finally those inclined at 45°.

In the case of fractures with an inclination of 45°, an adaptation had to be made. In fact, in order to represent a fracture (which therefore had to be interconnected) with an inclination of 45 degrees in a two-dimensional cell model, compromises had to be made. The solution used in this case was to represent a "ziz-zag" curve to be able to guarantee an interconnection between the various cells representing the fracture, without the connection between the various cells they would have resulted as various separate fractures and not as a single fracture of the chosen length. However, having to represent the fracture no longer as a line, but as a zig-zag curve led to a variation in its length, the choice fell on whether to represent the fracture with a number of "permeable" cells equivalent to the cases of parallel inclination and perpendicular; or whether to represent the fracture with its actual length with respect to the elementary area (more representative of reality) and to take into account in the results the number of excess cells used for the representation. For this model we have chosen to use the second option, and then to take into account in the results of the surface over the fractures (an attainable and oversimplified answer would have been to create a proportion between the surface (the variety of cells of the model) and the amount of infiltrated water, so as to recalibrate the values).

The different case studies regarding the number of fractures and their inclinations are shown in figure 26 to figure 34.

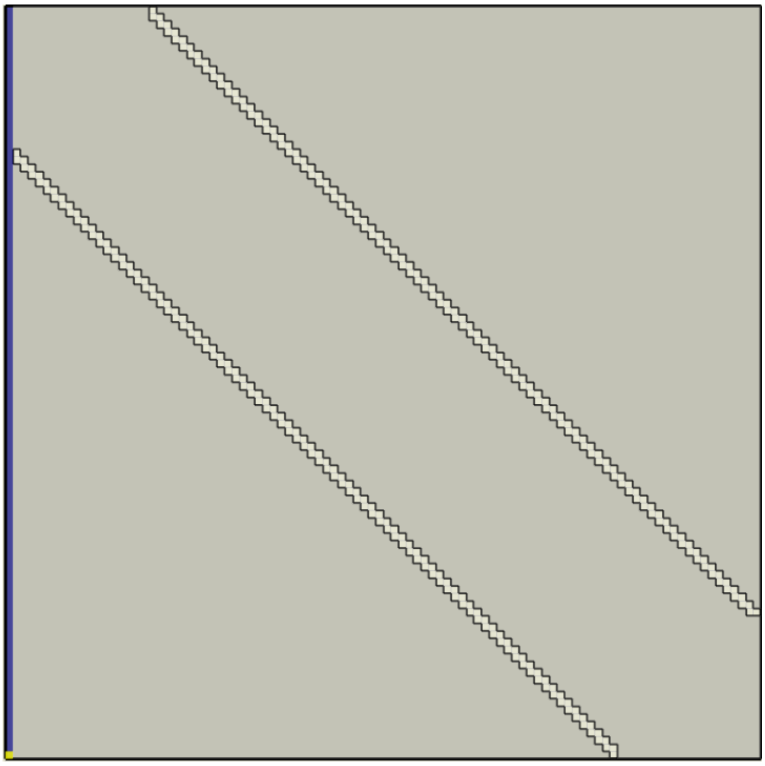

Figure 26 *Condition with 2 fractures inclined at 45 ° of 1000 meters*

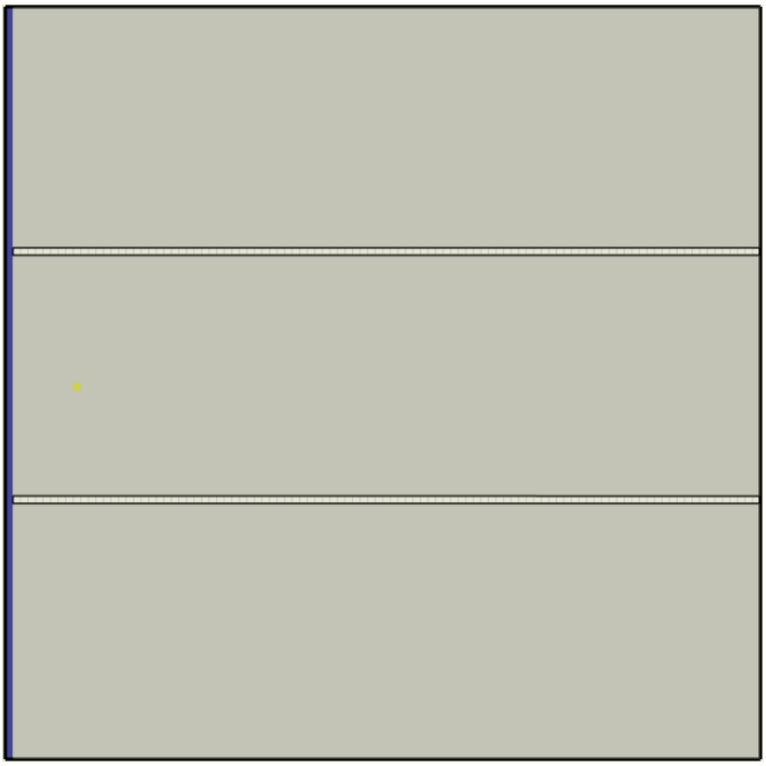

Figure 27 *Condition with 2 fractures parallel to the slope of the ground of 1000 meters*

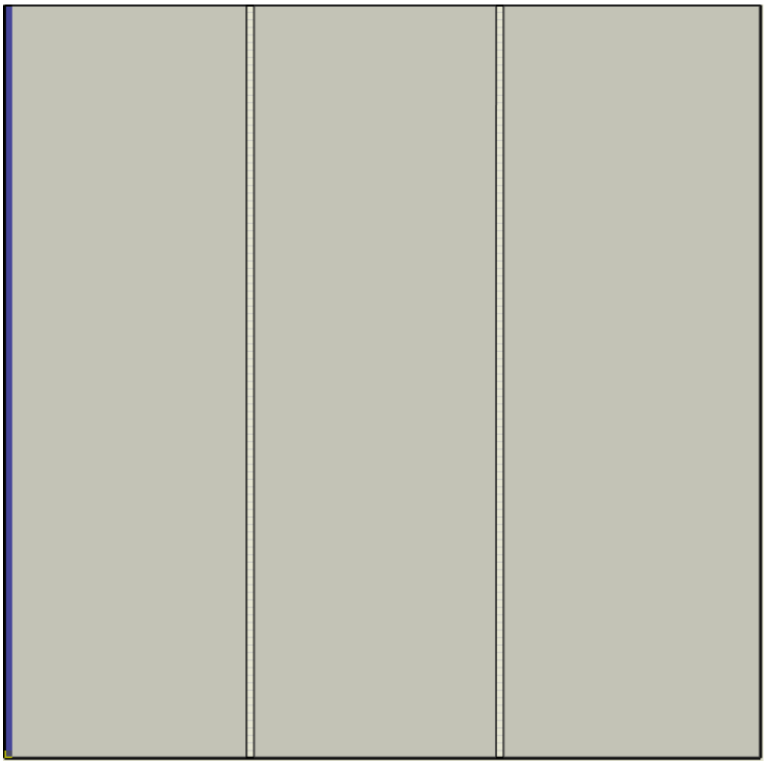

Figure 28 *Condition with 2 fractures perpendicular to the slope of the land of 1000 meters*

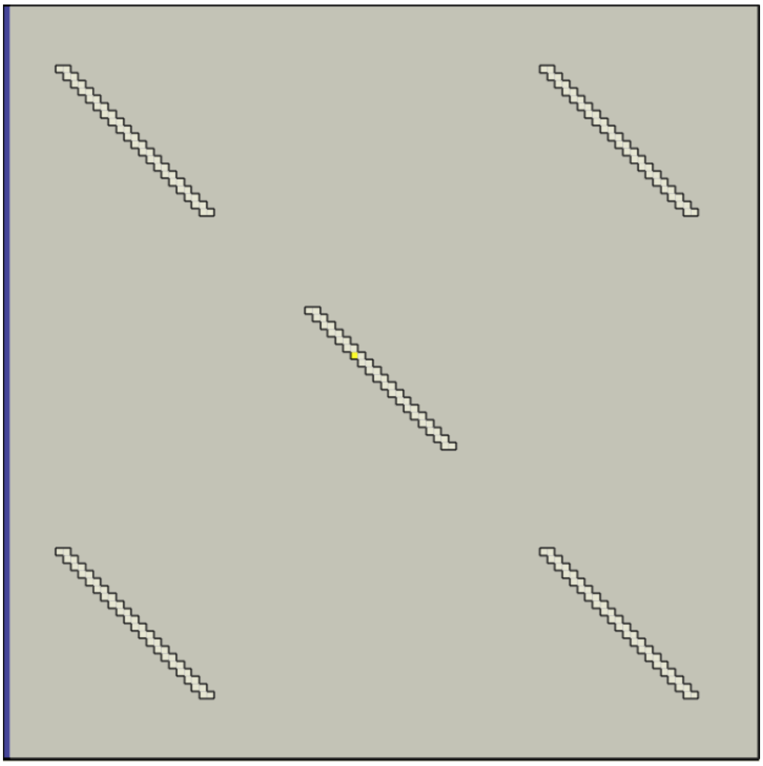

Figure 29 *Condition with 5 fractures inclined at 45 ° of 200 meters*

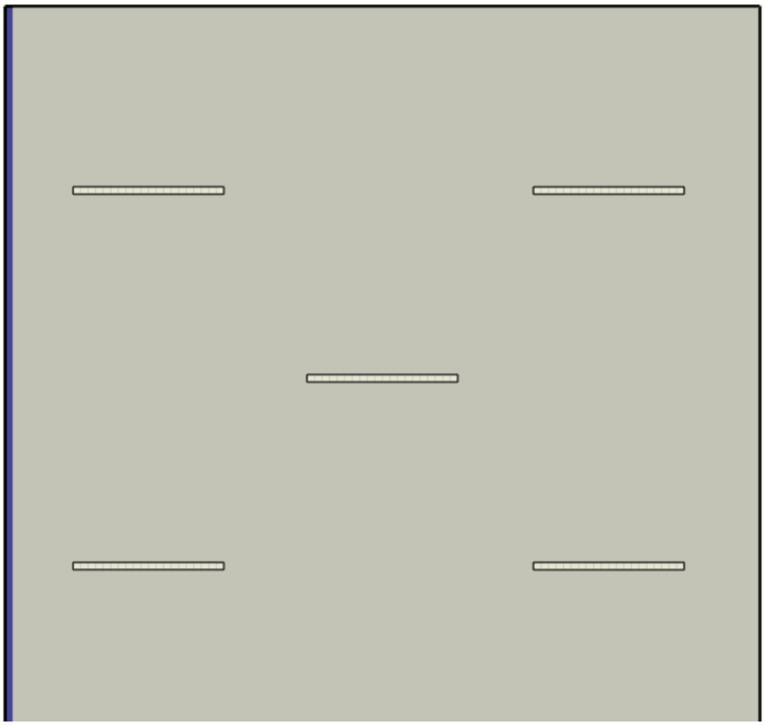

Figure 30 *Condition with 5 fractures parallel to the slope of the ground of 200 meters*

