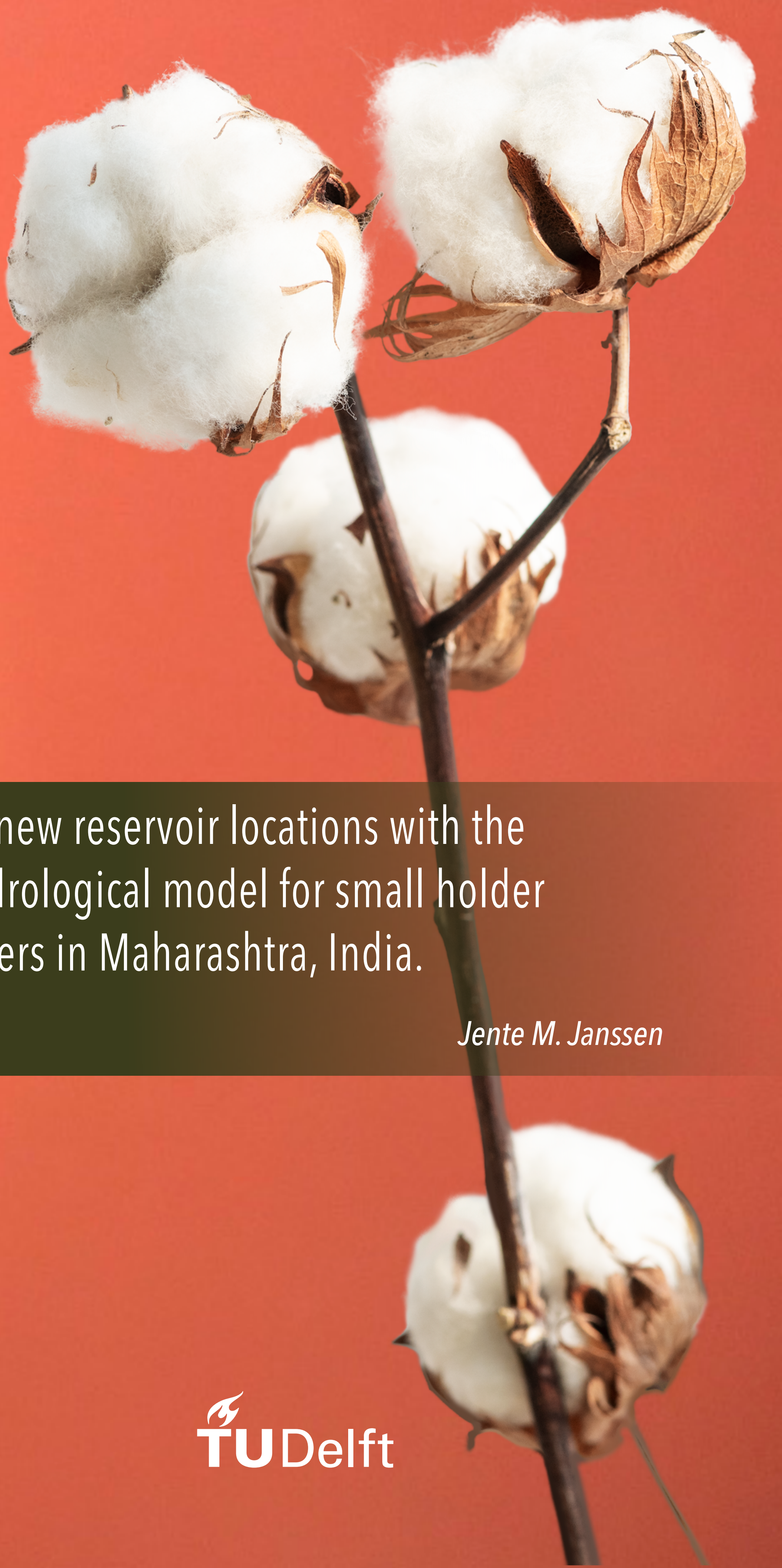

Estimating new reservoir locations with the use of a hydrological model for small holder cotton farmers in Maharashtra, India.

Jente M. Janssen

Solidaridad

TU Delft

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by

J. M. Janssen

to obtain the degree of Master of Science
at the Delft University of Technology,

Student number:	4151372	
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Thesis committee:	Dr. S. Pande,	TU Delft, supervisor
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	MSc. C. E. M. Luger	TU Delft (daily supervisor)

Acknowledgement

"Some people feel the rain, others just get wet. " - Roger Miller

I read or heard this quote at the start of my thesis, I cannot remember how and where it first appeared to me, but it did speak to me. And it also related to my research. At times I could feel the rain, but also at times I just got wet. Some people I want to thank to make me feel the rain again during these just wet times.

First I would like to thank my supervisor Saket for helping me throughout the entire project. At first by answering all my (minor) questions about going to India. After the trip was cancelled he supported me in redesigning my thesis into a 'stay at home' project instead of the interesting fieldwork in India.

Secondly I would like to thank Chris, my daily supervisor who took the time to meet me every other week and discuss whatever I needed to discuss with her. Even though she still was in the process of finishing her own master thesis and starting her PhD, she always made time for me to discuss my challenges. Especially in the last phase of my project, where she would take the time to read through my report several times and give me notes and comments to improve my thesis.

Lastly I want to thank my other supervisors Michael and Riccardo. Thanks for always being available for meetings and giving me your specialist view on my project. Thank you Michael for telling me at the start of my project that it is my project and my thesis and my path to accomplish and draw. It helped me during these Covid times to value my own process and see the hurdles I as a person had to overcome. Thank you Riccardo for helping me with my GEE programming even though you were very busy at that time with your own project. Also thanks for always making the meetings easy going by cracking a joke or two.

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Solidaridad, Ashray and Dr. Prashant: I hope I helped you with the outcomes of my thesis. I hope the project can continue with the use of my results and that you will accomplish what you aim to do in these 5 years. I hope I can come and visit the project before its ended because I am very curious how things are there and how you and we are doing.

J. M. Janssen
Delft, December 2020

Executive summary

For cotton cultivation, large amounts of water are necessary. One of the countries facing water challenges related to cotton cultivation is India. India experiences a monsoon weather pattern causing large amount of rain from June to October and no rain during the other months. One of the challenges India's small holder cotton farmers face is the lack of water after the monsoon. A solution to this problem could be the construction of (small) reservoir structures and renovation of currently present structures. One of the main questions arising here is 'how can a hydrological model estimate new reservoir locations for small holder cotton farmers and what is the potential of these new structures and current structures in Maharashtra India with Ghatanji block and Hinganghat block as case study areas?'. Estimating potential reservoir locations as well as determining which current reservoir structures have the potential to be renewed could increase the water availability for small holder cotton farmers in Maharashtra, India.

Four focus areas are chosen, these areas are Yavatmal, Nagpur, Wardha and Amravati. Within these focus areas, Ghatanji block and Hinganghat block are used as case study areas for developing and validating different models used for analysing current and suitable potential locations.Remote data based tools used to locate, validate and analyse the potential of current and potential suitable structures are QSWAT (hydrological model), Google Earth Engine (land cover analysis), Python coding, Zoom.Earth (locating current structures), socio-hydrological model (yield and benefit analysis).

Out of the initial 692 potential locations, 315 locations in Ghatanji block and 349 locations in Hinganghat block are classified as suitable potential reservoir locations. A location was marked suitable if a minimum size (200m^3) reservoir on this position has the ability to fill up completely at least once a year for an average monsoon season. Additionally, the structure was positioned in a location with more than 30% crop coverage and less than 25% urban coverage. Out of a total of 2212 current structures, 840 locations in Hinganghat and 970 locations in Ghatanji have a high potential of collecting water if renovated and in use. This high potential is a result of small distance to the nearest stream and suitable land cover on the position of the reservoir. Existing structures were classified as suitable if they adhere the same prerequisites as stated above regarding the coverage and for the additional requirement that a structure should be located less than 200 meters from the nearest stream point.

The results of this investigation show that a hydrological model can estimate new potential reservoir locations and that the use of a hydrological model is beneficial for locating these potential locations when compared to current or recently constructed locations. The benefit of using a hydrological model is that it can identify the surface runoff paths of water during and after a precipitation event. Furthermore, can remote data based tools help in identifying the suitability of both potential as well as current structures.

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Introduction

Cotton demand worldwide is rising due to both increase in global population as well as the surge in shopping behavior of people. As a result, the cotton production worldwide has to increase to supply enough cotton to keep up with the cotton demand (OECD Publishing, 2019). India is one of the main producers of cotton (Shahbandeh, 2019). The climate and soil in some regions in India are perfect to grow cotton without the necessity to irrigate the cotton crops with surface or groundwater, instead using only rainfed irrigation for crop cultivation. One of the major cotton producing regions is Maharasthra, located in Central India (Shende & Suryawanshi, 2009). The area has a large frost-free period, temperatures between 20 and 40°C and over 200 sun hours during pre and post monsoon season (Weather & Climate, 2019). Together with a relative humidity of over 60% during the monsoon months June, July, August and September, this climate is ideal to grow cotton (Shende & Suryawanshi, 2009). Yet, the cotton yield in Maharashtra is low compared to other regions. One of the reasons for this low yield is poor water management regarding both the lack of water storage for irrigation as well as increasing droughts in the area (Gutierrez, Ponti, Herren, Baumgärtner, & Kenmore, 2015). As a result, the farmer suicide rate in the Maharashtra region is the highest compared to other regions in India (Singh, Jha, & Chowdary, 2020). The reason for this high rate is often the high debts of a farmer. These debts are a result of high loans for seeds, fertilizers and pesticides.

Farmers in India rely on rain fed irrigation during the monsoon, and often do not possess a reservoir which they can use as a storage tank if the amount of precipitation is lower than necessary to cultivate their crops most efficient. This means that, during dry years, the cotton yield is not what they expect and as a result they cannot pay of their debts (Kamble & Bhoyar, 2020). In order to reduce the high number of cotton farmer suicides and increase the capital of the cotton farmers in Maharashtra, Solidaridad started a 5-year project called "Water Efficiency in Sustainable Cotton-based Production systems in Maharashtra, India". One of the aspects of this project is to increase the water availability for farmers by the use of reservoirs. Currently, there are several reservoir structures present throughout the area, however most of them are not in use due to a lack of water supply into the reservoir.

Figure 1: Woman hand-picks cotton during harvest season (Vishwanathan, 2019).

The 5-year project by Solidaridad aims to increase the capital of cotton farmers by making use of efficient water, crop and fertilizer usage. The first phase has been concluded after identifying hotspot areas and conducting a cost-benefit and water productivity analysis. The project is currently in its second year, and the next phase is to define and design locations for water storage possibilities. The ability for farmers to store water is one of the recommendations given by the MDP group (van Wirdum, Hatch, Mohammed Yasir Abbas, Raghunathan, & Willard, 2019). The focus area for reservoir construction is based on the hotspot identification analysis and will be Yavatmal, Wardha, Nagpur and Amravati districts in Maharastra, India. The water stress in these areas appears to be the highest when compared to other areas within the Maharastra state as discussed by the Cotton Water MDP group (van Wirdum et al., 2019).

The research objective in this thesis is how we can employ a hydrological model to determine new reservoir locations for small holder cotton farmers for irrigation of cotton fields and what the potential of these new locations and current locations is. The case study areas are Ghatanji block and Hinganghat block, located within the focus areas. If this model shows successful results by establishing reservoir locations which collect enough water to irrigate the cotton plots and thereby increasing the yield and benefit of that farmer, it can be used for the entire focus districts Yavatmal, Amravati, Nagpur and Wardha and eventually throughout the whole state of Maharashtra.

In this thesis, a hydrological model is combined with a socio-hydrological model researched by Dennis Djohan. This hybrid model aims to find the best possible locations for a reservoir structure in the previously mentioned case study areas from both a hydrological perspective as well as a socio-economical view. The hybrid model aims to find an optimum between the largest increase in yield and capital and the largest potential in collecting water for storage. The balance between these factors is important since a location could have the potential to store the highest amount of volume possible, but if this increase in water availability does not increase a farmers yield and/or benefit, the location is not optimal.

Currently there are over 8.000 reservoir structures present in the focus areas together. However, from field observations executed by Solidaridad it appears that the current pond locations are not sufficient as they are not collecting (sufficient) water to irrigate a small holder farmer's cotton plot. This insufficient water collection is possibly due to the lack of hydrological calculations when determining the locations of the ponds. The poor efficiency of the locations of the ponds does not lead to an increase in capital of cotton farmers in these regions. The locations of these current ponds are unknown, and have to be established in order to discover the potential of rejuvenation of a reservoir structure. If the GPS coordinates of these structures remain unknown, no hydrological model can be run on the location of the pond and reveal if this reservoir has potential to be replenished.

The first chapter of this thesis will describe the problem statement, research goal and research questions including some additional information on the main project carried out by Solidaridad. Chapter two begins by laying out the area characteristics such as terrain analysis, climate patterns and cotton farming practices. The third chapter is concerned with the methodology used for this research. Chapter four analyses the results obtained by the hydrological model. The fifth chapter discusses the results and gives recommendations for future and follow-up research. And last but not least chapter six contains the conclusion with answers to the research questions proposed in chapter 1

This research is a combination between a hydrological model to estimate potential reservoir locations as well as a socio-hydrological model to test the locations to certain social factors. The results of the socio-hydrological model will be included in this project. However, for a detailed description of the specific development and research on this model, refer to D. Djohan or Saket Pande. A summary of his research can be found in appendix A.

1

Problem statement and background information

With the increase in cotton demand, the cotton production has to increase and therefore the water availability to grow cotton crops has to be sufficient enough to live up to the increasing cotton demand. India is the largest producer of cotton due to the perfect growth conditions meaning plenty of heat and sunshine, and well drained soils which will be further explained in chapter 2. Cotton plants need water at very specific moments during the cultivation which can be supplied by (drip) irrigation or precipitation (Team, 2017). However, the challenge with relying on rainfall is that one does not know if sufficient rain will precipitate during the specific irrigation moments of the cotton cultivation due to both climate change as well as the unpredictability of weather in general. Nonetheless, one of the main obstacles cotton farmers in India face are droughts which result in less cotton yield than expected (Kamble & Bhoyar, 2020).

A solution to store enough water for later use could be the construction of reservoir structures for these smallholder (cotton) farmers (van Wirdum et al., 2019). Currently there are such reservoir structures present throughout the focus area. However, from current observations it appears that these structures do not always live up to the expectation of storing enough water or water at all due to dislocation of these reservoir structures. The exact way how locations are determined by construction companies is unknown. They are however, often not constructed with the use of a hydrological model and are therefore not located on a spot where water will runoff during rainfall events, as a result water will not be collected in the reservoir naturally.

Nowadays more attention is paid to the fact that "India's cotton cultivation consumes too much, produces too little" according to Dewan (2019). Multiple NGOs attempt to put this to a stop by educating farmers on how to use water, fertilizers, seeds and their plots efficiently with the goal to increase the cotton production per farmer. Hereby they aim to increase the cotton yield but also create a better livelihood for farmers. Besides the aim to educate farmers on farming habits, NGOs also try to bridge the gap between the government and farmers (Devyani, 2019). The government provides multiple support systems to farmers such as schemes and grants, however, the majority of the farmers do not know about these possibilities (Chethna, 2020; Tomar, n.d.).

The focus of this project will be on harvesting monsoon rainwater in a natural way with the use of small holder reservoir structures. Rainwater harvesting will be done both via direct harvesting of rainfall as well as harvesting surface runoff water. Both processes will take place mainly during the monsoon season. From previous research by van Wirdum et al. (2019), there appears to be a knowledge gap relating to determination of suitable reservoir locations which ensure water storage during the monsoon (van Wirdum et al., 2019). A suitable reservoir location is defined as a reservoir able to collect at least 200m^3 of water during an average monsoon season and store it until after the monsoon season maintaining the volume. This 200m^3 is the minimum reservoir capacity determined by the government. Both new locations as well as current locations are examined, and the feasibility of (current) locations is investigated. The goal is very practical by visibly increasing the number of working reservoir locations and creating a user friendly model for Solidaridad to estimate the suitability of potential locations.

The research goal will be described in the paragraph 1.1, second the research questions arising from this research goal are stated in paragraph 1.2.

1.1. Research goal

This master thesis research is part of the project 'Water Efficiency' carried out by Solidaridad. This master thesis' research covers a sub-goal of the main project. To understand what this sub-goal is and why this sub-goal is important in relation to the main goal, first the main goal of the project performed by Solidaridad will be explained in paragraph 1.1.1. In paragraph 1.1.2, the application of this master thesis will be described and how this is related to the main research goal.

1.1.1. Information on Solidaridad's project approach

The main goal of the project "Water Efficiency in Sustainable Cotton-based Production Systems in Maharashtra, India" is to increase the cotton farmers' capital in the Maharashtra state in India. The increase of the farmers' capital will be established by addressing different subjects such as establishment of fixed cotton pricing, education of sustainable use of pesticides and fertilizer and the increase of cotton yield by increasing the water productivity and water security. This master thesis research is developed around the topic of water security by increasing the water storage capacity with the use of reservoir structures for small holder cotton farmers in the case study areas Ghatanji block and Hinganghat block. The construction of reservoir structures is supported and partly funded by the government if a reservoir meets certain requirements. The requirement relevant for this research is the limitation in size of a reservoir structure: a reservoir structure cannot be smaller than 10x10x4m and not be larger than 30x30x4m. Structures larger than 30x30x4m are not considered a small holder farmer reservoir structure and therefore other rules and guidelines apply. For this research, only reservoirs within the size boundaries are taken into account for both potential new structures as well as current structures.

1.1.2. Master thesis application

The applicable goal of this master research is to increase the amount of working reservoirs in the different areas, Yavatmal, Wardha, Nagpur and Amravati - Maharashtra, India with a focus on Ghatanji block and Hinganghat block as case study areas. The aim is to obtain 1500 reservoir locations including both new locations as well as current locations with the potential to store water once renovated. As a result, an increase in working reservoir structures should increase the amount of water available per farmer and contributes to the project goal of Solidaridad. A working reservoir is defined as the ability of a 10x10x3m reservoir to fill up completely at least once a year for an average low (600mm) monsoon season.

However, to only increase the amount of working reservoirs in the case study areas Ghatanji block and Hinganghat block, is not a sustainable solution for the remaining focus areas since the goal of Solidaridad is to increase the amount of working reservoirs to 20.000 structures throughout Yavatmal, Wardha, Nagpur and Amravati. Therefore this research is build on using an existing model to check the ability of increasing the amount of working reservoirs in the four focus areas with potential expansion towards the whole of Maharashtra. This includes both estimating new locations as well as investigating if current locations can be used or renovated to store sufficient water for irrigation. Furthermore, the solution of finding reservoir locations or determine if a (current) location is a suitable location to construct a reservoir on, the solution established during this thesis should contain an easy to use deliverable for Solidaridad. Additionally this research should provide a user friendly model to Solidaridad with which they can determine suitable locations based on the hydrological model.

1.2. Research questions

This research aims to give answer to one main research question:

"*How can a hydrological model estimate new reservoir locations for small holder cotton farmers and what is the potential of these new structures and current structures in Maharashtra India with Ghatanji block and Hinganghat block as case study areas.*".

The main research question will be supported and answered with the following sub-questions:

- Which remote data based tools influence the determination of suitable reservoir location with sufficient water supply for cotton irrigation of 1 hectare cotton plots?
- Which current structures have the potential to be kjl[].=renovated and how is this potential determined?
- What can be learned from current reservoir locations and recently constructed reservoirs?

To answer these sub-questions two elements have to be explained further. The first element is the definition of a "suitable reservoir location", the second element are "remote data based tools".

Suitable new reservoir location

A suitable new location, in this case, is defined as the ability of a 10x10x3m reservoir to fill up completely at least once a year for an average low (600mm) monsoon season. Additionally, the structure must be positioned in a location with more than 30% crop coverage and less than 25% urban coverage. Existing structures can be classified as suitable if they adhere the same prerequisites as stated above, except for the additional requirement that a structure should be located less than 200 meters from the nearest stream point. This 200 meters is based on the length over which a channel or ditch can be constructed and maintained.

The threshold for crop cover fraction is determined as a result of the recently constructed reservoirs by Solidaridad. From analyzing the cover fraction per constructed reservoir it showed that all reservoirs were constructed on a location with over 30% crop coverage. Therefore it is assumed that a suitable reservoir location contains at least a crop cover fraction of 30%. The analysis can be found in paragraph 4.4.

Since none of the reservoirs constructed by Solidaridad has an urban cover fraction, it is difficult to make an assumption on the amount of urban cover fraction present on a suitable reservoir location. At least one can assume that no high urban coverage is preferred on a suitable reservoir location but that some houses or roads can be present on a 100x100m pixel. Therefore the threshold for urban cover fraction is set at 25%.

The results of the constructed reservoir analysis are described in paragraph 4.4.

Remote data based tools

With "remote data based tools" is meant the tools available to investigate the suitability of these potential and current structures from a place other than the project location. These tools are investigated during this research since it was not possible to do a field visit due to the Covid-19 pandemic. Initially, this research was supposed to contain a field trip of 3 months to the focus area in India. Unfortunately this could not go through and an alternative research had to be developed where still 1500 reservoir locations would be addressed as suitable locations. Therefore it had been decided to investigate the remote data based tools available to determine and validate suitable reservoir locations for the project of Solidaridad and future remote research.

2

Characteristics of the focus area

To understand the project and the outcome of the research described in chapter 4, it is of great importance to understand the different properties of the research area and its relation to cotton production. The purpose of this chapter is to elaborate on the location of the focus areas Yavatmal, Wardha, Nagpur and Amravati and the case study blocks Ghatanji block and Hinganghat block. It is important to know how and why these areas are chosen, the climate in the areas, soil types and land-use and lastly the current reservoir situation in the areas. All factors mentioned are described in this chapter.

2.1. Location of the focus districts and case study areas

The focus area for the 5-year project is Maharashtra state, located in central India. However, the focus area for this pilot study will be narrowed down to Yavatmal, Wardha, Nagpur and Amravati in Maharastra, India. The exact location of the districts can be found in figure 2.1. From the Baseline study conducted by van Wirdum et al. (2019), these areas are identified as hotspot areas. The hotspot locations are areas where the farmers' capital falls below the poverty line. The four districts are located in central India: a very arid region.

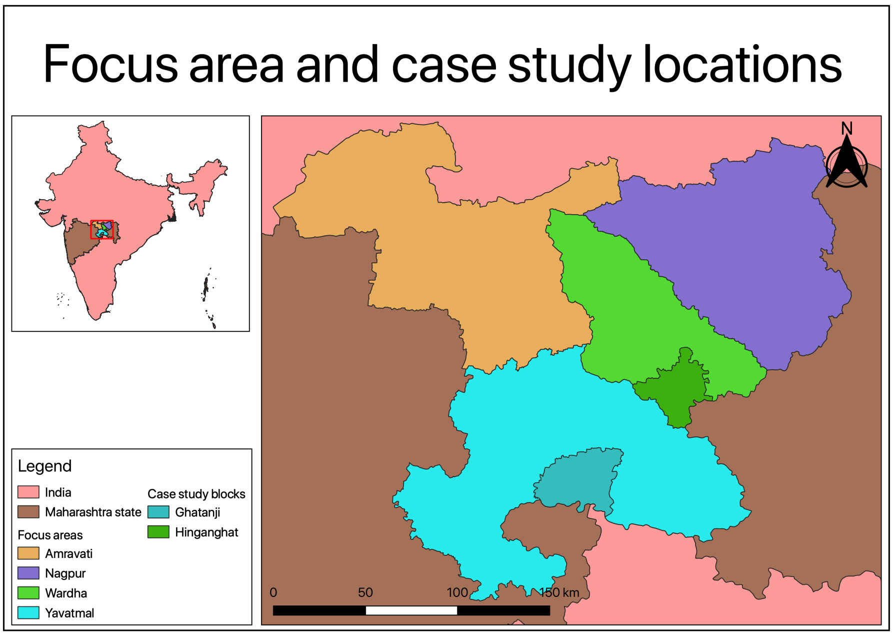


Figure 2.1: Locations of the focus areas Yavatmal, Wardha, Nagpur and Amravati and case study areas Ghatanji block and Hinganghat block within the Maharashtra district, India. Made by author.

The four districts will be used as pilot areas by Solidaridad. Ghatanji block within Yavatmal district together with Hinganghat block in the Wardha district are used as a case study areas. The pilot areas are chosen by Solidaridad based on the outcomes of the report by van Wirdum et al. (2019). These areas are chosen based on the hotspot data and their location. All areas are located next to each other and the head office of Solidaridad is based in Yavatmal city. Once successes are achieved in the pilot areas, other areas within the Maharashtra state will be approached. It is therefore of great importance that the framework around these four areas is clear and structured. However, to narrow down the scope of this research and test and develop an easy to use model, two blocks within the pilot areas were chosen as case study areas. From now on, the pilot areas will be referred to as *focus areas.*

2.2. Terrain analysis

The districts are located in central India in the Maharashtra province. This central location within the district comes with specific a soil composition namely the Deccan plateau. The Deccan plateau consists of hard basalt rock formed by volcanic eruptions over 65 million years ago (Gale et al., 2003). Furthermore these Deccan Traps[1] determine the land cover and altitude in the area.

To understand the soil type and geology of the districts, the soil type and geology of the entire Maharashtra state is discussed first in paragraph 2.2.1. Secondly the elevation in the focus districts as well as the case study areas are analyzed in paragraph 2.2.2. From the elevation maps it can be observed that the area is slightly hilly. However some parts do not contain any small hills at all and are said to be flat, other parts within the focus districts more hilly and have larger altitude differences.

Lastly the land cover types of both the focus districts as well as the case study areas are presented in paragraph 2.2.3. The main land cover type are croplands together with some forests and urban areas.

2.2.1. Soil type and geology

The soil type is determined by the geological location of the focus area. The entire area is located on the Deccan plateau and thus has a very specific soil composition consisting of mainly volcanic soils as can be seen in figure 2.2. These volcanic soils are formed by large volcanic eruptions million years ago creating the Deccan Traps and thus the Deccan Traps are composed of hard basalts (Gale et al., 2003).

The soil appears black because of the high iron concentration present in this volcanic rock and are therefore called "black soils". The advantages of these black soils for cotton growth are that the temperature remains high and the soil has a high moisture holding capacity due to its clayey material (Heitzman & Worden, 1995). The clayey material is made of a very fine coarse structure, excellent in holding moisture.

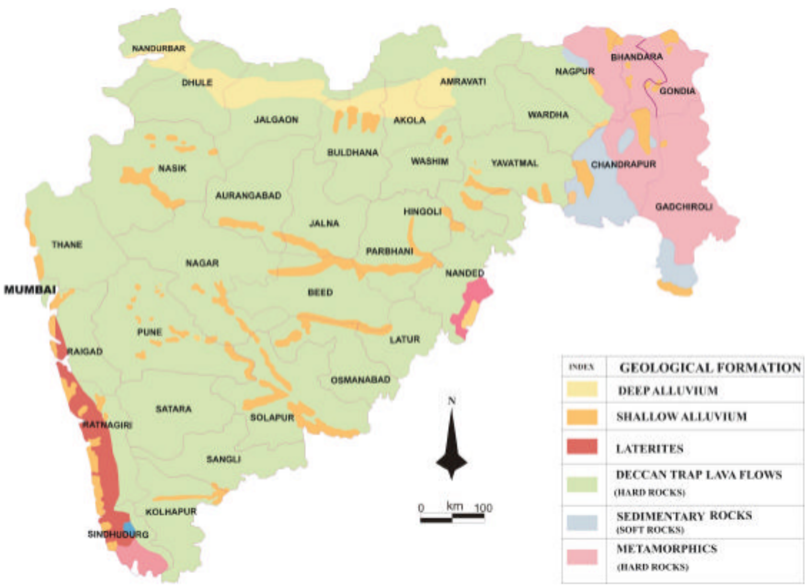


Figure 2.2: Geology of Maharashtra state including the geological specifications of the focus areas. The main rock type are the Deccan trap lava flows (hard rock) in all four districts. Yavatmal, Wardha and Nagpur contain a small part of shallow alluvium geology. Amravati contains some deep alluvium in the north west part of the district. Image from the Geological Survey of India (Gale et al., 2003).

[1]The term "trap" has been used in geology since 1785–1795 for such rock formations. It is derived from the Swedish word for stairs ("trappa") and refers to the step-like hills forming the landscape of the region *Trap* (n.d.).

2.2.2. Altitude

As will be explained in paragraph 2.3, the altitude in the area plays a role in the regional weather. The altitude data is obtained from https://bhuvan-app3.nrsc.gov.in/data/download/index.php?c=p&s=NI&p=wbf&g=TS.

From figure 2.3 left panel it can be observed that the altitude in the Ghatanji block ranges from 143m AMSL to 357m AMSL meaning that the area is slightly hilly. The difference in elevation is a positive feature when it comes to water collection by potential reservoirs: the hills provide a stream network and thus the estimation of how the water flows throughout the area is easier to determine compared to when the surface would be flat.

The Hinganghat block is more flat compared to the Ghatanji block. However, a stream path can be observed in figure 2.3 right panel, showing that water will run through this area on its way to the ocean. The water path originates from the catchment further stream upward. The elevation in Hinganghat block ranges from 119m AMSL to 198m AMSL.

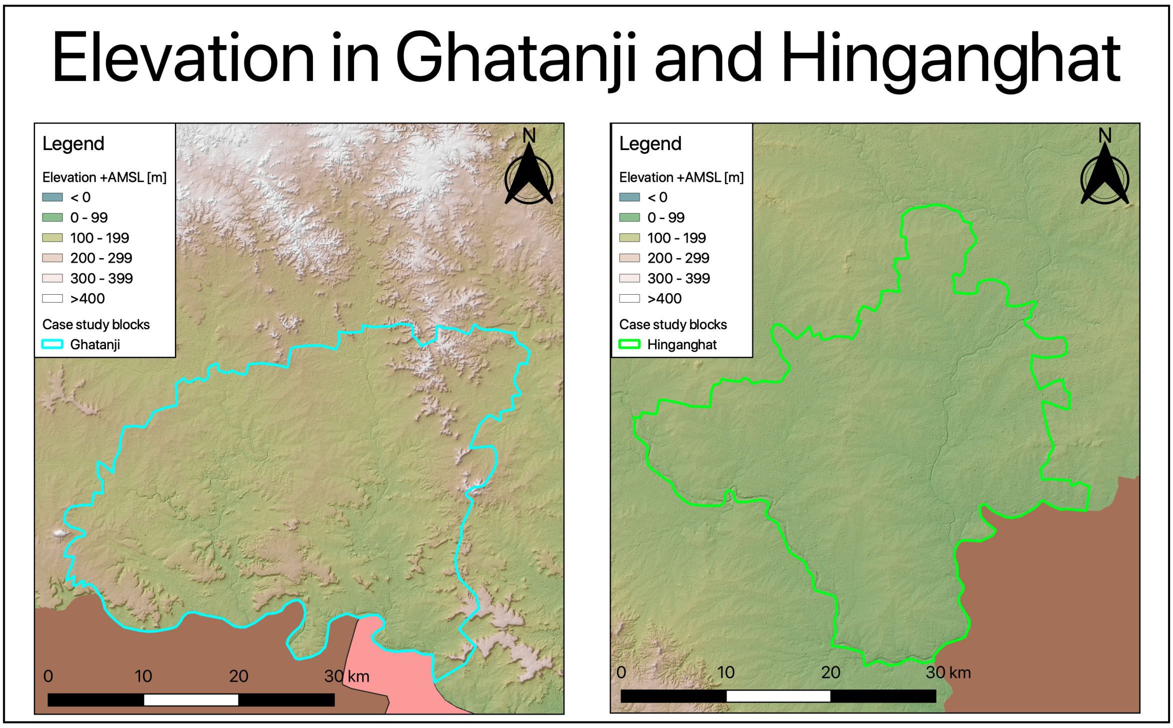


Figure 2.3: Elevation map of Ghatanji block (left) and Hinganghat block (right). Showing a hilly surface around the area with the highest elevation in the north east of the Ghatanji block. Hinganghat appears to be relatively flat, but a stream path can be observed from north east to south east. Made by author, data obtained from https://bhuvan-app3.nrsc.gov.in/data/download/index.php?c=p&s=NI&p=wbf&g=TS.

2.2.3. Land cover types

The land cover data is obtained from the Copernicus Global Land Service https://lcviewer.vito.be/2019 which collects land cover data on a yearly bases. For this project the most recent data from 2019 is used, the resolution of the data is 100x100m.

The land cover in both the focus districts as well as the case study areas consist for the majority of croplands as can be noticed in figure 2.4. The type of cropland is however unknown. Amravati district holds a large forestry area in the northern part of the district. Nagpur city located in the center of the Nagpur district can be observed together with the smaller main cities of the other three districts. Furthermore some permanent water bodies are present which will not be taken into account in this project.

It can be observed from figure 2.5 right panel that the additional main land cover type in the Hinganghat block is urban cover. Some minor permanent water bodies are present in the south west border of the block. In Ghatanji block (2.5 left panel) forest cover is the second main land cover type present. Also some permanent water bodies can be found on the south border of the block.

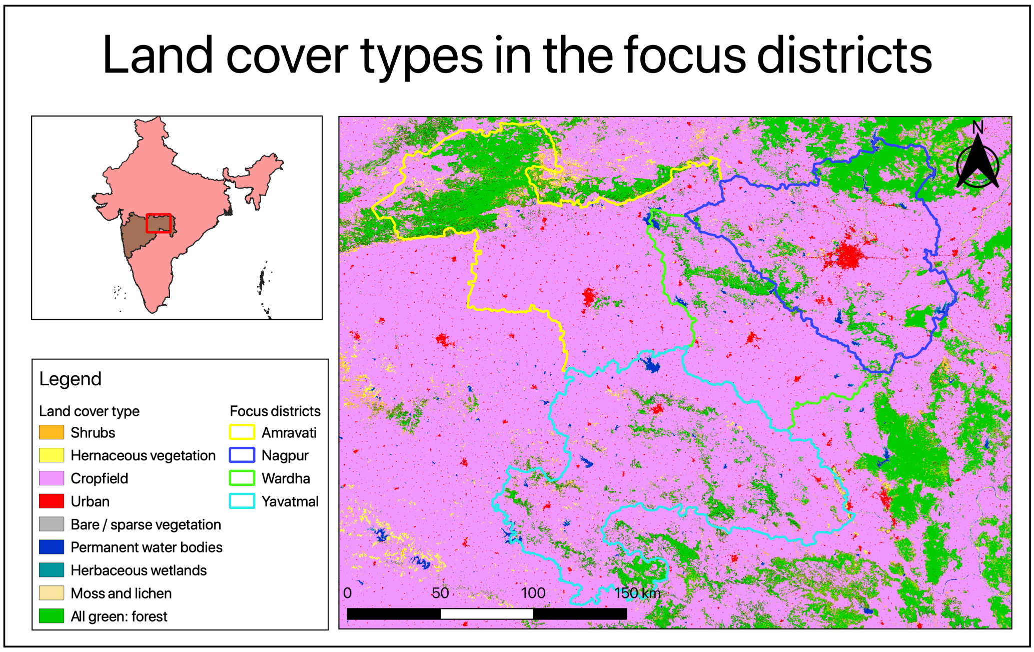


Figure 2.4: Land cover classification map of the four focus districts. The dominant land cover for the entire area are cropfields (purple). Amravati contains a lage forest area in the northern part of the district. The city of Nagpur can be observed in the center of the Nagpur district. Made by author, data obtained from https://lcviewer.vito.be/2019.

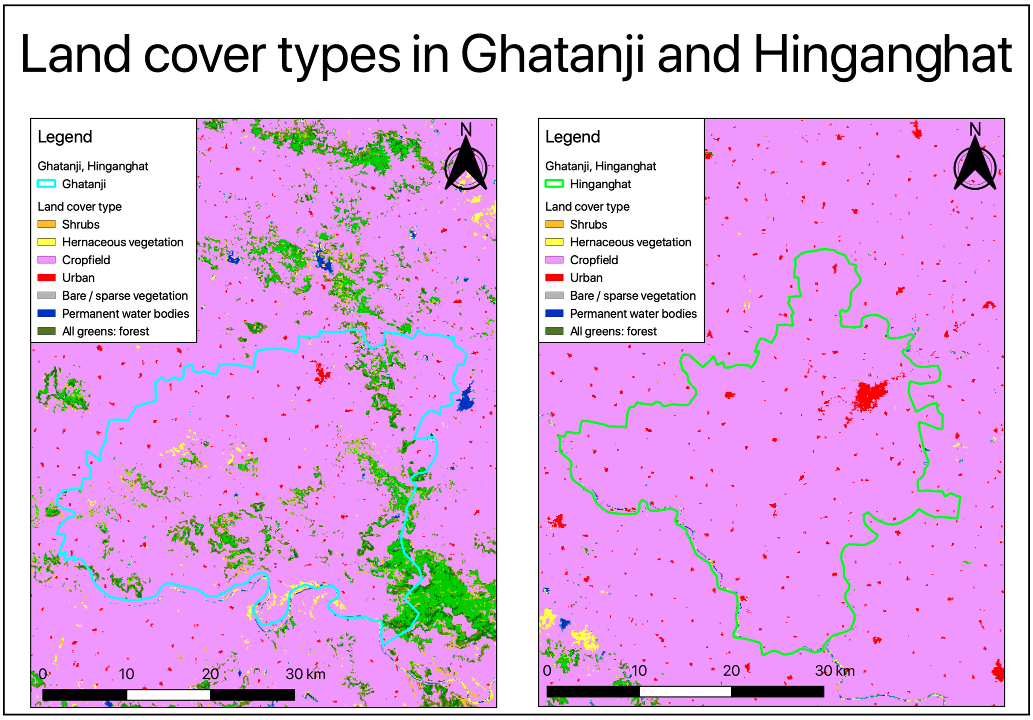


Figure 2.5: Land cover classification map of Ghatanji block (left) and Hinganghat block (right). The dominant land cover for both areas are croplands (purple). Ghatanji block has a larger variety of land cover types where forest is the main cover after croplands. Also some permanent water bodies can be observed on the south border of the area. Hinganghat block also has a fraction of permanent water bodies on the south west border and some coverage by urban constructions. Made by author, data obtained from https://lcviewer.vito.be/2019.

2.3. Climate

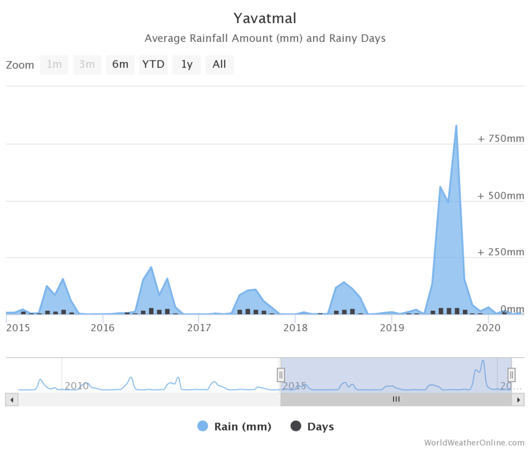
The climate in the region is ruled by the tropical south-west monsoon lasting from the first week of June until the end of September with a peak in July and August. The monsoon causes a period of heavy rainfall, depending on the area in the district, the precipitation ranges from 900 mm till 1200 mm (*Rainfall and Weather*, 2020). Followed by a cold period (post monsoon season) from October till February. The season from March to May is called the summer season (pre monsoon) and is dry and hot with temperatures reaching over 40°C in May. The monsoon does not only influence the amount of precipitation, but also has an effect on the humidity level, cloud coverage and temperature as can be observed in figure 2.7.

Other factors influencing the regional climate are latitude, altitude and landscape. The latitude divides the southern and northern part of India. The south belongs to the tropical area and the north is part of the subtropical zone. The focus area experiences a tropical climate since it is still located on the southern latitude as can be seen in figure 2.6.