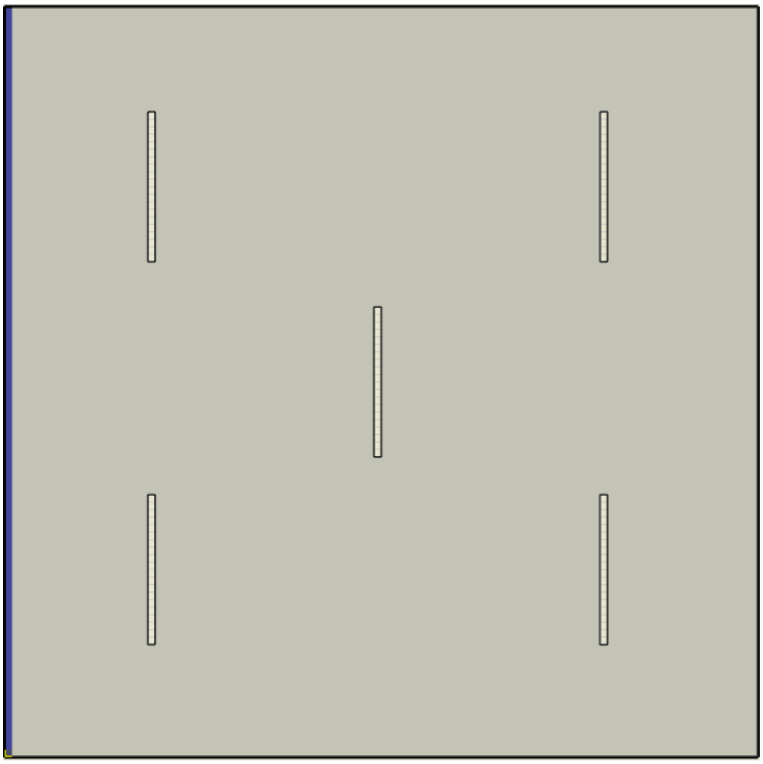

Figure 31 *Condition with 5 fractures perpendicular to the slope of the land of 200 meters*

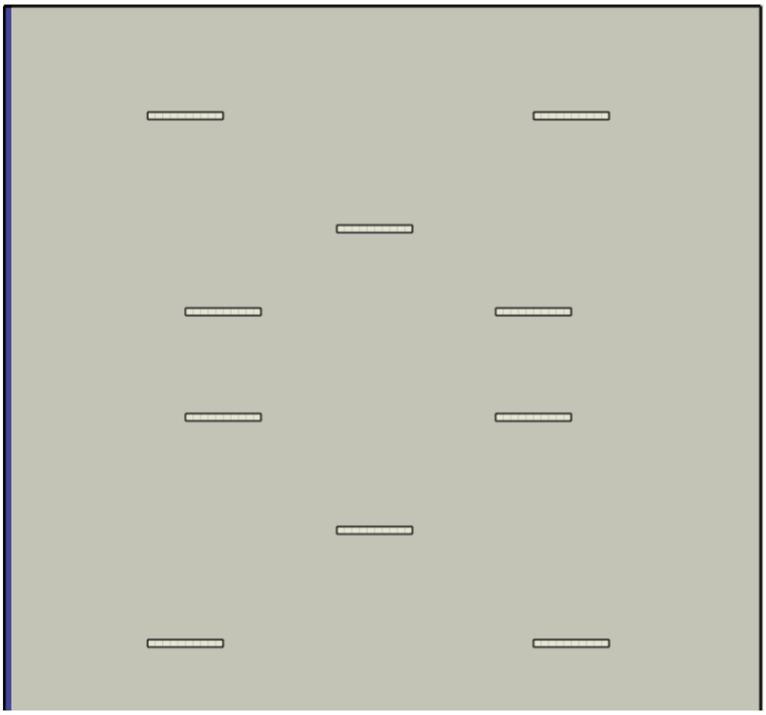

Figure 32 *Condition with 10 fractures parallel to the slope of the ground of 100 meters*

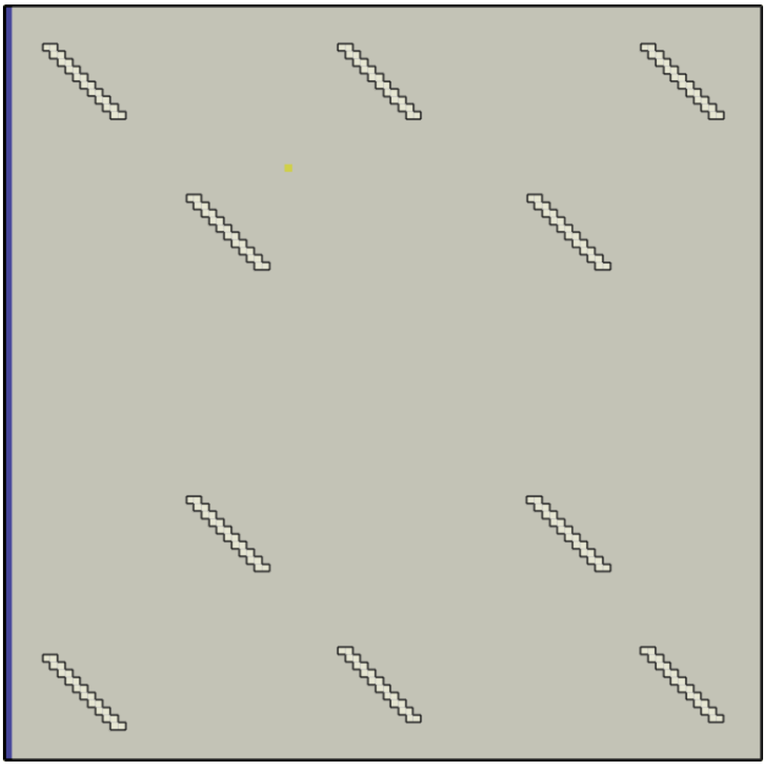

***Figure 33** Condition with 10 fractures inclined 45 ° of 100 meters*

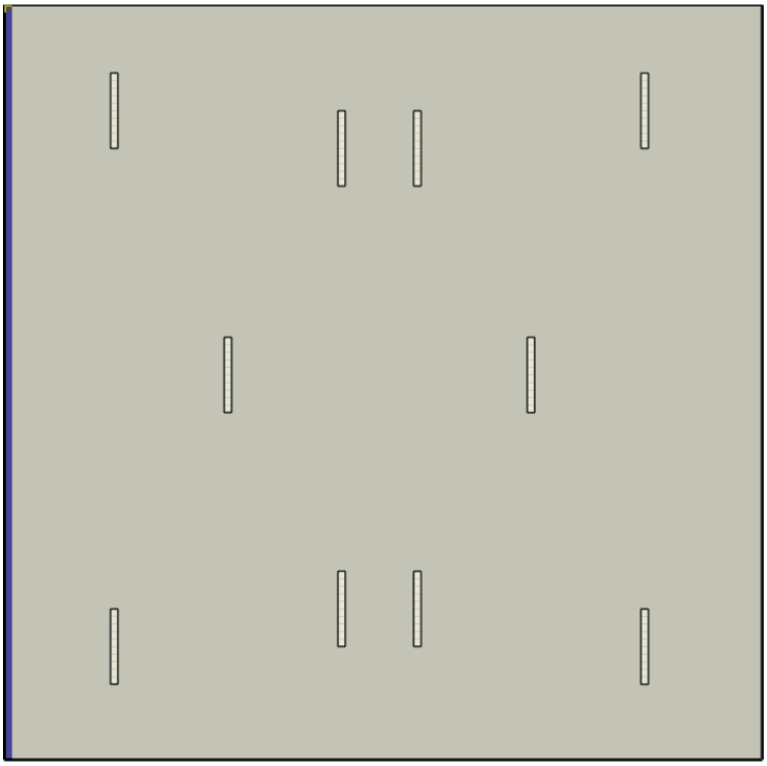

***Figure 34** Condition with 10 fractures perpendicular to the slope of the land of 100 meters*

Once the cases to be analyzed in the model we created were established, we then proceeded with the actual construction of the grid.

Model building

The first data to be entered in modflow for the creation of a new model concern the temporal discretization (see figure 35), within which the following info are requested: the date and time of the beginning of the model, in our case first March 2020 at 00:00 ; the length of the simulation, three hundred and sixty six days or one year being a leap 2020; the quantity of stress period; which we think about as months; the number of time steps for every stress period that we have chosen is adequate to 2; finally the program asks for 2 multiplier factor values that within the case of this model weren't necessary and are left equal to 1.

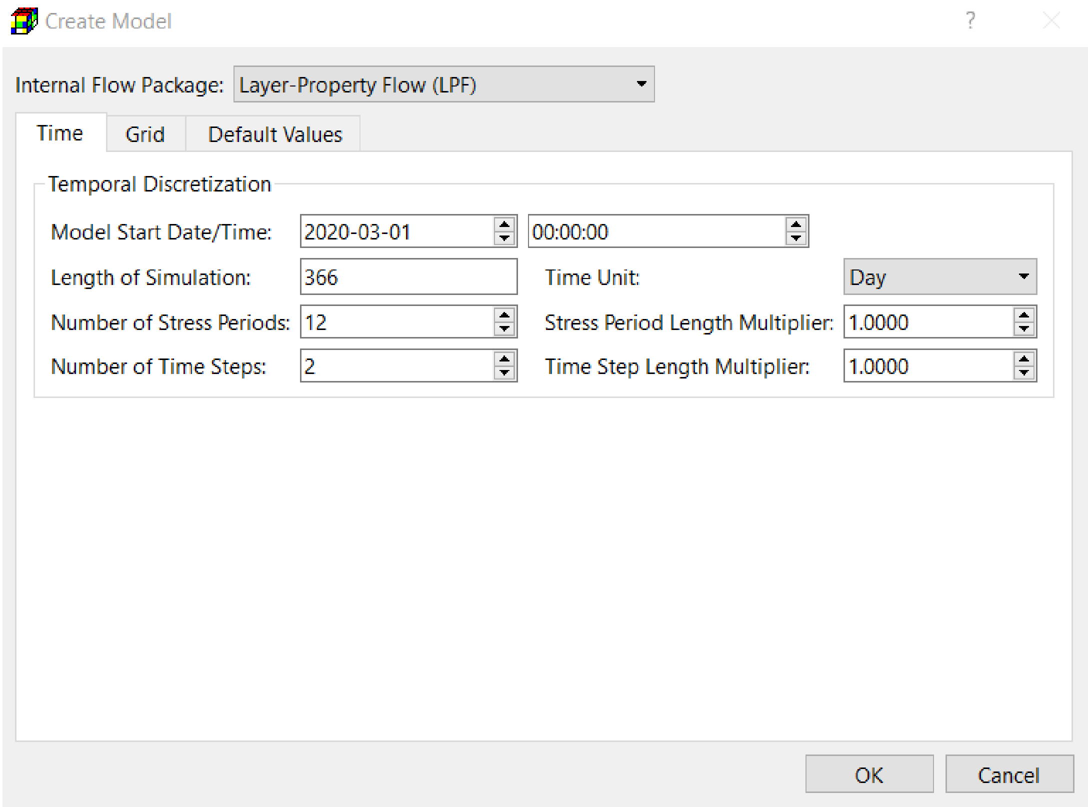

Figure 35 *Initial values for temporal discretization*

Once the discretization of the times was determined, we moved on to the definition of the grid which constitutes the representative volume of the study area. For practical purposes it was decided to start from an initial representative volume of 1 km^3. The model has a square base of 100x100 cells, in which each cell represents in physical reality 10x10 m^2. As regards the height, on the other hand, we proceeded unevenly and differently for each slope: 18 layers for a slope of 10%, 17 layers for a slope of 20% and finally 16 layers for a slope of 10%. All this information, together with the geographic coordinates of the study area, have been appropriately entered in the basic input data that requires modflow to create the elementary volume (see Figure 36).

For a more detailed explanation of slope creation, take the 20% slope case as an example. Starting from the bottom, 7 layers of thickness of 100 meters were created up to a base height of 700 meters. In order to obtain greater precision in the surface layers, it was decided to work in more detail, thus creating 10 thinner layers with a thickness of 10 meters each; with the exception of the penultimate layer (used to create the slope of the model), which has a constant height for each row and increasing by 10 meters for each column.

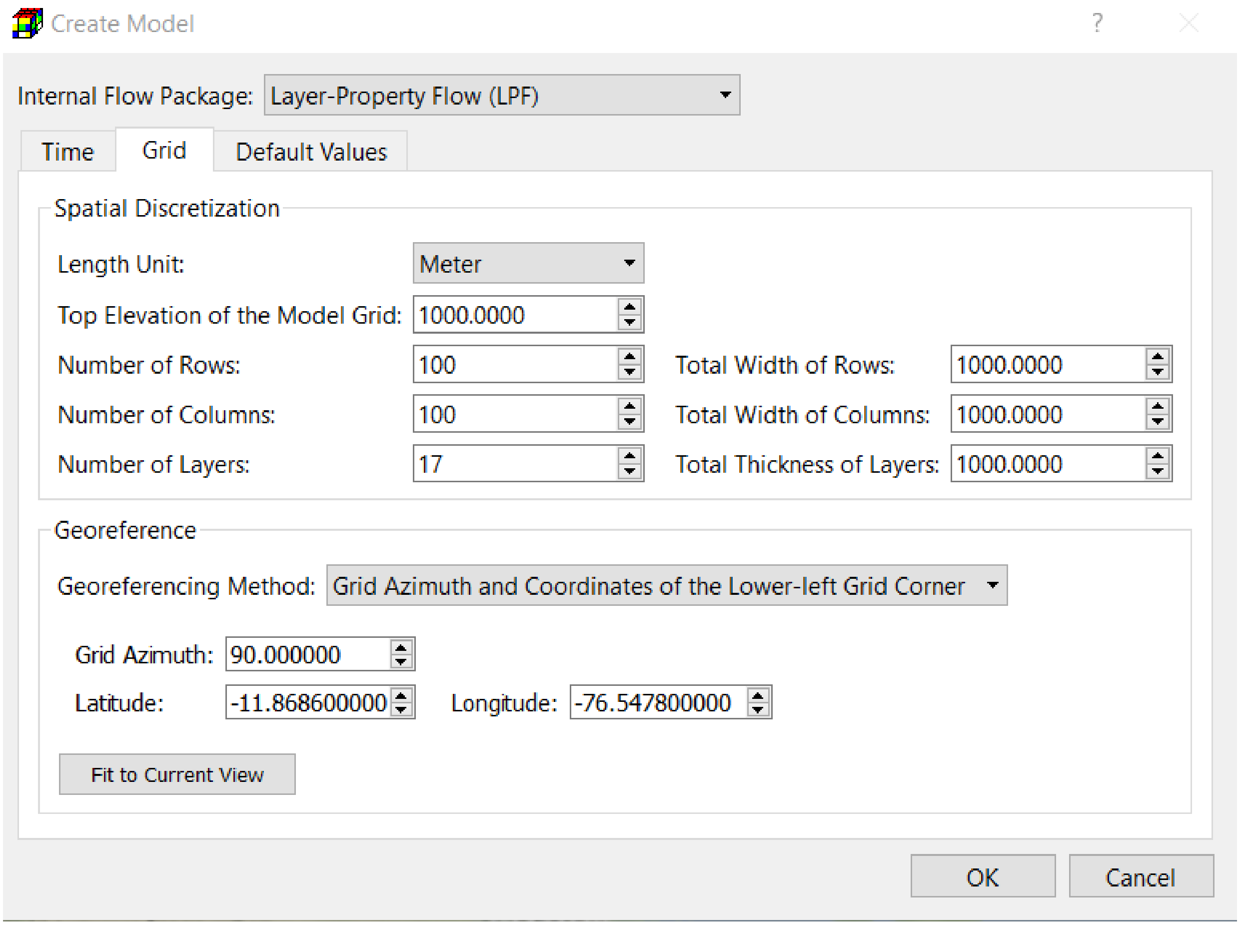

Figure 36 *Initial values for spatial discretization and georeference*

In order to create the penultimate layer, two matrices were created in Excel: a matrix with the heights of the base of each single cell reported, and a second matrix with the height of the roof of each single cell. Once created, the two matrices were loaded into Modflow as characteristic data of the 16th layer. The profile of the 20% slope model can be seen in Figure 37.

Once the basic grid mesh of the model was properly created, it was possible to proceed with its actual configuration.

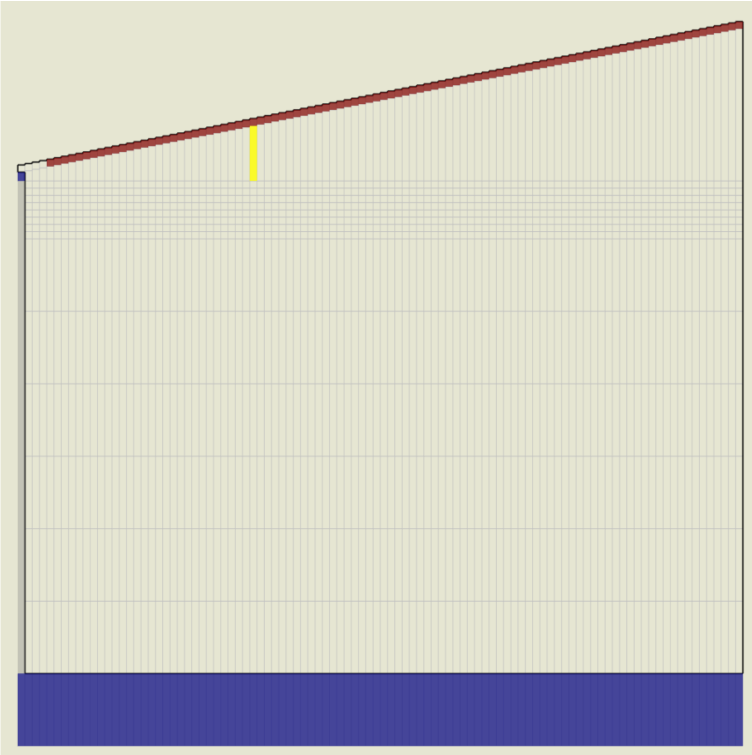

Figure 37 Model profile with 20% slope

Parameter configuration

IBOUND

The first fundamental step was to define the permeable, not permeable or cells with a constant hydraulic head level. This feature is assigned individually to each cell via the IBOUND command in the ModFlow program.

The IBOUND command is an array, which assigns a value for each cell of the model. There are three possible values: 1,0 and -1. The positive value is assigned when the cell has a variable head (or active level), in which the program is therefore asked to actively calculate the hydraulic head, in more concrete terms the positive value represents the cells, which allow the circulation of water inside them and are therefore "permeable". The value 0 indicates that the cell is inactive so there is no circulation inside it and therefore it results as "not permeable". Finally, the value -1 is equivalent to a cell with constant head, therefore a constant level edge such as a river or an aquifer.

Within the model, the value 1 for active cells was assigned to two different types of cells; the first type of cells is those belonging to the first layer (starting from the top) of the model, this first layer represents the surface layer of 10 meters that encloses the air and the soil, where the vegetation resides, and therefore allows a circulation of water inside it and to which a values or filters can be assigned to consider evapotranspiration. In the case of the study of the Coricancha mine area, however, we have already said that the evapotranspiration values are not considered, as they are negligible, and we can consider as if the first layer was simply air in direct contact with the fractures or the hard and impermeable ground; therefore, obviously permeable and with the possible circulation of water inside. The second type of cells with IBOUND 1 are instead the fractures themselves, along with their entire length, which will have their own characteristic conductivity and therefore allow the circulation of water inside them.

The IBOUND -1 was also assigned to two different types of cells. The first type of cells is those belonging to the deepest layer, the first starting from the bottom. The last layer represents the aquifer in the real physical model and is placed there to be able to collect all the contributions of the precipitation infiltrated through the fractures (directly connected to the aquifer). The second type of cells, on the other hand, is represented by the first row of the second layer (starting from the top), in fact it supposedly represents the river and is positioned there in order to collect the part of surface water that does not infiltrate through the fractures and that stream in the surface to then feed the surface waterways.