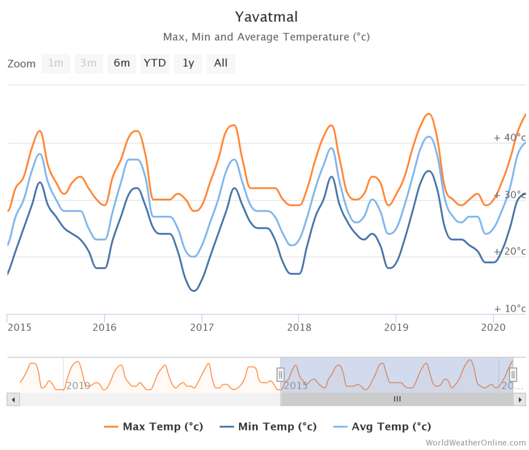
Figure 2.6: Climate map of India showing the monsoon development throughout June and the average climate within each region (*India Climate, Climate Map of India and Climatic Regions Map*, 2020)

Precipitation The precipitation in the area is most important for sufficient crop growth. Other sources of water, such as groundwater, are limited available for irrigation. Rain-fed irrigation is an outcome for irrigation of cash crops. As explained previously, the only wet months are during the monsoon from June to September. Since the focus area is located in the tropical wet/dry area of India, it does not receive as much precipitation compared to other areas in India. From figure 2.7a it can be observed that the average amount of precipitation during the monsoon is around 200 mm. However, during the monsoon season of 2019, the amount of precipitation reached a level of 750 mm.

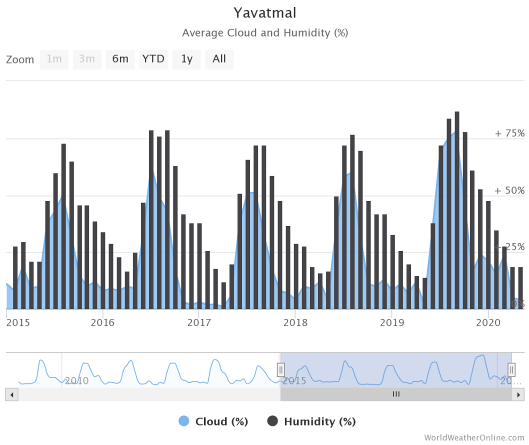
From figure 2.8 it can be observed that the rainfall throughout the area differs per district. The majority of rain in all areas occurs from June until September. The data used to obtain this figure is from 2019. Even though 2019 had a very large precipitation volume, the distribution as well as the months of rain are representive for an average monsoon season.



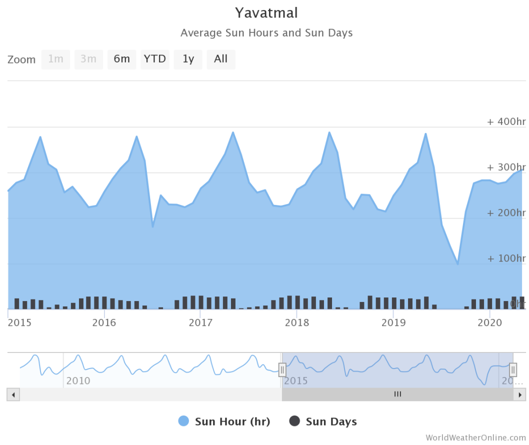
(a) Amount of precipitation per month in the Yavatmal district.



(b) Average, maximum and minimum temperature for different months starting in 2015 in the Yavatmal district.



(c) Level of humidity per month within the Yavatmal district.



(d) Amount of sunhours per month within the Yavatmal district.

Figure 2.7: 5-year climate data for Yavatmal (Maharashtra, India) located in the center of India. Data is obtained from Weather and Climate (2019).

Temperature The average temperature in the focus district ranges from 20 degrees to 42 degrees Celcius depending on the month as shown in figure 2.7b. The highest temperatures are observed in May, this correlates with the summer months observed in the region. The coldest temperatures are observed in December, corresponding with the winter period. During the monsoon season the temperatures remain relatively constant.

Humidity The level of humidity is in line with the cloud cover and the monsoon months. The higher the cloud cover, the higher the level of humidity and the higher the amount of precipitation observed in the area.

The humidity index is shown in figure 2.7c. Here clear peaks in both the average cloud cover as well as the relative humidity can be observed during the monsoon months June, July, August and September. April and May both have the lowest relative humidity and are therefore labeled as dry and hot months.

Sun hours and sun days The amount of sun hours depends on both the location of the earth in its orbital and the cloud coverage. The higher the cloud coverage, the less sun light reaches the surface, thus the less sun hours occur during the day. This is in line with the amount of sun days observed in figure 2.7d. As a result, during the monsoon months June, July, August and September, the least sun hours and sun days are observed and in May the most sun hours and sun days are present.

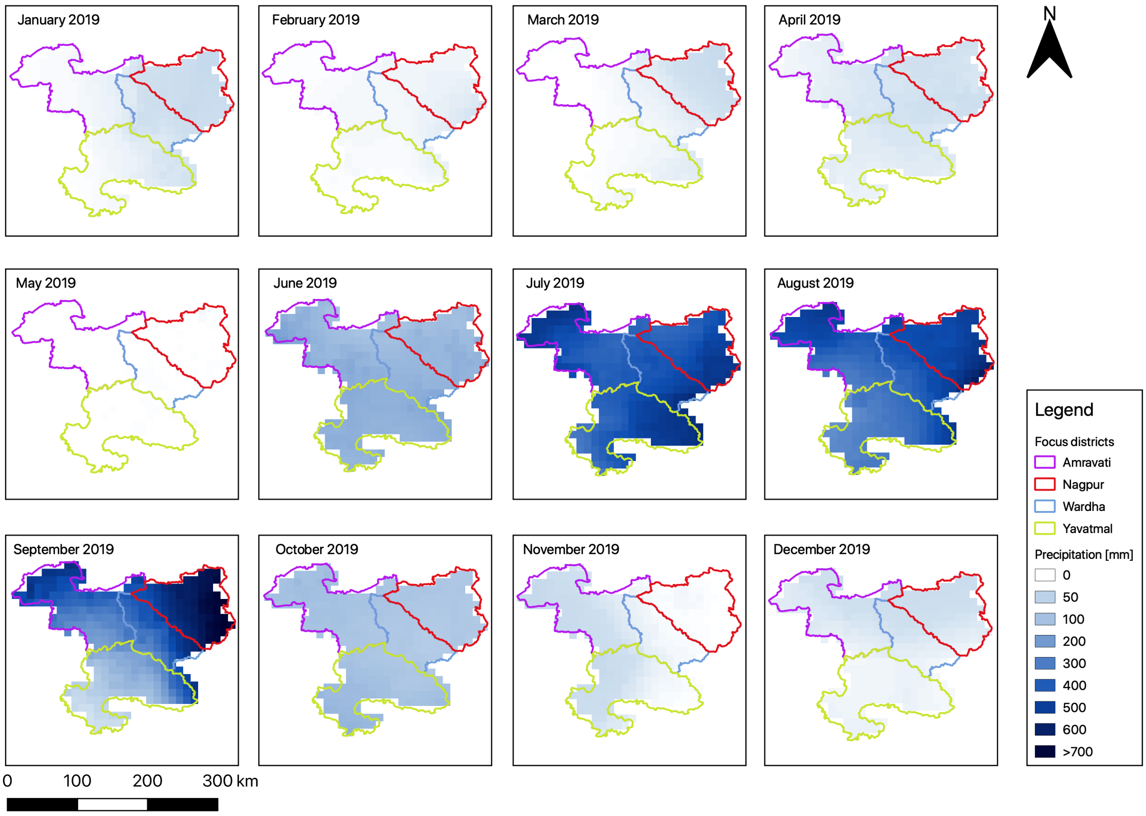


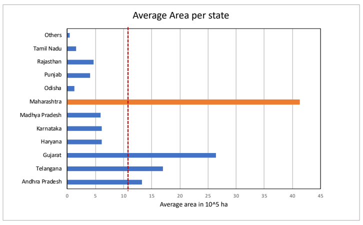
Figure 2.8: The monthly precipitation for entire 2019. From this image it can be observed that the majority of the rain fall between June and September. This is the monsoon season. May is extremely dry and throughout the other months, only little rain occurs. Furthermore it can be observed that the precipitation occurs homogeneous throughout the entire focus area. Made by author, data obtained from `https://pps.gsfc.nasa.gov/`.

2.4. Cotton farming in Maharashtra

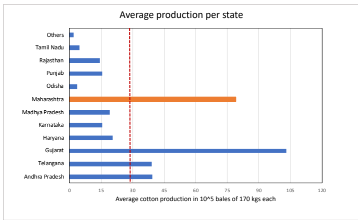
Maharashtra is known as one of the biggest cotton producers of India. However, it is interesting to see in figure 2.9 that indeed the cotton production and cotton area in Maharashtra are the largest compared to all other states in India but the cotton yield is the lowest when compared to all other states.

The project 'Water efficiency in sustainable cotton-based production systems in Maharashtra, India' aims to increase the capital of cotton farmers within the Maharashtra state by increasing the cotton yield. As described in section 2.1, this thesis focus' on a small part of Maharashtra. However, the aim is to help more farmers throughout the entire state. During the baseline study in the summer of 2019, the main bottlenecks of cotton farming in Maharashtra were exposed (van Wirdum et al., 2019). One of the issues resulting in such a low cotton yield is the water availability and usage.

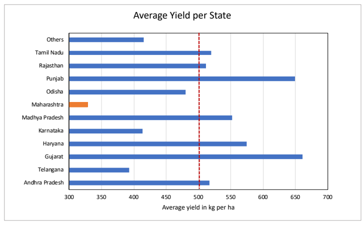
In this section the cotton water demand in the focus area will be further explained in paragraph 2.4.2. Also information is given on the current reservoir situation in the districts in paragraph 2.4.3.



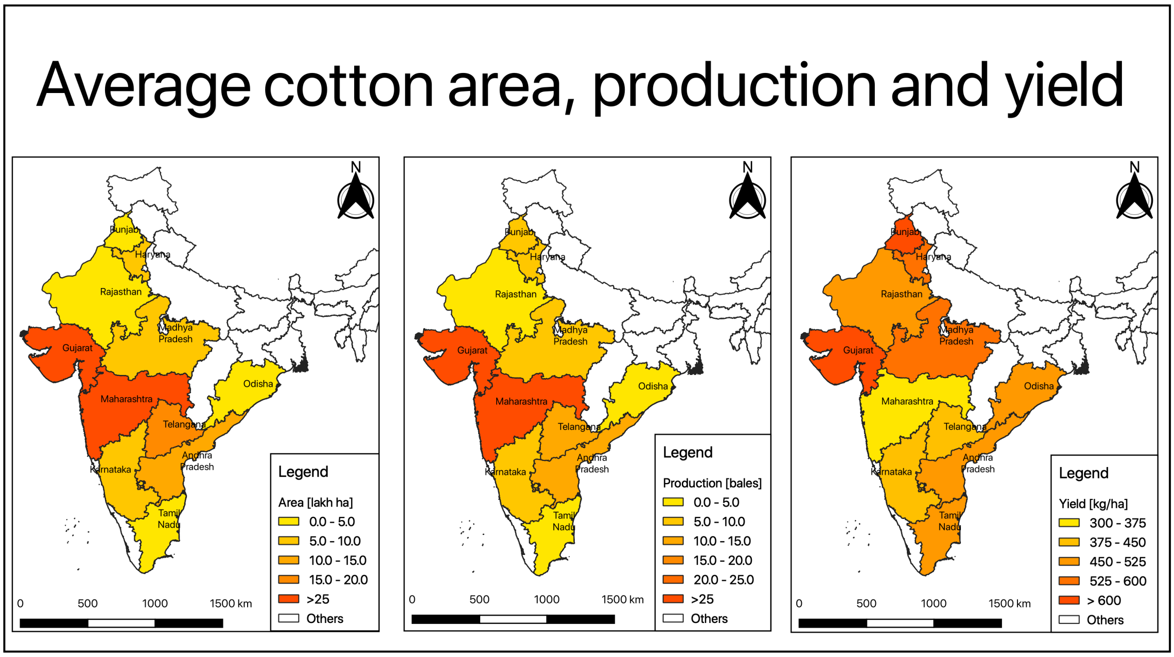
(a) Average cotton area per state



(b) Average cotton production per state



(c) Average cotton yield per state



(d) Visualization of areas with cotton area, production and yield range.

Figure 2.9: Average cotton area, cotton production and cotton yield per state in India. Maharashtra has the highest average cotton area and almost highest cotton production rate, however it has the lowest cotton yield compared to all other states. One of the reasons for this low yield is the high level of droughts in the post monsoon season.

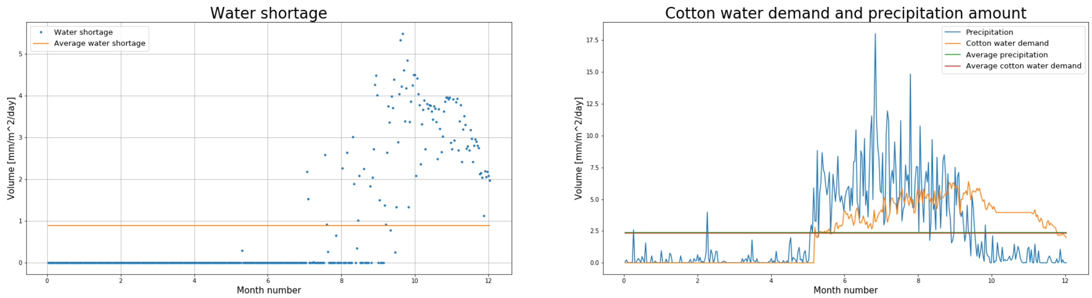
2.4.1. Cotton cultivation and harvesting process

Cotton is a so called "Kharif crop" meaning that it the crop is cultivated and harvested during the Indian monsoon season (Das, 2018). The crop is sown at the start of the monsoon season around June/July (depending per region) and is harvested between October and January (Trent, 2017). The further north, the earlier the crop is sown and harvested due to the possible frost period in the winter. In the Maharashtra province cotton is sown relatively late compared to other regions due to the frost free climate in the area. Here the cotton is harvested in January (Gopal & Srivastava, 2014). Thus the cotton cultivation season in Maharashtra starts and ends in January. The time range is also used for this project when weather data or volume data is analysed.

2.4.2. Cotton water demand in focus districts

The cotton water demand in the focus areas is 850 mm/m^2 per year according to Chapagain, Hoekstra, Savenije, and Gautam (2006). The total consumptive water use (538 mm/m^2/year) is the total sum of the artificial water (134 mm/m^2/year) use and the natural water use (405 mm/m^2/year) (Chapagain et al., 2006). Here "artificial" water use is defined as the water stored for later use (with the use of a reservoir for example), the "natural" water use, in this case, is the water directly irrigating a field from precipitation without storing it first. For cotton in Maharashtra it appears that the total water demand is higher than the consumptive water use, meaning there is a water shortage to sufficiently feed the cotton crops throughout the entire growing season. This results in a low(er) cotton yield. If the gap between the total water demand and the consumptive water use can be filled, the yield of the cotton will increase. One way to close the gap, is with the use of reservoirs to store water and increase the amount of artificial water .

Figure 2.10 shows both the water shortage as well as the cotton water demand. The water shortage is calculated from the water demand minus the amount of precipitation. The water demand is the highest after the monsoon season and the lowest right at the start of the monsoon season when the crops are just sown. The data is obtained from den Besten et al. (2016) and contains data over the year 2014.



(a) Water shortage

(b) Cotton water demand

Figure 2.10: Water shortage and cotton water demand for cotton crops in the Yavatmal district. The water shortage is only present after the monsoon, indicating that the amount of precipitation during the monsoon is sufficient to irrigate the cotton crops. Data obtained from den Besten et al. (2016) over the year 2014. Made by the author.

2.4.3. Current reservoir situation in the focus districts

Currently, there are reservoirs present in the focus districts. These structures are constructed between 2012 and today by construction companies within the area. Solidaridad reported over 900 structures within the regions of Yavatmal, Wardha, Nagpur and Amravati. However, none of these structures is documented by any governmental institute and thus no locations of these structures is known. Next to these unknown GPS coordinates, the majority of these structures do not collect any water due to unsuitable location of these structures as told by Solidaridad. Part of the goal of Solidaridad is to renovate these non working current structures and make them into working, water supplying reservoirs. To estimate the potential of a reservoir to be successfully renovated, the location of this reservoir has to be known. Chapter 3.2 describes how the locations of these current structures is determined.

3
Method

The method used to estimate hydrological favourable locations will be described in this chapter. It is of great importance to take into account the information regarding land cover and soil type given in chapter 2 since these features determine how and where the water in an area flows. The model used to establish the location is QSWAT. QSWAT is a plug-in for QGIS. The locations determined with QSWAT are tested with a Google Earth Engine (GEE) model to determine the suitability of a location. GEE determines the land cover a reservoir is placed on and is used to estimate whether a reservoir is located on a crop cover location or not. Next to the new locations, current locations are found via zoom.earth and examined using QSWAT's streamnetwork, a python model and GEE. The output of the examination of the current reservoirs will give insight into whether a location is collecting water, has the potential of collecting water with some (minor) adjustments (renovation) or cannot collect water in any way or with too many adjustments.

In this chapter, the QSWAT plug-in will be described including where the data for the model is obtained from. Secondly the validation of the current reservoirs is described. The third section deals with the validation of new potential structures done by GEE. The validation of proposed reservoir locations by Solidaridad with both QSWAT, GEE and python is explained in section 4. The last section describes the python model used to examine the suitability of current reservoir structures.

3.1. Implementation of QSWAT

QSWAT is a plug-in for the open source geographic information system QGIS. The handout to set-up the model can be found in Appendix B and are provided by UNESCO-IHE. QSWAT was chosen as hydrological method to obtain reservoir locations since it is easy to use once set up, the data necessary to run the model is accessible and for free, and the plug-in works via QGIS which creates visible results and is user friendly.

3.1.1. Data collection

Several data types are used for the QSWAT plug-in. The data necessary for the plug-in to run is a digital elevation map (DEM), landuse map, soil type map and weather data for the specific location. In this section all data sets will be explained. The weather data used for the set up of QSWAT is collected from https://swat.tamu.edu/data/, the DEM, land cover and soil type data are obtained from Bhuvan, Indian Geo-Platform of ISRO.

Digital elevation map (DEM) The DEM is obtained from the Indian Geo-Platform of ISRO (Bhuvan). Via the open data archive, one can obtain DEM data from the Cartosat mission. CartoDEM version-3 R1 is used to run the QSWAT plug-in for this research. The vertical resolution is between 3.6 meter - 4.4 meter and the horizontal resolution of the DEM is 10x10m which is suitable for this research since the reservoirs cannot be smaller than 10x10x4m and cannot be larger then 30x30x4m. This size limitation is a requirement given by the government. All reservoirs larger than 30x30x4m are not considered a small holder farmers' reservoir and therefore different rules and guidelines apply. Also the construction of reservoirs within these boundaries are (partly) funded by the government. Because of the reservoir size limitation, the 10 meter resolution of the DEM will give a proper and specific enough result on where the water will concentrate in the area.

The function of the DEM in the QSWAT model is to give significant information on elevation of the area. With this elevation map, the surface runoff of precipitation can be determined since water will flow from the highest to the lowest point in the area and follows the path of the least resistance (USGS, 2018). Surface runoff volume will be dominant compared to infiltration volume due to the soil composition previously described in paragraph 2.2.1. The path of the least resistance is in most cases formed by previous water runoff processes. The closer one will come to the sea, the more this path looks like a river since more water is collected from small channels, creeks and streams. However, on this small scale used for this project and due to the monsoon seasonality, the water path will not look like a constantly filled river or creek all year round. Since all the rivers are precipitation rivers, there is no constant flow of water throughout the year as described in section 2.3 and therefore a general river map will not give all the information on where the water concentrates in small channels and creeks during heavy rainfall. Smaller volumes of water do not appear in these river maps, hence a DEM is needed to estimate the paths of small volume surface runoff during precipitation events.

Land cover and soil type The land cover and soil type data of an area provide information on which types of land cover are present and what the soil composition is. Both features affect the water infiltration and runoff rate. The land cover data is obtained from https://land.copernicus.eu/global/products/lc and has a resolution of 100 meters horizontally. More technical details on what types are classified are described in paragraph 2.2.3. The soil data is collected from Bhuvan, Indian Geo-Platform of ISRO. The soil type map is classified according to the FAO-UNESCO Soil Map of the World (FAO/UNESCO, 2003). For this classification, three textural classes are recognized:

1. coarse: sands, loamy sands and sandy loams
2. medium: sandy loams, loams, sandy clay loams, silty loams, silt, silty clay loams and clay loams
3. fine: clay, silty clays, sandy clays and clay loams

The dominant soil type is determined for the upper 30 cm of the soil according to the textural classes. A soil can consist of two or three texture classes as long as the presence of the dominant soil for two texture classes is at least 50% and the presence of the dominant soil for three texture classes is at least 33%. As described in paragraph 2.2.1 the focus area is located on the Deccan Plateau which is composed of volcanic soils with a fine, clayey texture. Meaning the soil has an excellent water holding capacity and a slow infiltration rate thus more water will runoff via surface runoff (FAO, n.d.).

Weather data The weather data is obtained from https://globalweather.tamu.edu/. It contains locations of the weather stations in the area of choice. Of these weather stations the following daily data is present for a time frame between 1979 - 2014:

- precipitation amounts in mm
- wind velocity in m/s
- temperature in C
- relative humidity in %
- solar radiation in W/m^2

The weather data estimates the amount of water present to runoff during precipitation events and after these events. The model takes into account the amount of evaporation, transpiration and infiltration. The data is modelled over the weather station locations which are present in the area.

3.1.2. QSWAT model set-up

The QSWAT model is set-up and run in the QGIS application. For the exact guide on how to set up the model step by step Appendix B should be consulted. This paragraph briefly described how to set up the model, which assumptions are made and which thresholds are assumed at certain steps during the set-up. The thresholds assumed and assumptions made are explained for the main features in the model, the less important thresholds and assumptions can be found in Appendix B.

A QSWAT model set up flow chart can be found in 3.1. In this figure all steps are shown including the input and output features. The final output are the reservoir locations including latitude longitude coordinates, volume and inflow rates per time step.

Before the first step can be taken, all data should be downloaded from the different sources. Where the data can be found is described in the different paragraphs under section 3.1.1.

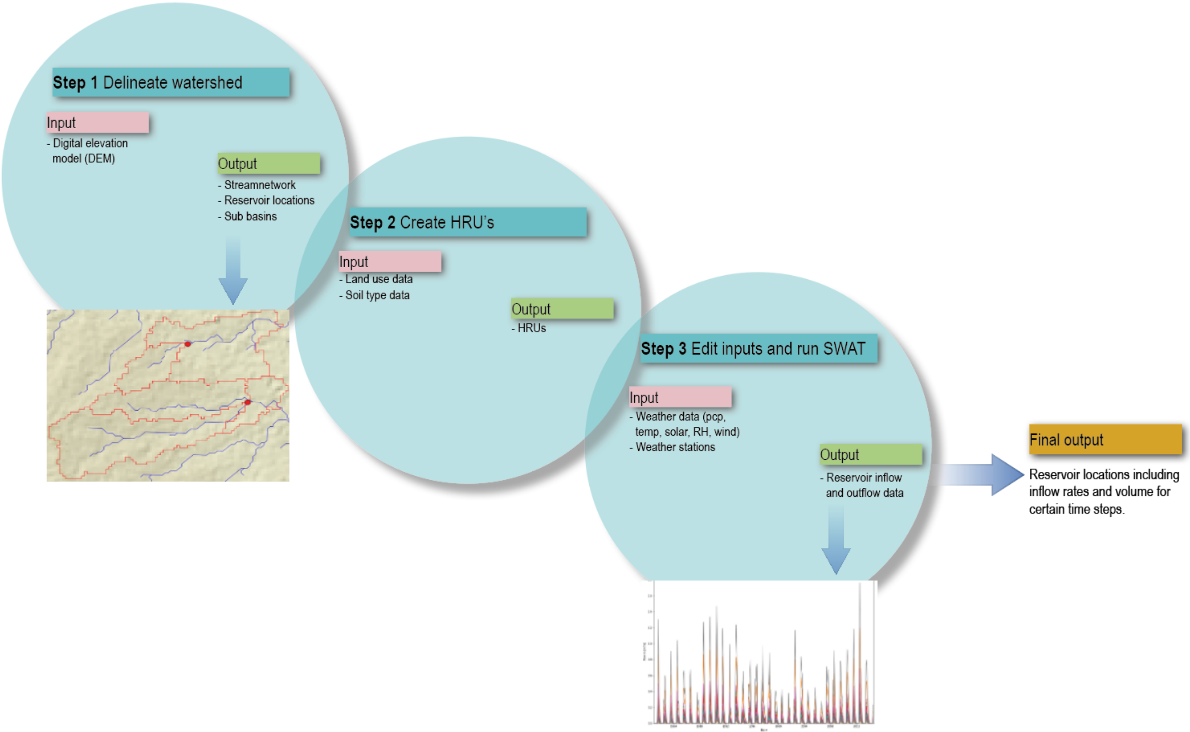


Figure 3.1: QSWAT flow chart including all major steps. Per step the input and output data is shown. The final output are reservoir locations including latitude longitude coordinates, volume and inflow rates per time step. Made by author.

Step 1 The first step in the model is to delineate the watershed. The end product of this step is a DEM of the desired area divided into sub-catchments which all contain one stream unless sub-catchments are merged manually. The DEM provides the stream network and creates the watershed with the information on the differences in height within the area. If the DEM obtained is too large for the area of interest, make sure to clip it first over to the extend of the vector layer of the area of interest. The DEM is loaded into the QSWAT model via the 'select DEM' option.

The next step is to create a stream network with the elevation data present in the DEM. The important feature in this step is the threshold of each gridcell. According to the QSWAT manual from Dile, Srinivasan, and George (2019) "the threshold is the number of cells required to form a channel or a stream: a cell will be made part of a channel or stream if it has at least the threshold number of cells draining into it". The smaller the threshold, the higher the stream density and the more streams appear in the outcome of the model. The advantage of such a small threshold is that even very small channels are taken into account and show up on the map. This is a big advantage for this project since the reservoirs have a small volume and the location of the reservoir can be matched better to the location of the farmer if the farmer's location is known. The disadvantage of such a small threshold is that the streams will not discharge enormous amounts of water, thus it is important to check the amount of water generated by these small streams individually to ensure enough water supply into the reservoir to provide a sufficient water supply for cotton irrigation.

After delineating the watershed, the option to merge sub basins appears. Depending on the size of the catchment and the amount of sub-basins present, one can choose to merge certain sub-basins. This can be done both manually as well as automatically. The automatic option provided in the model merges the sub-basins smaller then a certain percentage of the average sub-basin size. The larger the amount of sub-basins, the more time it takes for the model to run.

For this project, the sub-basins outside of the focus area were merged, together with small sub-basins up to 60% of the average basin size. For the current reservoir locations, all sub-basins outside the current reservoir sub-basin are merged. This increases the speed of the model to run.

In this first step one can also allocate reservoirs to certain subbasins. For this project reservoirs were first allocated on subbasins which had a label "hotspot" determined by the socio-hydrological model (van Wirdum et al., 2019). However, since that are not too many locations within the Ghatanji and Hinganghat block, also reservoirs are placed on other random subbasins. Once the model has run, the amount of water collected by these reservoirs is calculated. The reservoirs which did not collect enough water were taken out for the next run, the reservoirs which collected way too much water were split into multiple reservoirs by allocating reservoirs more upstream at smaller branches. Reservoirs are placed on branches of the main streams since the reservoirs cannot block the main stream due to governmental laws and regulations as well as negative impact on the ecology of the main stream. Also the main streams have a too large runoff volume for collecting water by these small reservoirs.

Step 2 The second step in the model is to create the hydrological response units (HRUs). For this step, the land cover and soil type files are imported. Before reading the land cover and soil type files, select for both the land cover table as well as the soil-use table the option "global_landuses" and "global_soils" to ensure the right classification for the land cover and soil type files. Next the 'Read' button is clicked and the land cover and soil type files are read into the model.

Now the HRUs can be created via different options:

- Dominant landuse, soil, slope
- Domanint HRU
- Filter by landuse, soil, slope
- Filter by area
- Target number of HRUs

For this project the option "Dominant landuse, soil, slope" is used. There appeared not much difference in the outcome for both the amount of HRUs and as well as type of HRU per sub-basin between the first three options. The fourth and fifth option are not considered since the area sizes differed too much and the target number of HRUs did not matter to the project. The "Dominant landuse, soil, slope" option was eventually chosen since it was the fastest compared to "Dominant HRU" and "Filter by landuse, soil, slope".

Step 3 In step 3 the weather data is imported to the model. First the weather stations of the focus area are clipped from the world weather data grid. The manual on how to clip the data from the world weather data provided by SWAT.tamu.edu can be found in Appendix B. Secondly this weather station data is imported in the Access file of the project as described in the guide. Once the weather stations are imported, one can proceed with setting up the QSWAT model. The first step is to "Write Input Tables". Choose the just imported weather station file as locations table in the weather generator data option. For all the other weather data input options the input data obtained from https://globalweather.tamu.edu/ should be implemented as follows:

Weather Data Definition	Corresponding Tamu weather data file
Rainfall Data	pcp.txt
Temperature Data	tmp.txt
Relative Humidity Data	rh.txt
Solar Radiation Data	solar.txt
Wind Speed Data	wind.txt

Table 3.1: Table showing corresponding Tamu weather files for Weather Data Definition input.

Once all data files are imported, click "ok" and the data is implemented in the model. Next "Write SWAT Database Tables", select all tables and click "Create Tables" to create the tables. Now via the "Edit SWAT Input" option the reservoir sizes can be set.

To run the simulation, go to the option "Setup and Run SWAT Model Simulation" under the "SWAT Simulation" option. Use the 64-bit, release option under SWAT.exe Version and select the preferred starting and ending date. For this project the start date is set on 1/1/2000 and the ending date on .../2014. No further data is available after this date. First "Setup SWAT RUN", if finished accordingly, "Run SWAT".

Once the model is run, the SWAT Output can be generated. For more information on how to create the SWAT Output files and how to access them, consult Appendix B.

3.1.3. Determining potential reservoir locations in QSWAT step1

Since a large amount of current structures is already present in both areas, the potential structures should be located on unique positions eliminating overlap between current and potential locations. For locating potential locations in QSWAT, first the current structures are added to the watershed. Then the new locations are placed first on hotspot areas without current locations and secondly on small streams without any current locations. The hotspot data resulting from the research of van Wirdum et al. (2019) was used for determining the areas where an increase in capital is most needed.

3.2. Validation of current reservoir structures

Within the four focus districts, over 900 current structures are present as described in section 2.4.3. However the majority of this structures is not in use as a reservoir simply because no water is collected in this reservoir due to dislocation of the reservoir meaning it is not connected to any water stream or surface runoff path. Nevertheless these structures are present and the potential to renovate these non-working structures should be investigated. For the investigation on why these structures are not collecting water, the location of the structures should be known so the distance to the nearest stream can be measured with a Python code. Once the distance from the location to the nearest stream is known, the land cover type can be determined. The land cover type gives insight on the position of the reservoir, this does not exclude if a location has potential, but it provides information on which locations are worth visiting for the final validation step. First the distance to the stream will determine if a reservoir has the potential to collect water based on the natural surface runoff paths. The locations for which doubts arise with respect to both distance to stream as well as land cover cannot be validated remotely and therefor need a field visit to estimate if renovation is an option. However, when a location is positioned on a land cover with very little (less than 30%) crop cover, this location does not have the priority to visit since the amount of agricultural land is very limited.

In this section, first the method of determining these current structures is explained in paragraph 3.2.1. Secondly in paragraph 3.2.2 information is given on the distinction between working and non-working reservoirs and to what extend this distinction can be done.

3.2.1. zoom.earth satellite imagery to detect current reservoir structures

To collect the locations of the current reservoirs, `https://zoom.earth/` is used. The websites provides two time-frames of satellite imagery data: the first time-frame is the average figure between 2011 and 2017, the second time-frame is taken between December 2018 en February 2019 and differs per area. The difference in time frame per area is due to the satellite orbital and swath. The *swath* of a satellite is the horizontal scanning range which a satellite can view within the same time frame. Since the swath is never the range of the entire earth, a satellite moves around the earth in a path called *orbit*. Due to both the orbit and the swath of a satellite, different areas are figured on different times. These features result in the different data time frame range.

For the allocation of the current reservoir structures, these two data sets are compared to determine changes in the area and estimate (new) current reservoirs. Figure 3.3 shows a clear change in the composition of the area between the two time-frames. The more recent figure obtained in November 2018 clearly shows four squared structures which do not appear in figure 3.3a. Together with the figures in figure 3.2 it can be concluded that these structures present in figure 3.3b are constructed reservoirs.

(a) Reservoir structure not in use concluded by the amount of vegetation and water present in the reservoir.

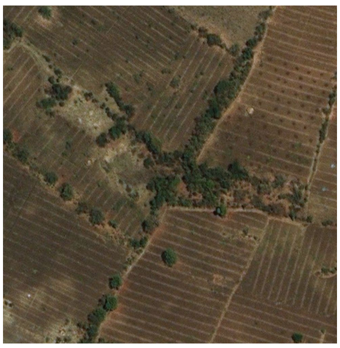
(b) Reservoir structure filled with water for irrigation. Reservoir is a working structure assumed by the amount of water present in the reservoir.

Figure 3.2: Two reservoir structures: one in use (b), one not in use (a). Both pictures are taken by TU Delft MDP group during their visit to the area for their project, summer 2019.

(a) Satellite imagery of the area between January 2011 and February 2015 showing no squared reservoir structures on any of the fields.

(b) Satellite imagery of the same area as figure (a) showing four squared reservoir structures located on (crop)fields. figure is obtained in November 2018.

Figure 3.3: Two images of the same area processed via satellite imagery showing the change in structures in the area. figure (b) shows a clear change in amount of reservoir structures present within this area compared to figure (a). Obtained from zoom.earth by author.



(a) figure of the area taken between January 2011 and February 2015.

(b) figure of the area taken in November 2018 showing a reservoir construction.

(c) Measuring the size of the reservoir to check if it is within the boundary conditions.

Figure 3.4: Classification of a reservoir structure in figure 3.4a and 3.4b. Size measurement of this reservoir location to check size boundaries in 3.4c. The size should not be smaller then 10x10m and not larger then 30x30m. If not, the object is classified as a current reservoir structure.

The last check in determining if a construction is a reservoir is a size check. The reservoirs cannot be larger then 30x30 meter and not be smaller then 10x10 meter. Zoom.earth provides a measuring tool with which all potential current reservoir structures can be measured. Objects within this range are classified as *current reservoir structures*. Figure 3.4 shows the measuring technique of one of the reservoirs, here it can clearly be seen that the reservoir is within the size range.

3.2.2. Distinction between working and non-working current reservoir structures

The distinction between working and non-working current reservoir structures cannot be done via satellite imagery unless figures are available for the time just after the monsoon. The monsoon will provide large amounts of precipitation and thus large amounts of discharge which will partly end up in these reservoir structures if they are functioning. If the reservoir is not in function and is dislocated, water will not be discharged in the reservoir. Unfortunately this data is not available for a recent year with a high enough resolution (at least 30 meters horizontally).

Hence, a Python script is used to evaluate which of the reservoirs are located on or near a stream line delineated with the QSWAT model. Appendix C shows the python code for calculating the distance between a reservoir and nearest stream location. It is assumed that all locations located on a streamline are collecting water. Next to these locations, constructions located within 200 meters of a stream line are assumed to collect water. Over this distance water can easily be transported with a small adjustment, such as a ditch or channel from the stream line to the reservoir.

The equation used for calculating the nearest distance between a reservoir and a stream line is based on the Euclidean distance method. This method can be used since the coordinates are in coordinate reference system WSG 84 (authority ID is EPSG:4326). The formula used is the following:

$$NearestDistance = \sqrt{(R_{lat} - S_{lat})^2 + (R_{long} + S_{long})^2} \tag{3.1}$$

Where R is the reservoir coordinate and S is the stream coordinate. For a fixed reservoir coordinate, the code checks all the stream coordinates and determines which coordinate is the closest to the fixed reservoir coordinate.

Since the stream line shapefile from QGIS does not contain any latitude longitude information, the stream line file is converted to a stream point file with SAGA's "convert line to points" tool. In figure 3.5 the original stream line (blue line) is shown together with the corresponding stream point network (red dots). The stream points are created with a distance of 1 meter in between every point which is sufficiently accurate for determining the nearest distance between a reservoir and a stream.

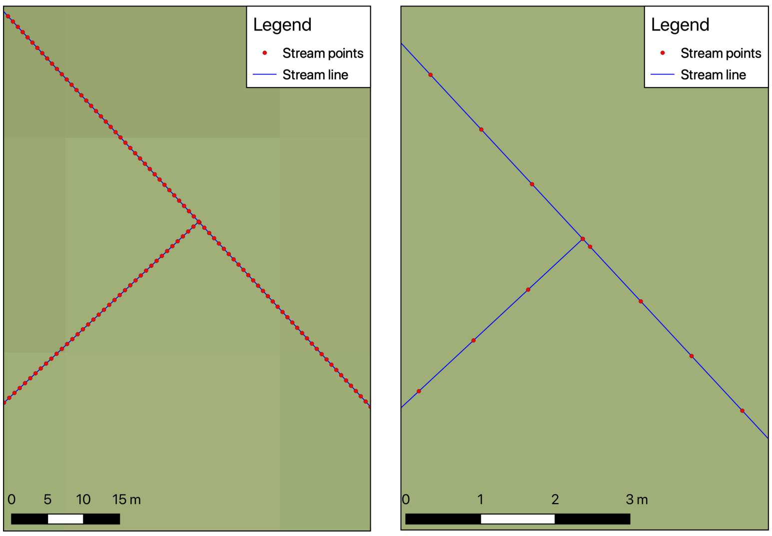


Figure 3.5: Stream points and stream line of the same stream of two different scales showing the distance between every stream point. The distance between stream points is 1 meter. Made by author.

3.3. Validation of new potential structures by Google Earth Engine

Google Earth Engine (GEE) is a relatively new online tool used for analyzing and visualizing geospatial information (*FAQ – Google Earth Engine*, n.d.). All Landsat, Sentinel and other satellite data is available within the tool, making it easy accessible and user friendly to work with. The coding is done with JavaScript and there are multiple examples available within the tool to get you started. For this project, GEE is used to estimate whether a current or potential reservoir location is located on an agricultural plot or not.

The data used for this analysis, is the Copernicus Global Land Cover data set provided by the Copernicus Global Land Service (CGLS). This data set contains information on the fraction of land cover type within a pixel. The pixels are of a 100x100 meter resolution and contain information on several landcover types:

- forest_type: Forest type for all pixels with tree percentage vegetation cover bigger than 1%
- bare-coverfraction: Percent vegetation cover for bare-sparse-vegetation land cover class
- crops-coverfraction: Percent vegetation cover for cropland land cover class
- grass-coverfraction: Percent vegetation cover for herbaceous vegetation land cover class
- moss-coverfraction: Percent vegetation cover for moss and lichen land cover class
- shrub-coverfraction: Percent vegetation cover for shrubland land cover class
- tree-coverfraction: Percent vegetation cover for forest land cover class
- snow-coverfraction: Percent ground cover for snow and ice land cover class
- urban-coverfraction: Percent ground cover for built-up land cover class
- water-permanent-coverfraction: Percent ground cover for permanent water land cover class
- water-seasonal-coverfraction: Percent ground cover for seasonal water land cover class

The data is obtained over the period 2015-2019 and can be set to the year of preference, which results in a very recent data set. The combination of both the recent data as well as the 100 m time-series derived from the PROBA-V creates an accuracy of 80% over the data set (Buchhorn, Bertels, Smets, Lesiv, & Wur, 2017). For this project, the data set of 2019 is used since it contains the most recent information on the ground composition.

The code used in GEE for obtaining the land cover data per reservoir can be found in Appendix D. With this model the land cover per pixel where a reservoir is located on is determined. The fraction per land cover for this specific reservoir location is then added to the reservoir table. This table is then exported as a csv file and read in a python script which can be found in Appendix E. The python code sets certain fraction thresholds which can be adjusted to any preferred fraction value. This threshold determines if a pixel is suitable for constructing a reservoir on this location. Suitable pixels are those characterized with at least 30% crop cover fraction provided the urban fraction is below 25%.

3.4. Validation of proposed reservoir locations by Solidaridad

Solidaridad constructed 29 reservoirs mid-July for farmers who requested a reservoir structure for cotton irrigation. Nonetheless it is important to determine the potential of these structures for both water collection as well as capital increase and yield improvement. To estimate if a reservoir could collect water, it is checked with both the Python code for nearest distance as well as the GEE code for land cover classification. The data containing the water volume per reservoir location are run through the socio-hydrological model to determine the capital and yield improvements of the locations.

3.5. Deliverable to Solidaridad

This master thesis project aims to provide suitable and sustainable reservoir locations to Solidaridad for the case study regions Ghatanji block and Hinganghat block. It will therefore deliver 1500 locations including both potential new locations as well as potential renovatable locations. However, for the long term usage of the results of this project it is important to provide an user-friendly and easy accessible deliverable to Solidaridad with which they can determine reservoir locations throughout the Maharashtra state. This is necessary since Solidaridad has the ambition to construct a large amount of reservoirs to collect 14.5 million m^3 of water with all new and renovated constructions together.

As discussed with Solidaridad, this project will provide a stream point file of all sub areas throughout the four focus districts Amravati, Yavatmal, Nagpur and Wardha together with an easy to use python code. The python code is based on the nearest distance code described in paragraph 3.2.2 but easier to use since it can already run on one latitude longitude combination. The code measures the distance to the nearest stream of a proposed reservoir location and reveal the coordinates of the nearest stream. The stream network will be tested on worst case, average and best case rainfall events and will contain all streams discharging sufficient water volume to fill a reservoir construction of 200m^3. This volume is based on the reservoir volumes constructed by Solidaridad in July 2020. A person assigned by Solidaridad will be trained on how to use the code and read the output of the code. Also a manual on the code will be provided as a handout for future use. The code can be found in Appendix F.

3.6. Connection between hydrological model and socio-hydrological model

It is important to describe and understand the connection between the hydrological model described in this thesis and the socio-hydrological model improved by Dennis Djohan for the Solidaridad project. When both models are used optimally and if they are connected, the most beneficial location of a reservoir structure can be determined. An ideal location fulfills the requirement of gathering enough water to build a reservoir of maximum 3000m^3 and minimum 200m^3, while at the same time presents a cotton farmer with very low yield and capital, whose production can benefit the most from the construction of such a reservoir. A flowchart of the hybrid model is shown in figure 3.6.

For the hydrological model the QSWAT plug in is used. The input data for this model are elevation data, land cover and soil data and weather data containing precipitation, temperature, relative humidity, solar radiation and wind velocity. Furthermore as additional data, the hotspot locations determined in the baseline report collected by van Wirdum et al. (2019) are used as starting data. Once the QSWAT model determines the best possible location with respect to water volume, the reservoir location together with the reservoir volume is used as input data for the socio-hydrological model. Next to the output data form the QSWAT model, the model uses weather data (precipitation and temperature data) and the socio-economic characteristics (SEC) of the survey data. The output of the socio-hydrological model is the farmer benefit and contains both the increase in cotton yield as well as increase in capital. The locations with low benefit are examined to determine the reason why the benefit is low. If the reason for a low benefit is the water volume, the location is examined again with the use of QSWAT to find a better location with a larger water suply. For more information on how the socio-hydrological model is set-up and run, please contact Dennis Djohan, Saket Pande or consult https://repository.tudelft.nl/islandora/search/?collection=education. A short summary of his thesis can be found in Appendix A.

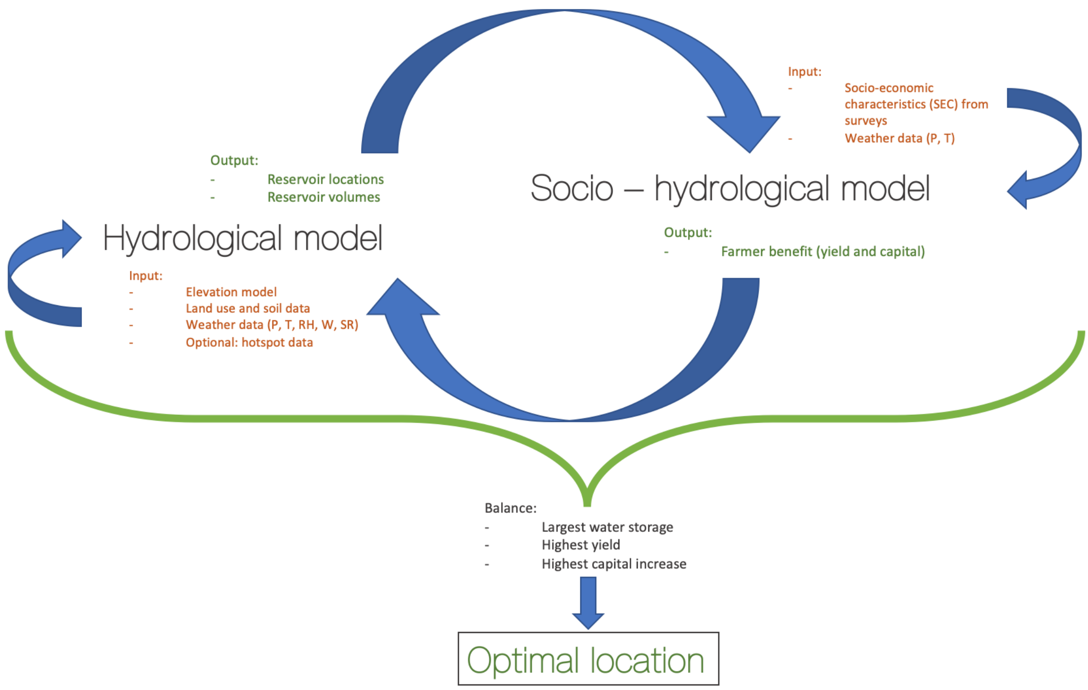


Figure 3.6: Connection between hydrological model and socio-hydrological model. For both models the input data and the output data is shown. The optimal location is defined when the balance between largest storage, highest yield and highest capital increase is met. Made by author.

4

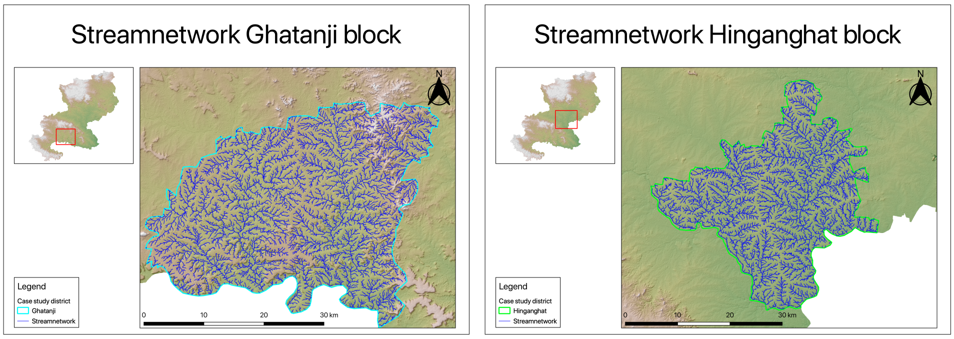
Results

The reservoir locations obtained by the QSWAT method as described in chapter 3 are discussed in this results chapter. The validation of the results was first planned to be in the form of a field visit to the locations in the focus districts. However, due to the unexpected pandemic, this was off the table and another validation solution had to be found. It was decided to validate the results obtained by QSWAT with remote sensing data and remote data based tools. The Ghatanji block and Hinganghat block serve as case study areas for both determining new potential reservoir locations as well as finding current locations and estimating the potential to rejuvenate those. The goal was to obtain 1500 reservoir locations including both new locations as well as current locations with the potential to store water once rejuvenated.

Section 4.2 describes the results of the QSWAT model and validation techniques used to verify the suitability of potential new locations. The second section 4.3 elaborates on the position of the current locations and the potential of these current structures is determined with the use of both the python code described in appendixC as well as the GEE code for land cover classification described in 3.3. Section 4.4 reviews the locations constructed by Solidaridad over the summer of 2020 by also using both the nearest distance python code as well as the GEE land cover classification model. However, to obtain the results for both the new locations as well as the current locations, first a stream network of the case study areas was delineated which is explained in section 4.1.

4.1. Stream network delineation

First the stream networks of the case study areas Ghatanji block and Hinganghat block were delineated to observe how the water flows in the area during precipitation events. This stream network was needed to determine new potential reservoir locations, and at the same time was used to estimate the potential of current structures. The stream network is obtained with a threshold of 0.2 km^2 meaning that for roughly every 0.2 km^2 a sub-basin is created. This threshold is considered high and was chosen because the amount of water a reservoir potentially can store is maximum 3000 m^3 and a reservoir has a maximum area of 900m^2 which is 0.45% of the threshold area. However, the majority of the reservoirs constructed during July 2020 have a volume of maximum 200 m^3. As a result an intensive stream network was delineated where all the minor streams, creeks and channels appear on. Furthermore it was assumed that all water flows in the direction of the south or south east towards the Indian ocean. Nevertheless, QSWAT determines the flow direction of a particular stream and gives an error when an outlet is placed on the upstream side of a stream. The outlets are all located on the borders of the case study area to ensure coverage by a stream network throughout the entire area. From figure 4.1 it can be observed that both areas are covered by a dense stream network. In this stage it is however unknown how much water is discharged per stream. For the deliverable to Solidaridad a stream network of all four focus districts was created with the same threshold as the ones for the case study areas. This was then exported to a stream point csv including the latitude and longitude coordinates of each point. These files are stored on the Github `https://github.com/Jente77/Hydrological_model`.



(a) Streamnetwork Ghatanji block. (b) Streamnetwork Hinganghat block.

Figure 4.1: Stream network of the case study areas Ghatanji block (left) and Hinganghat block (right). Here it can be observed how the water flows during precipitation events. These stream networks are used to estimate the reservoir locations and to investigate the potential of renovating current reservoirs. Made by author with QSWAT.

4.2. New reservoirs

New reservoir locations are obtained with QSWAT. An explanation on how these locations are established can be found in chapter 3. In this section first the modelled potential new reservoir locations by QSWAT are investigated determining the water suitability of a location. Secondly the potential locations are run through the GEE code to estimate the land cover fraction of a location. With this land cover classification it can then be remotely determined if a location is on a suitable location with respect to its ground position. QSWAT eliminates all locations not collecting sufficient amount of water to fill a reservoir. GEE eliminates all locations located on a too little crop cover fraction (less than 30%) or a too large urban cover fraction (more than 25%).

4.2.1. Validation of QSWAT results

The validation of reservoir locations established with the QSWAT model is of great importance. If these reservoir locations in the Ghatanji block and Hinganghat block are well placed in terms of water runoff, water collection and land cover classification, and socio-economic factors, the models can be used for the entire Maharashtra province as aspired by Solidaridad. The validation of these locations to determine if they are suitable to construct a reservoir is done with the following remote sensing data:

- Land cover data: what type of land cover is present on the plot where the reservoir is located?
- Comparison with the socio-hydrological model: is the location of the reservoir on a hotspot or close to a hotspot? How large is the benefit of each reservoir for the farmer in the area.

Water inflow into potential reservoir locations

First of all, all potential locations are modelled on a stream line, meaning that water is flowing in. The amount of water flowing into the reservoir is determined with the QSWAT model. The locations are established based on a trial and error process meaning that during the first run, the inflow volumes of each reservoir are carefully examined. When the volumes are too high, the reservoir collects more water then necessary thus can be split into multiple reservoirs by moving the reservoirs more upstream and onto smaller stream lines. When the volume is too little, the reservoir does not collect sufficient water to fill the reservoir and thus has to be placed more downstream. The minimum reservoir capacity is 200 m^3, meaning that the inflow during the monsoon should be able to at least provide 200 m^3 water into the reservoir. This value is based on the reservoir volumes constructed by Solidaridad over the summer of 2020. The maximum reservoir capacity is 3000 m^3 since this is the maximum volume a reservoir of 30x30x4m can hold. The inflow time starts during the monsoon season and lasts until either the storage capacity of the reservoir is met or until the runoff path dries up.

4.2.2. Potential locations Ghatanji

The potential locations in the Ghatanji block provided by QSWAT are examined with the use of QSWAT, GEE, python and the socio-hydrological model. In this paragraph the results of all four validation steps are observed and analysed. The last paragraph provides a small summary on the described results for the potential locations in the Ghatanji block.

Note: the reservoir numbers are not given in each graph since this creates very cluttered graphs. All the volumes and corresponding reservoir numbers can be found on the Github. In appendix [add ref] the reservoir details of the excluded reservoirs can be found.

QSWAT: analysis of reservoir inflow volume

The QSWAT model established 352 reservoir locations with an unlimited volume based on the stream network for the Ghatanji block. The resulting inflow per reservoir location from 1981 to 2014 is shown in figure 4.2. From this figure, the average, worst and best case scenario are determined according to the worst, best and average monsoon season. These monsoon seasons are used to check which reservoirs have the ability to collect enough water for small holder cotton irrigation. The average year is 2008, the worst year is 2006 and the best year is 2012.

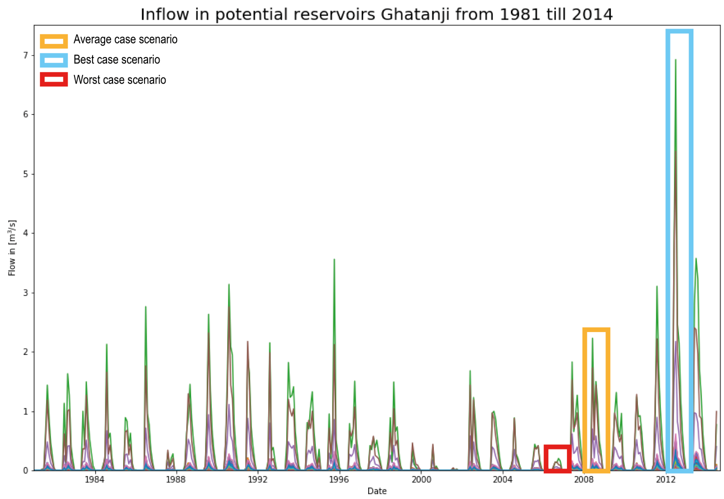


Figure 4.2: Inflow in potential reservoirs in Ghatanji block from 1981 till 2014. The graph gives insight in the amount of precipitation occurring every year per reservoir. Each color presents a different reservoir number. For further analysis of the suitability of the reservoir locations, 2006 is chosen as worst case scenario. 2008 as average case scenario and 2012 as best case scenario. Made by author.

QSWAT provides the cumulative volumes per reservoir starting from 1981. To determine if a reservoir can collect enough water for every scenario, it was assumed that the reservoir was empty at the start of the monsoon season. The data is plotted for one year starting in January and ending in January the next year since this is the month were cotton will be harvested in Maharashtra so therefore after January no water storage is necessary for cotton irrigation as described in paragraph 2.4.1. The minimum storage capacity of a reservoir is 200m^3 and the maximum reservoir storage capacity is 3000m^3 as explained previously. The starting point is that a reservoir can fill up to at least 200m^3 during the average monsoon season of 2008.

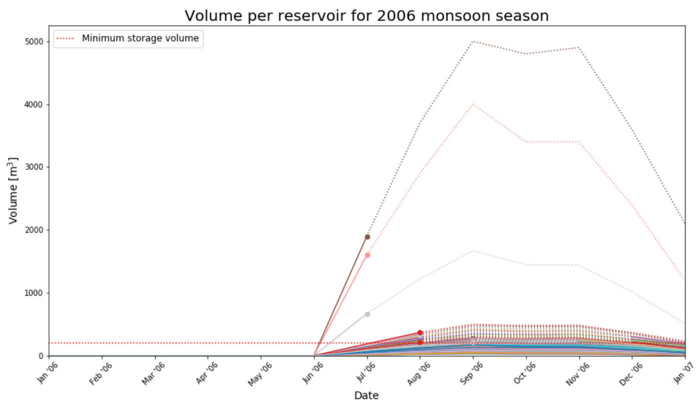


Figure 4.3: Monsoon season of 2006 showing a worst case scenario with very low precipitation. 239 locations do not have the ability to collect 200m^3 water during this worst case scenario. 2 locations have the potential to collect over 3000m^3 water. One location is out of the range of the average reservoir volume, but collects less than 3000m^3. Made by author.

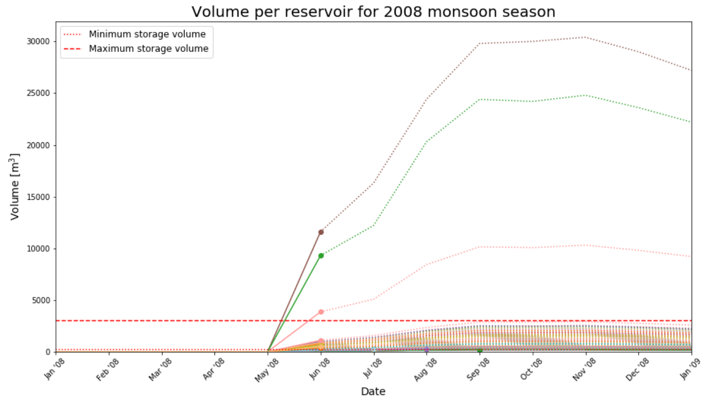


Figure 4.4: Monsoon season of 2008 showing an average scenario including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. The majority of the reservoirs can collect the minimum amount of water. 3 locations can collect over 3000m^3 water and 3 locations collect less than 200m^3 water. Made by author.

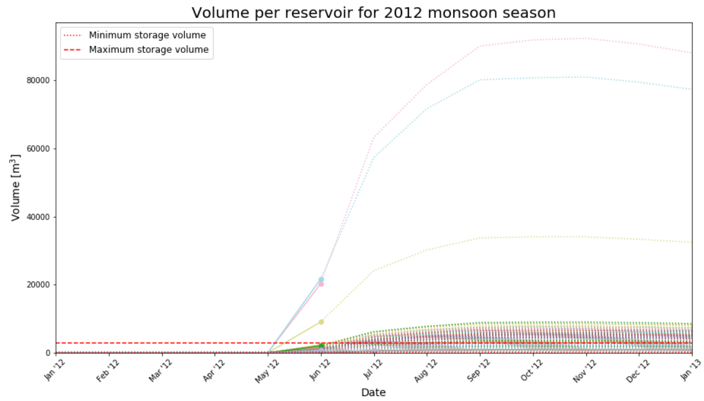


Figure 4.5: Monsoon season of 2012 showing the best case scenario including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. The majority of the reservoirs can collect the maximum amount of water, all locations can collect 200m^3 water. Made by author.

Analysis of the different scenarios from figures 4.3, 4.4 and 4.5 results in the rejection of several reservoirs. Since a reservoir should be able to collect the minimum amount of water during an average season, three reservoirs are excluded from the potential reservoir locations. Furthermore, it can be observed that three reservoirs have a very large volume exceeding the maximum volume during the 2008 season, even two of these reservoirs exclude the maximum storage capacity during the low monsoon scenario. These three reservoirs were excluded from the data set for the next validation techniques. Reducing the data set by these 6 reservoirs results in figures 4.6, 4.7 and 4.8.

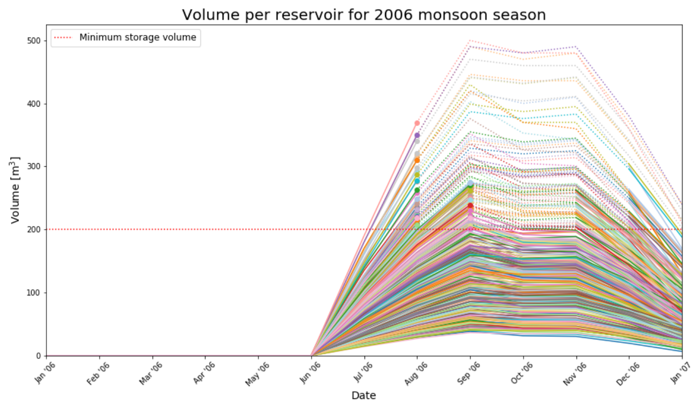


Figure 4.6: Monsoon season of 2006 showing the worst case scenario after reducing reservoirs including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. The majority of the reservoirs can collect 200m^3 water. Made by author.

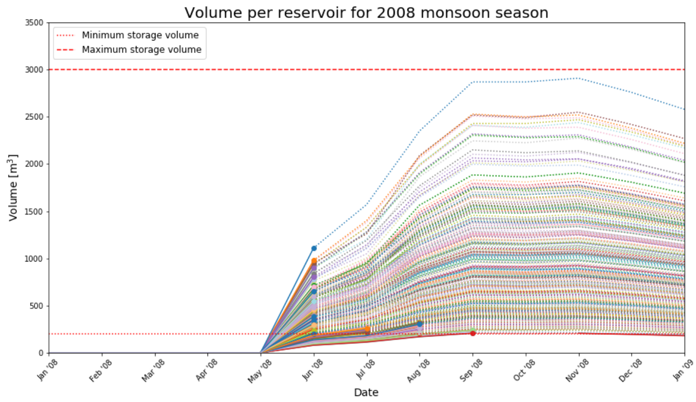


Figure 4.7: Monsoon season of 2008 showing the average case scenario after reducing reservoirs including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. All locations can collect 200m^3 water. Made by author.

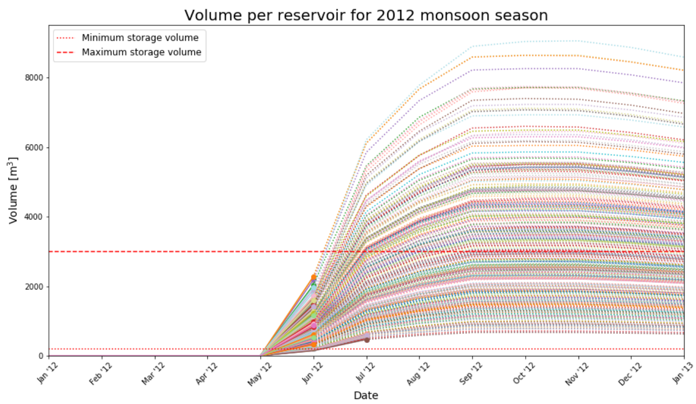


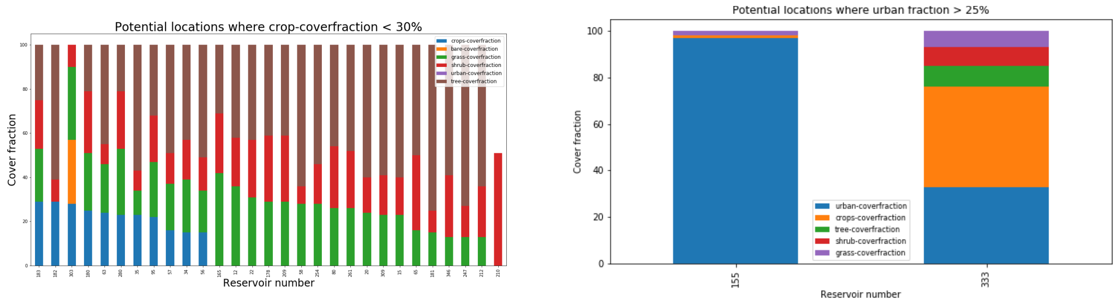
Figure 4.8: Monsoon season of 2012 showing the best case scenario after reducing reservoirs including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. The majority of the reservoirs can still collect the maximum amount of water, all locations can collect 200m^3 water. Made by author.

GEE: land cover classification analysis of reservoir locations

In this paragraph the results on land cover per potential location will be discussed. For the complete overview of land cover for each reservoir, please consult Appendix G.1. In this paragraph only the locations which have a low crop cover or high urban cover are discussed. Since all locations with a crop coverage of more than 30% are estimated to be on a sufficient location when it comes to ground position.

Figure 4.9 shows both the locations with crop coverage less than 30% as well as the locations with an urban coverage of more than 25%. Graph 4.9a shows 29 locations with a crop coverage of less than 30%. Even 18 locations do not contain any crop coverage at all. Meaning that on these 18 locations, one can assume no agricultural practices are present and thus no reservoir is needed on these locations. Therefore the locations with no crop cover fraction are eliminated from the potential locations. The 11 locations with some crop cover fraction need a field visit to estimate if a reservoir is needed on these locations and if the location is sufficient in therms of coverage.

Figure 4.9b shows the two locations with an urban fraction of more than 25%. These locations do not need a field visit for further investigation and are excluded from the potential reservoir locations.



(a) Not suitable locations in Ghatanji based on crop cover. The crop cover fraction is below 30% of the total cover fraction.

(b) Not suitable locations in Ghatanji based on urban cover. The urban cover fraction is above 25% of the total cover fraction.

Figure 4.9: Not suitable locations in Ghatanji block due to a too little crop cover fraction or a too large urban cover fraction. Made by author.

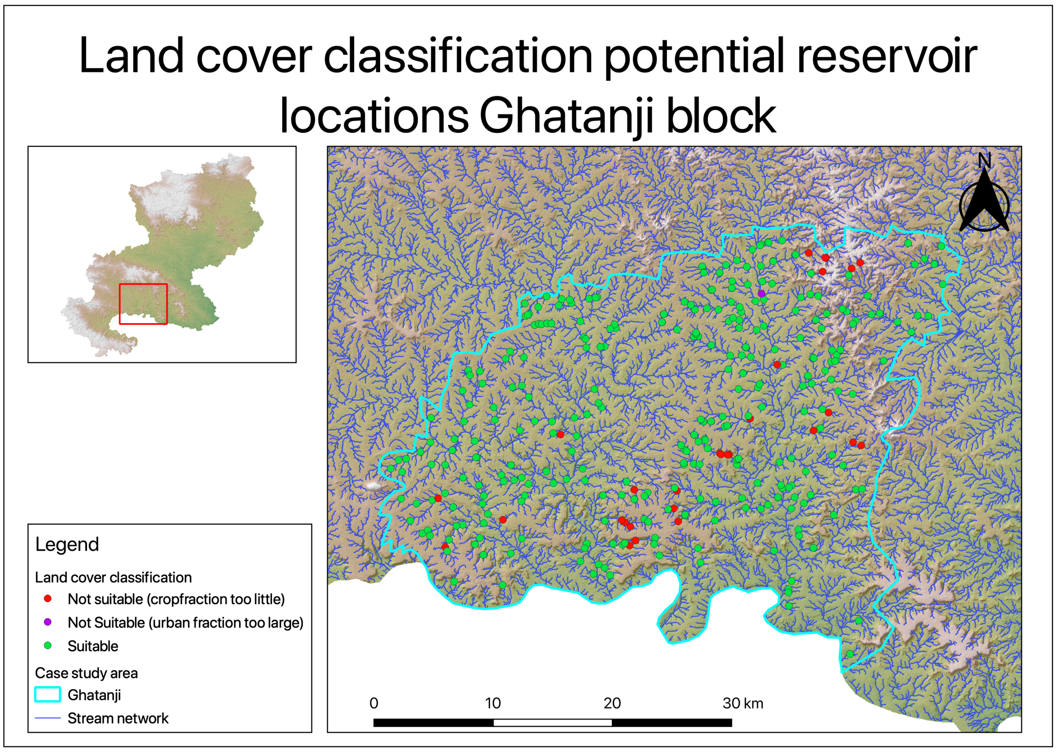


Figure 4.10: Land cover classification per reservoir location. Made by author

Socio-hydrological analysis of potential reservoir locations

The last validation step is the check of yield and benefit increase with the use of the socio-hydrological model described in section 3.6. The resulting graphs per reservoir location of the socio-hydrological model can be found in Appendix H.1. The increase in both yield and benefit is influenced by the socio-economic factors of a farmer and the volume of water in the reservoir.

It can be observed from figure 5.1 that the majority of the reservoirs has an increase of less than 200 kg/ha/y. Part of the reservoirs has an increase of more than 200 kg/ha/y. The largest yield increase is 450 kg/ha/y. Figure 4.12 shows the increase per reservoir per category. The darker the red, the lower the yield increase, the darker the green, the higher the yield increase. The larger the increase in yield, the better the location. This increase depends not only on the water availability, but also on the socio-economical factors discussed by D. Djohan. The increase in yield is distributed evenly over the area. There are no specific areas where the increase is low or high compared to other areas.

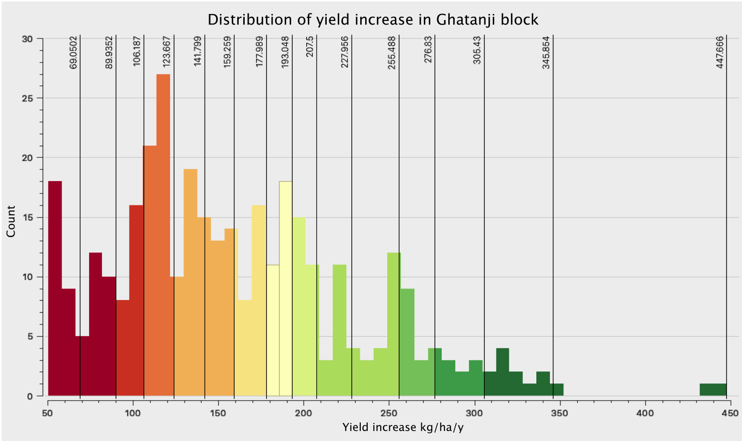


Figure 4.11: Yield distribution in the Ghatanji block. The majority of the reservoirs has a yield increase of less than 200 kg/ha/y. There are reservoirs with an increase of more than 200 kg/ha/y. Made by author

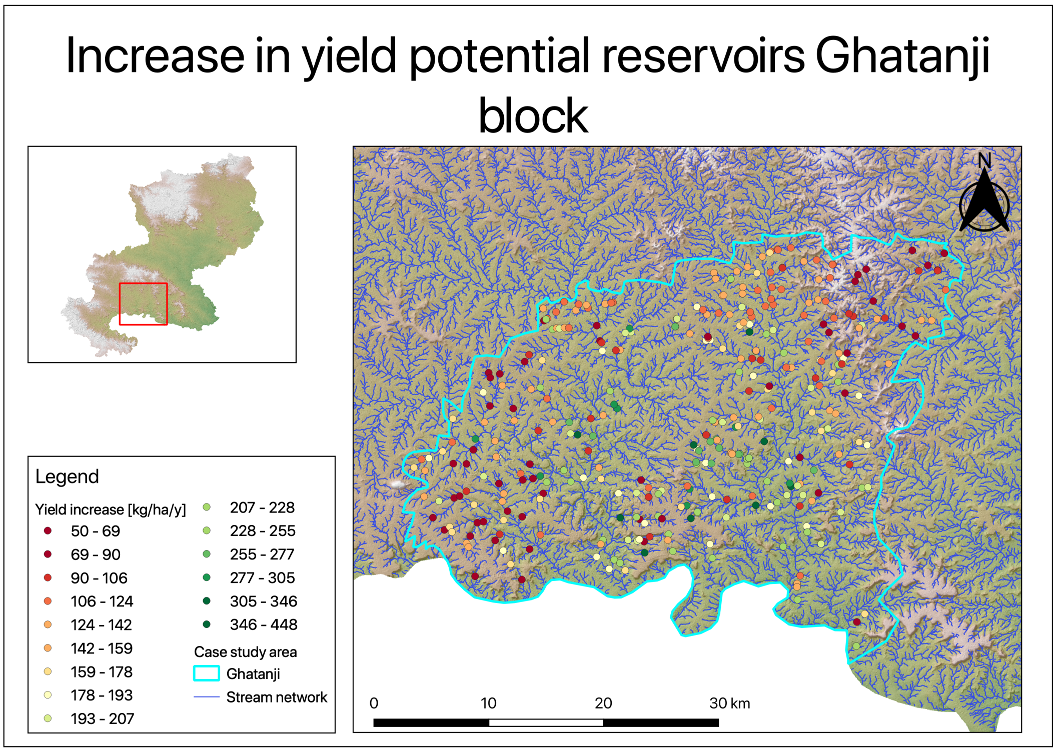


Figure 4.12: Increase in yield per reservoir in kg per hectare per year. The darker the red, the lower the increase in yield, the darker the green the higher the increase in yield. Made by author.

Summary of potential reservoir locations Ghatanji block

With QSWAT 352 potential reservoir locations were identified. After analysing the volumes and inflow rates of each reservoir, six reservoirs were eliminated because the volume is exceeding the maximum capacity or is lower than the minimum capacity of a reservoir during the average monsoon scenario. Out of these 349 reservoirs, 11 potential locations need a field visit to estimate the suitability of the location. This is due to the land cover type mix of the selected location, which contains less than 30% crop coverage. Furthermore, 18 locations were eliminated due to the absence of crop cover, two locations were eliminated since the percentage of urban cover of the identified locations exceeded 25%. The remaining reservoirs have a very high potential when it comes to the increase in both yield and benefit.

4.2.3. Potential locations Hinganghat

The potential locations in the Hinganghat block provided by QSWAT are examined with the use of QSWAT, GEE, python and the socio-hydrological model. In this paragraph the results of all four validation steps are observed and analysed. The last paragraph provides a small summary on the described results for the potential locations in the Hinganghat block.

QSWAT: analysis of reservoir inflow volume

For the Hinganghat block in the first QSWAT run 358 reservoirs with an unlimited volume were estimated based on the stream network. The resulting inflow per reservoir is shown in figure 4.13. From this graph the worst, average and best case scenarios are determined according to the worst, average and best monsoon season. The worst case scenario is 2006, average case is 2008 and best case is 2012.

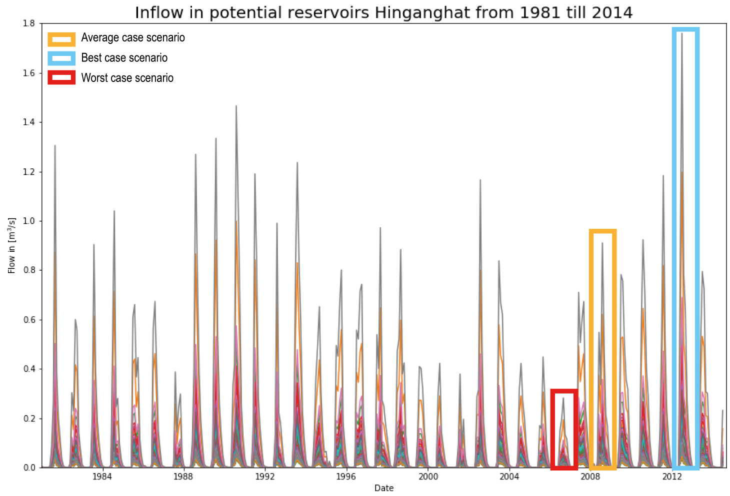


Figure 4.13: Inflow in potential reservoirs in Hinganghat block between 1981 and 2014. The graph gives insight in the amount of precipitation occurring every year per reservoir. Each color presents a different reservoir number. For further analysis of the suitability of the reservoir locations, 2006 is chosen as worst case scenario. 2008 as average case scenario and 2013 as best case scenario. Made by author.

QSWAT provides the cumulative volumes per reservoir starting from 1981. To determine if a reservoir can collect enough water for every scenario, it was assumed that the reservoir was empty at the start of the monsoon season. The data is plotted for one year starting in January and ending in January the next year since this is the month were cotton will be harvested in Maharashtra so therefore after January no water storage is necessary for cotton irrigation as described in paragraph 2.4.1. The minimum storage volume of a reservoir is 200m^3 and the maximum reservoir storage capacity is 3000m^3 as explained in. The starting point is that a reservoir can fill up to at least 200m^3 during the average monsoon season of 2008.

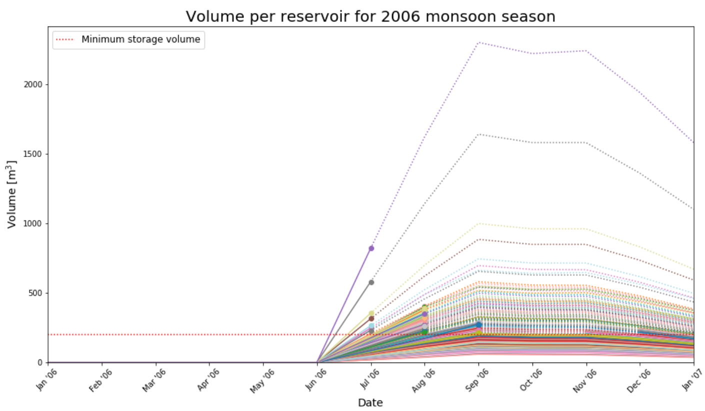


Figure 4.14: Monsoon season of 2006 showing a worst case scenario with very low precipitation. 197 locations do not have the ability to collect 200m^3 water during this worst case scenario. No locations have the potential to collect over 3000m^3 water. Made by author.

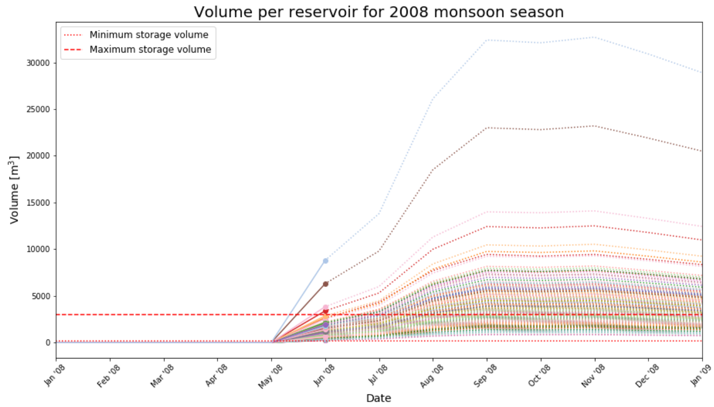


Figure 4.15: Monsoon season of 2008 showing an average scenario including the minimum and maximum storage capacities of a potential reservoir in Ghatanji block. The majority of the reservoirs can collect the maximum amount of water. No reservoirs collect less than 200m^3 water. Made by author.

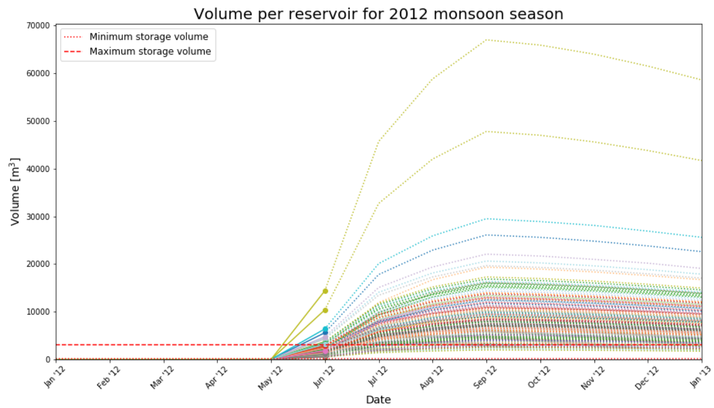


Figure 4.16: Monsoon season of 2012 showing the best case scenario including the minimum and maximum storage capacities of a potential reservoir in Hinganghat block. The majority of the reservoirs can collect the maximum amount of water, all locations can collect 200m^3 water. Made by author.

Analysis of the different scenarios from figures 4.14, 4.15 and 4.16 results in the exclusion of several reservoirs. No reservoir collects less than 200m^3 during the average scenario, meaning that no reservoir is excluded based on the minimum volume threshold. Furthermore, it can be observed that no reservoirs exceed the maximum reservoir capacity during the worst case scenario. A large number of reservoirs exceed the maximum storage capacity for the average case. Nonetheless, not all these reservoirs are excluded from the data set. It was chosen to exclude reservoirs with a larger maximum volume of 8000m^3. This value still exceeds the maximum storage capacity, but all the water not stored in the reservoir, will runoff downstream to supply water to other areas. A volume of 8000m^3 was chosen since a boundary had to be set. This results in the termination of 9 reservoirs.

Reducing the data set by these 9 reservoirs results in figures 4.17, 4.18 and 4.19. From these figures the volumes per reservoir location can be observed clearly. From these graphs it can be observed that all reservoirs have the ability to collect at least 200m^3 water during an average monsoon season. During the best case scenario, all reservoirs have the potential to store 3000m^3. For the worst case scenario, 197 locations do not have the ability to store at least 200m^3.