Finally, IBOUND 0 is assigned to all the remaining cells, which represent the non-permeable cells and therefore considered by the program as inactive cells.

Once the IBOUND values have been set, the assignment of the different zones of the study area has been completed, having therefore defined the fractures, the aquifer, the surface watercourse, a first layer of soil or air and the impermeable rock.

Vertical and horizontal conductivity

Following the IBOUND value, it was essential to establish the actual hydraulic conductivity of the different cells of the model. Hydraulic conductivity has a unit of measurement [L/T] and in the case of our model m/s , it is also often symbolized by the symbol K; since it is thus calculated in Darcy's Law $v = K \times i$ (Wikipedia, n.d.) or the constitutive law that describes the motion of a fluid in a porous medium. It can be defined as the specific flow rate per unit of hydraulic gradient and is a rotor that expresses the ease with which a fluid is transported in the interstitial spaces.

In the case of our model we consider, for simplification, conductivity as a scalar and therefore the same value has been used for vertical and horizontal conductivity. It is important to specify that conductivity is not a synonym of permeability, even if it is often defined as such in common language, in fact while conductivity is dependent on the characteristics of the fluid, intrinsic permeability depends exclusively on the size, position and arrangement of the pores of the ground.

Being one of the main parameters for determining the model and then for its subsequent calibration, we started by imposing indicative values (with an appropriate logical sense) to start managing the model. Also, in this case, according to the different areas and their function, it was necessary to proceed in a different way. Starting from the surface head, which as described in our model would be equivalent to air and therefore almost infinitely permeable, we proceeded by assigning an extremely high conductivity value of 100,000. Obviously, if the presence of soil is to be considered, this parameter could vary according to needs. Even in the need to assign a high value, however, it was necessary to take into account the finite difference of the input values of the model, in fact in the first steps of advancing the model not taking into account the finite difference of the values created numerous problems as it led to numerous errors in the calculation of outputs. The entire work done to create this model was in fact an iterative process of "learning by doing and overall, by making mistakes".

Once the values of the first layer were established, it was possible to proceed by assigning the conductivity values to the cells assigned to the fractures (from the second head to the penultimate along their entire length), which obviously will have a different conductivity value compared to the rest of the rock around waterproof. Initially, we started on a value of 0.01 m/s, a relatively low value considering the almost empty fractures and to ensure that the infiltrated water could flow easily to the bottom of our fictitious aquifer, obviously the possibilities are endless here too; once the real physical medium to be studied has been determined, the conductivity of the fractures can also be varied, for example in the event that they are to be considered filled by other means.

Subsequently, it was necessary to establish the hydraulic conductivity for the two areas delimited by an IBOUND of -1, that is the last layer starting from the top equivalent to the aquifer for the collection of infiltration water and the first row of the second equivalent layer to the river for the collection of surface water. As already happened previously, here too there was the highest possible conductivity value (100.000), within the limits of the finite difference, in fact our goal is

that the water is collected from these two limits as quickly as possible and without creating computational errors or accumulation; the aquifer and the river are just two fictitious tools used in the model to have a water collection basin and must not in any way interfere with and compromise the calculations of the model.
Finally, for all the remaining cells (those with IBOUND 0) that represent the impermeable rock, the assignment of the hydraulic conductivity is superfluous, since having already classified them as non-active cells they do not allow the circulation of water inside them and therefore do not they need a particular conductivity value. In any case, the Modflow program assigns it by default a value of 1 m/s, which, as already said, has no relevance in the final result.

Specific Storage and Specific yield

The next step was the definition of two other fundamental parameters, the specific storage, and the specific yield.
The specific storage is the quantity of water that a portion of an aquifer releases from storage, per unit of mass or volume of the aquifer, per unit of variation in hydraulic load, while remaining completely saturated; its unit of measurement corresponds to [L-1] and in our case m^{-1}.
Whereas the specific yield, is "The ratio of the volume of water that a given mass of saturated rock or soil will yield by gravity to the volume of that mass." (mindat.org, n.d.) and it can be expressed as a percentage or as a variation between 0 and 1 and does not have a characteristic unit of measurement as it is dimensionless.
Also, in this case it was necessary to proceed by assigning values for each class of cells by now widely defined previously.
Even in the case of specific storage and specific yield, we started by setting indicative values (which had a physical sense) to start managing the model; once finished the idea is to use these parameters to be able to calibrate the model. The modus operandi was the same used previously, thus analyzing each characteristic area (fractures, impermeable medium, aquifer, river and first layer) and assigning it a corresponding meaningful value.
For the first layer it was decided to use the value of 1 for both parameters, which also corresponds to the maximum value potentially assignable to both. We must in fact take into account that the goal was to simulate a real physical area, in this case 10 meters of air as already mentioned above these 10 meters in the future can also be considered as terrain and therefore have different values in the parameters. The same value of the parameter have also been applied

to the cells with IBOUND -1, which is the last layer representing the aquifer and the first line of the second layer that simulates a surface water course; the reason is the same applied for the assignment of the conductivity value, in fact the value of the parameters is the highest possible because the "task" of those layers is to receive the water as quickly as possible, without creating accumulations and without affecting the calculation of infiltration and runoff of water.

Furthermore, when it concerns the cells with an IBOUND of 0, that corresponds to those that represent the waterproof medium, the conditions are the same as the previous one; in fact, since the water does not flow inside for the purposes of our simulation, the value of the specific storage and specific yield in those cells has no influence on the results or on the infiltration per se. Despite this, modflow still requires a value for each cell, which is why for both values they have been assigned 0.001 as value.

Finally, the two parameter values for the cells that correspond to the fractures were assigned, that is, those characterized by an IBOUND of 0. The values of the parameters in the fractures are then changed to calibrate the model, while those of the impermeable ground, of the aquifer, the surface watercourse and the air layer remain unchanged (except if we consider a porous soil instead of the air layer, a case that is not addressed in this project). As far as the specific storage is concerned, we started by placing it at 0.0001, therefore the lowest possible value (always within the limits of the finite difference), while for the specific yield it was decided to start with a value of 0.001. As already mentioned, these two values may vary depending on the calibration of the model, in reality these values may vary depending on what we consider to be inside the fractures like air if they are empty, earth, ice etc …

Starting Hydraulic Head

Once all the characteristic parameters had been assigned, it was possible to proceed by defining the starting hydraulic head values.

The hydraulic or piezometric head is a specific measure of the liquid pressure above a point. The characteristic unit of measurement is [L] in the case of this model the meters; the hydraulic head is usually measured as the elevation of the liquid surface. Inside an aquifer the level is measured as corresponding to the depth of the water inside a piezometer (i.e. a specialized small well), thus measuring the height of the water surface in the pipe with respect to a given common.

Starting from the last layer, an initial level of 102 meters was imposed, the value 102 was chosen to be able to have it just above the last layer representing the aquifer. Putting it higher (for example from the second layer down) would be a mistake because even if the water did not arrive by itself through infiltration, the cell would be fed by the underlying aquifer (resulting absurd and devoid of physical sense). As far as the rest of the model is concerned, a different reasoning had to be made. The first idea was to place the initial level at 1000 meters, i.e. above the roof of the first layer, but it was then realized that this reasoning could not work as it would have stored 10 meters in the first layer of air. 1000X 1000 meters square or 10 cubic hectometers of water, a quantity of water that would then be counted as input of the model and would add up to the values of the effective rain, true input of our model, which at that point would be practically insignificant by comparison and the sense of the overall project would have been lost. It was therefore understood the need to impose an initial level in which the accumulation of water was minimal, assuming that only the fractures were full of water while the first layer was completely dry. In response to this problem, we tried to set the roof of the second layer as the initial level (not going to touch the first), but when we tried to do the first tests we noticed a big problem of the software, the same that unfortunately led to the complete abandonment of the model; in fact in modflow if at the beginning of the calculation process a cell is dry, the program gives it the status of IBOUND 0 and therefore does not allowing the circulation of water through it and in this case resulting in the whole first layer as waterproof and effectively preventing rain from infiltrating through the first layer. Also stumbled upon this second problem, it was therefore decided to find a compromise to circumvent the two previous errors, the initial level was placed one centimeter above the second layer, although it is still an error due to the same reasons as the first point in this case we are talking about a quantity of water 0.01X1000X1000 m^3 much lower than the previous one and also in comparison to the effective rain input imposed by us so that the error is considered negligible.

Zone Budget

As a last step to characterize the cells of the model, the characteristic modflow command "Zone Budget" was used.

Zonebudget is a ModFlow command that calculates sub-regional water budgets using the result data of the calculation just performed. The user has the ability to designate sub-regions and number them as desired. Once the calculation has been performed, Modflow creates an excel sheet in the same folder where its data is saved. The excel sheet presents the results of the budget calculated for each zone and for each zone the flow (in all directions) between cells is calculated and reported.

For this case, 3 main areas have been defined:

- Zone 11, which in the real physical medium corresponds to our hypothetical river, in the first line of the second layer corresponding to the cells with IBOUND -1;
- Zone 12, which in the physical medium corresponds to our hypothetical aquifers, in the last layer always corresponding to the cells with IBOUND -1;
- The zone 1 to which they belong all the remaining cells of the model.

Thanks to this division into zones at the end of the calculation process, the fundamental output data of the model are obtained; that is how much water infiltrates, thus arriving at zone 12 from zone 1, and when instead it flows, from zone 1 to zone 11. Furthermore, this tool can also be used to see if the program is performing the calculations correctly and that there is no settings error. For example, thanks to the subdivision into zones we realized that the aquifer was feeding the cells above (when we had imposed a Hydraulic head of 1000 meters) as there was a flow of water from zone 12 to 1 which in reality should not exist.

Model input

Rainfall

As already mentioned above, Modflow has a calculation package called "Recharge Package" which allows you to assign the values of atmospheric precipitation in the form of flow to each single cell of the model $[LT^{-1}]$ see figure 38. In our case we have chosen to assign the same value to all the cells of the top layer.