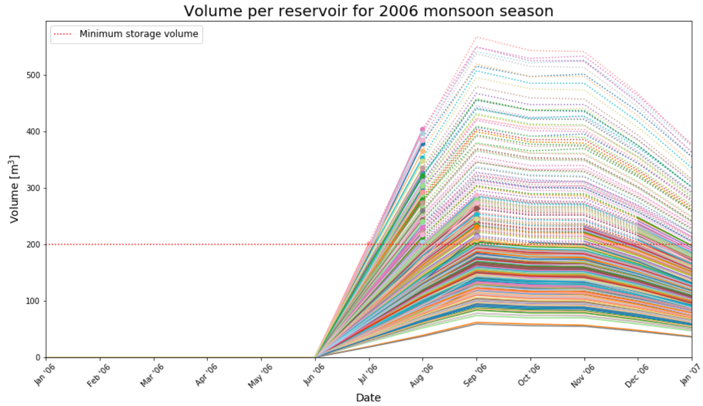


Figure 4.17: Monsoon season of 2006 showing an average scenario including after reducing reservoirs the minimum and maximum storage capacities of a potential reservoir in Hinganghat block. The majority of the reservoirs can collect 200m^3 water. Made by author.

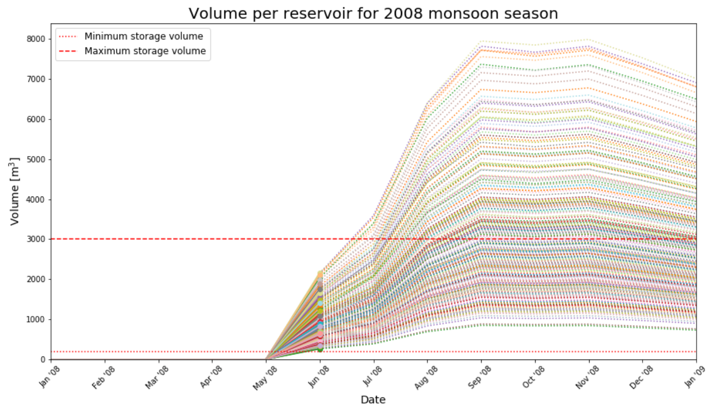


Figure 4.18: Monsoon season of 2008 showing an average scenario after reducing reservoirs including the minimum and maximum storage capacities of a potential reservoir in Hinganghat block. The majority of the reservoirs can collect the maximum amount of water. Made by author.

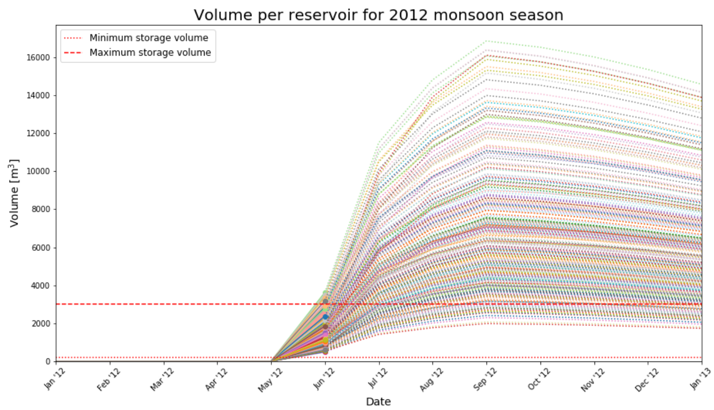
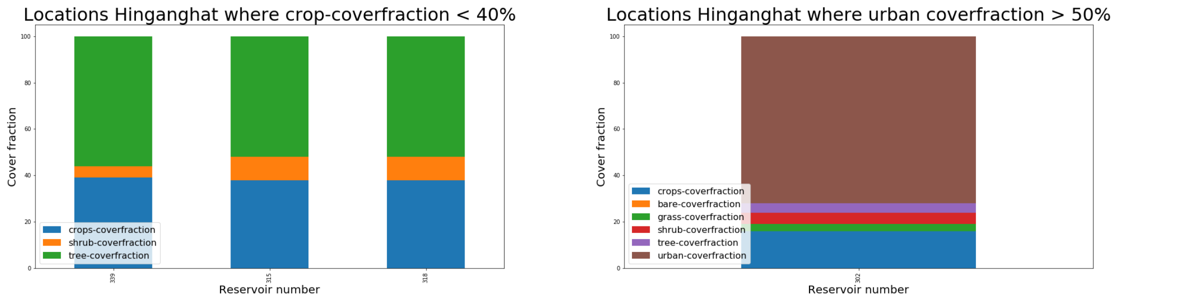


Figure 4.19: Monsoon season of 2012 showing an average scenario including the minimum and maximum storage capacities of a potential reservoir in Hinganghat block. The majority of the reservoirs can collect the maximum amount of water. Made by author.

GEE: land cover classification analysis of reservoir locations

Next GEE was used to estimate the land cover on which the potential reservoirs were located. The majority of the reservoirs is placed in a suitable spot with respect to limiting the urban cover fraction and ensuring a large crop cover fraction. In appendix G.2 all land cover data per reservoir can be found. In this paragraph only the not suitable locations will be discussed.

Three locations are placed on a grid cell with less than 30% crop cover as shown in figure 4.20a and one location is placed on a grid cell with a too large urban fraction 4.20b. The crop cover fractions for these locations in figure 4.20a are 39 and 38%. These locations still can have potential for reservoir construction due to the high tree cover fraction, a field visit has to be carried out to estimate if a reservoir is possible on this location or not. The location showed in figure 4.20b is definitely not suitable for construction of a reservoir since the urban cover fraction is 72% and only 16% is cover by crops. No field visit is needed to estimate the potential of this location.



(a) Not suitable locations in Hinganghat based on crop cover. The crop cover fraction is below 30% of the total cover fraction.

(b) Not suitable locations in Hinganghat based on urban cover. The urban cover fraction is above 25% of the total cover fraction.

Figure 4.20: Not suitable locations in Hinganghat block due to a too little crop cover fraction or a too large urban cover fraction. Made by author.

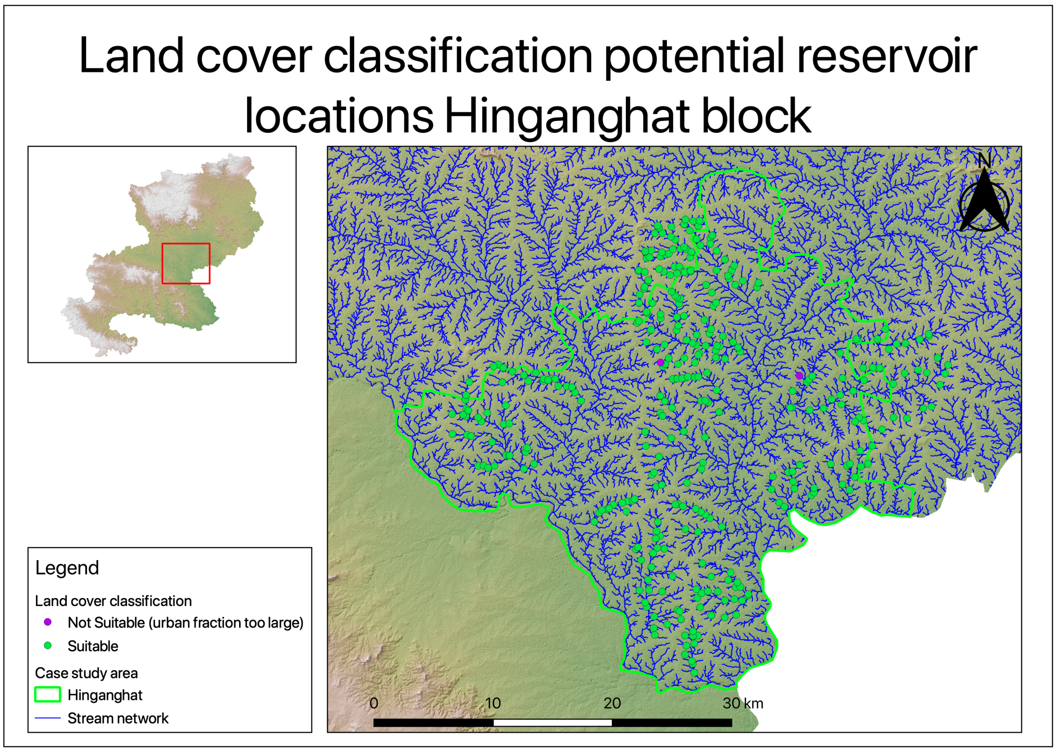


Figure 4.21: Land cover classification per reservoir location. Made by author

All together are 354 out of the 358 locations suitable for constructing a reservoir, 1 location is not suitable and 3 locations need a field visit to determine the potential based on both water collection as well as land cover fraction.

Socio-hydrological analysis of potential reservoir locations

The final check is the benefit in both yield as well as capital increase. This check is done with the socio-hydrological model described in section 3.6. The resulting graphs of the increase in yield and benefit per reservoir location can be found in appendix H.2.

It can be observed from figure 4.22 that the majority of the reservoirs has an increase of less than 100 kg/ha/y. Part of the reservoirs has an increase of more than 100 kg/ha/y. The largest yield increase is 178 kg/ha/y. Figure 4.23 shows the increase per reservoir per category. The darker the red, the lower the yield increase, the lighter the orange, the higher the increase. The same categorization is used for both blocks. Since the yield increase in Hinganghat block is lower compared to Ghatanji block, the majority of the reservoirs are marked red. Only a few reservoirs have a relatively high increase (light orange).

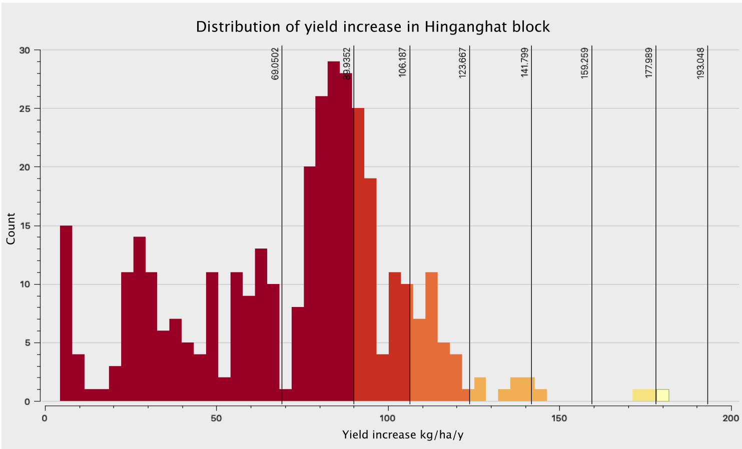


Figure 4.22: Yield distribution in the Hinganghat block. The majority of the reservoirs has a yield increase of less than 100 kg/ha/y. There are reservoirs with an increase of more than 100 kg/ha/y. Made by author

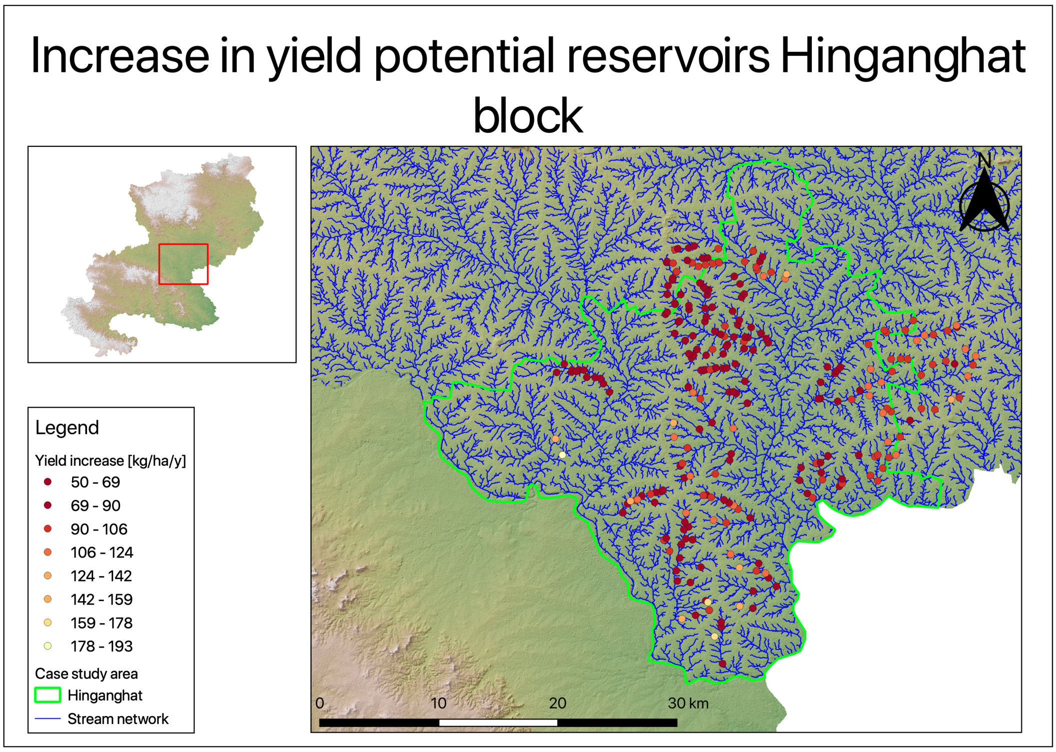


Figure 4.23: Increase in yield per reservoir location in Hinganghat block. The increase categories are grouped around the region. No category stands out for containing the majority or minority of the reservoirs. Made by author.

The larger the benefit and yield increase for the farmer, the better the location of the reservoir. The small increase in yield and benefit are due to the social factors in the specific locations. For more information on these factors and their influence, please consult D. Djohan his master thesis.

Summary of potential reservoir locations Hinganghat block

Out of the 358 potential reservoirs provided by QSWAT, 6 locations had the potential to collect too much water and were excluded from the data set. One reservoir is located on a spot with a too large urban fraction, three reservoirs are located on a location with a crop cover fraction of less than 30% which need a field visit to estimate if the location has the potential of constructing a reservoir. Furthermore, 160 have a high potential of supplying water as well as increasing the yield and benefit of each farmer. 90 locations have medium potential when it comes to increase in yield and benefit for farmers. Another 104 have a small increase in yield and benefit.

4.3. Current reservoirs

Based on information given by Solidaridad and the search for this locations via zoom.earth according to the method described in paragraph 3.2.1, over 1300 current reservoir structures are present and found in Ghatanji block area. Many of theses structures are currently not in use due to insufficient positioning of the structures according to Solidaridad. The insufficient positioning of the structures has as a consequence that the reservoir does not collect rainwater during the monsoon via the runoff paths formed by the difference in altitude in the area. Since over 1300 of these structures are already present in the area, it would be a sustainable (and potentially cost efficient) option to explore the option of rejuvenation of (some of) these structures. Since the zoom.earth satelite imagery only provides images until February 2019th latest, not all structures are localized. All structures constructed after February 2019 are not taken into account. According to Solidaridad, over 5000 structures are present in the area, meaning that over 3000 structures are constructed between February 2019 and June 2020. Nonetheless can the method used to locate these structures and determine the suitability of these structures be tested for future use.

4.3.1. Analysis of current reservoirs in Ghatanji block

To determine the potential of the current reservoir structures in the Ghatanji block, the locations first had to be found with zoom.earth. Secondly the distance from the nearest stream to the reservoir location is measured. Thirdly the land cover fraction of each location is checked with the use of GEE.

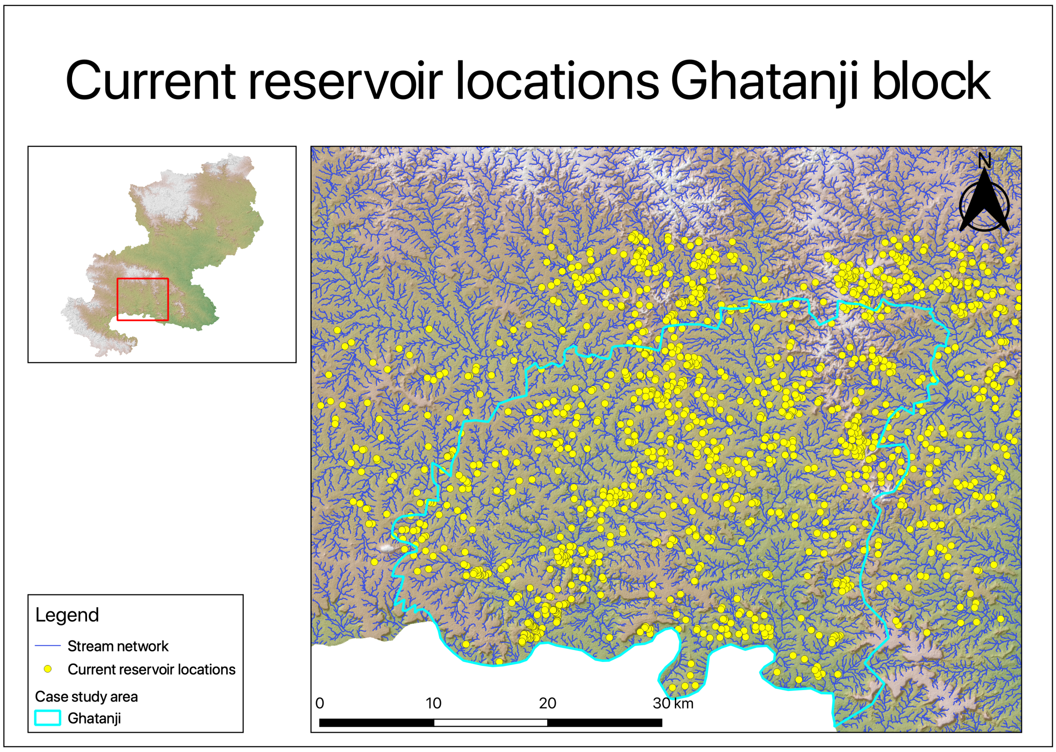


Figure 4.24: Current reservoirs present in the Ghatanji block. Made by author.

Locating current reservoir structures

The validation of the current reservoir structures is done via the method described in section 4.3. Since this method is sufficient enough to estimate if an object is a reservoir, no further research has been done via remote sensing or field observation to determine if an object is a reservoir.

1356 reservoirs were found within and just outside the boundaries of Ghatanji block. Since it is not possible to visualise the block boundaries in zoom.earth, some reservoirs outside the area were found as well. These reservoirs are also analysed. Figure 4.24 shows all reservoirs found and the boundaries of Ghatanji block. There is no specific area were very little or heaps of reservoirs are present.

Distance between reservoir and nearest stream

To estimate the potential of current structures, the current structures are run in the python 'Nearest distance' code to estimate the distance to the nearest stream. The distances are divided into ranges starting from 0 - 100 meters, 100 to 200 meters, etc. The closer a reservoir to a stream, the higher the chance of the reservoir collecting water naturally or with the help of a (short) ditch. Figure 4.25 shows the reservoirs collor based on the distance to the nearest stream. It appeared that of the 1356 structures, 1156 structures are within a distance of 200 meters (dark green and light green) from a stream, 826 reservoirs are even within a distance of 100 meters (dark green) from a stream. These results are very promising when it comes to the suitability of these current locations. Only 6 locations are further than 400 meter from a stream. Since the majority of the reservoirs is located relatively close to a stream, it is worthy to check the rejuvenation possibilities with a field visit.

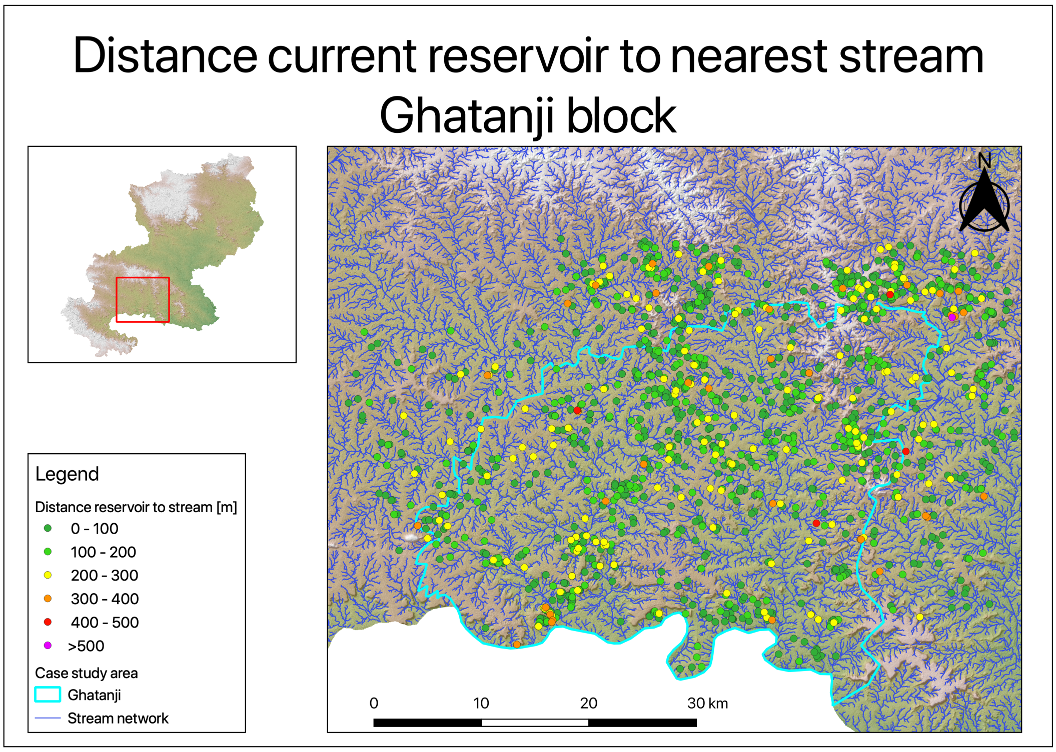
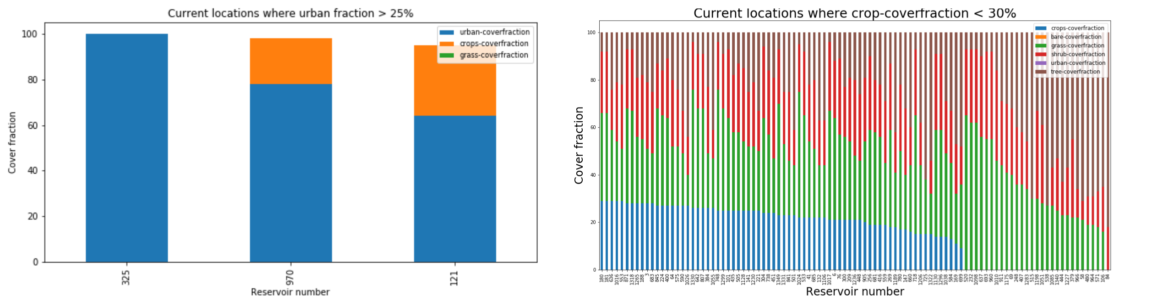


Figure 4.25: Locations of current reservoirs in Ghatanji block including the distance classification given to a reservoir based on the distance between the reservoir and nearest stream location. The majority of the reservoirs is within a distance of 200 meters of the nearest stream. Made by author.

Land cover fraction classification

The land cover thresholds used are described in section 3.3, all locations with more than 25% urban cover and less than 30% crop cover are assumed to be not suitable for reservoir construction. This results in only 3 current reservoirs locations not being suitable due to a too large urban fraction and 183 current locations not being suitable due to a too little crop cover fraction as can be seen in figure 4.26. Figure 4.27 shows the reservoirs based on land cover classification. The figure shows the majority of the locations (green) is located in a good position with a large enough crop cover fraction and a not too large urban fraction.



(a) Not suitable current locations in Ghatanji block based on urban cover. The urban cover fraction is above 25% of the total cover fraction.

(b) Not suitable current locations in Ghatanji block based on crop cover. The crop cover fraction is below 30% of the total cover fraction.

Figure 4.26: Not suitable locations in Ghatanji block due to a too little crop cover fraction or a too large urban cover fraction. Made by author.

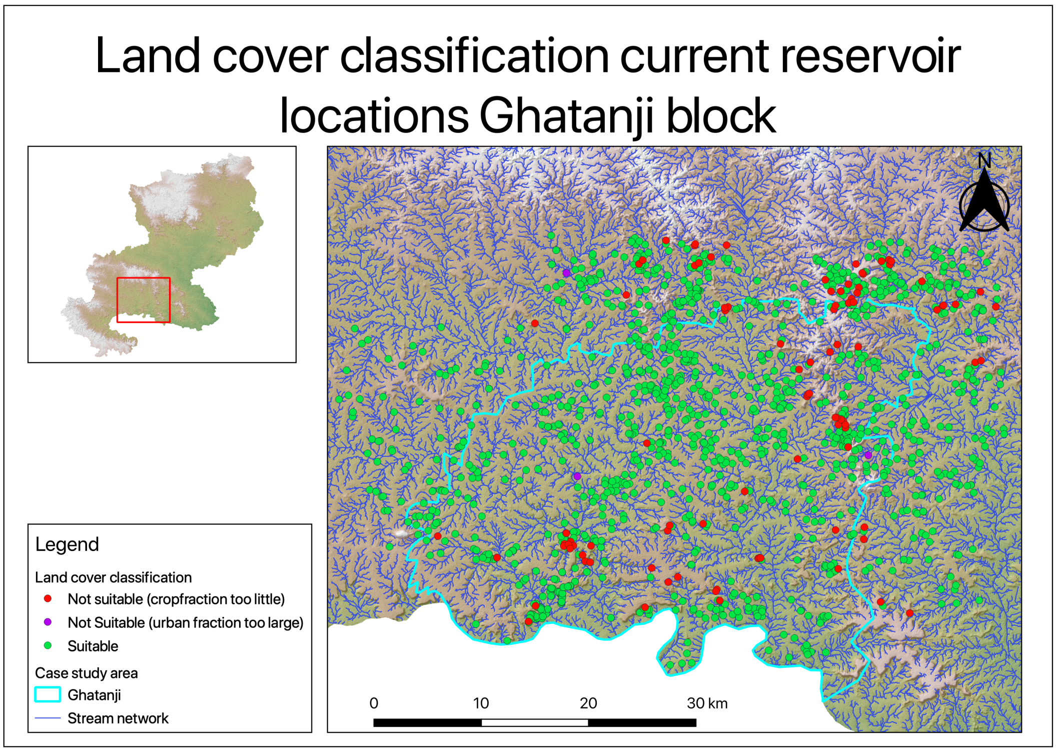


Figure 4.27: Land cover classification of current locations in Ghatanji block. The red and blue locations are classified as not suitable due to a too little crop cover fraction or too large urban cover fraction.

4.3.2. Analysis of current reservoirs in Hinganghat block

This paragraph analyses the location and the potential of the current reservoirs in Hinganghat block. First the locations of the reservoirs were found with the use of zoom.earth as described in section 4.3. Secondly the locations are analysed with both taking a closer look to the type land cover the location is based on as well as the yield and benefit increase the current location can provide. With these two results, something can be said if rejuvenation of a structure is beneficial or not.

Locating current reservoir structures

The reservoir locations found in the Hinganghat block are shown in figure 4.28. This map contains 856 current reservoir structures within the area and partly outside the boundaries of the Hinganghat block. The reason part of the locations are outside the Hinganghat block is due to the lack block boundaries in zoom.earth. Therefore a guess had to be made were the block boundary was located. Nonetheless, the locations outside the Hinganghat block are also analysed. Interestingly, on the right side of the Hinganghat block very few locations are found. The reason for the lack of reservoirs in this area is could be due to the presence of the city Hinganghat in the north east of the block. For Solidaridad it would be very good to know why there is a lack of reservoirs in this area, unfortunately this can only be guessed remotely with satellite data.

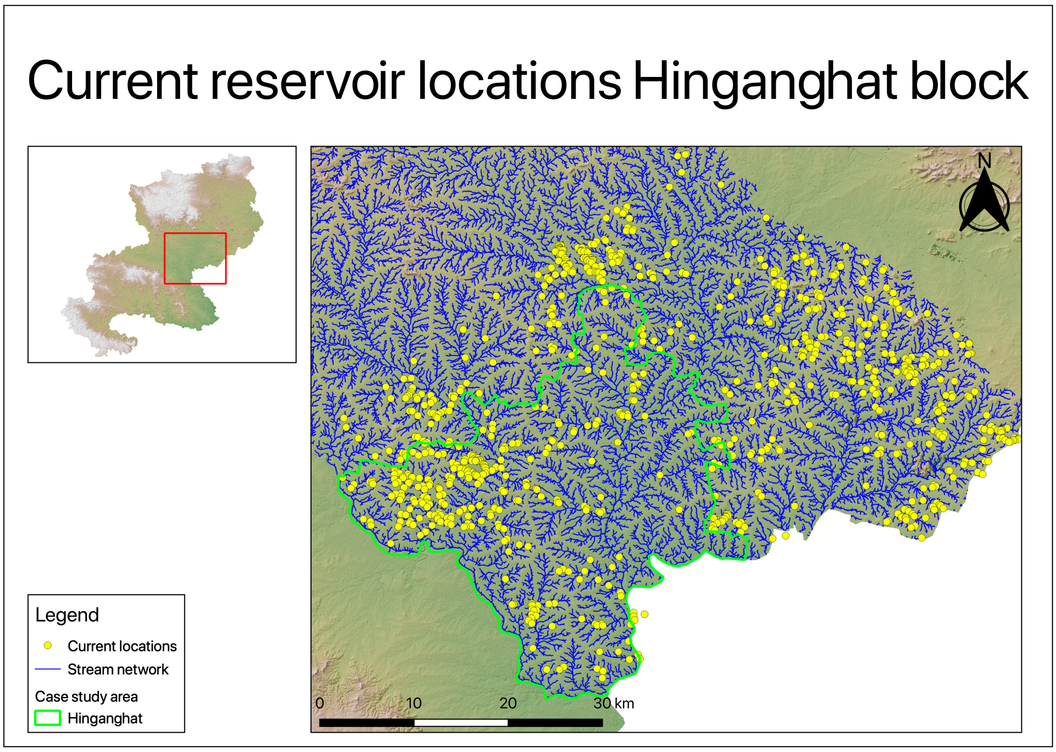


Figure 4.28: Locations of current reservoirs in Hinganghat block. High reservoir density is found in the west of the block, low reservoir density is present in the east of the block. The reason for this low reservoir density is unknown. Made by author.

Distance between reservoir and nearest stream

The potential of collecting water of these current structures is determined by measuring the distance from the current reservoir to the nearest stream and analyzing on what type of land cover the reservoir is located. Figure 4.29 shows the distance from each reservoir to the nearest stream based on different classes (less than 100m, between 100 and 200 meters, etc.). The majority of the reservoirs lies within a distance of 200 meters to a stream. Only 8 locations (purple) have a larger than 500 meters distance to a stream. As can be seen are some of these locations located outside of both the Hinganghat borders as well as the Wardha district border. For that region no stream network is prepared, thus the locations are classified as further than 500 meter of a stream. Since these locations are outside the focus districts, they will not be taken into account. The locations with a distance of less than 200 meters of a stream have the potential to collect water. The 200 meters is based on the distance one can dig a ditch or small channel from the stream to the reservoir. However, per non-water-collecting location has to be determined with a field visit if a ditch can be constructed. This depends for example on the area between the reservoir and the stream: if there is agricultural land of another farmer or a house located between the reservoir and the stream, it will be harder to construct a ditch.

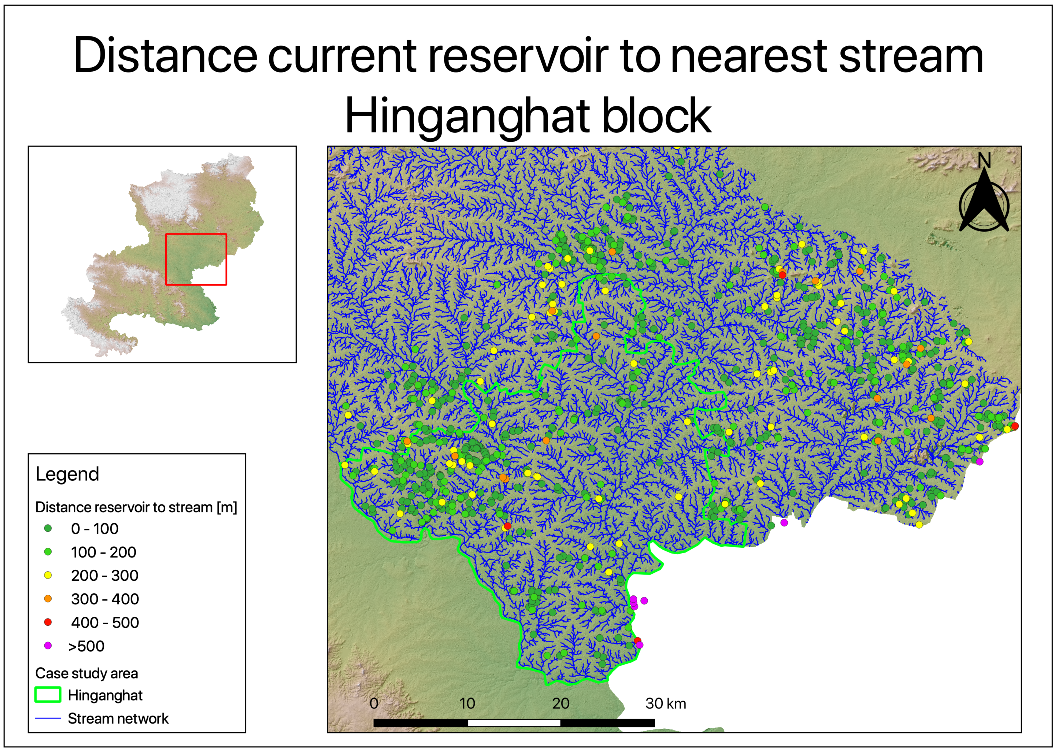
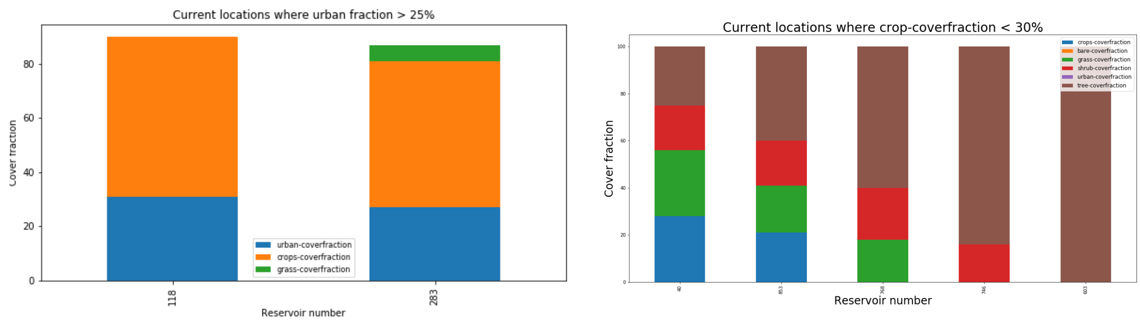


Figure 4.29: Distance between current reservoirs and nearest stream point. The green locations show a smaller distance to the nearest stream, the more red/purple, the further a reservoir is from a stream. Made by author

Land cover fraction classification

The land cover fraction of each reservoir is determined with the GEE model. Figure 4.31 shows that none of the reservoirs is based on a location with a too large (>25%) urban fraction. The majority of the reservoirs is based on a position with a crop cover fraction larger than 30%. Only 8 reservoirs are located on a spot with a crop cover fraction of less than 30%. Figure 4.30b shows the cover fractions of each reservoir located on a not suitable position with less than 30% crop cover and includes the corresponding distance to the nearest stream. Interesting to see is that the two reservoirs with a relatively high crop cover fraction, are located 200 meters from the nearest stream. The reservoirs with no crop cover fraction, are closest to the nearest stream. A field visit to these locations with no crop cover and close to a stream would be needed to get an answer to the question why a reservoir is placed on that location.



(a) Not suitable current locations in Hinganghat block based on urban cover. The urban cover fraction is above 25% of the total cover fraction.

(b) Crop cover fraction of not suitable locations where crop cover fraction is less than 30% including distance to nearest stream. Made by author.

Figure 4.30: Not suitable locations in Hinganghat block due to a too little crop cover fraction or a too large urban cover fraction. Made by author.

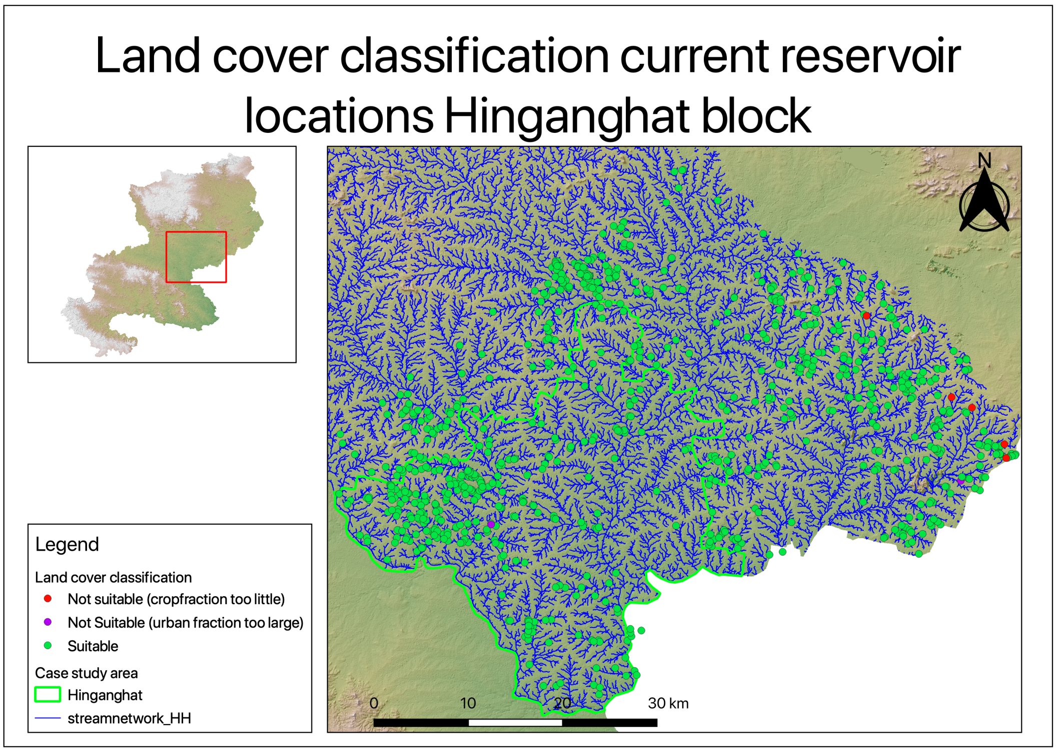


Figure 4.31: Land cover classification per reservoir location. None of the locations is located on a too large urban fraction. The majority is located on a suitable location, meaning a large enough crop cover fraction. Made by author

4.4. Proposed reservoir locations by Solidaridad

Solidaridad proposed 29 reservoir locations mid-July. To determine the potential and suitability of these reservoir locations, the locations were checked on the distance to the nearest stream and the potential volume each reservoir would be supplied with was estimated with QSWAT. Therefore the stream network of Amravati and Nagpur was also delineated with QSWAT. The stream network of every area is also used for the model provided to Solidaridad for future use. The estimation of volume per reservoir made it possible to calculate the yield and benefit improvements each reservoir potential can provide. A note has to be taken that the volume is an estimation based on the water supplied by the nearest stream. It is uncertain if all this water will drain into the reservoir or if only part of the water will drain into the reservoir.

Additionally, the land cover analysis of these constructed reservoirs was used to establish a threshold value for the suitability of potential and current locations. From figure 4.32 it can be observed that all reservoirs except one are constructed on a spot with more than 30% crop coverage. None of the reservoir locations contains an urban fraction. From the crop cover fraction analysis it was assumed that a suitable reservoir location should contain at least 30% crop coverage. The one location with less than 30% crop cover fraction contains a large bare cover fraction. Likely this location is on the edge of a farmers' plot but this cannot be confirmed remotely. Therefore this location is excluded for the identification of the threshold for potential reservoir locations. Furthermore regarding the urban cover fraction threshold, since no urban fraction is present at any of the locations, one could assume that for a suitable reservoir location, 0% urban coverage is preferred. However, since the resolution of the land cover data is 100x100m, it would be possible to construct a reservoir on a location with a small urban cover fraction. Therefore it was assumed that a maximum of 25% urban coverage could be present on a suitable reservoir location.

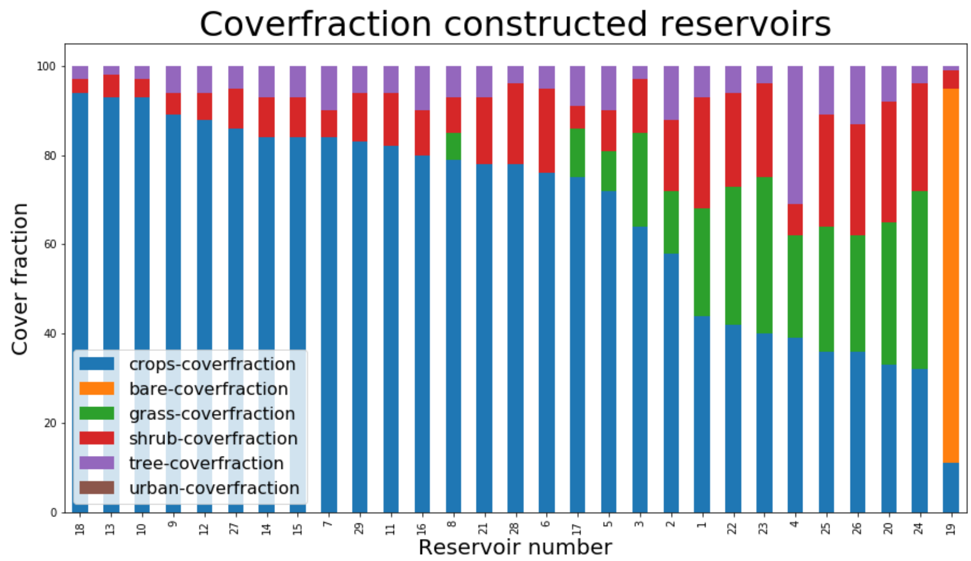


Figure 4.32: Land cover fraction per reservoir location for constructed reservoirs by Solidaridad. Made by author.

Distance to nearest stream

To analyse the position of the reservoir, the locations were run through the nearest distance model. From figure 4.33 it can be observed that 20 reservoirs is within a distance of 200 meters of a stream. However, 9 reservoirs are located further than 200 from a stream. Even 4 reservoirs are further than 300 meter from a stream. The closer the reservoirs to a stream, the easier the reservoir can collect water since it will be located near the natural runoff path of a water stream. The further away a reservoir from a stream, the more work, such as creating a ditch or channel, has to be done to ensure water runoff into the reservoir.

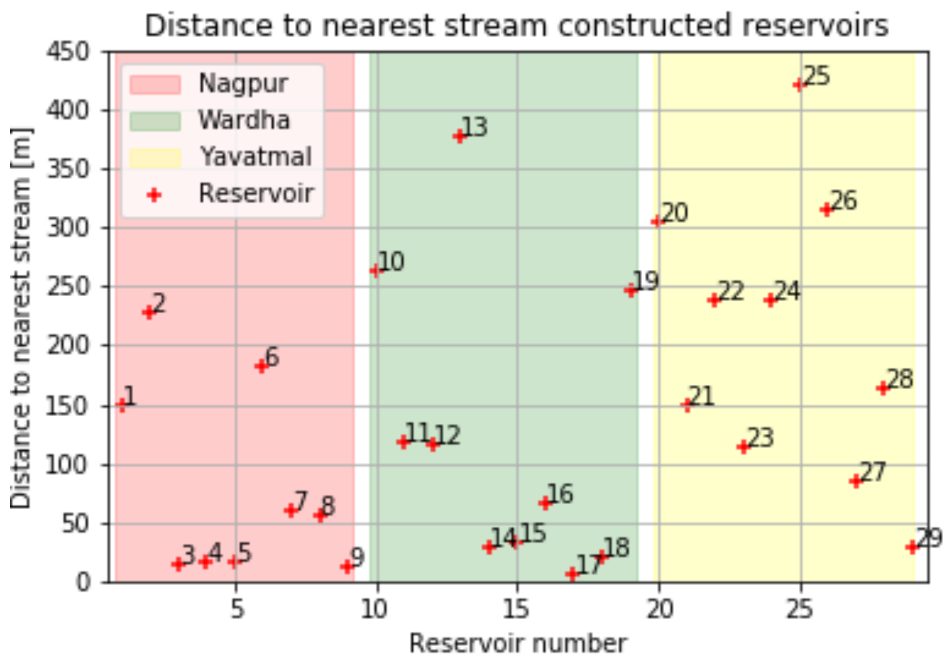


Figure 4.33: Distance to nearest stream for constructed reservoirs by Solidaridad over the summer of 2020. Made by author.

QSWAT analysis including yield and benefit improvements

Next to the ability of storing water, the increase in yield and benefit is of major importance to analyse since this will immediately affect the farmers livelihood. The estimate the increase in yield and benefit, the reservoirs constructed by Solidaridad are run through the QSWAT model. The subcatchment on which the location is in is assumed to supply the inflow rate and volume for that reservoir. These values can however differ somewhat from the real values since not all locations are located on a stream directly and QSWAT assumes a reservoir to be located on a stream instead of next to it. Nonetheless will this assumption give some realistic values for the analysis of yield and benefit improvements.

Figure 4.34 shows all benefit and yield increase per reservoir constructed by Solidaridad. Reservoir 5, 6, 7, 8 and 9 all have a large yield increase, but only reservoir 6 has a large benefit increase as well. The opposite is true for reservoirs 14, 15, 16, 20, 21 and 22: these reservoirs have a large benefit increase, but a not so large yield improvement. Figure I.1, I.3 and I.2 in Appendix I show the reservoirs per district. From these figures it is apparent that there is no significant difference between each district regarding the increase in yield and/or benefit. The value per reservoir is unique and not related to the area due to the difference in reservoir inflow and social factors. For more in-depth information on the results regarding the yield and benefit, please consult the thesis of D. Djohan.

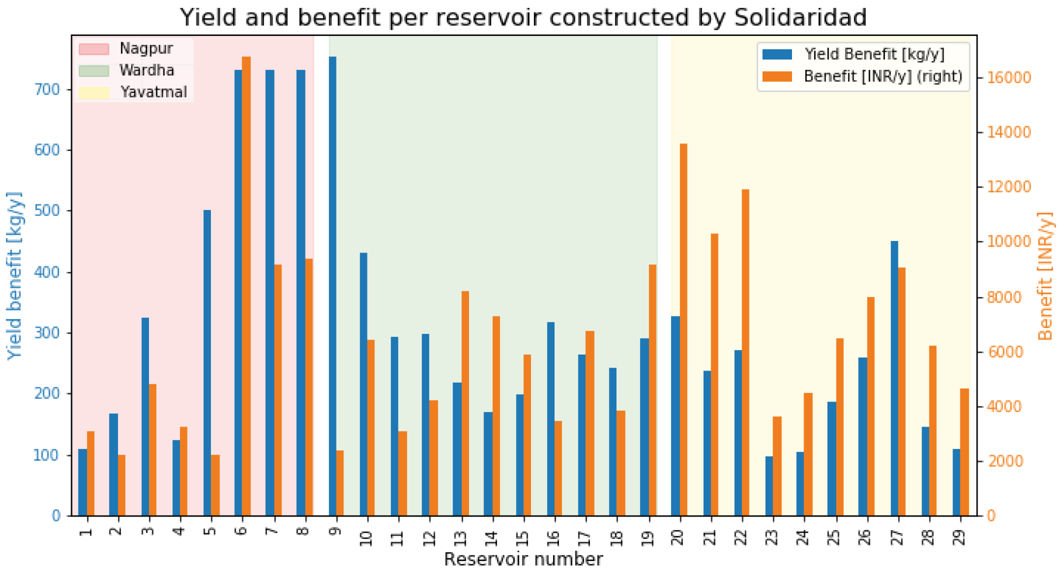


Figure 4.34: Yield and benefit of each reservoir constructed by Solidaridad. Made by author.

Model for Solidaridad

As agreed upon with Solidaridad, this research would provide a user friendly model to them for determining the suitability of potential and current reservoir locations. This model can be found in appendix F. It is in the form of a Python code in Jupyter Notebook including guidelines on how to use the model. The model calculates the distance to the nearest stream and provides the latitude longitude data of the nearest stream.

5 Discussion

In this chapter the methodology and results are discussed based on the research questions given in chapter 1. Several limitations arise from the methods finding answers to the research questions and the answers to the research questions. In this chapter all research questions are discussed including the limitation(s) per question. Some of these limitations are used in chapter 6 for future recommendations.

5.1. Estimation of new reservoir locations

The QSWAT model was used to determine new reservoir locations. The model creates a stream network from the digital elevation map of the area. Weather data together with this stream network then determines the amount of inflow into and volume of each reservoir. The model is user-friendly once one knows how to set it up. The difficulty lies in the little documentation available on the different factors and thresholds present in the model. The lack of clear documentation makes it hard to figure out how all the thresholds and in-between-steps have to be determined.

A second limitation of the QSWAT model is that QSWAT is being designed for estimating larger reservoirs, therefore it is not the optimal model for determining these small scale reservoirs. Nonetheless, the model can be used easily and quick to determine the surface runoff path since the model uses high resolution DEM data of 30x30m for delineating a stream network. The high resolution data is able to creates a very accurate and precise runoff chart. Hence, for the other input files (land cover, soil type) the data resolution is much lower and less accurate. Unfortunately it is not possible to use more recent data set since these sets are not provided on the QSWAT website and are not adjusted for the QSWAT model.

The third limitation of determining potential reservoir locations during this research was that no data on the locations of farmers was present. As a result, the locations are randomly chosen without knowing if there is a farmer in need of a reservoir at the location the structure is positioned.

Lastly, it should be remembered that the output from QSWAT is provided by a technical and mathematical model. For this research it was assumed that indeed all the streams appearing as output of the 'stream network delineation' step are indeed present on the ground. However, this is an uncertainty which cannot be checked remotely unless one has stream network satellite imagery of such a high resolution. Unfortunately this data is not present on this scale with a resolution of at least 10x10m.

All in all can be said that the QSWAT model delivers suitable locations from a hydrological perspective and with the use of different validation techniques described in the following paragraphs, one can estimate remotely if a location is suitable or not.

5.2. Potential of new and current structures

The potential of new and current structures is determined with different validation techniques:

- Estimation of inflow amount with QSWAT (potential reservoirs)
- Measuring distance to nearest stream as the crow flies with python model (current reservoirs)
- Estimation of ground position with land cover database with GEE (current and potential reservoirs)
- Estimation of increase in yield and benefit with socio-hydrological model (potential reservoirs)

The potential of a reservoir is measured according to the definition of "a suitable structure". A suitable new structure, in this case, is defined as the ability of a 10x10x3m reservoir to fill up completely at least once a year for an average low (600mm) monsoon season. Additionally, the structure must be positioned in a location with more than 30% crop coverage and less than 25% urban coverage. Existing structures can be classified as suitable if they adhere the same prerequisites as stated above, except for the additional requirements that a structure should be located less than 200 meters from the nearest stream point. This 200 meters is based on the length over which a channel or ditch can be constructed and maintained. At the end of this project, 1500 reservoir locations, including both potential new locations as well as potential renewable current locations, had to be delivered to Solidaridad for Ghatanji block and Hinganghat block.

In Ghatanji block, 1356 current structures were found. Of these current structures, 970 locations have the potential to collect water based on the qualifications stated before. 856 structures were found for Hinganghat block of which 853 locations have the potential to collect water. The amount of potential new locations in Ghatanji block is, after applying the different validation techniques, reduced from 352 to 309 and another 21 locations need a field visit to determine if the location is suitable or not. For the Hinganghat block out of the 358 locations, 348 locations have a high potential of collecting water. All together, a total of 1607 locations are suitable for water storage for small-holder cotton farmers.

Yet there is a large difference in increase in yield and benefit observed between the potential locations in Ghatanji block and Hinganghat block. The distribution of both blocks is shown in figure 5.1. The maximum increase in yield for the Ghatanji block is much larger than for the Hinganghat block. For the Hinganghat block, the minimum increase in yield is 7.2 kg/ha/y and the maximum yield increase is 172.6 kg/ha/y. When comparing these values to the minimum (50.3 kg/ha/y) and maximum yield (447.7 kg/ha/y) of the Ghatanji block, one can observe a large difference for both the minimum and maximum yield and benefit increase. The mean value of Ghatanji block is almost double the mean value of Hinganghat block. There is no hydrological reason for this difference since the average amount of volume for the reservoirs in both areas are roughly the same. The reason is due to the difference in socio-economic factors in each area. The outliers in both distributions could be due to an error in either the socio-economic model or data or in the hydrological model or data. More on this difference is discussed in the research of D. Djohan.

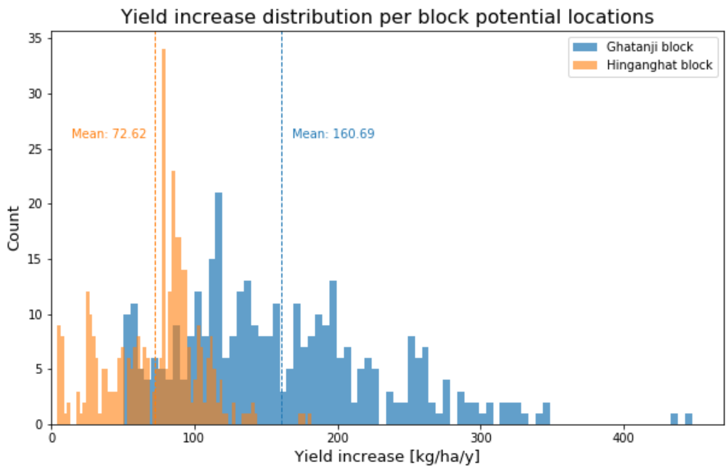


Figure 5.1: Histogram of yield increase distribution per block for the potential reservoir locations. The mean yield increase for Hinganghat block (orange) is lower compared to the mean yield increase of Ghatanji block (blue). Also the distribution for Hinganghat block is more concentrated to the left where the distribution for the Ghatanji bock is more evenly distributed over the entire range. Made by author.

All in all can be said that there are over 1500 locations established with a high potential of collecting water for small-holder farmers in Ghatanji block and Hinganghat block.

5.3. Remote data based tools

The remote data based tools used to determine the suitability of potential locations are:

- input data in QSWAT for hydrological calculations
- Land cover classification with GEE
- Locating current locations with zoom.earth

- Socio-hydrological model

The reason for determining tools is described in 1.2. The first three tools can be used remotely and there is no input needed from the field. From the validation of the potential new and current structures it is observed that the suitability of the majority of the locations can be determined remotely. However, some current reservoir structures or potential locations do need a field visit to estimate the potential because from these remote observations they cannot either be included or excluded as suitable locations. The socio-hydrological model needs input from the farmers for producing better results, this is further explained in the research of D. Djohan.

Another factor which could help determining the suitability of a reservoir location is the soil moisture content and perhaps the ground water level of a location. Both factors influence the infiltration rate of water into the soil. QSWAT takes the infiltration into account during its calculations, however the data used for the soil type is somewhat outdated (1978) and has a very low resolution (1 : 5.000.000).

5.4. Potential current structures

The potential of a current structure is based on the location of the structure which is less than 200 meter away from a stream and a crop cover fraction of more than 30% and less than 25% urban coverage. As described before, the majority of the current structures has the potential to collect water. However, there are two limitations:

1. Not all current structures in the area are found. This is a result of manually locating the current structures via zoom.earth.
2. The amount of inflow in each reservoir cannot be calculated with QSWAT since a reservoir should be located on a stream to estimate the runoff via the stream into the reservoir. Also QSWAT is

A limitation in determining the potential of current structures is that no calculations can be made with QSWAT on the amount of water flowing in the current reservoirs. QSWAT is not able to calculate this since it only can determine the volume of a reservoir located on a stream directly. This is not the case with the current reservoirs. Also, QSWAT is not able to run more than 380 locations at the same time and finish it in less than 8 days.

Nonetheless, the distance between a reservoir and a stream could be calculated easily with the use of the stream network provided by QSWAT. This distance gives an estimation on the possibility of a reservoir to collect water naturally or with some (minor) adjustments such as creating a ditch or channel between the reservoir and the stream. The closer a reservoir to a stream, the higher the potential of naturally draining water in the reservoir. The distance is measured as the crow flies and does not take into account the elevation in the area.

5.5. Notes to take from current and recently constructed structures

From current structures and recently constructed structures it is hard to draw conclusions since no field visit or long-term data is available. Some minor notes can be taken such as that the further a location is from a stream, the more adjustments need to be made to collect water naturally in the reservoir structure. As observed, the majority of the current and recently constructed structures lies within a distance of 200 meter from a stream. However, from recent field observations by Solidaridad it appeared that some of the recently constructed structures with a distance further than 200 meter from a stream are also (partly) filled with water. This water level should be checked for a longer period of time to determine if the level stays the same or if it perhaps drops due to high infiltration or evaporation rates. Another reason for the water present in the reservoir could be that it is the water directly fallen into the reservoir during the monsoon and that it does not contain any surface runoff water.

The last important note to take is that if a reservoir is located several meters from a stream, one should ensure that the elevation of the reservoir is always lower than the intake point at the stream. If the reservoir has a higher elevation than the intake point at the stream, no water will naturally flow and fill the reservoir. When the elevation of the reservoir is lower compared to the intake point, the water will flow automatically from the stream through the channel into the reservoir. One should ensure that the height of the maximum storage level of the reservoir is the same or lower than the level of the intake point to secure a natural and automatic inflow.

6 Conclusion

The main goal of this study was to determine how a hydrological model can estimate new reservoir locations for small holder cotton farmers for irrigation of 1 hectare cotton plots and what the potential of these new locations and current locations was. The case study areas were Ghatanji block and Hinganghat block located in Maharashtra (India). In addition, several sub-objectives were set:

- Which remote data based factors influence the determination of suitable reservoir locations?
- Which current structures have the potential to be rejuvenated and how was this potential determined?
- what can be learned from current reservoir locations and recently constructed reservoirs?

A suitable new structure, in this case, is defined as the ability of a 10x10x3m reservoir to fill up completely at least once a year for an average low (600mm) monsoon season. Additionally, the structure must be positioned in a location with more than 40% crop coverage and less than 50% urban coverage. Existing structures can be classified as suitable if they adhere the same prerequisites as stated above, except for the additional requirements that a structure should be located less than 200 meters from the nearest stream point. This 200 meters is based on the length over which a channel or ditch can be constructed and maintained.

This project was carried out on behalf of Solidaridad, who aim to provide over 20.000 water collecting reservoir structures for small-holder cotton farmers throughout the Maharashtra province by the end of 2024 and in doing so, collecting 14.5 million m^3 rainwater per monsoon season . The deliverable to Solidaridad of this project was to provide 1500 potential and/or renewable reservoir structures in two case study areas (Ghatanji block and Hinganghat block) and to provide a suitable and easy to use method for determining new reservoir locations for Solidaridad for the duration of the project. This method was determined by the determination of the main and sub goals stated before.

The results of this investigation show that a hydrological model can estimate new potential reservoir locations and that the use of a hydrological model is beneficial for locating these potential locations when compared to current or recently constructed locations. The benefit of using a hydrological model is that it can identify the surface runoff paths of water during and after a precipitation event. These runoff paths show the way the water flows and thus on which route water can be collected. Since the purpose of a reservoir is to collect as much water as the reservoir can hold, the reservoir needs to be located on a runoff path or as close as possible to a runoff path. If a reservoir is not located on a runoff path, a ditch or channel should be constructed between the runoff path and the reservoir to ensure water supply into the reservoir.

The remote data based factors influencing the determination of suitable reservoir locations are:

- a hydrological model providing the surface runoff paths of water during and after a precipitation event including the evaporation and infiltration rates
- the land cover fraction classification with a horizontal resolution of 100 by 100 meters

By taking a closer look at both factors, a location can be addressed as suitable or not-suitable. From this analysis 692 potential locactions were defined out of which 315 locations in Ghatanji block and 349 locations in Hinganghat block are determined as suitable reservoir locations

Out of the 2212 total current structures in both case study areas, 840 locations in Hinganghat block and 970 locations in Ghatanji block have a high potential of collecting water once restored. This potential is based on the location of the structure which is less than 200 meter away from a stream and a crop cover fraction of more than 40% and less than 50% urban coverage for a total land cover resolution of 100x100m. From the 29 recently constructed reservoirs by Solidaridad, 20 have a large potential of collecting water since they are located near a stream. Moreover, 9 have a low potential of collecting water due to the distance to the nearest stream determined with the hydrological model is more than 200 meter.

An observation made by analysing existing structures is that the closer a reservoir is located to a stream, the easier it is to naturally supply water into a reservoir. This should be taken into account when constructing new reservoirs on new locations. Moreover, recently constructed reservoirs have shown that consulting a hydrological runoff model increases the potential of water collection by a reservoir naturally.

All in all, these results will aid Solidaridad in identifying suitable reservoir locations to achieve their goal of creating 20.000 reservoir constructions for small holder cotton irrigation. In addition to these technical outcomes, 2474 locations are marked as potential reservoir locations or are worthy to rejuvenate which exceeds the requirement of Solidaridad of providing 1500 locations during this research.

6.1. Recommendations

The results of this study trigger some questions and expose some future research opportunities and recommendations. Not only for the project of Solidaridad but also when developing methods and models for a broader use within the water sector.

The first recommendation as a follow up of this study is to do a field trip to all the potential and current reservoir locations, and compare the outcomes of this field observation with the remote data observation. Which factors are similar? Which factors are different? How can a remote data observation be improved? The collaboration between a remote data analysis and field observations will help Solidaridad establish the goal of constructing 20.000 reservoir locations.

The second recommendation is to create a user-friendly model with the surface runoff paths on a small scale, especially one that can be used in the field. One option is to create a mobile app, in which the GPS location of a farmer's land is registered. Based on this information and the hydrological model, the app should then be able to identify the best possible reservoir location within a certain radius. This application would not only be beneficial for the project of Solidaridad, but also for other areas were knowledge on small surface runoff paths are required.

A third recommendation is to study the effects of water volume and quality downstream when multiple small reservoirs are constructed upstream. Since water should be divided equally between agricultural use, domestic usage and keeping nature in balance, it is important to consider and state the effects. From previous research it is shown that these effects are often not taken into account, but are highly important to consider when establishing a sustainable ecosystem.

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A

Summary D. Djohan's thesis

A.1. Research questions

The first research question of my thesis is using the sh model from Saket Pande and Huub Savenije and incorporate water stress mechanics to improve the theoretical basis of the model.

Secondly, this also includes the modelling of the peoples behavior regarding irrigation use (used to be about expenses but now this is just a small part of my thesis because I cant obtain the data). I will compare the performance of the old model to the new one with the stress mechanics see if it is better or not.

Also in the end I will do some statistical analysis to check what factors help to improve the capital of the farmer. This relates back to the original research question.

A.2. Brief methodology description

First, climate data such as temperature, precipitation, and potential evaporation are used to calculate the soil moisture. The model is also used in conjunction with a QSWAT model to calculate water available for filling up the reservoirs. It determines the closest water intake location to a farmer and the available water from that intake point. The presence of (or the lack thereof) moisture in the water determines the water stress level, whereas the mean temperature affects the temperature stress. The water stress and temperature stress affects the growth of canopy cover and the biomass respectively, which in turn affects the crop yield. Further, the soil fertility, application of fertilizer, and available labour adjust the yield value as well.

The yield value is then used with other sources of income in the calculation for the household income. Additionally, the crop costs, livestock costs, and other costs provides the expenditure value. If the capital goes below zero, livestock sales and expenditure cuts are done in an attempt to bring the capital above zero. If the attempt fails, it is assumed that the farmer somehow has the capability to continue into the following year.

This framework is run twice to calculate the benefit of building a reservoirs for the farmers. First the model is run with the existing (or lack of) reservoirs and second with the newly added structures. The increase in water storage available can sometimes increase the crop yield which in turn increases the capital of the farmer.

A.3. More information

For more information on the model please contact Saket Pande (TU Delft).

B

QSWAT model set-up

Building a catchment model with QSWAT

Version 1.1, October 2019

(Work in Progress Version!)

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1. Introduction

1.1 Building your own model with QSWAT

SWAT is a GIS based hydrological modelling tool and building a model with it requires three spatial data sets and a set of weather data. Preparing these datasets is reasonably complicated for first time users. The three spatial datasets required are 1) Topographic data as a DEM, 2) Landuse data (raster data) and 3) Soil data (also raster). For the weather data, the minimum requirements are daily precipitation and daily minimum and maximum temperature for the entire period of simulation. Depending on the type of potential evaporation method chosen additional weather data are required, such as daily solar radiation, relative humidity and wind speed.

This document should be viewed as a supplemental to QSWAT user manual available through SWAT website. It presents a brief step-by-step procedure for building a catchment model in QSWAT starting from spatial data downloading and processing to running the model simulation.

This supplementary manual assumes that you have already installed QGIS and QSWAT in your computer to proceed building a model. If you have not installed yet, I suggest to follow the procedure explained in the SWAT webpage, which I copied in Box 1.1.

Box 1.1 Installation (Source: https://swat.tamu.edu/software/qswat/)

- Install QGIS by running QGIS-OSGeo4W-2.6.1-1-Setup-x86.exe. Use the default folder C:\Program Files\QGIS Brighton as the installation folder, or C:\Program Files (x86)\MQGIS Brighton on a 64-bit machine. Currently you must use the 32-bit version on 64-bit machines. It is also currently necessary to use version 2.6 rather than 2.8. From now on we will use Program Files as a folder name, even though it will be Program Files (x86) on a 64-bit machine.
- Install SWAT Editor 2012 in its standard place C:\SWAT\SWATEditor.
    - Refer to Appendix I of the QSWAT Manual for help updating a database.
    - Refer to the SWATEditor_Documentation.pdf in C:\SWAT\SWATEditor\SWATEditorHelp for help getting started.
- Install QSWAT (Download link: https://swat.tamu.edu/software/qswat/). This adds some files to the SWATEditor: a project database and a reference database in Databases, SWATGraph in the SWATGraph folder, and also stores the TauDEM executables in a new directory C:\SWAT\SWATEditor\TauDEM5Bin. The QGIS plugin QSWAT is put into the user's home directory in .qgis2\python\plugins\QSwat, which we will refer to as the QSWAT directory.

After installing QGIS, SWAT Editor and QSWAT

- Add QSWAT to QGIS:
    - Open QGIS
    - From the menu select 'Plugins – Manage and Install Plugins…'
    - From the list of plugins, find QGIS (they are in alphabetic order), and check the box to select it (Fig 1.1). Close the Plugins form.

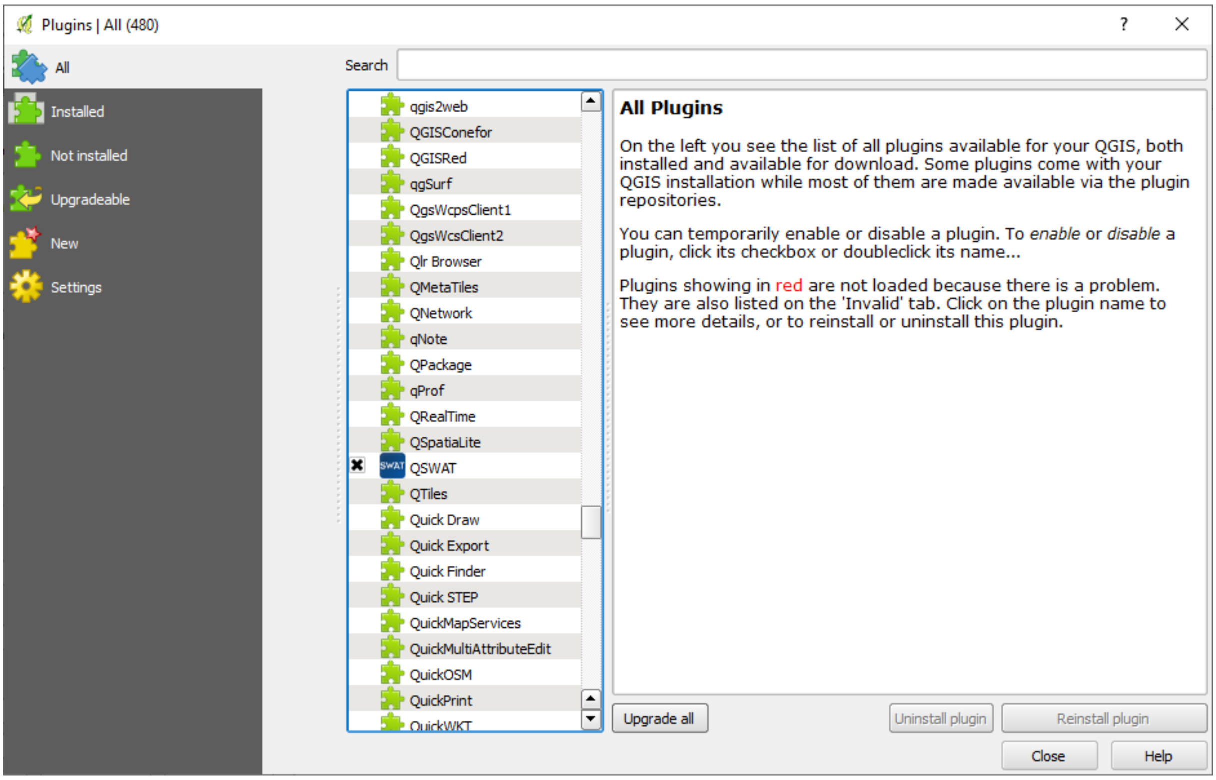

Figure 2.1a. Adding QSWAT to QGIS.

1.2 How to use this document?

This brief guide is intended to use in class room exercises. I recommend to use this document together with the following documents and more detailed SWAT user manuals.

- Dile, Y., Srinivasan, R. and George, C. (2019). QGIS Interface for SWAT (QSWAT), Version 1.9. URL: https://swat.tamu.edu/software/qswat/, accessed 20-09-2019.
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2. Preparing spatial data for QSWAT

2.1 The spatial data source

The WaterBase project website (www.waterbase.org/download_data.html) provides links to all three spatial data sources required for SWAT. These are global data, meaning they cover the entire globe, and so we have to be able to extract the data for the basin we are interested in and transform into a projection system applicable with SWAT. **It appears that this project website is currently not working!** Alternatively, the links for the Landuse and Soil data are now added to the SWAT website (https://swat.tamu.edu/data), and for the DEM data you can use the SRTM link: http://srtm.csi.cgiar.org/srtmdata/.

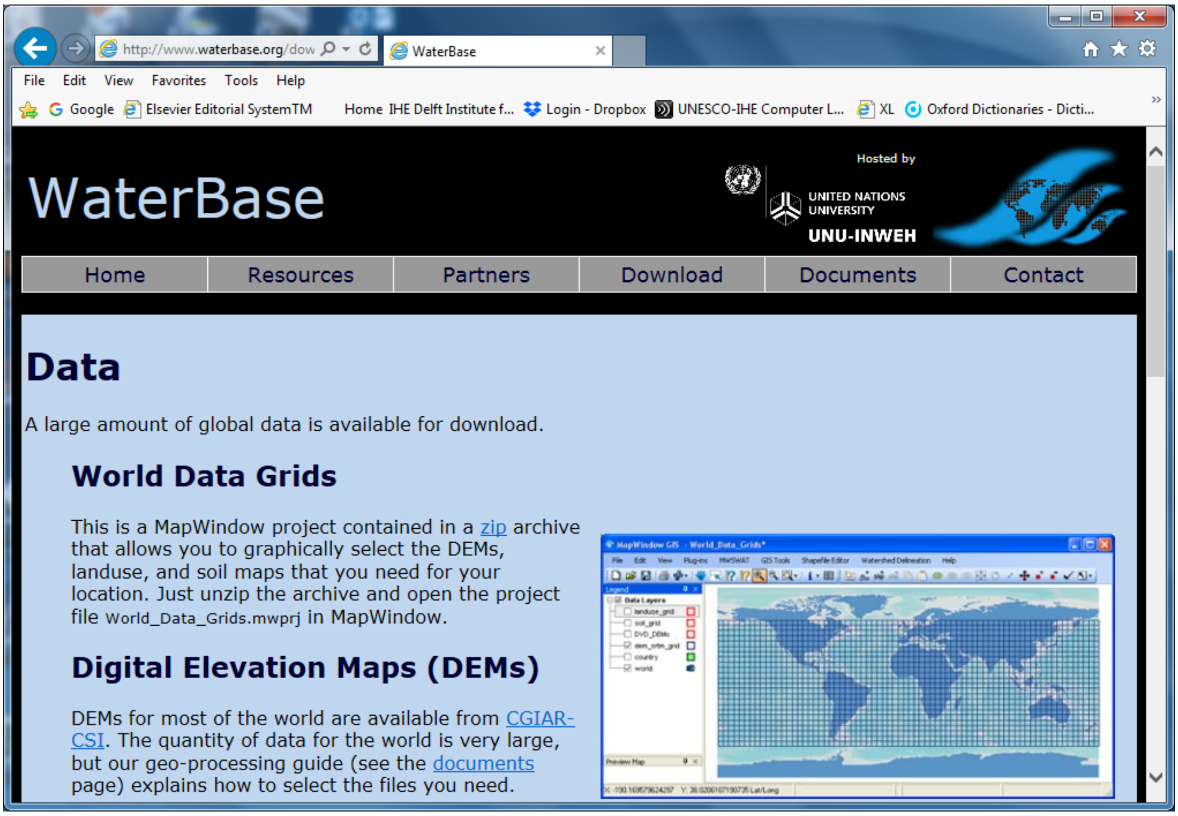


Figure 2.1a. The WaterBase webpage (www.waterbase.org/download_data.html) [**Currently not working!**]

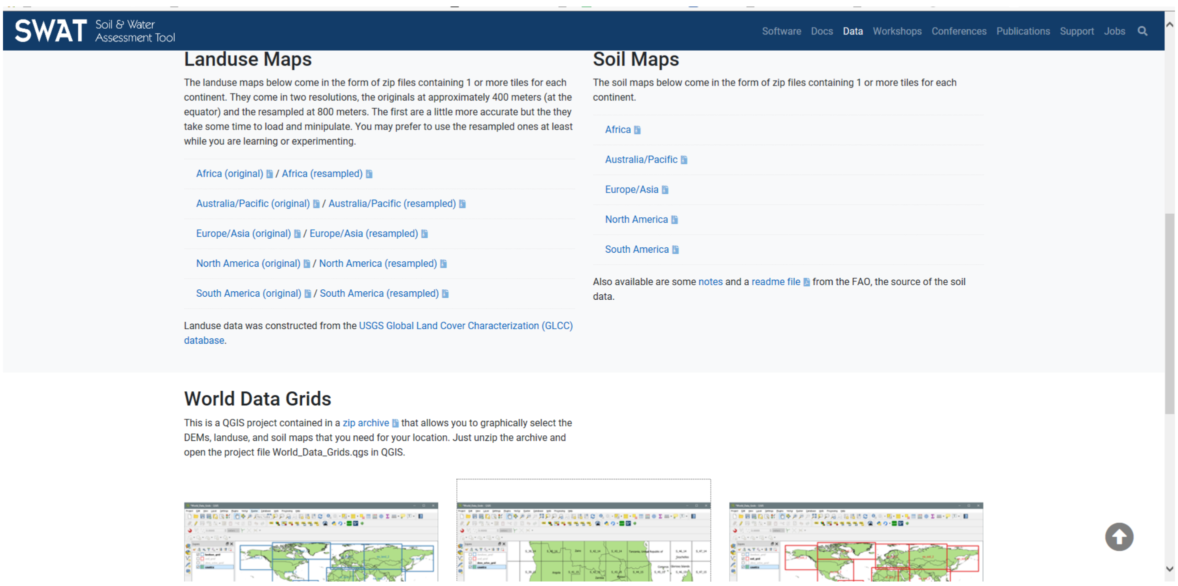


Figure 2.1b. Links to landuse and soil data through SWAT webpage (https://swat.tamu.edu/data)

Before starting to download the DEM data, find out where is your catchment located. You need to know at least the approximate latitute/longitude box that covers your catchment (use a table shown below to note the lat/long. If you do not know this, find out from any global map.

Table 2.1a. Fill in the Latitude/Longitude extent for the catchment of your interest

	Left longitude / Bottom latitude	Right longitude / Top latitude
Longitude (x)	…	…
Latitude (y)	…	…
Note: latitude on the Northern hemisphere is + and Southern hemisphere is –, and longitude east of 0 degree (passing through Greenwich) is + and west of 0 degree is –.		

Table 2.1b. Latitude/Longitude extent for the Indrawati Catchment in Nepal

	Left longitude / Bottom latitude	Right longitude / Top latitude
Longitude (x)	85.3	85.9
Latitude (y)	27.5	28.3

2.2 Prepare DEM data for QSWAT

2.2.1 Download DEM data

To download DEM data

- On the WaterBase web page (www.waterbase.org/download_data.html) find the link to the DEM data. Or you can directly do to the link here: http://srtm.csi.cgiar.org/srtmdata/ (See Fig. 2.2.1). These are SRTM based DEM from USGS, and available in at least two spatial resolutions: 3 arc-second (more commonly known as 90 m x 90 m) and 1 arc-second (30 m x 30 m resolution). Currently the 30 m DEM can be downloaded only with a registration, but 90 m DEM can be downloaded without. The registration is a simple procedure, so do not hesitate to do so if you want the 30 m DEM.
- A DEM of these resolution is big data, and of course finer the resolution the bigger. To give you an example, for an area of 1000 km^2, the 90 m DEM will have 123,457 pixels. If you choose for the 30 m, there will be 9 times as many pixels. So there will be 1,111,111 pixels.
- For a hydrological model you may not need very high resolution. Go for 30 m if you really need it. My thumb rule would be to use 30 m DEM if the catchment is around 1000 km^2 or smaller.
- In the download form, specify a coordinate (Lat, Long) that falls within the catchment you are interested, it does not have to be the centroid. It will show you the DEM tile corresponding to the coordinate specified.
- Check what area this tile covers. If you are lucky, one tile may be enough to cover the entire catchment. You may need two or more tiles. Download all the tiles you need.