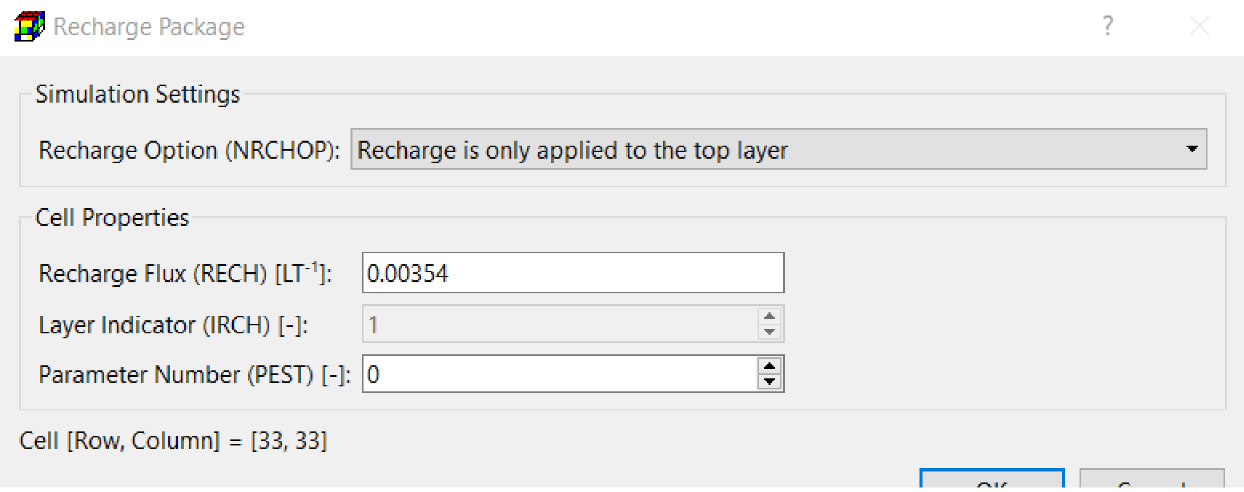

Figure 38 *Initial settings and values for the Recharge package*

Furthermore, modflow also allows you to assign a different Recharge value for each stress period from which the model is composed. In our case, the stress periods were 12 and to represent approximately twelve months of the year.

In order to adequately choose the Recharge values to be included in the model, it was therefore necessary to analyze the data of the rain gauges of the study area available (see table 1).

***Table 1** Average monthly values of rainfall (Iglesias López, 2021)*

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dic	Total	Altitud
Huascacocha	116,8	123,0	123,6	59,7	29,9	15,6	13,9	18,3	48,1	68,9	73,0	92,6	783,3	4.380
Morococha	122,8	135,9	125,0	69,4	27,8	16,7	18,0	25,1	55,2	72,4	69,8	100,6	838,7	4.500
Casapalca	115,0	125,4	120,1	55,2	19,1	7,8	7,8	13,5	31,3	58,3	56,7	98,8	708,9	4.330
La Oroya	84,7	99,5	84,3	49,1	21,8	8,3	12,5	14,7	35,6	57,4	59,1	91,3	618,2	3.910
Average	109,8	121,0	113,3	58,3	24,7	12,1	13,0	17,9	42,6	64,2	64,6	95,8	737,3	
Maximum	122,8	135,9	125,0	69,4	29,9	16,7	18,0	25,1	55,2	72,4	73,0	100,6	838,7	
Mínimum	84,7	99,5	84,3	49,1	19,1	7,8	7,8	13,5	31,3	57,4	56,7	91,3	618,2	
Dev.Sta.	17,1	15,3	19,4	8,6	5,1	4,7	4,2	5,2	11,1	7,5	7,9	4,6	95,5	
Variance	291	235	377	73	26	22	18	27	122	57	63	21	9.126	

Available data were the monthly averages of four different rain gauges located near the Coricancha mine: the Huascacocha, Morococha, Casapalca and finally La Oroya stations.

To obtain the data necessary for our model, it was decided to take the monthly average of each station of the model (see figure 39) to impose it in an orderly fashion as the Recharge input at each stress period.

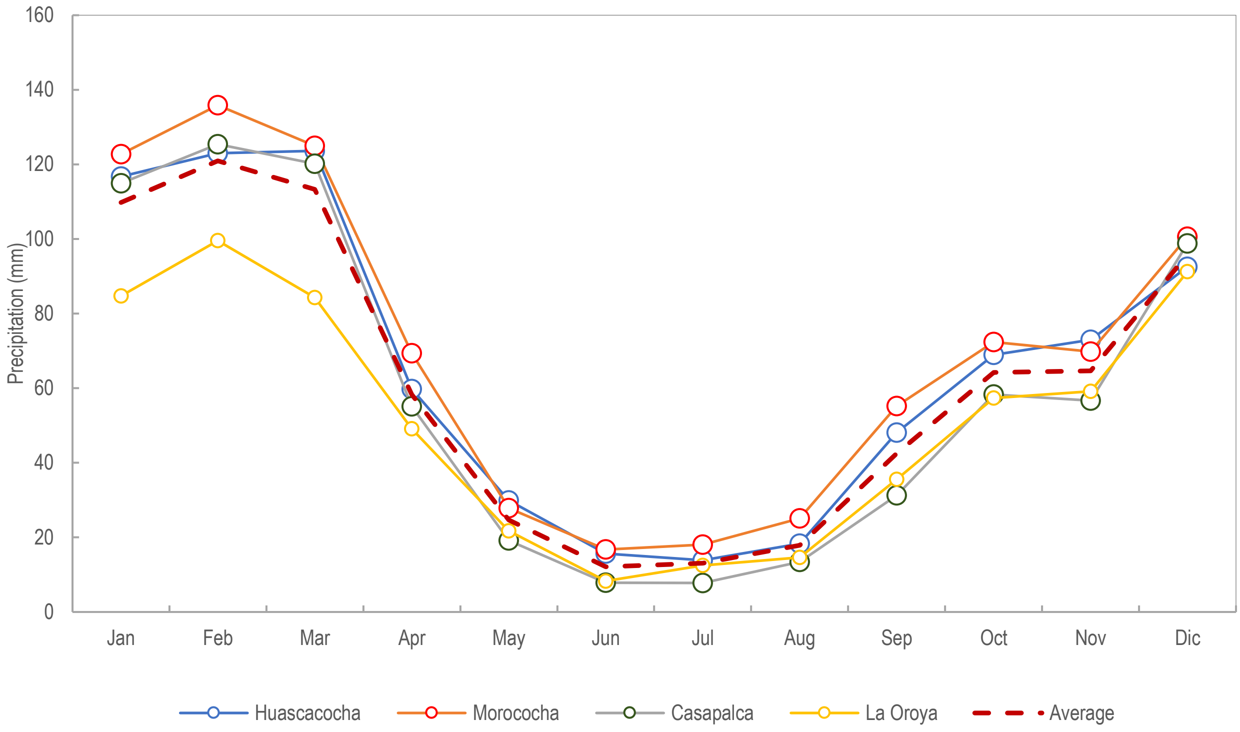

Figure 39 *Graph of calculated monthly rainfall averages (Iglesias López, 2021)*

However, the software requires that the data be presented in the form of flow $[LT^{-1}]$ which, given the basic settings of Modflow, is equivalent to $m/(day)$ and not in the form of [L] as are the mm/m^2 per month in which the data is arranged.

The first step for calculating the Recharge flow was therefore an equivalence from the value of millimeters available to meters (the unit of measurement with which you are working in the program).

Once the value in m/m^2 per month was obtained, it was necessary to switch to m/m^2 per day. Not having the daily rainfall data to obtain the value, the data of each month were taken and then subsequently divided by the number of days of that month, thus finally obtaining the input data for the system recharge. The calculations are carried out in excel and the results are shown in table 2.

Finally, it should be remembered that although the model requires effective rain as input data, since the evapotranspiration for this study area is considered negligible, it was decided to directly use the rainfall data recorded by the local rain gauges.

***Table 2** Model input rainfall values (Iglesias López, 2021)*

Month	Precipitation mm/m2 per month	Precipitation m/m2 per month	Precipitation m/m2 per day	number of days
Jan	109,8	0,109788965	0,00354158	31
Feb	121,0	0,120950604	0,00417071	29
Mar	113,3	0,113267876	0,003653802	31
Apr	58,3	0,058341474	0,001944716	30
May	24,7	0,024666872	0,000795706	31
Jun	12,1	0,012118506	0,00040395	30
Jul	13,0	0,013038846	0,000420608	31
Aug	17,9	0,017872939	0,000576546	31
Sep	42,6	0,042552526	0,001418418	30
Oct	64,2	0,064228089	0,002071874	31
Nov	64,6	0,064634597	0,002154487	30
Dic	95,8	0,095796147	0,003090198	31

Calculations

Problems running the model

Once the model and its characteristics were set up, it was finally possible to proceed with the first calculation attempts, in which, however, other problems were immediately encountered.
In fact, under the conditions imposed by us and with our choice of parameters, the program failed to perform the required calculations. Analyzing the calculation error in ModFlow it was reported as the impossibility of meeting the convergence criteria, thus leaving us three possible ways to operate:

1. Use a different calculation solver than the default one of Modflow.
2. Soften the criteria, also considering that in our model we do not need absolute precision to the centimeter.
3. Double-check that the parameters entered by us do not make it impossible to return the results, it is possible that the program cannot calculate with our parameters.

Having paid particular attention to the choice of parameters and believing that we are using sensible values on a physical level, we first decided to proceed step by step going to display what type of calculation model the default program was using and evaluate if it was possible run the program using another calculation model.

First, ModFlow's default computation solver is the Preconditioned Conjugate Gradient (PCG) used to solve finite difference equations at each stage of a MODFLOW stress period. In mathematics the preconditioned conjugate gradient is an algorithm for the numerical solution of particular systems of linear equations, namely those whose matrix is positive-definite, the matrix used in the calculation is preconditioned to ensure fast convergence of the conjugate gradient method. This method is often used as an iterative algorithm, applicable to sparse systems that are too large to be handled by a direct implementation (Wikipedia, n.d.).

In Figure 40 you can see the default conditions imposed on the model, with the iteration parameters that it was believed were correct and there was no need to change and with a convergence criterion of 0.01.

A convergence of 0.01 implies that the difference in the sum of the hydraulic heads of the 170,000 cells (100x100x17) must be less than the desired convergence between the before and after calculations. Thus distributing 1 cm of error for 170,000 knots, which as mentioned above

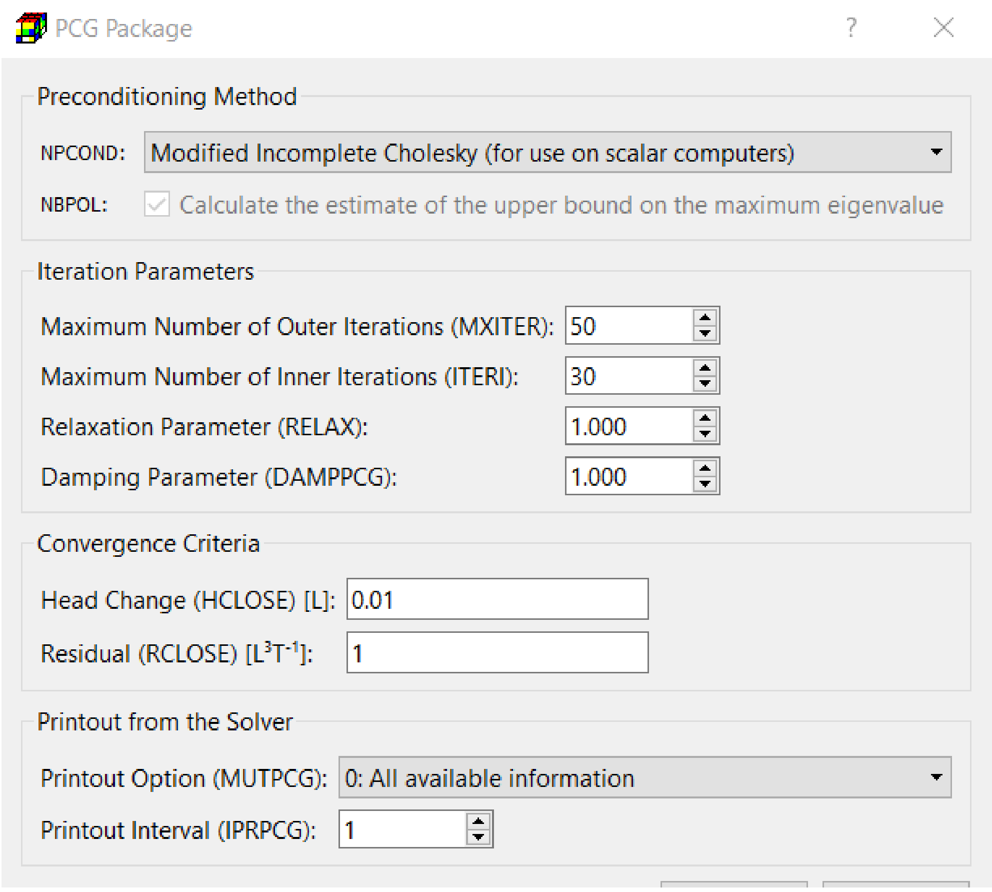

Figure 40 *Initial values for the PCG package*

are unnecessarily excessive conditions compared with the type of results we need or even just within respect to our input data on rainfall.

However, before changing the convergence criteria of the PCG method, it was decided to try a different solver for the execution of the model, the SIP Strongly Implicit Procedure, without necessarily having to soften the conditions of initial convergence. The implicit processes lead to a slower execution because there is a need to calculate the future Hydraulic Head without knowing the ones that are present at that moment, while the explicit ones with the PCG already have the Hydraulic Head and proceed to calculate the ones after and therefore they have stability problems that the implicit ones do not have.

The SIP method is an algorithm used to solve a linear system of sparse equations; the method uses an incomplete LU decomposition (a sparse approximation of the LU factorization often used as a preconditioner) to obtain an iterative solution to the problem (Wikipedia, n.d.).

Also, in this case (see Figure 41) we have the possibility to choose the iteration parameters, which however we continue to consider sufficient and adequate for our requests, and we notice a convergence criterion equal to 0.01, the same as the PCG model. With the criteria of Figure 41 it was tried again to have the program calculating but even with the application of this algorithm it reports as an error the failure to meet the convergence criteria.

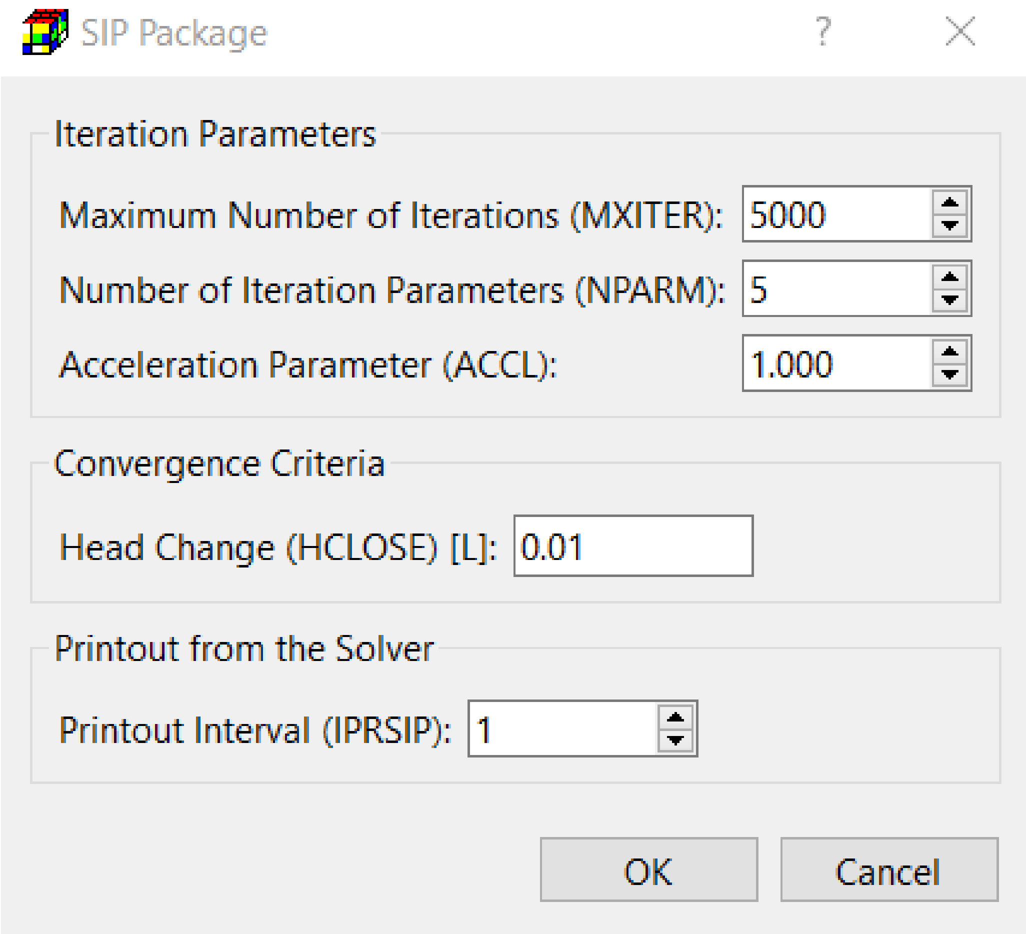

Figure 41 *Initial values for the SIP package*

Once attempted to proceed with two different solvers, it was decided to try the second previously established way, always using both solvers in order to be able to compare the results with the two different solvers in the future. In the first step, the convergence was increased from 1 centimeter to 1 decimeter, despite the increase (for both solvers) the software was still not able to finish the computation, reporting the same error for the umpteenth time. Although the second attempt did not work, however, we could still notice that while with the convergence of 1 centimeter the software stopped almost immediately at the first iterations and at the calculation of the first period of time, softening the convergence criteria modflow was able to calculate up to the second period of stress with both solvers, making us think we have had a good intuition by increase the convergence criteria. It was therefore decided to proceed by further softening the criteria from 1 decimeter to 1 meter (a convergence that despite being 100 times softer than the initial default one is still largely acceptable in our model).

Unfortunately, even with a convergence criterion of 1 meter in both solvers, the program was not able to complete the end of the required calculation, which is why it was realized that most likely there was some error in setting the parameters that were imposed in the beginning. Given the conditions, the parameter that could most easily compromise our calculations was certainly the conductivity (vertical as well as horizontal) and to facilitate the calculation of the model it was decided to further decrease its value within the fractures, passing from a value of 0.01 to 0.001 (leaving its values unchanged in the remaining parts of the model). Before starting the calculation of the program, it was decided to go back to using the convergence criteria to the default ones to understand if the problem could only be solved by changing the conductivity data or if instead both methods were needed to be changed or none (if neither these methods were affective), forcing us to proceed with a completely different reasoning. As in the calculation of the model also for the construction of our model we have decided to use an iterative procedure, analyzing each component and its influence separately so as to be able to handle it in the best possible way.

In the end, it was possible to finally finish calculating the program (with both solvers that are therefore always able to calculate under the same conditions) with a good compromise between our last two attempts: a convergence criterion of 0.1, therefore softer than the default; and 0.001 as the value of both horizontal and vertical conductivity in fractures. It should be noted, however, that with the more stringent convergence criterion and a conductivity of 0.001 the two solvers were able to calculate up to the 5 stress period, thus advancing much more than the initial settings, it is therefore possible to further understand how important it was to lower conductivity. Unfortunately, the fact that the conductivity value can affect the results of the model turned out to be the first sign of the instability of our model. When modeling, it should never be forgotten that in order to create the model we are referring to a physical reality and that we need to be able to find the right point of union between the two.

Changing the Recharge Package settings

Once the problem of the convergence criterion was solved, by verifying the first results, we realized that the model did not admit water and it turned out as if the overall Recharge was zero. Then, by further rechecking the data and parameters of the problem, we realized a wrong setting applied to the model in the Recharge Package settings. In fact, within the Recharge package it is possible to choose the simulation settings, in our first initial attempt we had left the setting to the default mode of "Recharge is only applied to the top layer". The rainfall data were therefore only applied to the upper part of the layer, but the problem with this command is related to the setting of the program that had already created problems previously, that is, if the cells of the first layer are empty. In this command, when the Hydraulic head level is below the cell, the cells are dry and the IBOUND value is converted to 0 and therefore when the Recharge is applied (rainfall) the water cannot be infiltrated inside, thus resulting as if the total Recharge on the model were zero. The program reconverts the cells to IBOUND 1 only when the Hydraulic head rises, but by the time that it happens the recharge is already considered to be zero.

To avoid the problem, the setting was then switched to "Recharge is applied to the highest variable-head cell in each vertical column" (see figure 42).