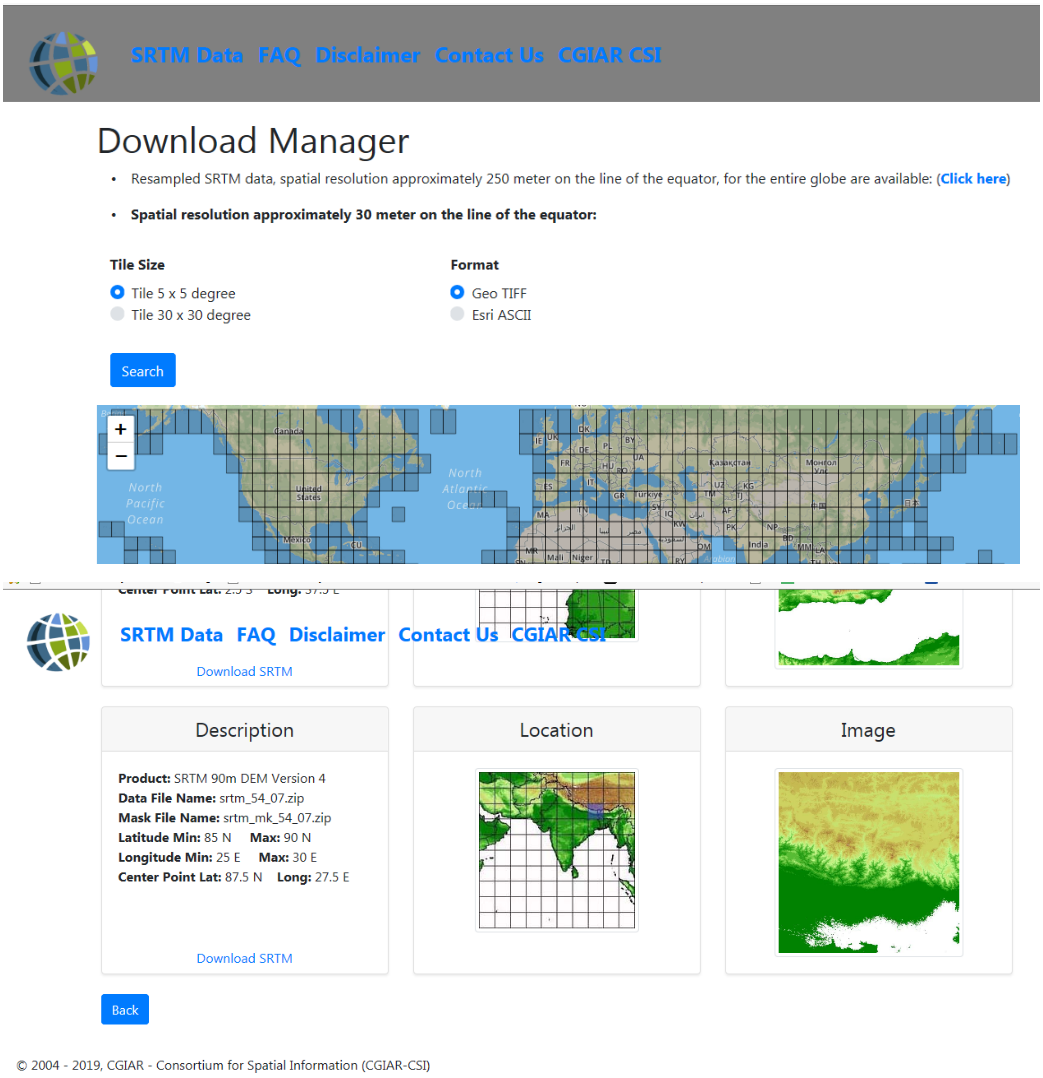


Figure 2.2.1a-b. DEM download form from SRTM (http://srtm.csi.cgiar.org/srtmdata/)

2.2.2 Load the downloaded DEM data

Now you have DEM tile(s). As I said earlier, these are big files. The next step is to extract only the area necessary for your catchment. If you have more than one tile, you need to stich them first before extracting. After extracting, we need to transform it to a required projection system. All of these we will do with QGIS. You can also do these steps with other GIS software if you have and are more comfortable with.

To load the DEM data

- Open QGIS Desktop.
- Save as new file where you want, e.g. D:\DataPrep\Dataprep.qgis
- First you need to add the DEM on QGIS. To do so click the icon for 'Add Raster Layer', or select from the menu: Layer – Add Layer – Add Raster Layer. Then find the folder where you saved the downloaded DEM and select the file. The DEM will appear on the screen. If you have more than one tile, add them one by one.

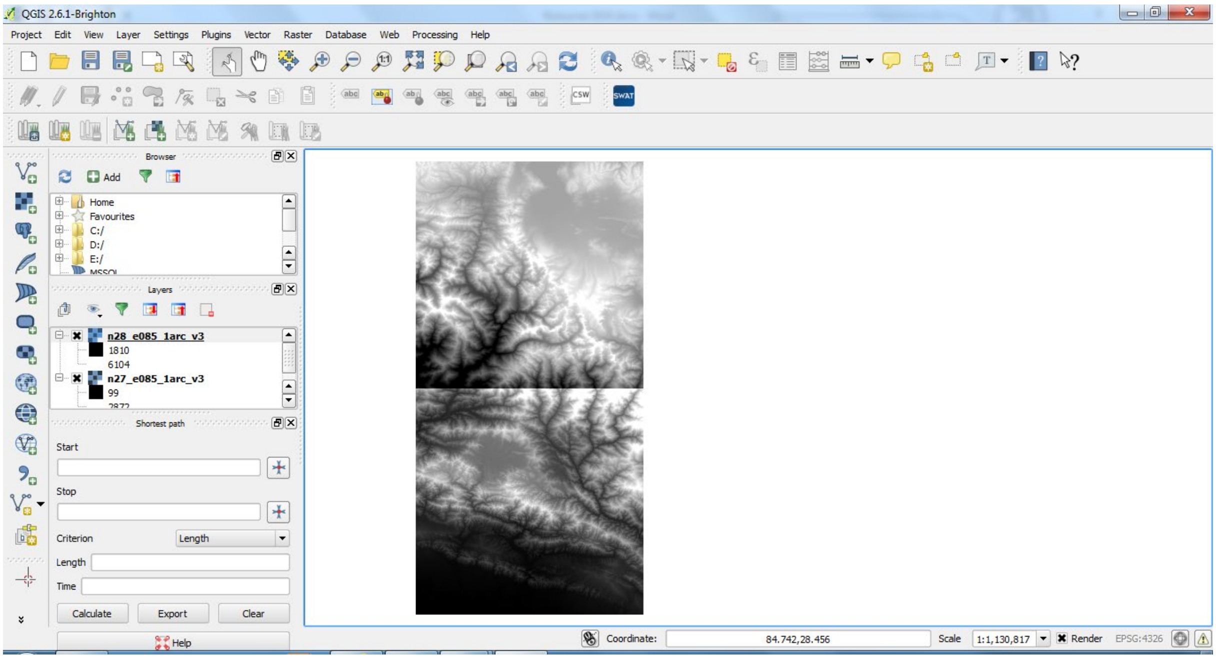


Figure 2.2.2a. Loading DEM data tiles.

Before going further, you need to know two properties of DEM tiles you have. The 'No-data value' and the 'Coordinate reference system'. Both of them you can see by opening the properties ('right-click' on the DEM list in the panel and select 'Properties'). They are under the 'General' Tab (Fig 2.2.2b). If your DEM is SRTM 1 arc-second: No-data value = -32767, and Coordinate reference system = EPSG: 4326 – WGS 84. So note them.

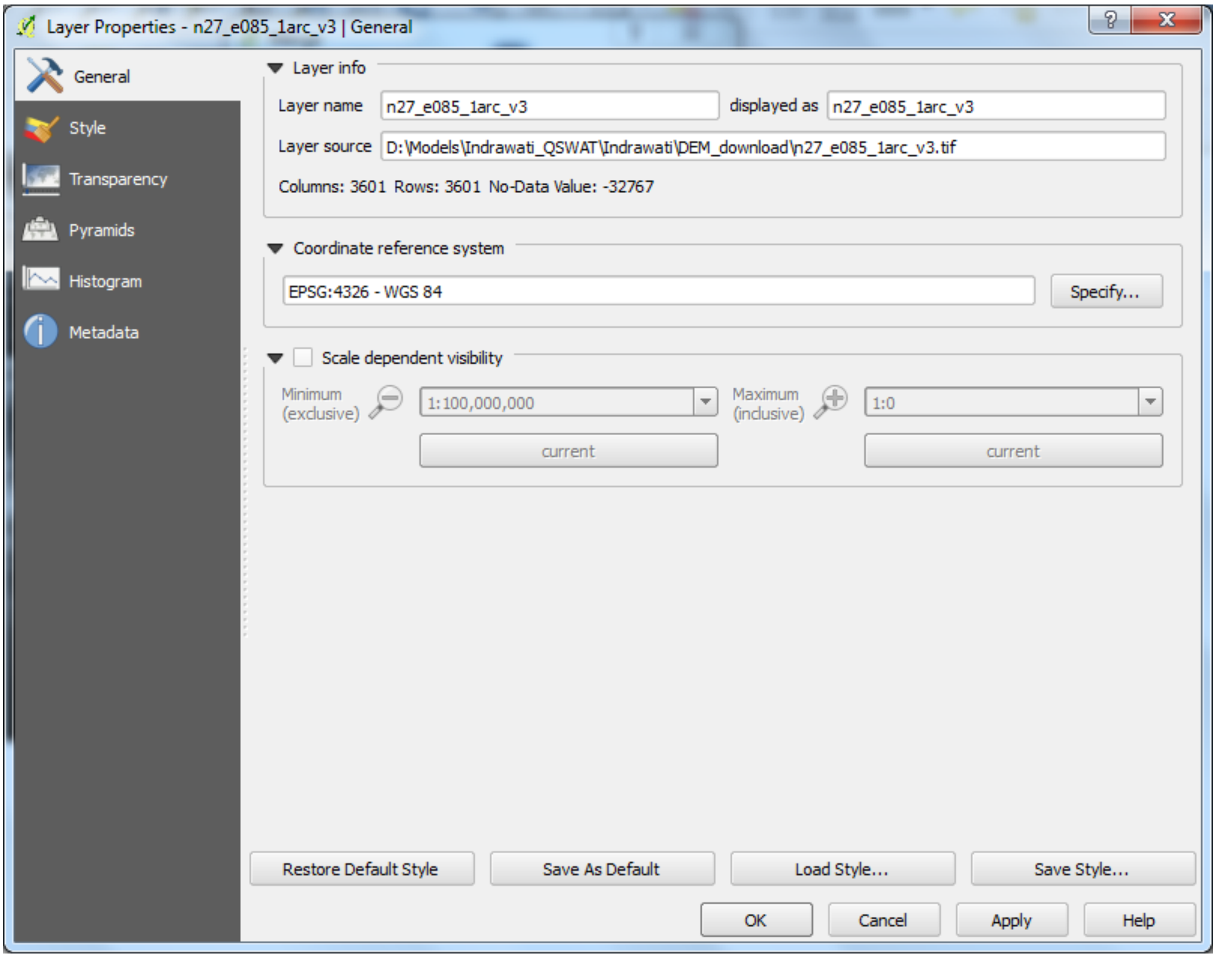


Figure 2.2.2b. Checking data properties (e.g. No-data value and coordinate reference system).

2.2.3 Stitch (or merge) DEM data file

To stich the tiles [If you have only one tile skip this step!]

- Select from the menu: Raster – Miscellaneous – Merge.
- For the input files box, choose the right folder and select all the tiles holding the Ctrl key. Give a new name for the output file box, e.g. 'My_Merged_DEM.tif'. You see that the selected files appears in the box at the bottom panel of the form. Specify the 'No-data value' you noted earlier from the DEM properties.
- Click 'OK' to proceed merging. If everything goes fine, you will need two more OK clicks and you will have your merged DEM!

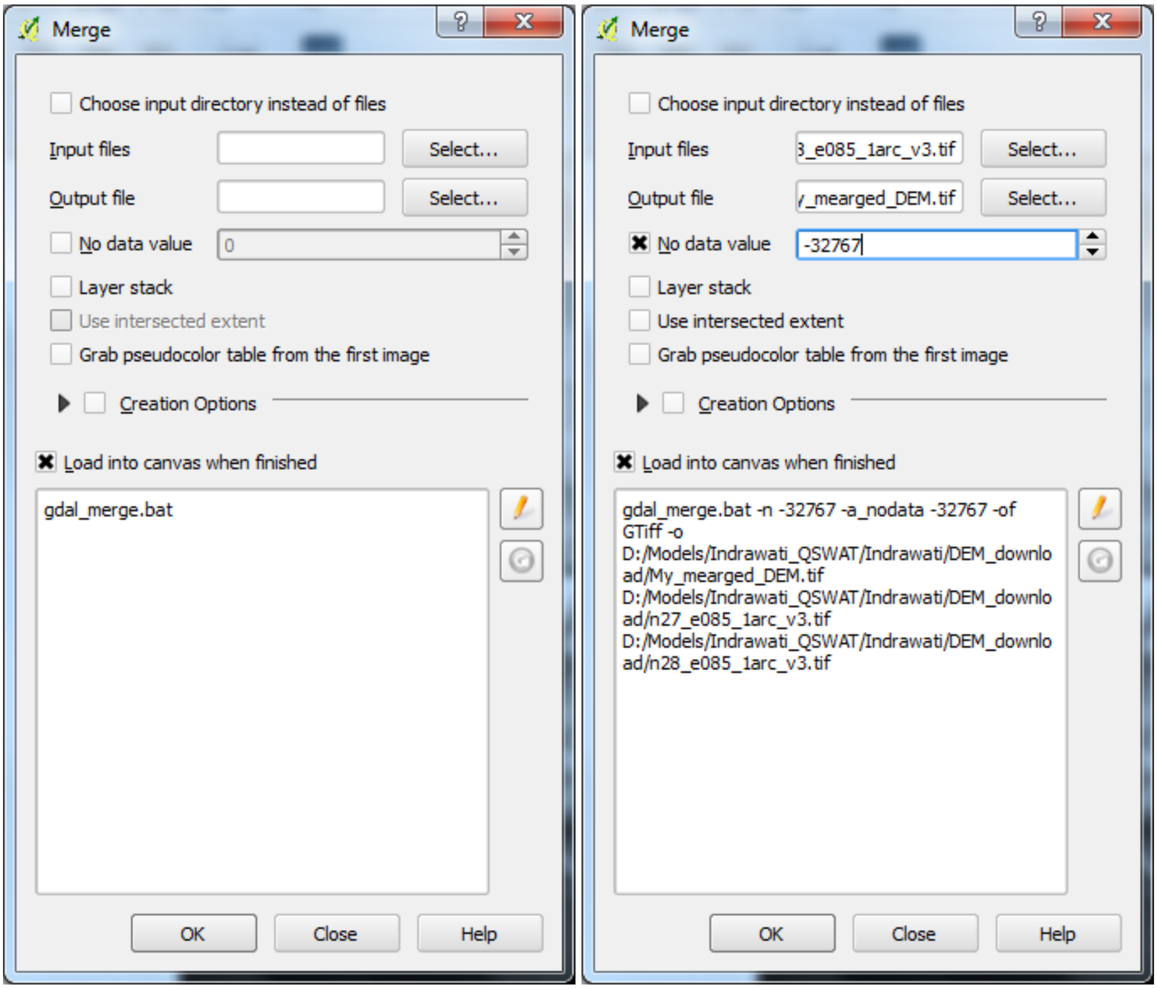


Figure 2.2.3. Stich (Merge): Selecting input/output files - before (left), after (right).

2.2.4 Extract (or clip) DEM data

Now you have stitched all the necessary tiles, but most likely you do not need the entire area covered by the merged (or stitched) DEM. So the next step is to extract only the area (rectangular) within the merged DEM necessary for your catchment. To do this we use the Clipper in QGIS.

- Select from the menu: Raster – Extraction – Clipper.
- For the Input file selected the merged DEM (from the draw-down box), and give a new name for the Output file, e.g. My_Clipped_DEM.tif. Similarly specify the same No-data value as you did while merging the DEM.
- In the x/y box specify the Longitudes (X) and Latitudes (Y) to cover the catchment boundary, which you have noted at the beginning of this exercise. If you have noted exact lat/lon boundaries of the catchment, specify a little more space adding about 0.1 to 0.2 (a thumb rule) to all four side of the boundary.
- Click OK to get the clipped DEM.

You see (Fig. 2.2.4) that there is an option to use a catchment boundary mask if you have one. If you prefer this option, I invite you to try this yourself.

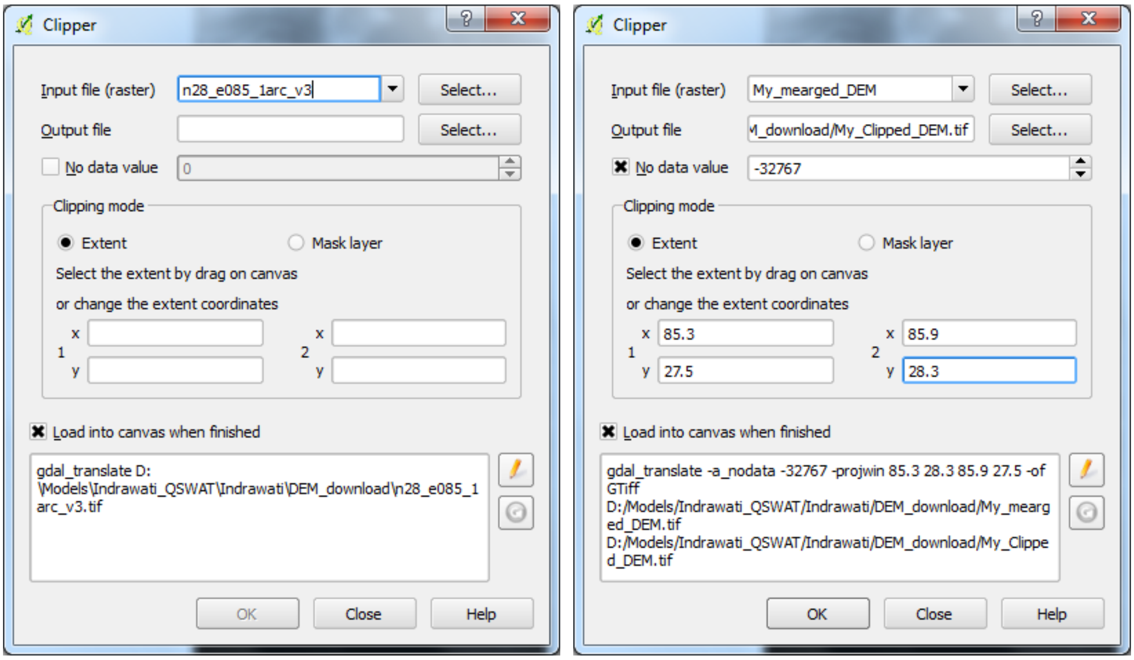


Figure 2.2.4. Extract (Clip): Specifying parameters for clipping - before (left), after (right).

2.2.5 Reproject DEM data

The final step for preparing DEM file is reprojection. You checked the coordinate reference system used for the SRTM DEM. It is in WGS 84 (World Geodetic System 84), which uses longitude and latitude for X and Y coordinates. The GPS (Global Positioning System) also uses WGS 84. For SWAT model, we need to convert this to a unit (e.g. meter) with equal area projection. A commonly used transformation for SWAT is UTM (Universal Transverse Mercator) system, which is not exactly equal-area transformation but considered close enough for catchment sizes commonly used in SWAT modelling[1]. If your catchment is very large with considerable difference in latitudes, you may need to use an equal-area projection. Note that all the spatial data used for SWAT must be in the same projection system.

UTM grid zone

To reproject to UTM, you also need to know the grid zone number for your catchment location, which you can find from this link: http://www.dmap.co.uk/utmworld.htm. For example for the example catchment (Indrawati catchment, Nepal) the Zone number is 45N. So the UTM conversion system you are looking for is WSG 84/UTM Zone 45N. N for northern hemisphere. You can also calculate the zone number from the central longitude of the catchment as follows: (Longitude + 180) / 6, and round up to the next integer number[1].

[1] George, C. (2015). Preparing global DEM data for QSWAT, Version 2. URL: https://swat.tamu.edu/software/qswat/, accessed 20-09-2019.

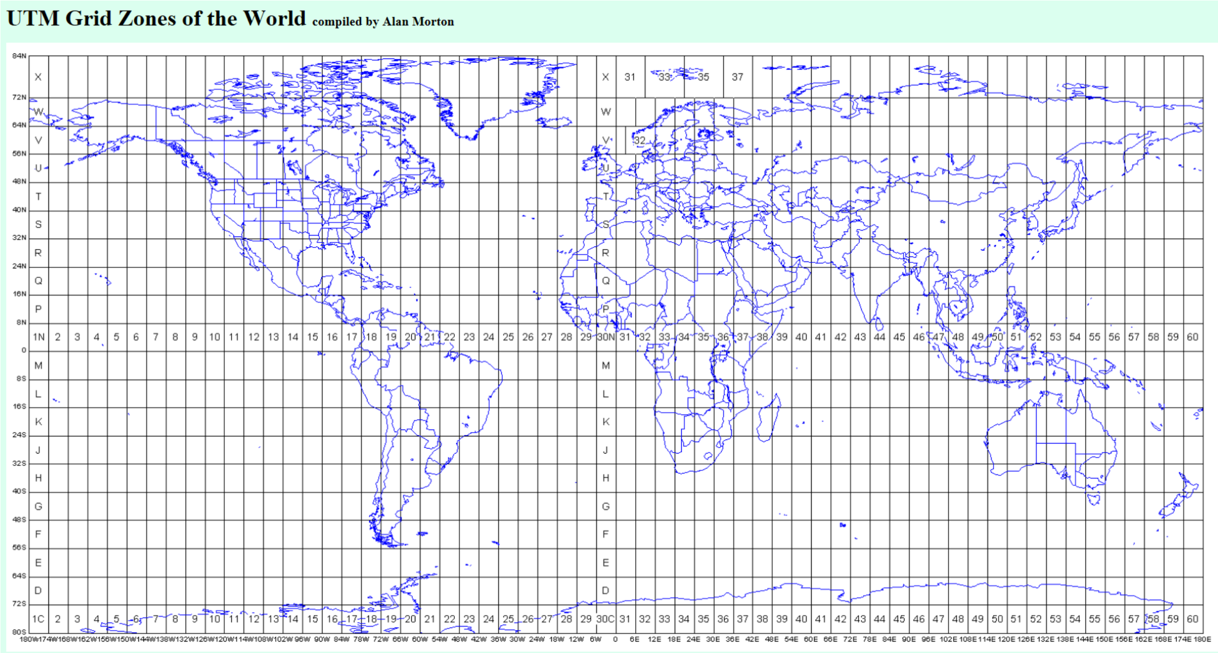


Figure 2.2.5a. UTM grid zones (http://www.dmap.co.uk/utmworld.htm).

For reprojection,

- Select from the menu: Raster – Projection – Wrap (Reproject)
- Select the earlier clipped DEM file for the 'Input file' box and give a new name for the output file, e.g. My_Projected_DEM.tif. Similarly the 'No-data value' -32767 as earlier. There are two selections: the Source SRS and Target SRS. SRS represents Spatial Reference System. When you check the boxes for the Source SRS the reference system of the clipped DEM already appears; remember the coordinate system you noted earlier (EPSG: 4326 – WGS 84). You see only the first part in the box, which is the EPSG[2] code of the projection.
- The name for the Target SRS is blank; click the selection tab. A new form will appear, where you can select the required projection, in our case WGS 84 / UTM Zone 45N.
- To make the selection easier, type WSG 84 in the filter, then the other two boxes show only those related to WGS 84. In the next box, you will likely see WGS 84, select it. Then in the next box, select WSG 84 / UTM with the correct Zone (in this example 45N), which is under 'Projected Coordinate…' / 'Universal Trans…(UTM)'. Look at the 'Selected CRS' box to make sure you selected the correct projection. Then click OK. This returns you to the earlier window 'Wrap (Reproject), and the selected projection appears in the Target SRS box.
- Click OK here again, and if everything goes fine, you will have your reprojected DEM!
- Now you have the required DEM for your SWAT model. Hurrah!

[2] EPSG = European Petroleum Survey Group.

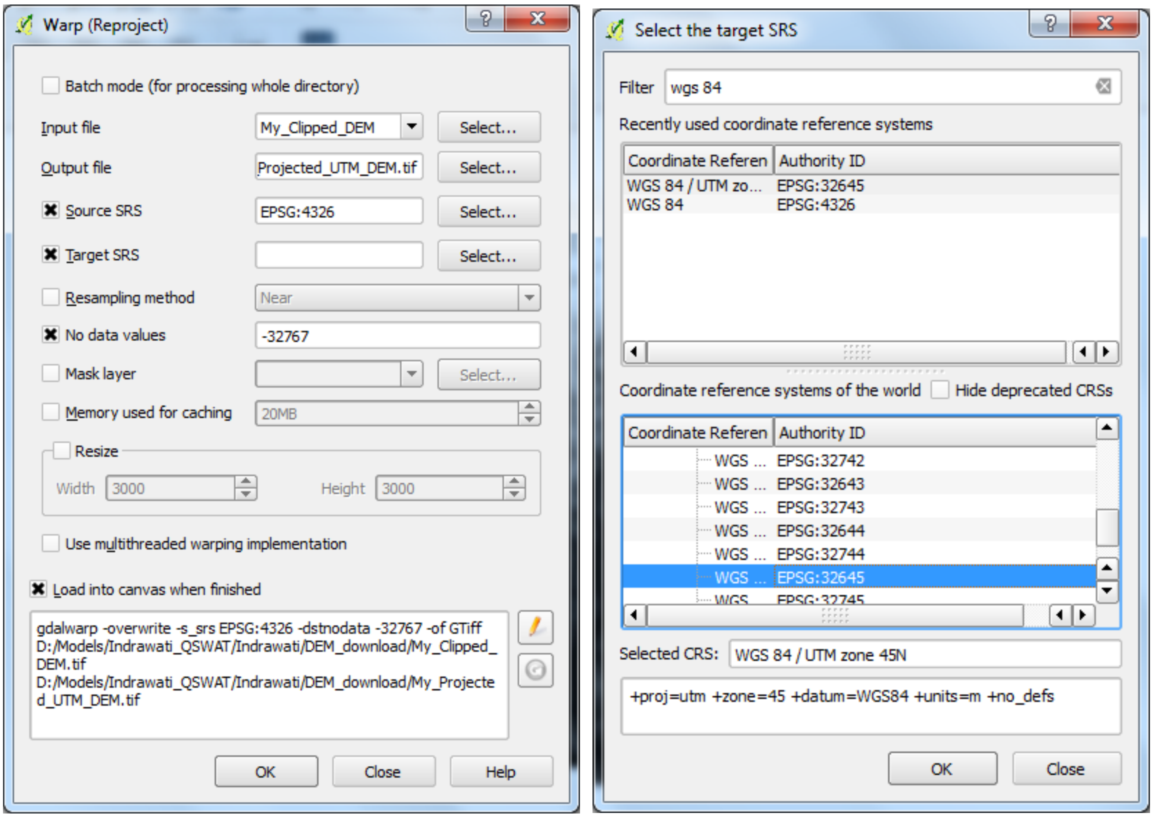


Figure 2.2.5b. Reprojection (Wrap): Specifying input/output files (left), selecting the Target SRS (right).

2.3 Prepare landuse data for QSWAT

Remember the steps used for DEM data preparation? **Download**, **Load**/open with QGIS, **Stitch** (Merge), **Extract** (Clip), and **Re-project**. We follow the same steps for landuse data preparation.

2.3.1 Download landuse data

The WaterBase also has a link to global Landuse and Soil data. It is the same web page where you find link to download the landuse data (www.waterbase.org/download_data.html). As you can see in Fig. 2.3.1a, the landuse maps are shown in five continental groups, and in two spatial resolutions. The spatial resolutions are 400 m (at the equator) for the original version and 800 m for the resampled version.

To download the landuse data,

- Open the WatarBase website: www.waterbase.org/download_data.html
- Find out which continent you need and which resolution you want. For our example (Indrawati catchment, Nepal), we need Euro/Asia, and let's choose the 400 m resolution, i.e. the Euro/Asia (original).
- So, right-click on the 'Euro/Asia (original)' link, and choose 'Save target as'. Choose the folder where you want to download. It will download a zipped file 'ea_landuse.zip'.
- If you unzip 'ea_landuse.zip' file, you will see that there are four sets of landuse data that cover different parts of Euro-Asia. These four sets are named ea_land_1, ea_land_2, etc. The Indrawati catchment (and Nepal) is on ea_land_3. Note that each set has five files with

different extensions, e.g. .bmp, .prj, etc. The land coverage by ea_land_3 is shown in Fig. 2.3.1b.

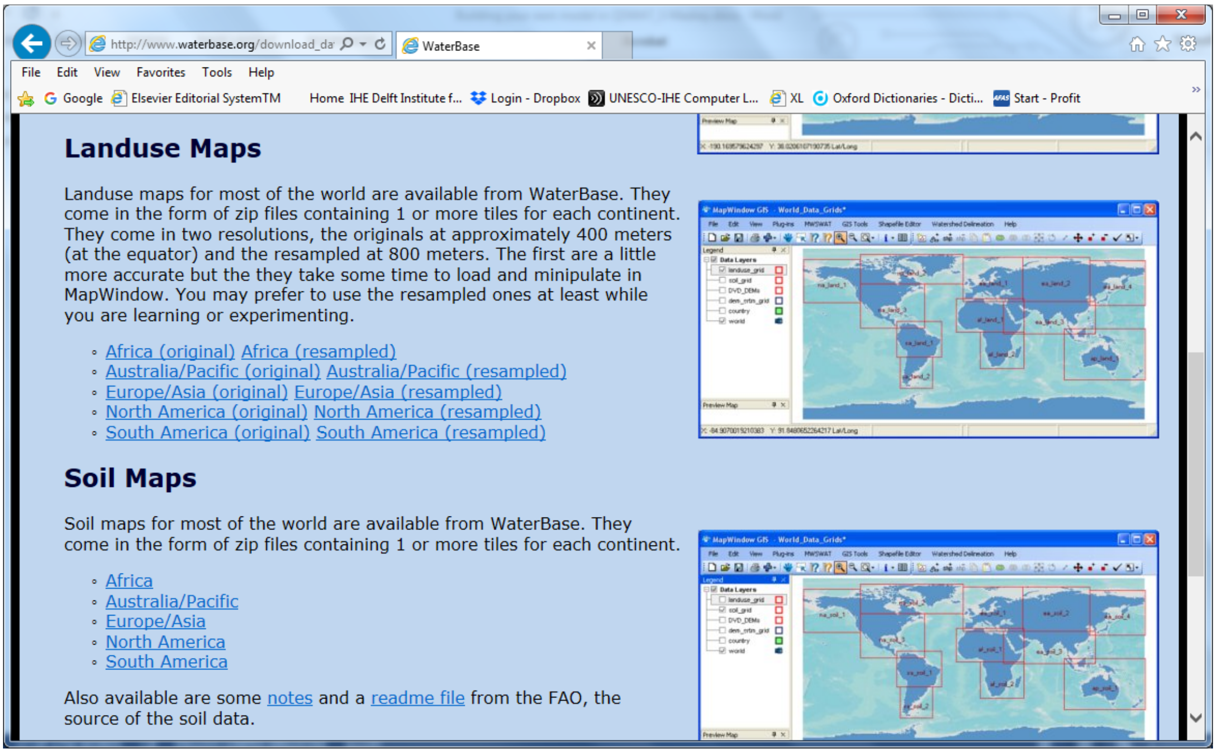


Figure 2.3.1a. Links to landuse and soil data download

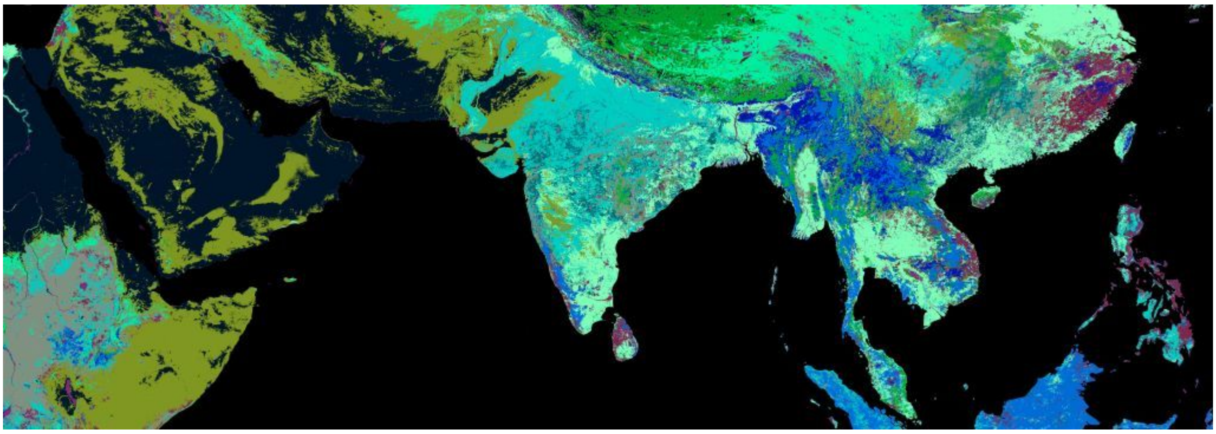


Figure 2.3.1b. Landuse map: ea_landuse -> ea_land_3.

2.3.2 Extract (or clip) landuse data

You see that you actually need only a small area covered by ea_land_3. So we need to extract the area for your catchment (Indrawati) using the same extraction procedure we did with the DEM. Note also that we do not need the Stitch (or merge) step here that we used with the DEM data because one tile covers the whole basin. To Extract (Clip),

- Select from the menu: Raster – Extraction – Clipper.

- For the Input file select the ea_land_3.tif (from the draw-down box; if not in the drop-down list, then click the select button and choose the file from the folder where you have saved it). Give a new name for the Output file, e.g. My_Clipped_landuse.tif.
- Specify the same No-data value; use the same No-data value that is in the unclipped landuse file, which you can see by opening its properties. As you can see this landuse data has -9999 for No-data values.
- In the x/y box specify the Longitudes (X) and Latitudes (Y) to cover the catchment boundary, which you have noted at the beginning of this exercise. If you have noted exact lat/lon boundaries of the catchment, specify a little more space adding about 0.1 to 0.2 (a thumb rule) to all four side of the boundary. To have an uniformity it is recommended to use the same lat/lon extend to all spatial files (DEM, landuse, soil) but does not have to be.
- Click OK to get the clipped landuse.

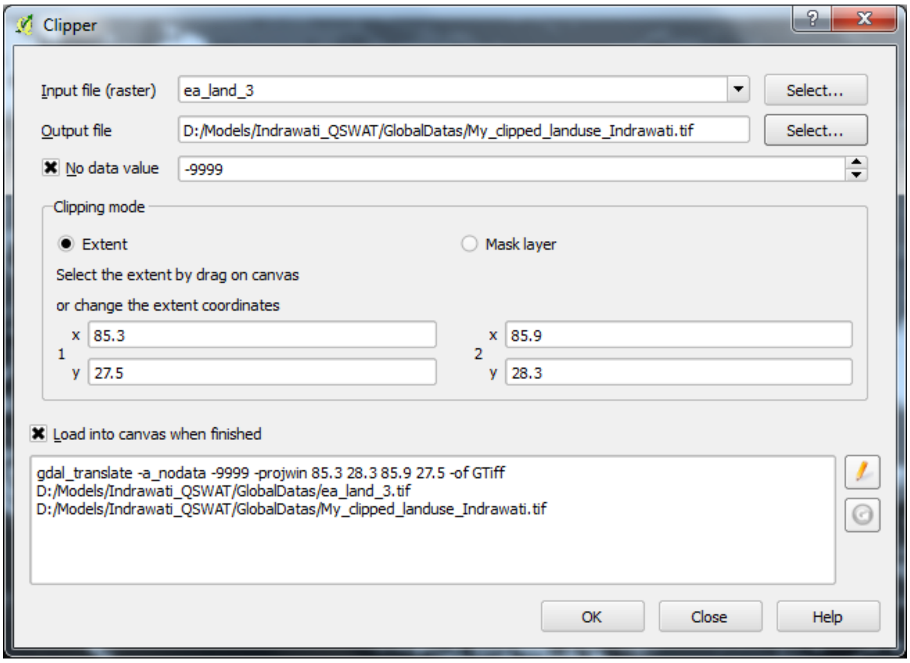


Figure 2.3.2. Extract (Clip): After specifying parameters for clipping.

2.3.3 Reproject landuse data

You also need to reproject the landuse data in the same way the DEM was reprojected to the same projection system. Remember? You used the WSG 84/UTM Zone 45N?

For reprojection,

- Select from the menu: Raster – Projection – Wrap (Reproject)
- Select the clipped landuse file for the ‘Input file’ box and give a new name for the output file, e.g. My_Projected_Landuse.tif. Similarly use the ‘No-data value’ -9999 as earlier.
- There are two SRS selections: the Source SRS and Target SRS. SRS represents Spatial Reference System. When you check the boxes for the Source SRS the reference system of the clipped landuse already appears; remember the coordinate system you noted earlier (EPSG:

4326 – WGS 84). You see only the first part in the box, which is the EPSG[3] code of the projection.

- The name for the Target SRS is blank; click the selection tab. A new form will appear, where you can select the required projection, in our case WGS 84 / UTM Zone 45N.
- To make the selection easier, type WSG 84 in the filter, then the other two boxes show only those related to WGS 84. In the next box, you will likely find WGS 84, select it. Then in the next box, select WSG 84 / UTM with the correct Zone (in this example 45N), which is under 'Projected Coordinate…' / 'Universal Trans…(UTM)'. Look at the 'Selected CRS' box to make sure you selected the correct projection. Then click OK. This returns you to the earlier window 'Wrap (Reproject), and the selected projection appears in the Target SRS box.
- Click OK here again, and if everything goes fine, you will have your reprojected landuse map of the Indrawati basin ready to be used with the SWAT model. Congratulations!

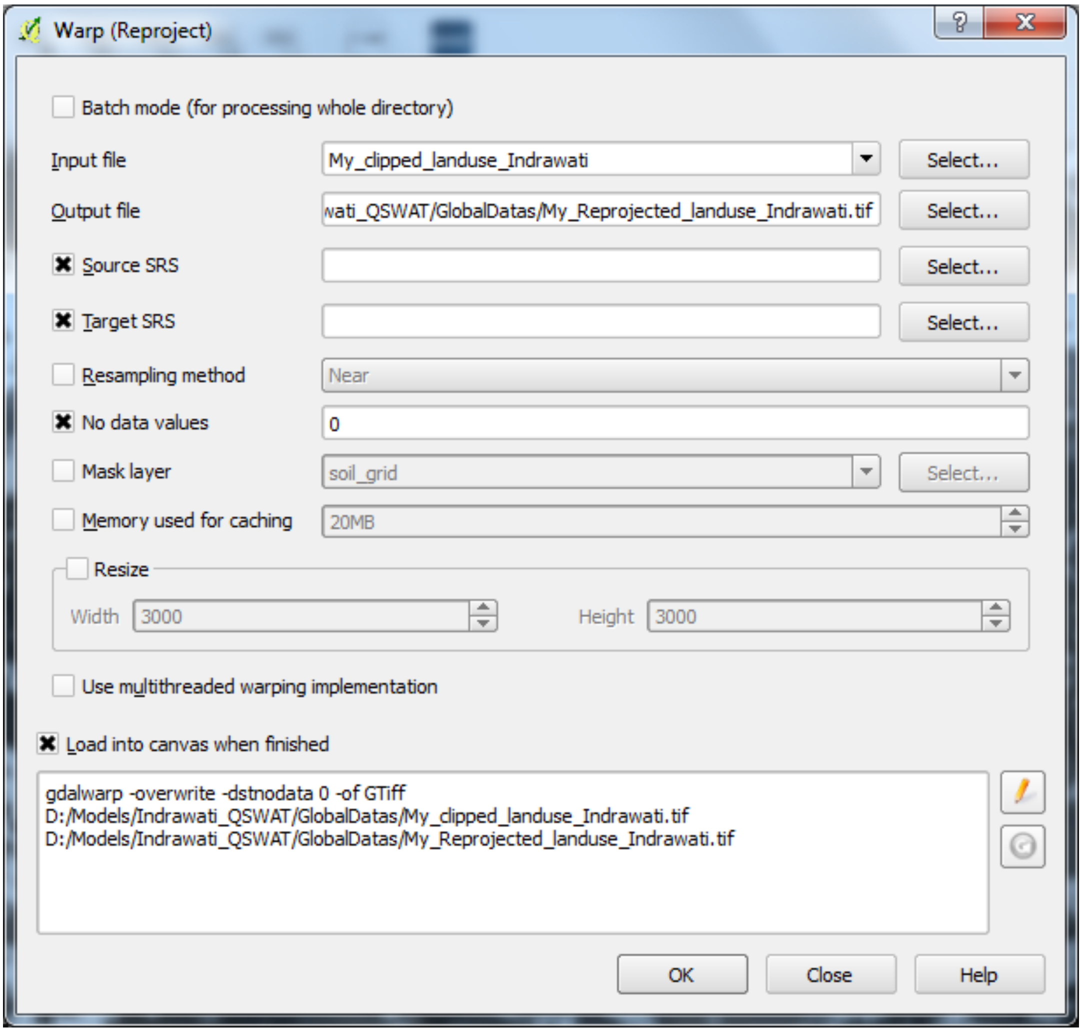


Figure 2.3.3a. Reprojection (Wrap): Specifying input/output files (left), selecting the Target SRS (right).

[3] EPSG = European Petroleum Survey Group.

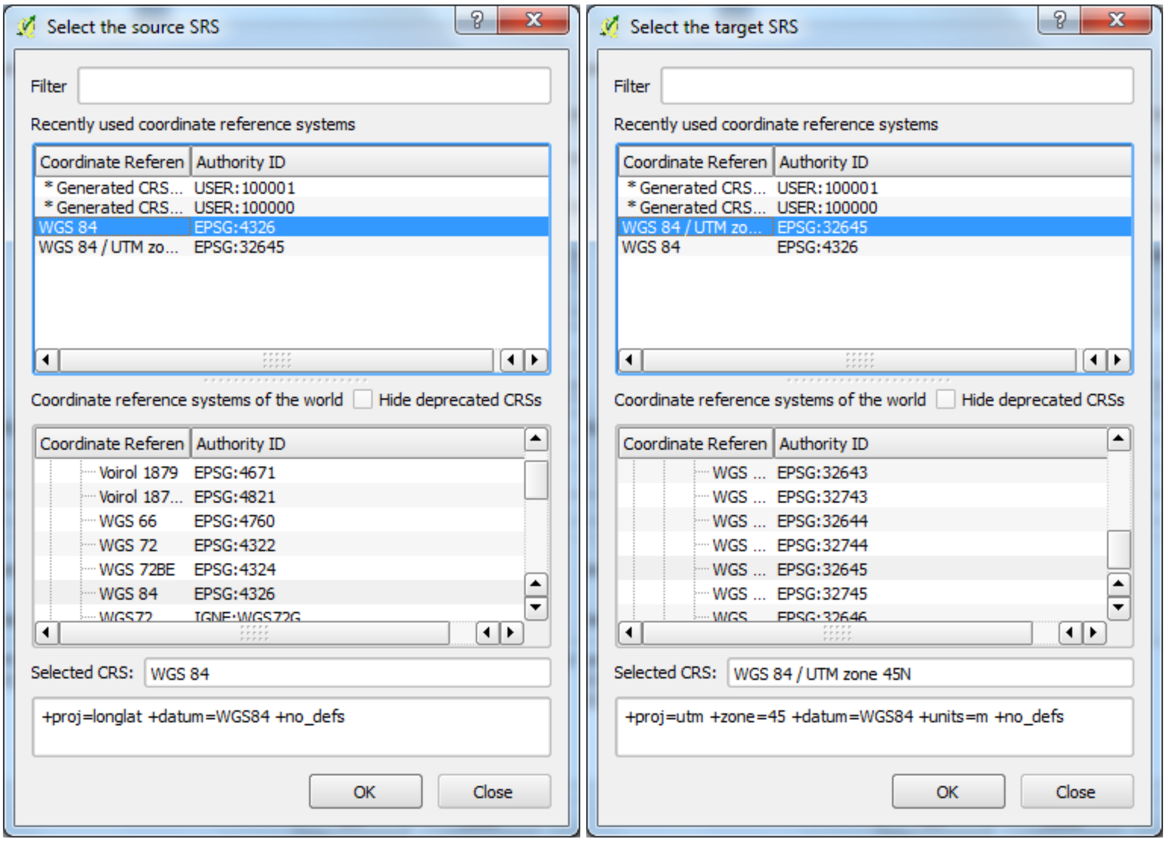


Figure 2.3.3b. Reprojection (Wrap): Selecting the Source SRS (left) and Target SRS (right).

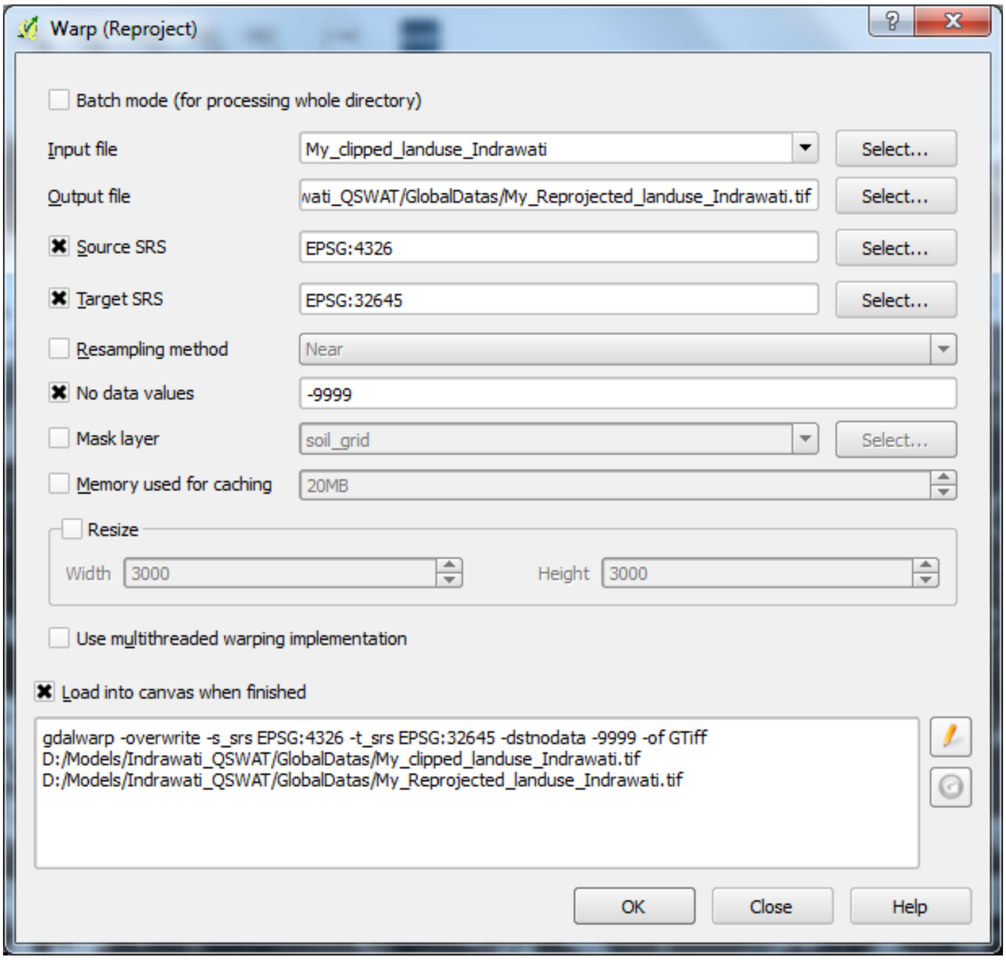


Figure 2.3.3c. Reprojection (Wrap): After parameters specified.

2.4 Prepare soil data for QSWAT

2.4.1 Download soil data

The link to the soil data (in the WaterBase web page) is shown in Fig. 2.3.1a. The links are listed according to the continents. To download

- Find out which continent you need. For our example (Indrawati catchment, Nepal), we need Europe/Asia.
- So, right-click on the 'Europe/Asia' link, and choose 'Save target as'. Choose the folder where you want to download. It will download a zipped file 'ea_soil.zip'.
- Unzip the 'ea_soil.zip' file, and you will see there are four sets of soil data files numbered 1 to 4. Each set has five different files indicated by different file extensions. The Indrawati catchment (and Nepal) is on the third tile, ea_soil_3. The land coverage by ea_soil_3 is shown in Fig. 2.4.1.

Figure 2.4.1. Soil map: ea_soil -> ea_soil_3.

2.4.2 Extract (or clip) soil data

You probably noticed that we actually need only a small area covered by ea_soil_3. So we need to extract the area for your catchment (Indrawati) using the same extraction procedure we did with the DEM. To Extract

- Select from the menu: Raster – Extraction – Clipper.
- For the Input file select the ea_soil_3.tif (from the draw-down box; if not in the drop-down list, then click the select button and choose the file from the folder where you have saved it). Give a new name for the Output file, e.g. ea_soil_3_clipped_Indrawati.tif.
- Similarly specify the same No-data value; use the same No-data value that is in the unclipped landuse file, which you can see by opening its properties. (In this case -9999)
- In the x/y box specify the Longitudes (X) and Latitudes (Y) to cover the catchment boundary, which you have noted at the beginning of this exercise. If you have noted exact lat/lon boundaries of the catchment, specify a little more space adding about 0.1 to 0.2 (a thumb rule) to all four side of the boundary. To have an uniformity it is recommended to use the same lat/lon extend to all spatial files (DEM, landuse, soil) but does not have to be.
- Click OK to get the clipped soil map.

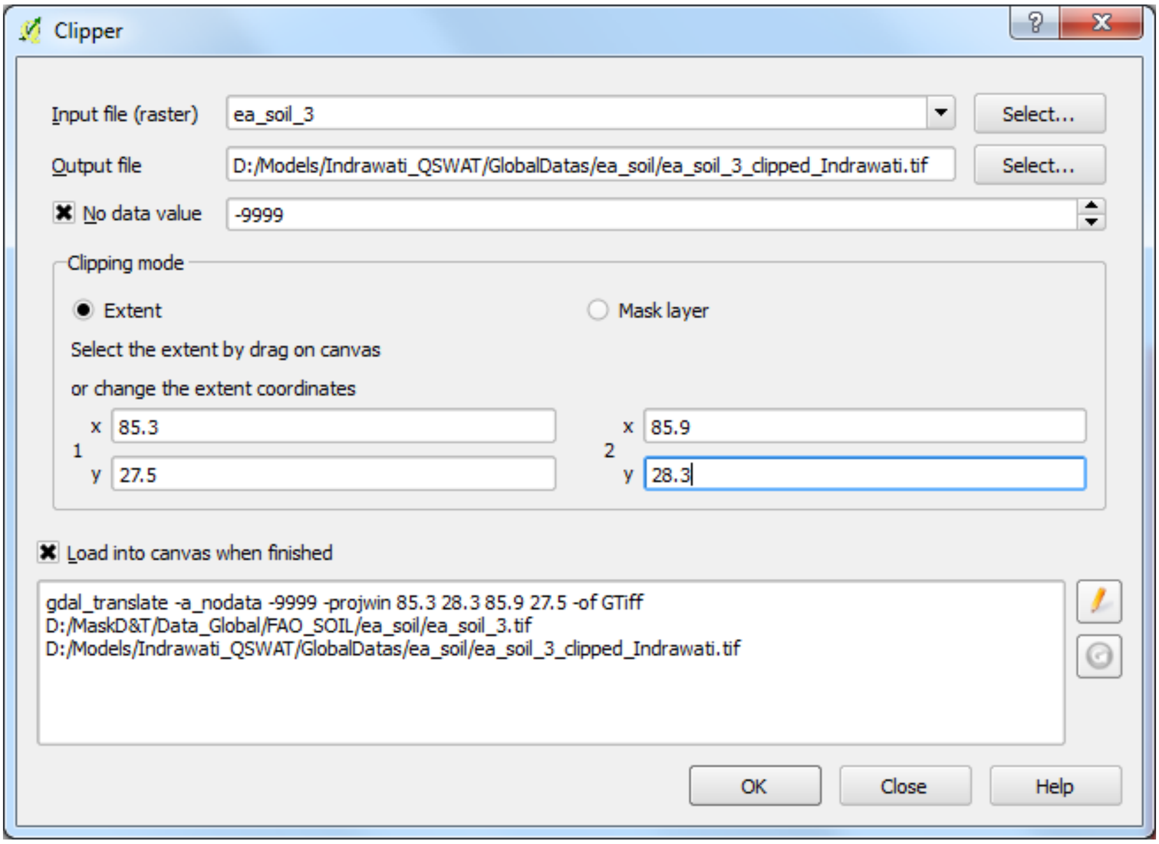


Figure 2.4.2. Extract (Clip): After specifying parameters for clipping.

2.4.3 Reproject soil data

You also need to reproject the landuse data in the same way the DEM was reprojected to the same projection. Remember? You used the WSG 84/UTM Zone 45N.

For reprojection

- Select from the menu: Raster – Projection – Wrap (Reproject)
- Select the clipped Soil data file for the 'Input file' box and give a new name for the output file, e.g. My_Projected_Soil_Indrawati.tif. Similarly use the 'No-data value' -9999 as earlier.
- There are two SRS selections: the Source SRS and Target SRS. SRS represents Spatial Reference System. When you check the boxes for the Source SRS the reference system of the clipped soil map already appears; remember the coordinate system you noted earlier (EPSG: 4326 – WGS 84). You see only the first part in the box, which is the EPSG[4] code of the projection.
- The name for the Target SRS is blank; click the selection tab. A new form will appear, where you can select the required projection, in our case WGS 84 / UTM Zone 45N.
- To make the selection easier, type WSG 84 in the filter, then the other two boxes show only those related to WGS 84. In the next box, you will likely find WGS 84, select it. Then in the next box, select WSG 84 / UTM with the correct Zone (in this example 45N), which is under 'Projected Coordinate…' / 'Universal Trans…(UTM)'. Look at the 'Selected CRS' box to make sure you selected the correct projection. Then click OK. This returns you to the earlier window 'Wrap (Reproject), and the selected projection appears in the Target SRS box.

[4] EPSG = European Petroleum Survey Group.

- Click OK here again, and if everything goes fine, you will have your reprojected soil map of the Indrawati basin ready to be used with the SWAT model.
- Congratulations!

3. Building a SWAT hydrological model

3.1 Make a project folder and copy data

You already have a folder where you processed the DEM, landsue and soil data. You also have a QGIS file (.qgs), which you used to process these data. Now we are doing to build a QSWAT model. Once you start working with the SWAT model you will be overwhelmed with the number of files/folder the model generates. You may find it convenient later if you keep the QSWAT files separate from data processing. So I suggest to create a new folder for your QSWAT model.

- Create a new folder for the QSWAT model you are going to build. You may choose a folder name, something like MyQSWAT.
- Now start QGIS or open the .qgs file that you used to process the data earlier.
- Click on the SWAT tab, which you can find on the QGIS interface. [I am assuming here that you already have QSWAT plugged in to the QGIS.] This will open a QSWAT interface (see Fig. 3.1)
- On the QSWAT interface, select New Project, locate the folder you have created for QSWAT model and give a file name. The file name should better represent your basin. So give a name something like MyBasin.
- Now you will see a new folder under the MyQSWAT folder with a name MyBasin. You will also find the MyBasin.qgs file under the same folder. Under the MyBasin there are three folders (Scenarios, Source and Watershed) and two .mdb files (MyBasin.mdb and QSWATref2012.mdb), like this

  D:\MyQSWAT

  \MyBasin

  \Scenarios

  \Source

  \Watershed

  …MyBasin.mdb

  …QSWATref2012.mdb

  …MyBasin.qgs

- Have a look inside MyBasin folder. There are more files and folders! Guess what each of these files/folders is for.
- If you like you can add a new folder under MyQSWAT to copy the processed DEM, landuse, soil data sets (clipped/reprojected). This way you will always know where your source data for your QSWAT model. This is useful if you need to rebuild your QSWAT model. This is an optional step. If you want to do this, create a new folder, e.g. SourceData and for the time being create three more folders under SourceData, one for DEM, Landuse and Soil each. Then copy the final processed DEM, landuse and soil data sets into the respective folders.

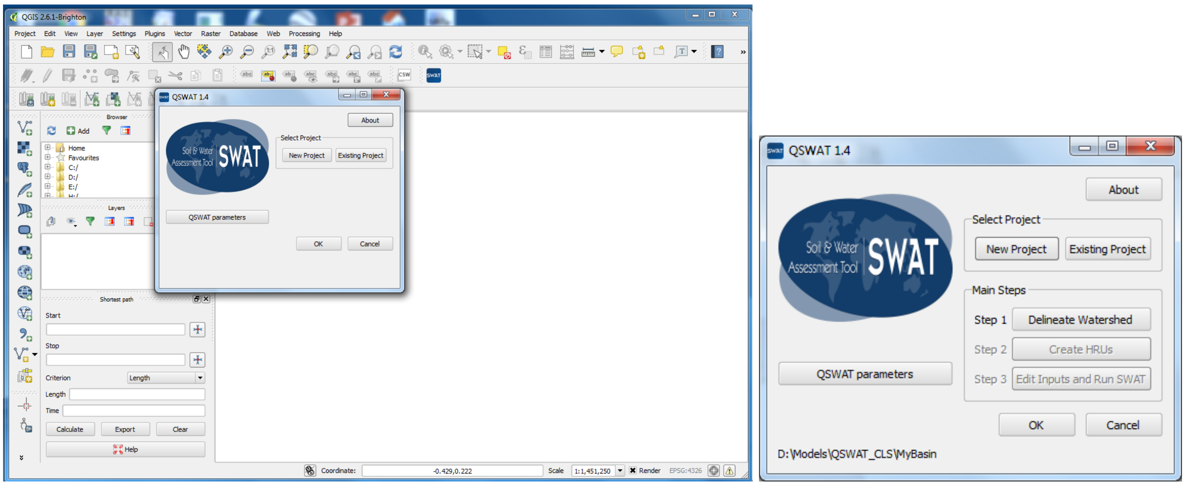


Figure 3.1. QSWAT interface on QGIS: before (left) and after (right) the QSWAT file has been created.

3.2 Delineate the catchment

After you have all the data files and folders ready, the first step to build a SWAT or QSWAT model is to delineate the catchment. To delineate, first

Specify the DEM file

- Select 'Delineate Watershed'
- On the new interface page (Fig. 3.2a), click the button for Select DEM and locate the folder where you have your final DEM file.
- If you select a valid DEM file, the file name will appear in the box on the interface (Fig. 3.2b). Look at the file location (folder). QSWAT saves this file into the folder Source under basin folder MyBasin.

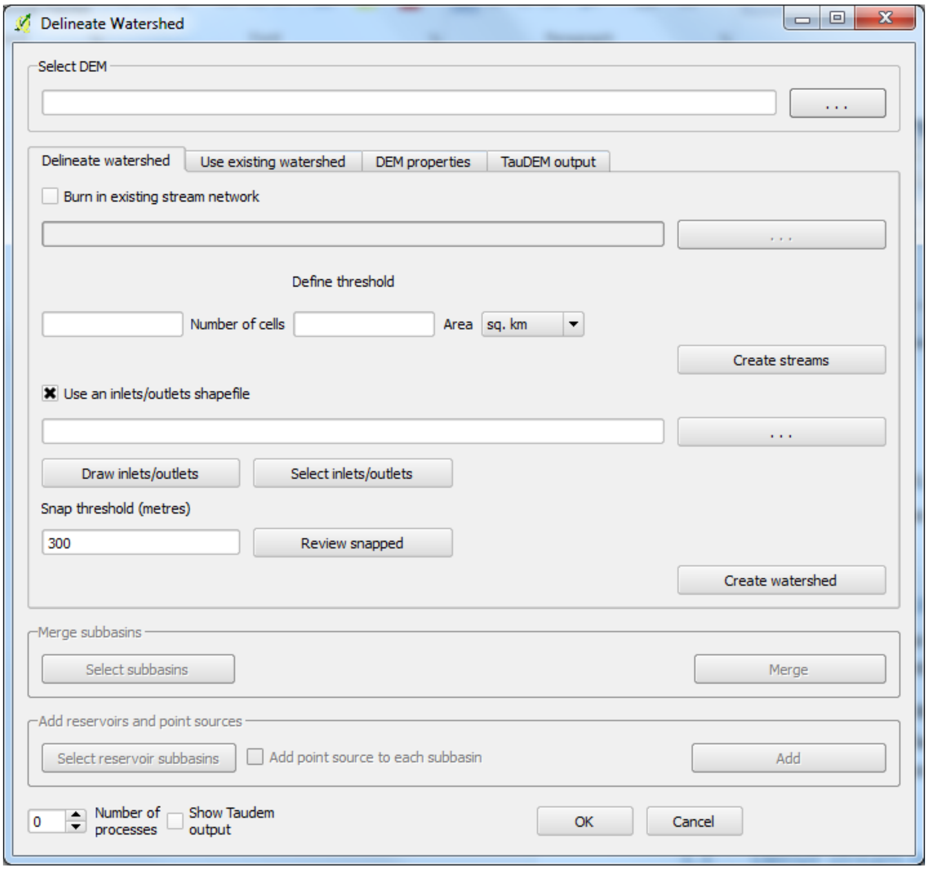
Derive stream network

- In a panel below the file name you can see 'Define threshold' below which you see a suggested threshold (number of cells and area in km^2).
- You can change the threshold area for delineation. It depends on how small watershed areas do you want to represent as a separate subcatchment. E.g. if you specify 100 km^2 for the threshold, it will generate roughly one subcatchment for every 100 km^2 – not exactly but close to. [We will discuss more about this in the class.]
- In practice you may need a couple of trials to get the right number of subcatchments. For now let's keep the default threshold area and see how it goes. With the correct DEM and specified threshold, we can now create streams.
- Click the 'Create stream' button to derive stream network. This process takes some time. It depends on the DEM resolution, stream density, computer speed etc. When complete, you can see the streams as a separate map layer on the DEM (Fig. 3.2c). Note also the added layer "Streams…" on the left panel.

Delineate watershed

- There is one more thing to specify before we can delineate subcatchments, which is to specify the outlet point. Here we do this by directly clicking on the river network. To be able to mark the outlet more accurately, I suggest to zoom in to the outlet point on the DEM/streams map before selecting the create button.

- Click the 'Create watershed'; a new form appears with 'Outlet' as a default selection.
- Then click at the outlet point on the river line. A triangular mark appears on the river indicating the outlet (Fig. 3.2d).
- Note that in reality the area is many times larger than we see on the map. So the point we marked seemingly on the river line is in reality may well be at some distance from the river. That is why there is the 'Snap threshold' is indicated below the 'Create streams' selection option. The default value is 300 m.
- If you make a mistake in indicating the outlet point, you can remove it by selecting Remove with right-click on the "Draw inlets/outlets…" on the left panel. Then you can draw a new point repeating the procedure explained above.
- If you are using the Indrawati basin example, the outlet point is a tricky one. It has to be point very close d/s of the first confluence but upstream of the confluence with large tributary joining from the East.
- When the outlet is properly marked click OK to return to the main form. The select "Create watershed" (Fig. 3.2e). This step may take some time.
- If it worked properly you now have delineated catchments! (Fig. 3.2f, g)
- If necessary you can merge unnecessary catehments, if any, but for now let's skip this step, and select OK to return to the main QSWAT interface.



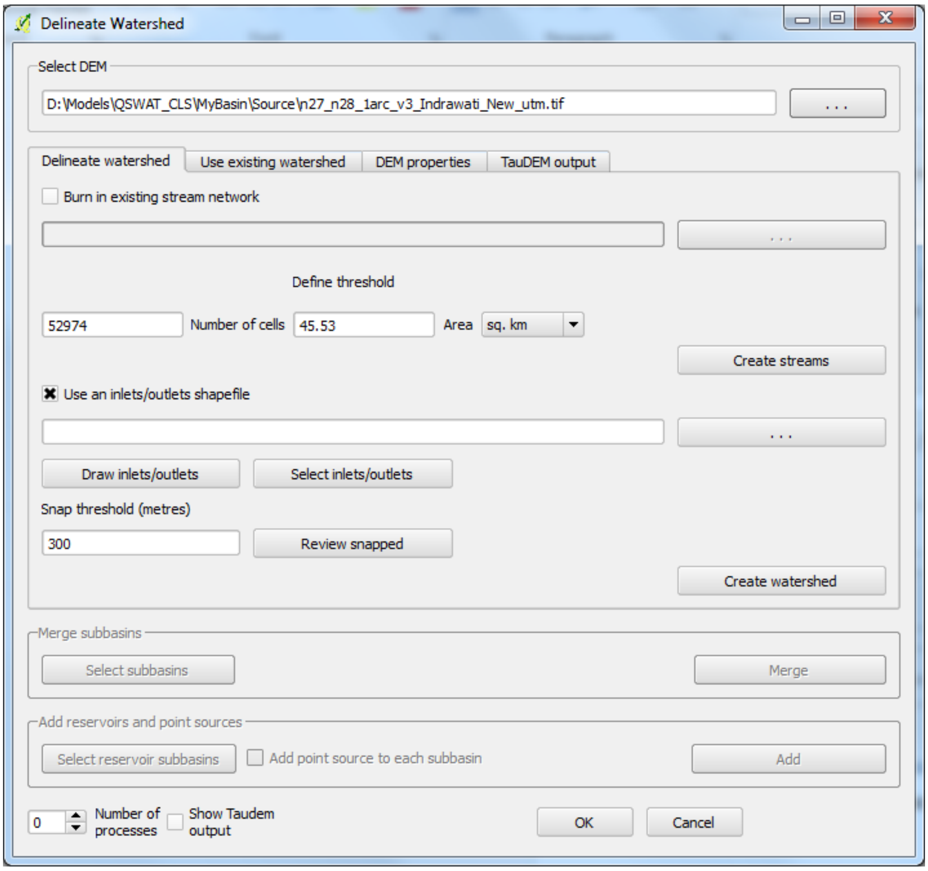


Figure 3.2a, b. Catchment delineation: before (top) and after (down) DEM file selection.

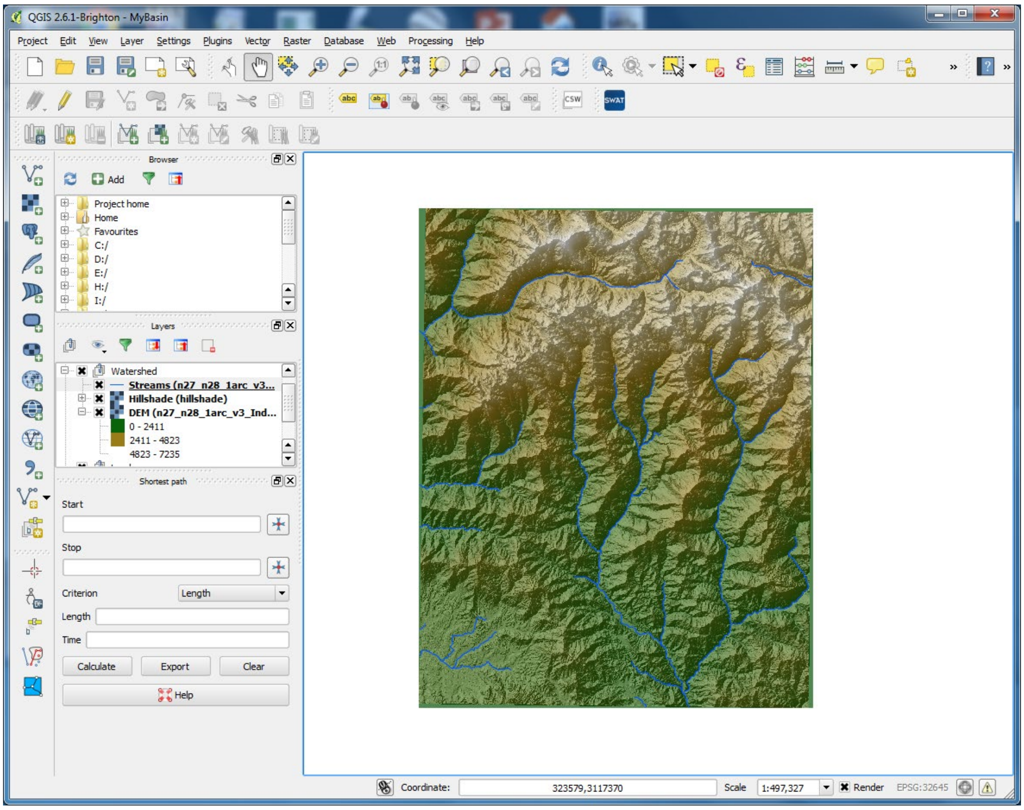


Figure 3.2c. Catchment delineation: after streams have been derived.

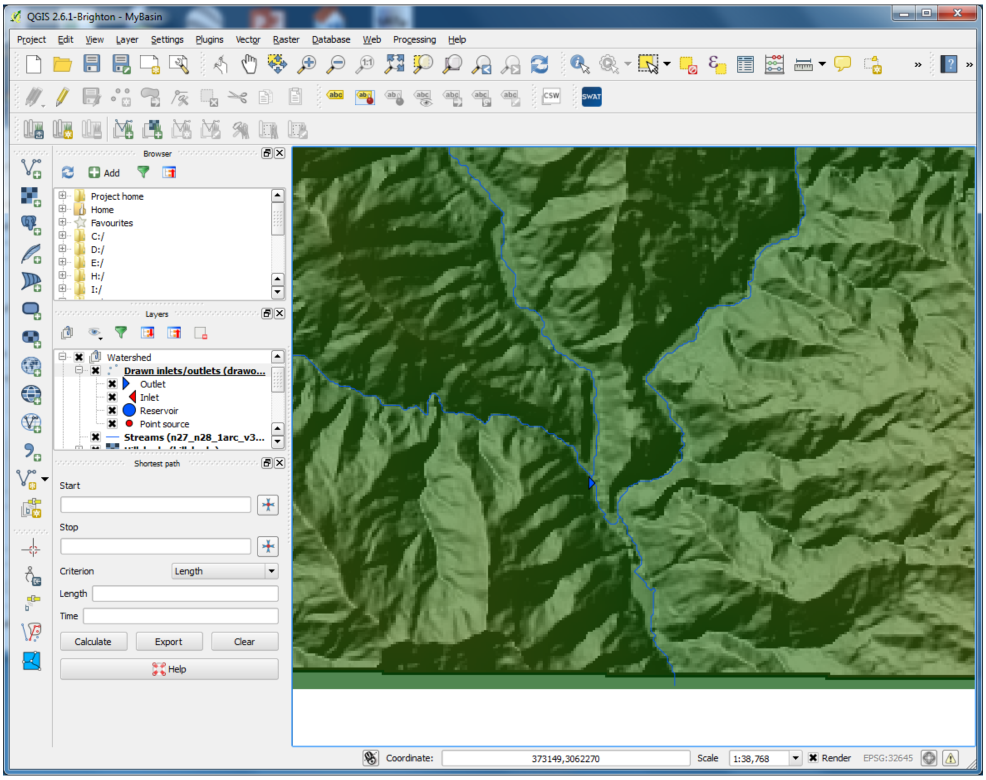


Figure 3.2d. Catchment delineation: The outlet point marked.

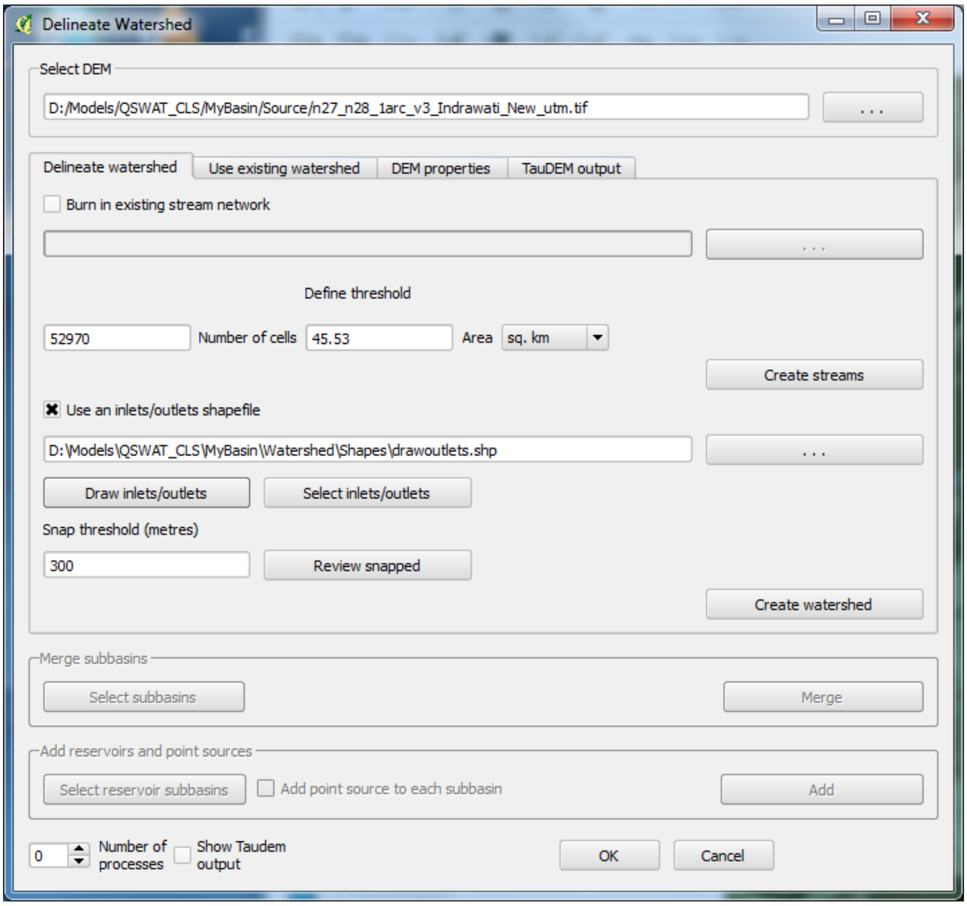


Figure 3.2e. Catchment delineation form after the 'Outlet' point has been marked.

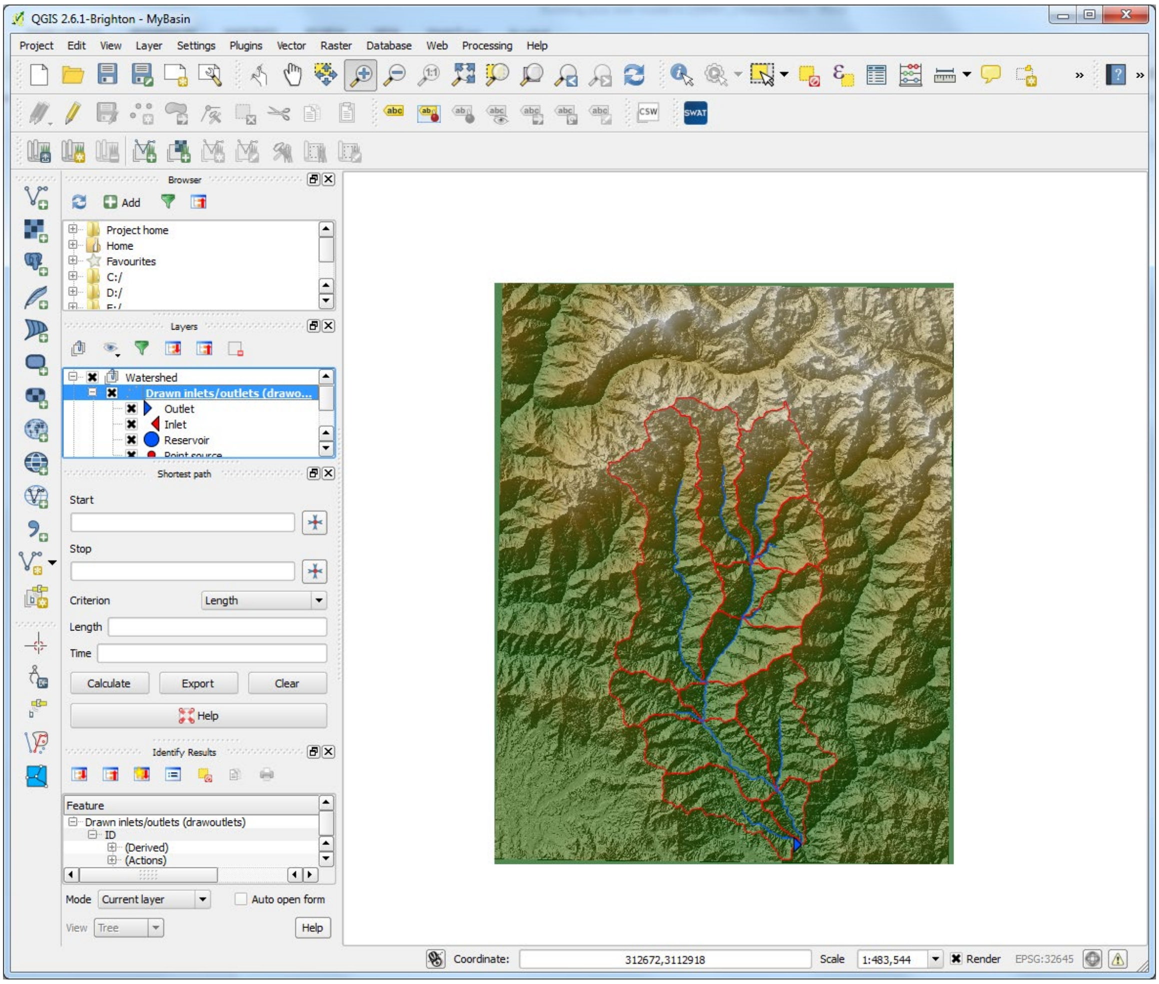


Figure 3.2f. QSWAT after catchment delineation.

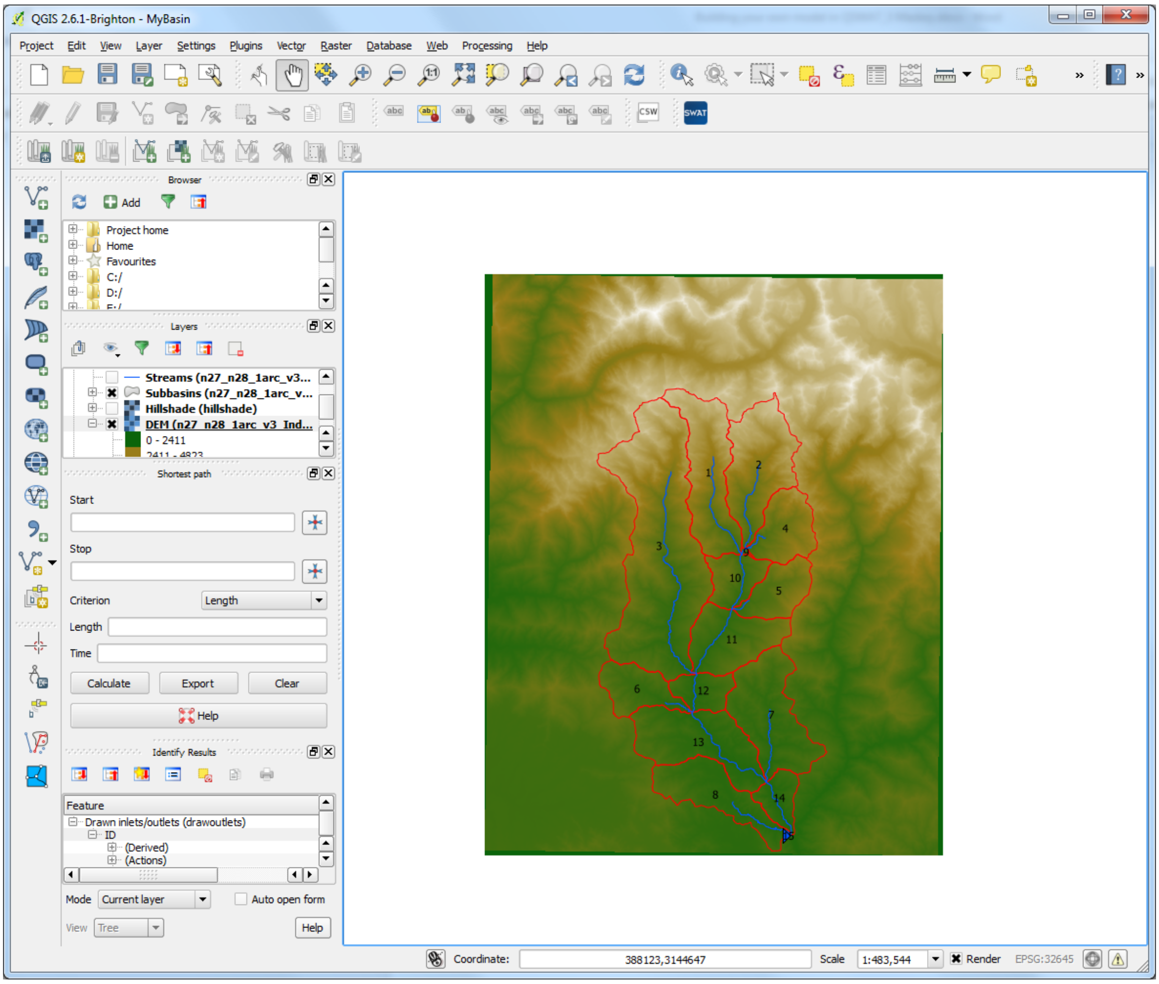


Figure 3.2g. QSWAT after catchment delineation; with Hillslope layer deselected.