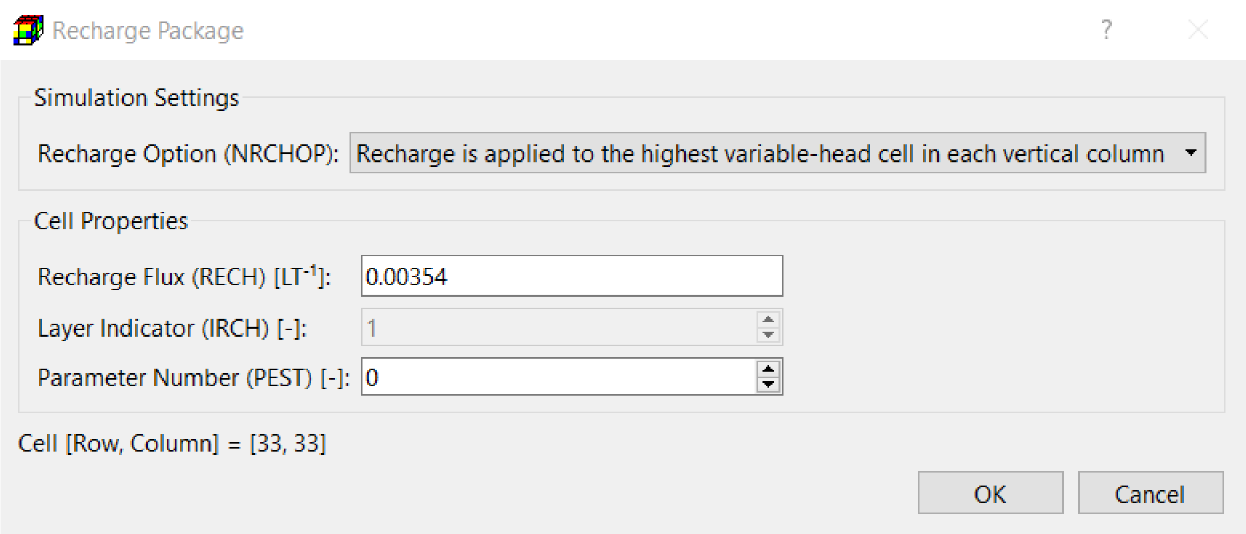

Figure 42 *Modified values for the Recharge Package*

Thanks to this command it is possible to divert the problem, because in this case the Recharge must be applied directly to the cell of each column that has the Highest value of Hydraulic head, which in some cases can be the first layer or in others also the second and the third; by doing so we are sure that the precipitation values can infiltrate and not be discarded as before.

Enlargement of the surface water receptor

Finally, before being able to proceed with the analysis of the results, a final adjustment had to be made. In fact, once the first results were visualized and by going to see the iso-piezometric lines and the level of the hydraulic head (see figure 43), we realized how the surface waters, that flow instead of infiltrating, struggled to be assimilated by our simulated watercourse, creating an accumulation of water at the watercourse and raising the level of the hydraulic head above the first layer, which in reality cannot happen.

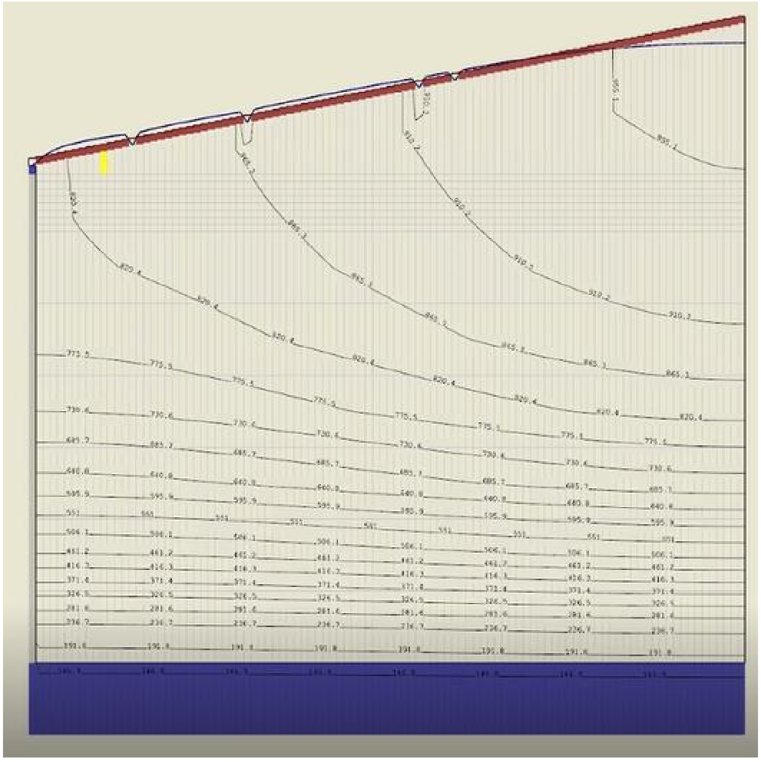

Figure 43 *Error in the over-raising of the starting Hydraulic head*

In order to remedy this error, it was therefore decided to expand our hypothetical watercourse, placing IBOUND -1 not only on the first line of the second layer, but also on the second and the two overlying lines of the first layer (see figure 44), widening the hypothetical watercourse by 4 times and thus mitigating the problem created.

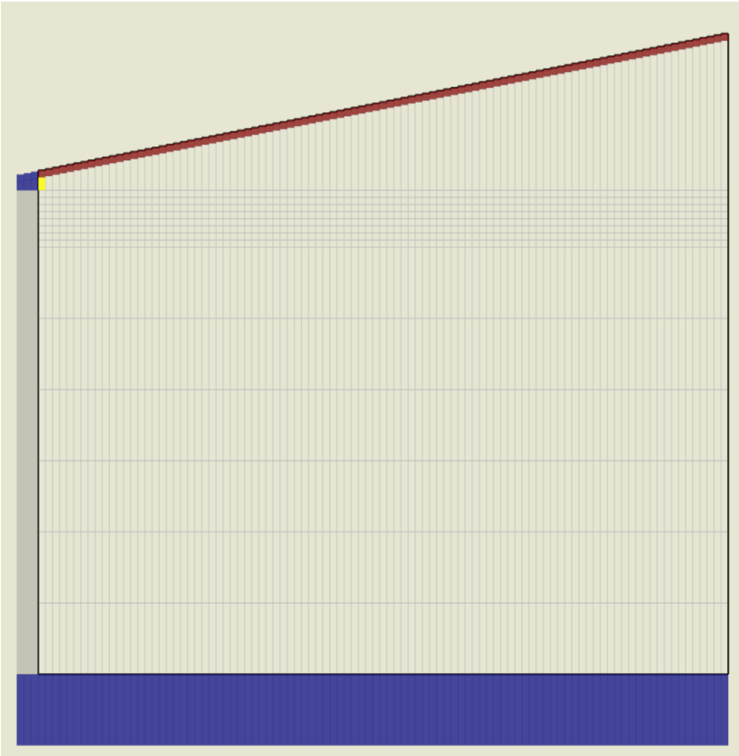

Figure 44 Enlargement of the surface water receptor

Results

Once the corrections to the model had been completed (see the diagram of the finished model in Figure 45 below) it was finally possible to proceed with the analysis of the results. Unfortunately, even once the model was set up, the concern about the problem of the conversion of dry cells to IBOUND 0 that had already arisen several times remained. Due to these worries it was therefore decided to firstly proceed by calculating the three cases with two fractures, parallel to the slope of the land according to the three slopes of 10, 20 and 30% to check the impacts of the issue as soon as possible.

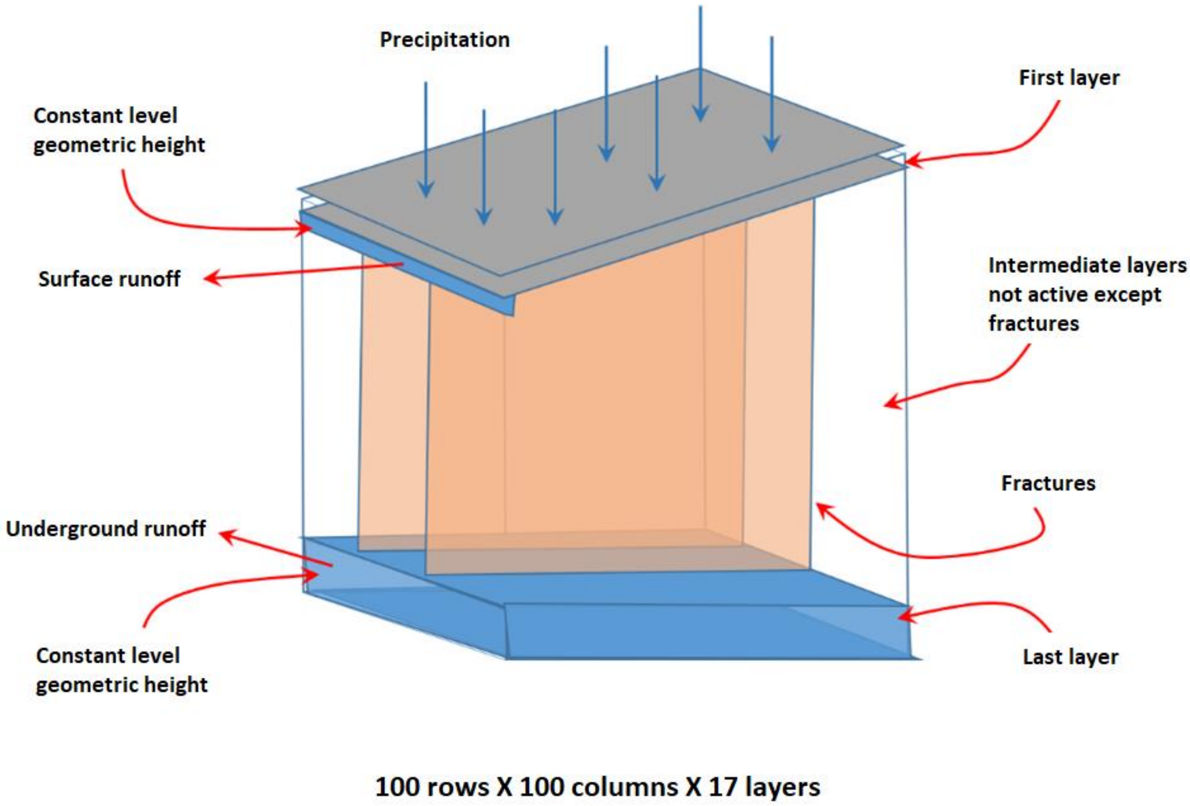

Figure 45 Schematic of the entire model

During the first case series, a slope of less than 10%, we did not encounter any problems; the results obtained from the excel sheet resulting from the budget zone showed an acceptable recharge and a clear distinction between the infiltrated precipitation water and the residual water that flowed on the surface. In addition to the results of the budget zone, the iso piezometric lines could also be seen on the profile of the model, in correspondence with the fracture, which showed how the water infiltrated without problems inside them. However, once continued with the 20% pending, the first problems began to show; in fact, although the first steps of the period worked very well, around the eighth time step the level of the Hydraulic Head dropped again below the first layer, the program automatically converted the first layer to IBOUND 0, no longer allowing Recharge from there forward and making the data no longer reliable. We then tried to analyze the results also in the case of the slope at 30% and in this case all the time steps presented the same problem found in the last steps with a slope of 20%. It was the n deduced that with a greater slope the level of the Hydraulic Head dropped too abruptly, thus leaving the first layer as dry cells and thus making them completely impermeable to precipitation, rendering the model unusable. At this point, having no longer found a way to solve the problem, we had to surrender to the evidence that through the modflow software and with our basic ideas it was not possible to obtain a robust model capable of simulating the infiltration of a fractured medium.

Reason for the failure of the model

The main reason why the creation of the model failed is certainly attributable to the inability of the model to admit the "Recharge", precipitation input data, when the Hydraulic head falls below the base of the first layer. As already explained, when a cell becomes dry, the program converts it directly to IBOUND 0, until the moment in which the hydraulic load level does not rise above the base of the cell. When the cells, and in this case the entire first layer, are converted to IBOUND 0, they become waterproof and are no longer able to admit precipitation, thus nullifying the entire intent of the model.

Best and worst results obtained

Although the model did not work, we managed to obtain some cases that did work. Figures 46 and 47 below show the iso piezometric of 2 different time steps in the case of the slope at 20%. In figure 46 we can see how for the first time step the result of the test is perfect, the level of the hydraulic load is in correspondence with the first layer, except for a small part in the high areas (already a symptom of error which will continue later); from the iso piezometric lines we can deduce the flow lines as perpendicular to them, being the isotropic model. By studying the flow lines, we can see how water easily infiltrates through the fractures to reach our hypothetical aquifer. This image is representative of one of the best results obtained in the simulations.

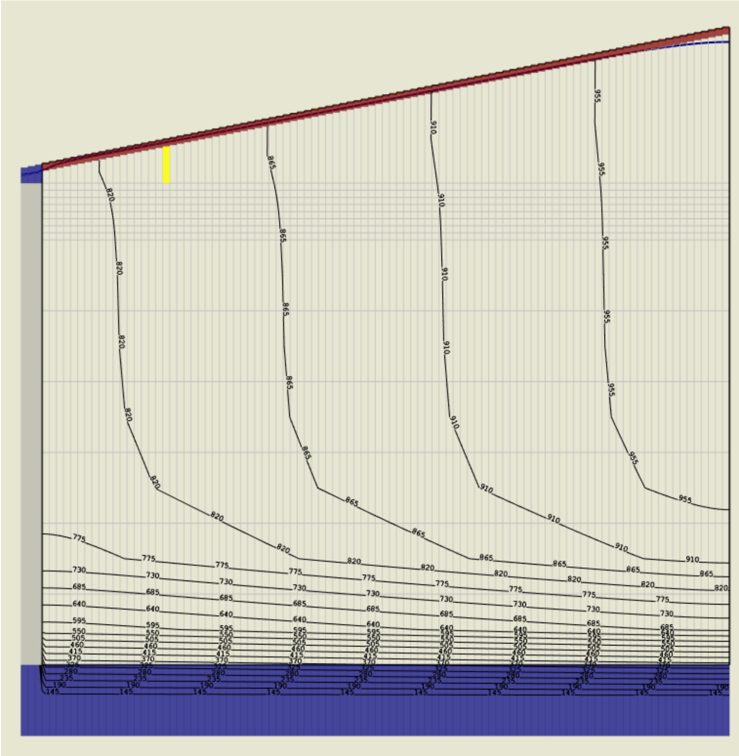

Figure 46 Evidence of proper infiltration through the fractures

The figure 47 below, on the other hand, represents the case with the pending at 20% but in the tenth time step; in this case it is immediately evident how the level of the hydraulic load has significantly lowered below the base of the first layer, thus leaving it completely dry. As already explained, once the cell is dry it is automatically converted into IBOUND 0, no longer admitting precipitation.

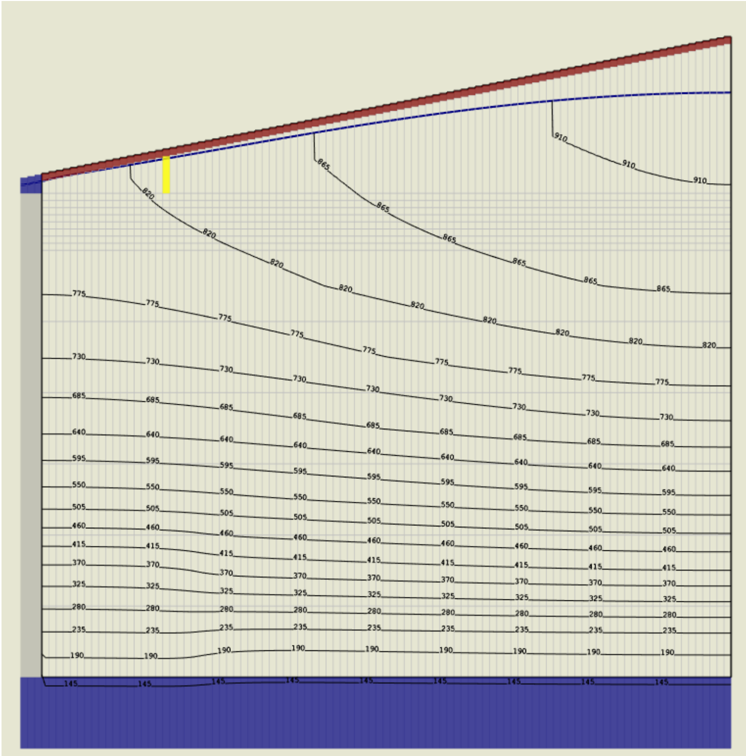

__Figure 47__ Lowering of the starting hydraulic head

Prospects for the future

This modeling project was certainly very difficult and ambitious and although the model did not lead to the desired results, the failure of the latter is also an interesting fact. In fact, thanks to the work done, we are aware that this type of modeling with these hypotheses and this software is not feasible, and we are thus a step closer to achieving the actual result. Furthermore, having already obtained a single working case study even if it does not make the model robust, suggests that the basic idea of the model is not yet completely discarded. For this thesis project it was decided to terminate with there conclusions, but in the future, for example through the use of different software with different calculation settings, the possibilities remains open to maybe be able to research in this area and to use the basic ideas of this model to continue experimenting.

Conclusions

Peru is a nation with vital resources each at a geologic and water level and sadly both within the past, and partly still today, are poorly managed by the government itself.

Thanks to the mining industry, Peru has experienced sturdy economic growth that has considerably improved the standard of life of its inhabitants. At the same time, however, mining is the subject of strong conflict in Peruvian politics, several inhabitants would like the whole halt of all mining activities. This is due to the fact that in the past mining was dispensed with none reasonably regard for the environment, affecting the health of the entire population; in fact, in the past, acidic mine waters were released into the surface waters without any form of control, and the waste from cultivation, which often contains high concentrations of cyanide and arsenic, was merely abandoned along the rivers and streams beds with none form of cover o regard and sadly still remain so, as never-ending supply of pollution. Despite this, it's believed that the answer isn't to utterly stop operations, but rather to subject industries to stricter environmental legislation and additional frequent controls; the mining trade is one among the cornerstones of the Peruvian economy and its halt would risk putting an end to the exceptional economic process to which Peru is subject.

Furthermore, within the last decade, the government has already taken steps to manage the environmental impacts. Most of the industries in the sector are currently forced to implement their treatment system, each of water and of waste materials; especially the mining industries that thanks to these new restrictions have greatly reduced the environmental impact and no longer are the main or most impacting supply of pollution in the country, as several still tend to believe.

Analyzing the state of the Peruvian water resource, 2 different major issues have arisen. The first one resides in the industries, several of which still these days do not treat the washing water in the slightest degree before releasing it into the environment; and the second, most likely the foremost impacting at the moment, is the complete mismanagement of wastewater by the Peruvian government, simply assume that 70% of wastewater isn't even treated. Fortunately, though significantly late, also in this respect the Peruvian government is getting down to act, having already started in 2014 to cover the whole capital and having planned and have already allotted an oversized part of the funds to cover the water treatment of wastewater of the whole nation by 2030.

However, the matter of South American country's water resources does not lie solely in pollution; Peru incorporates a great amount of water storage in its glaciers that reside on top of its mountains. These glaciers, however, thanks to climate change, are perceptibly receding, thus decreasing the provision of the resource itself related to global warming, to worsen the situation, we also studied the characteristic environmental condition phenomenon of that area: El Niño. Although it has not yet been proven, several studies suggest that climate change will induce a stronger and more frequent El Niño phenomenon. If this happened, the results would be devastating, each from an environmental and an economic point of view. Furthermore, as regards the matter of water resources, they would accelerate the melting of glaciers even more, further decreasing the available freshwater resource.

Although the analysis of the study area has brought to relevant information, the model on which this thesis was mostly based on was not ready to do the same. When you attempt to undertake an experimental study, you cannot be sure that it will lead to the required results. The concept of the model of this thesis was complex which made the whole project terribly ambitious, so, sadly, it was no surprise that it did not work. Anyhow, though it is not what we hoped for, the realization that this sort of modeling (in these conditions and with this software) cannot work is also a result. Due to this failure, we have been able to exclude a possible approach of operating and we are therefore one step nearer to getting the real desired results. Moreover, having already been ready to obtain results, even though in a few and outlined cases, suggests that the fundamental idea of the model is not yet to be discarded, rather it provides hope that within the future, most likely with the employment of a distinct software, this approach can lead to the right way to really model the infiltration in a fractured medium.

List of Figures

List of Tables

Reference list

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