3.3 Derive Hydrologic Response Units

Once the catchments are delineated, the next step is to derive hydrologic response units (HRUs). SWAT divides subbasin into a number of HRU's based on landuse, soil and topographic slope. Most computations in SWAT takes place at a HRU level.

When the catchment delineation step was successfully completed, you probably have noticed that the 'Create HRUs' button in QSWAT interface has become active (Fig. 3.3a). To create HRUs

- Click the 'Create HRUs'. A new form will appear (Fig. 3.3b) where you can specify landuse and soil data files and other parameters for HRU generation.
- Select correct files for landuse and soil maps (the one that you prepared for your catchment) by clicking respective buttons.

This is important to understand: The landuse and soil maps you specified have numbers or labels representing different types of landuse or soil, but not any properties of them. What SWAT needs are their properties for hydrological computations. SWAT has a comprehensive reference database which also includes properties of various landuse and soil types. SWAT already copied the reference database named 'QSWATRef2012.mbd' into your basin folder. You may want to look into the MyBasin folder. There are two .mdb files: QSWATRef2012.mbd and MyBasin.mdb. We need to link the numbers in our landuse/soil maps to the correct landuse/soil type in the QSWAT reference database. This we do through a table, called Lookup Table. The LuT should include two columns, one with the landuse/soil type numbers that are in our landuse/soil map and one with a name representing that number, such that the name exists in the QSWAT ref database.

How it works for SWAT? For example for a particular landuse type in our map, it finds a number. It looks in the LuT for that number and find a name attached to the number. Then it looks in the landuse table in the QSWAT ref database for that name. If it finds the name, then there are all necessary properties in the database for that landuse.

It may sound easier, but finding the right name (that exists in the QSWAT database) for a given landuse/soil type (number) in our map is not straight forward, to say the least. [We can discuss about it in the class.] But luckily for QSWAT uses, if you are using the landuse and soil data from the WaterBase link as explained in document, these tables are already there in the project database, in our case, MyBasin.mdb. Have a look into the MyBasin.mdb file. These tables are named 'global_landsues' and 'global_soils'.

To specify the landuse/soil connection to the database

- From the drop-down box (below the Landuse map selection), select 'global_landuses'.
- Similarly from the drop-down box (below the Soil map selection), select 'global_soils'.
- The next step would be instruct SWAT to read and make these connections, but clicking the 'Read' tab, BUT don't do that yet!

Specify slope bands (DO THIS BEFORE selecting 'Read'!) and read landuse and soil maps

- In the right panel, you see there is box for specifying bands for slope. Default is no bands, so slope class is (0, 9999). Suppose you want to make three slope bands (in percentage): 0 to 10, 10 to 30 and more than 30. Then fist type 10 in the box and select 'Insert', and repeat the same for 30. Then you will (0, 10, 30, 9999) in the slope bands.
- Now you can click 'Read' to let QSWAT read the landuse and soil maps.

Specify threshold values (in percentage of area) for landuse/soil/slope classification

- Note that the threshold values in percentage of area under a landuse, soil type or slope class.
- See in the middle panel, for various options. If you select the third option (i.e. 'Filter by landuse, soil, slope'), the right panel will be active where you can specify the threshold percentages.

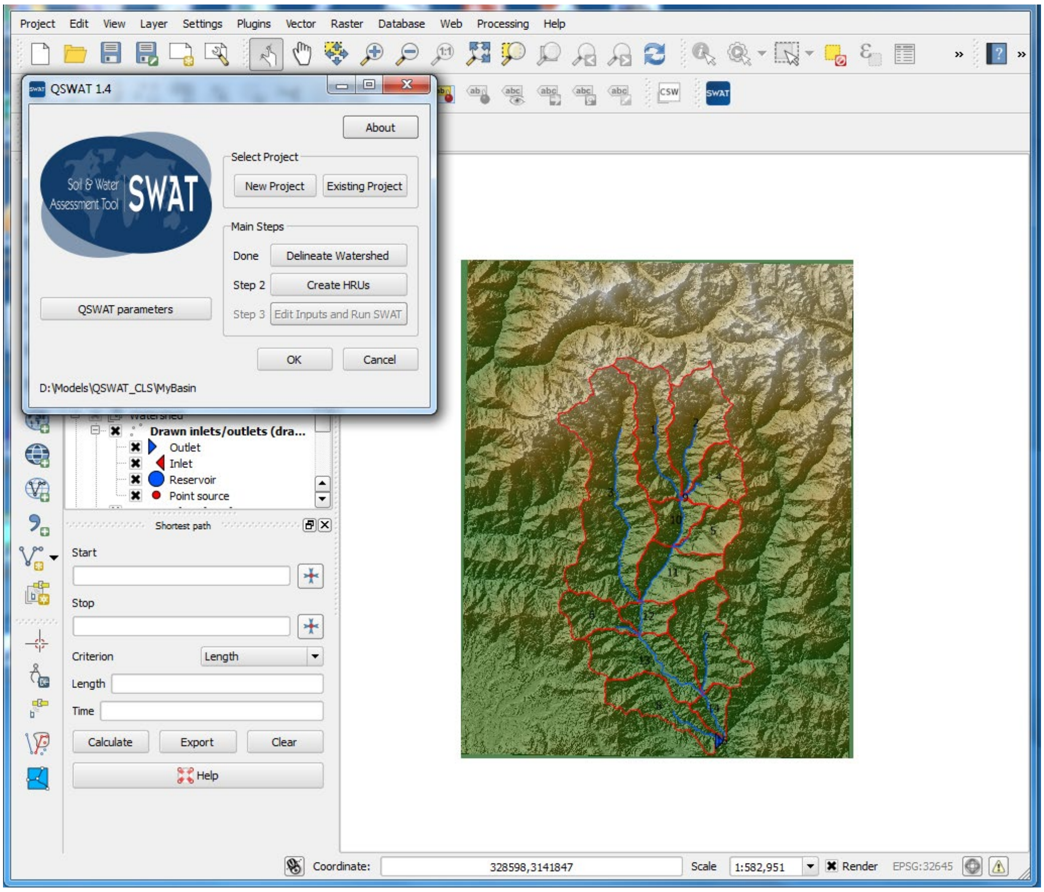
Generate HRUs

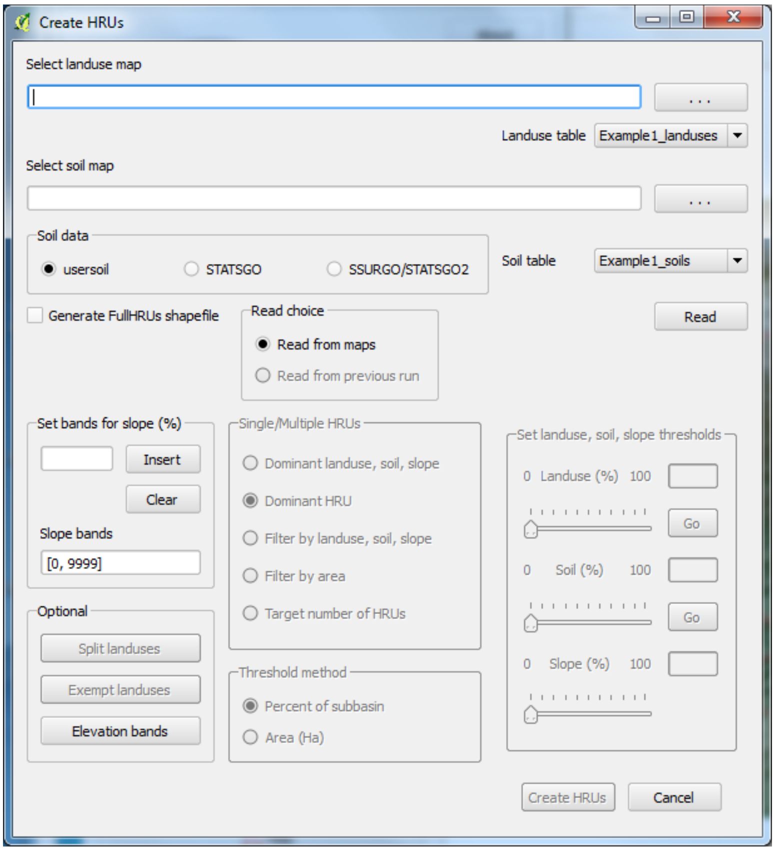
- Finally select the 'Create HRUs' at the bottom of form to generate HRUs.

Table 3.3. An example LOOKUP table: landuse (left), soil (right)

global_landuses	
LANDUSE_ID	**SWAT_CODE**
1	URMD
2	CRDY
3	CRIR
4	MIXC
5	CRGR
6	CRWO
7	GRAS
8	SHRB
9	MIGS
10	SAVA
11	FODB
12	FODN
13	FOEB
14	FOEN
15	FOMI
16	WATR
17	WEHB
18	WEWO
19	BSVG
20	TUHB
21	TUWO
22	TUMI
23	TUBG
24	WATR

global_soils	
SOIL_ID	**SNAM**
3660	Bc26-2c-3660
3661	Bd29-3c-3661
3662	Bd32-2bc-3662
3663	Bd34-2bc-3663
3664	Bd35-1-2b-3664
3665	Bd61-2c-3665
3666	Be66-2c-3666
3667	Be70-2-3a-3667
3668	Be71-2-3a-3668
3669	Be72-2a-3669
3670	Be72-2c-3670
3671	Be72-2c-3671
3672	Be72-3c-3672
3673	Be73-2c-3673
3674	Be74-2a-3674
3675	Be74-2a-3675
…	…


Project
Edit
View
Layer
Settings
Plugins
Vector
Raster
Database
Web
Processing
Help
QSWAT 1.4
About
Soil & Water Assessment Tool
SWAT
Select Project
New Project
Existing Project
Main Steps
Done
Delineate Watershed
Step 2
Create HRUs
Step 3
Edit Inputs and Run SWAT
QSWAT parameters
OK
Cancel
D:\Models\QSWAT_CLS\MyBasin
Drawn inlets/outlets (dra...
Outlet
Inlet
Reservoir
Point source
Shortest path
Start
Stop
Criterion
Length
Length
Time
Calculate
Export
Clear
Help
Coordinate:
328598,3141847
Scale
1:582,951
Render
EPSG:32645


Create HRUs
Select landuse map
. . .
Landuse table
Example1_landuses
Select soil map
. . .
Soil data
usersoil
STATSGO
SSURGO/STATSGO2
Soil table
Example1_soils
Generate FullHRUs shapefile
Read choice
Read from maps
Read from previous run
Read
Set bands for slope (%)
Insert
Clear
Slope bands
[0, 9999]
Single/Multiple HRUs
Dominant landuse, soil, slope
Dominant HRU
Filter by landuse, soil, slope
Filter by area
Target number of HRUs
Set landuse, soil, slope thresholds
0
Landuse (%)
100
Go
0
Soil (%)
100
Go
0
Slope (%)
100
Optional
Split landuses
Exempt landuses
Elevation bands
Threshold method
Percent of subbasin
Area (Ha)
Create HRUs
Cancel

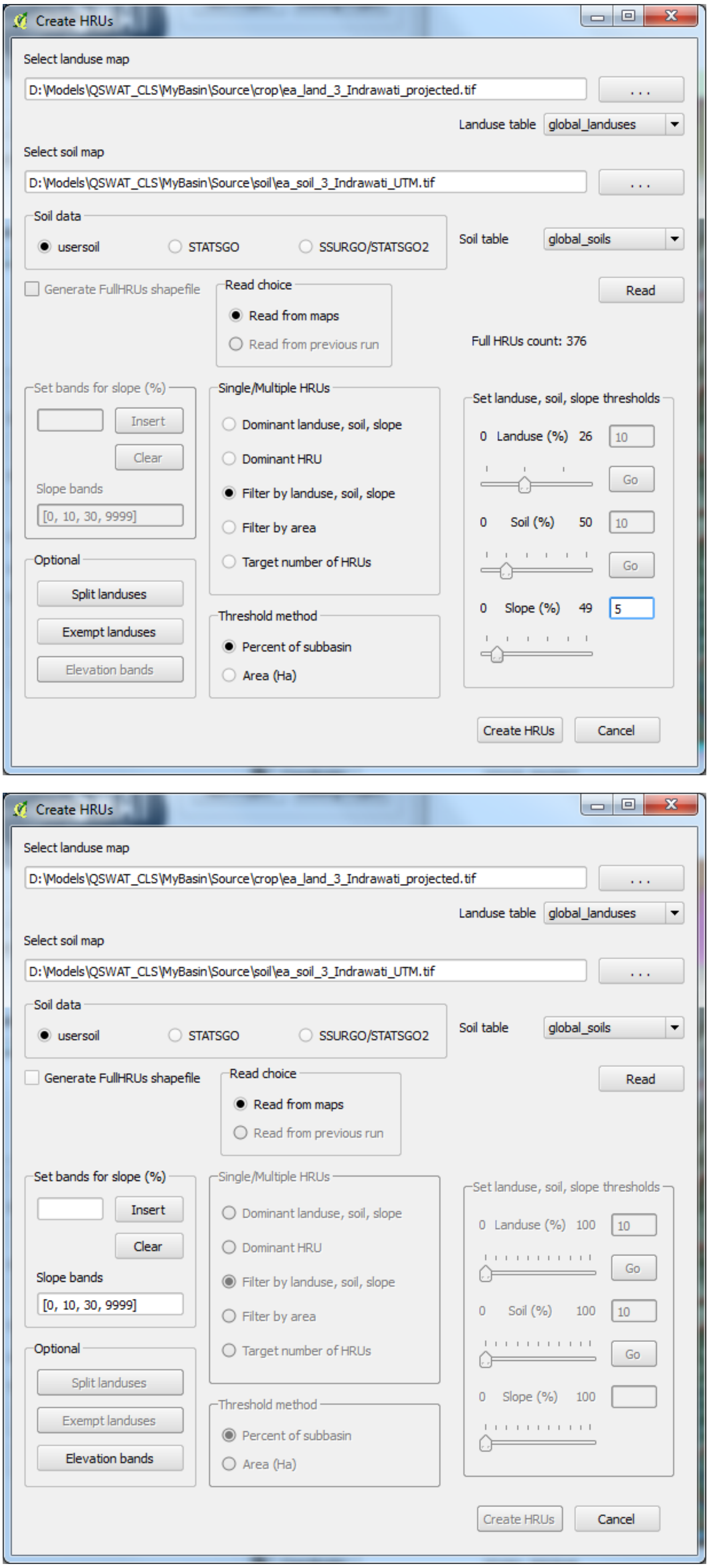


Figure 3.3a-d. Create HRUs with QSWAT.

3.4 Prepare meteorological (weather) data

For meteorological (or weather) data input, we have to prepare three types of files. One to define the name and location of the weather data stations, one with the time series of the weather data, and one for generating weather data in-case of missing values in the time series file within the period of simulation. The weather data are daily precipitation, daily maximum and minimum temperature and depending on the PET method, daily radiation, relative humidity and wind speed.

3.4.1 Weather station definition

The weather location definition is required for all weather parameters (P, T, etc.) in a separate file. It is a simple text file, comma separate, as shown below. The name of this file can be anything, give a name that is short and easy to recognise its content. For example, 'P_Stn_MyBasin.txt' and 'T_Stn_MyBasin.txt'.

Table 3.4.1. An example of a weather station definition file.

```
ID,NAME,LAT,LONG,ELEVATION
1008,P1008,27.816,85.623,1592
1016,P1016,27.95,85.597,2625
1018,P1018,27.799,85.572,845
…
```

<-- *This is the header* (beside the first line, ID,NAME,LAT,LONG,ELEVATION)

3.4.2 Weather station data

This is a time series file for each weather input variable, e.g. P and T. The first line of the file is the starting date in yyyymmdd formate without any separator. From second line to end of the file are daily values of the variable. For precipitation each value is a daily cumulative (24h) depth in mm. For temperature, there are two values daily (24h) maximum and minimum temperature in degree C separated by a comma. As you see there is no date in each row values, which means there cannot be any missing rows. Missing values must be indicated by -99.00.

Table 3.4.2. Examples of weather variable input file: Precipitation (left), Maximum and Minimum Temperature (right).

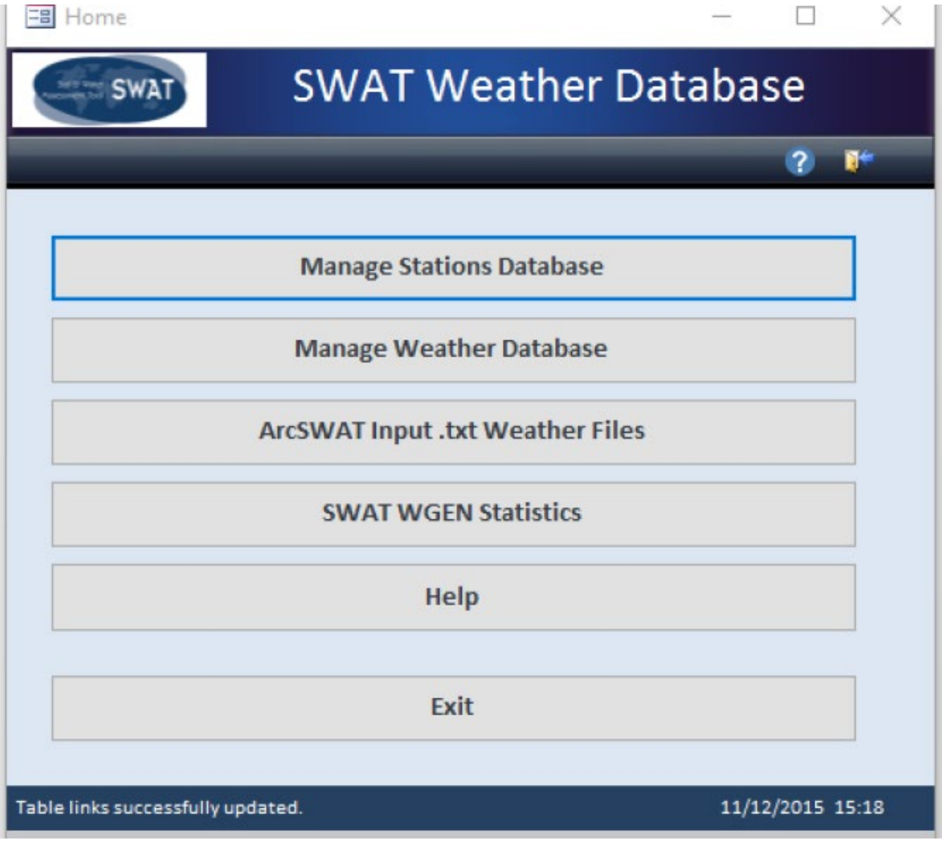
```
20040101  <-- starting date
0.00
0.00
4.60
1.00
10.80
14.20
0.00
-99.00
-99.00
0.00
…
```

```
20040101  <-- starting date
20.50,7.00
18.50,4.00
20.00,3.00
23.00,3.40
24.00,3.20
-99.00,-99.00
24.00,3.30
24.00,4.00
24.00,5.30
24.50,5.00
…
```

3.4.3 Weather generation data

SWAT also requires an additional for weather generation, which it uses to filling missing values, if any, in the weather input time series file. This file will only be used if there are missing values in any of the weather input time series within the simulation period. It contains long-term average statistics of each weather variable. You can prepare this file in MS Excel with a name starting WGEN, e.g. WGEN_MyBasin.xlsx. All the values are in one row for each weather generating stations. There must be at least one station.

Preparing this file is not easy as it involves a lot of computations. Luckily are tools available through SWAT web pages to derive the parameters from a time series file. One such recently added tool is an MS Access program called 'WeatherDatabase.accdb' (Essenfelder, 2016)[5], available through https://swat.tamu.edu/software/. I find this program relatively simple to use with a convenient interface (Fig.3.4.3a).



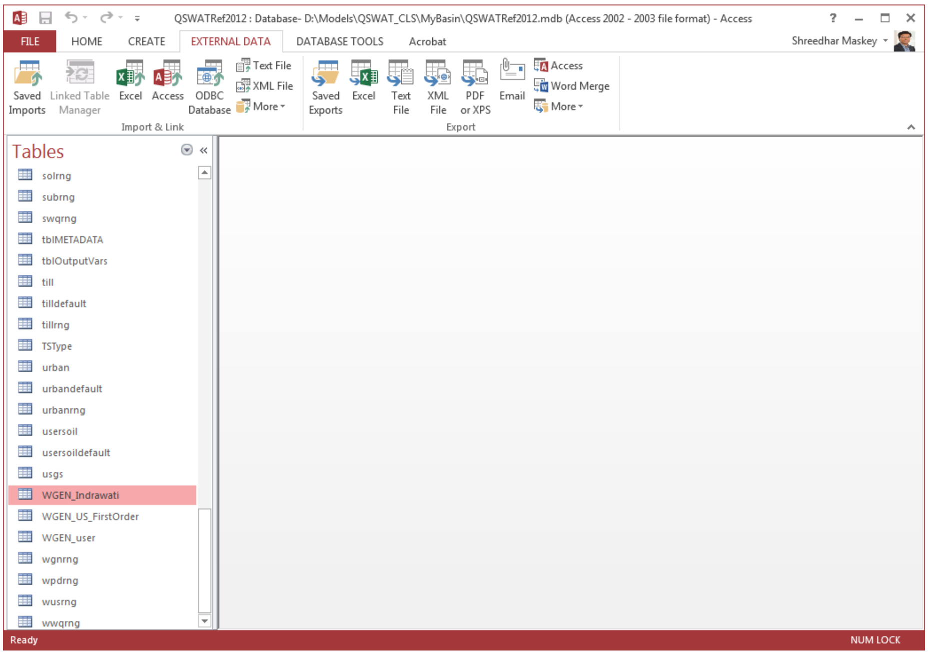
Figire 3.4.3a. The main interface of WeatherDatabase.accdb.

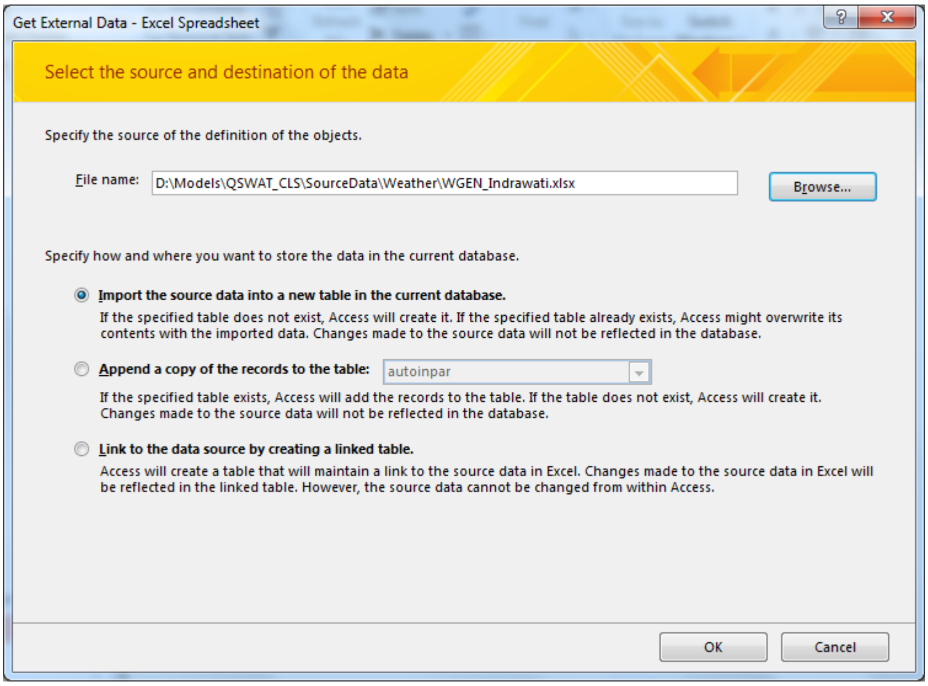
Once we prepare the WGEN file in excel, we need to add it to the QSWAT reference database which is under your project folder. To add

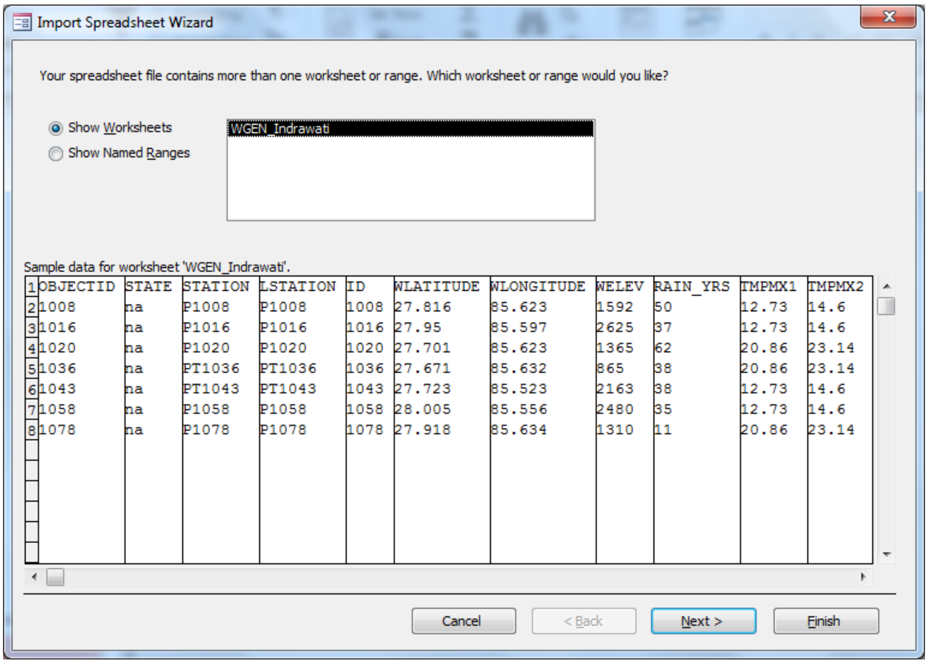
- Open the QSWATRef2012.mbd file. Refer to Fig. 3.4.3b–f for the following steps.
- Under the EXTERNAL DATA menu, there are tabs. In the first group of tabs, select Excel. (Alternatively, on the left panel, click any table list, right-click and select Import—Excel.)

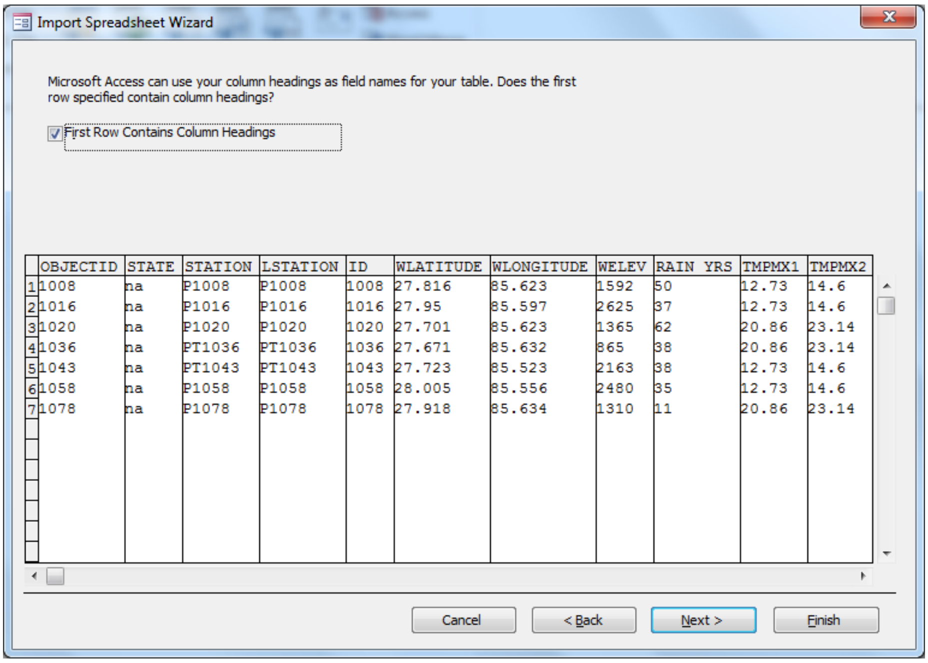
[5] Essenfelder, A. H. (2016). *SWAT Weather Database: A Quick Guide*. Version: v.0.16.07. DOI: 10.13140/RG.2.1.4329.1927.

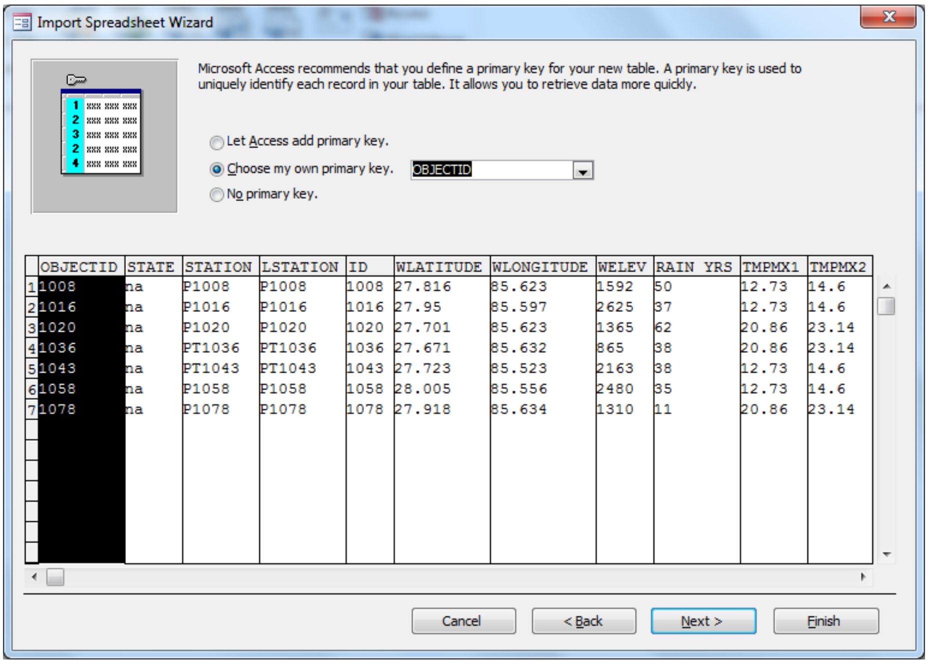
- On the new form, browse to the where you have your WGEN file, select the file, and click OK. The file will appear in the form. With the default selection for the type of import (i.e. as a new table), click OK.
- Then you need to select 'Next' few times. In between the Next clicks, there are two important selections to make.
- In one form, check the box for 'First Row Contains Column Heading'.
- In the next form, select the option 'Choose my own primary key' and select OBJECTID as the primary key.
- When all next step is done, select "Finish". In the next form, select Close without selecting the check-box for saving the import steps.
- The new table will be added in the database. Open the table to check if is properly added, save it and close the database.
-

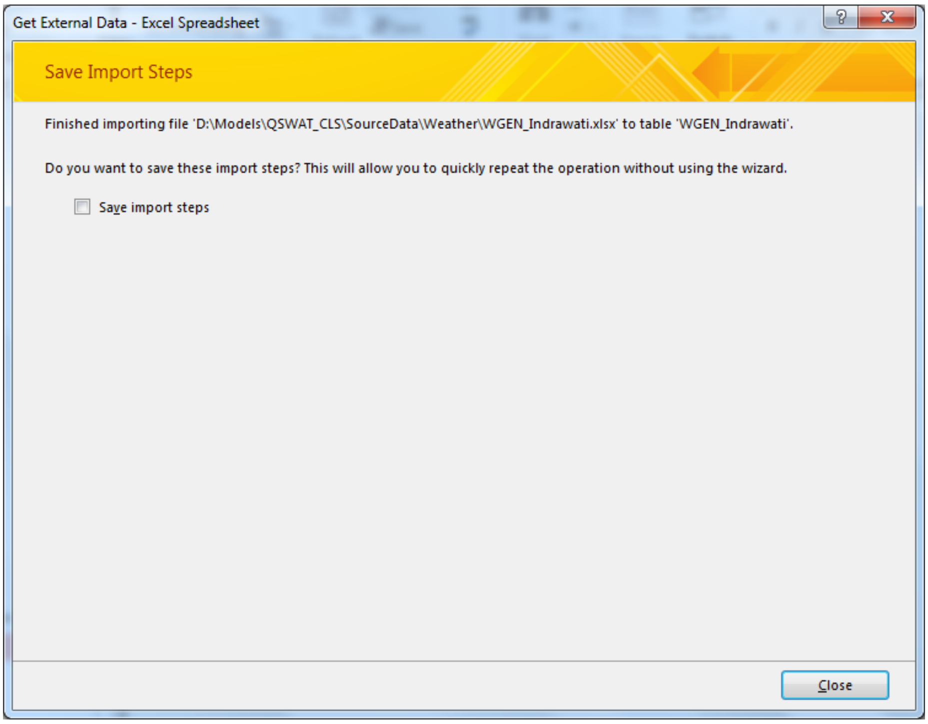


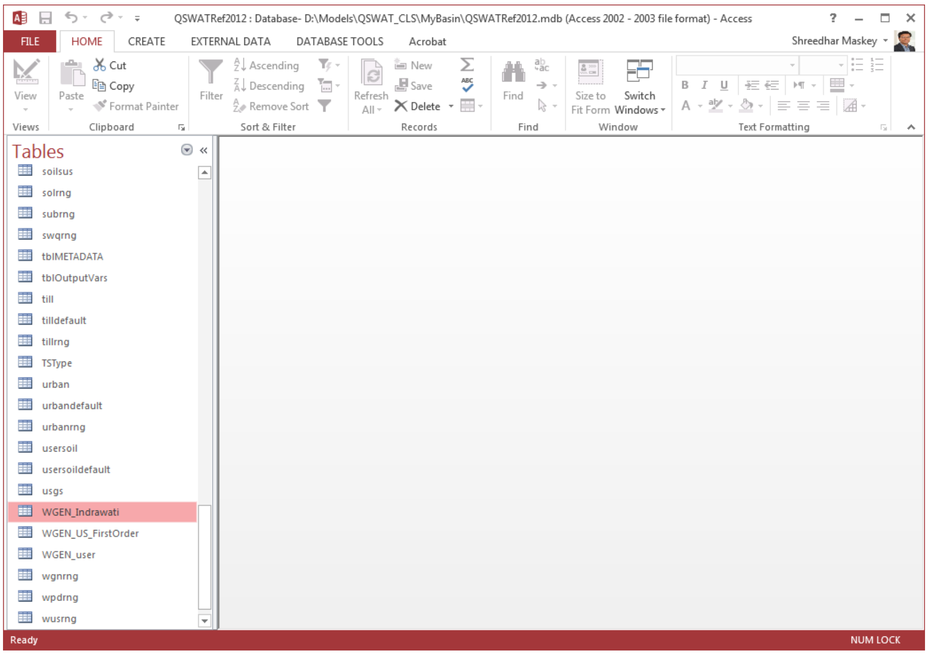



Import Spreadsheet Wizard
Your spreadsheet file contains more than one worksheet or range. Which worksheet or range would you like?
Show Worksheets
Show Named Ranges
WGEN_Indrawati
Sample data for worksheet 'WGEN_Indrawati'.
1 OBJECTID STATE STATION LSTATION ID WLATITUDE WLONGITUDE WELEV RAIN_YRS TMPMX1 TMPMX2
2 1008 na P1008 P1008 1008 27.816 85.623 1592 50 12.73 14.6
3 1016 na P1016 P1016 1016 27.95 85.597 2625 37 12.73 14.6
4 1020 na P1020 P1020 1020 27.701 85.623 1365 62 20.86 23.14
5 1036 na PT1036 PT1036 1036 27.671 85.632 865 38 20.86 23.14
6 1043 na PT1043 PT1043 1043 27.723 85.523 2163 38 12.73 14.6
7 1058 na P1058 P1058 1058 28.005 85.556 2480 35 12.73 14.6
8 1078 na P1078 P1078 1078 27.918 85.634 1310 11 20.86 23.14
Cancel
< Back
Next >
Finish


Import Spreadsheet Wizard
Microsoft Access can use your column headings as field names for your table. Does the first row specified contain column headings?
First Row Contains Column Headings
OBJECTID STATE STATION LSTATION ID WLATITUDE WLONGITUDE WELEV RAIN_YRS TMPMX1 TMPMX2
1 1008 na P1008 P1008 1008 27.816 85.623 1592 50 12.73 14.6
2 1016 na P1016 P1016 1016 27.95 85.597 2625 37 12.73 14.6
3 1020 na P1020 P1020 1020 27.701 85.623 1365 62 20.86 23.14
4 1036 na PT1036 PT1036 1036 27.671 85.632 865 38 20.86 23.14
5 1043 na PT1043 PT1043 1043 27.723 85.523 2163 38 12.73 14.6
6 1058 na P1058 P1058 1058 28.005 85.556 2480 35 12.73 14.6
7 1078 na P1078 P1078 1078 27.918 85.634 1310 11 20.86 23.14
Cancel
< Back
Next >
Finish


Import Spreadsheet Wizard
Microsoft Access recommends that you define a primary key for your new table. A primary key is used to uniquely identify each record in your table. It allows you to retrieve data more quickly.
Let Access add primary key.
Choose my own primary key. OBJECTID
No primary key.
OBJECTID STATE STATION LSTATION ID WLATITUDE WLONGITUDE WELEV RAIN_YRS TMPMX1 TMPMX2
1 1008 na P1008 P1008 1008 27.816 85.623 1592 50 12.73 14.6
2 1016 na P1016 P1016 1016 27.95 85.597 2625 37 12.73 14.6
3 1020 na P1020 P1020 1020 27.701 85.623 1365 62 20.86 23.14
4 1036 na PT1036 PT1036 1036 27.671 85.632 865 38 20.86 23.14
5 1043 na PT1043 PT1043 1043 27.723 85.523 2163 38 12.73 14.6
6 1058 na P1058 P1058 1058 28.005 85.556 2480 35 12.73 14.6
7 1078 na P1078 P1078 1078 27.918 85.634 1310 11 20.86 23.14
Cancel
< Back
Next >
Finish


Get External Data - Excel Spreadsheet
Save Import Steps
Finished importing file 'D:\Models\QSWAT_CLS\SourceData\Weather\WGEN_Indrawati.xlsx' to table 'WGEN_Indrawati'.
Do you want to save these import steps? This will allow you to quickly repeat the operation without using the wizard.
Save import steps
Close



Figire 3.4.3b–h. Adding a weather generator parameter file (MS Excel) to the QSWAT reference database: seven forms b–h from top to bottom.

4. Writing input data and running SWAT

4.1 Write weather input data to the database

If you have successfully carried out all the steps up to Chapter 3, now you are ready assign weather input files write them to the database.

To write weather data,

- Select ‘Edit Inputs and Run SWAT’, and in the new form click the tab ‘Connect Databases’
- From the menu, select Write Input Tables – Weather Stations
- Select the tab ‘Weather Generator Data’ and from the drop-down box, select WGEN_Indrawati (or the WGEN file/table you’ve given). Select OK and wait until it reads the file.
- Click the tab ‘Rainfall Data’; select the option ‘Raingages’.
- Browse to specify the file with weather station definition. E.g. P_Stn_MyBasin.txt, and select OK.
- Click the tab ‘Temperature Data’; select the option ‘Climate Stations’.
- Browse to specify the file with weather station definition. E.g. T_Stn_MyBasin.txt, and select OK.
- If you have other weather files (Relative Humidity, Solar Radiation and Wind), repeat the same procedure as for rainfall and temperature.
- When all the weather files are specified and read properly, close this form.
- In the previous form, select from the menu ‘Write Input Tables -- Write SWAT Input Tables’
- For the first time writing the table, click ‘Select All’ and click ‘Create Tables’.
- It takes some time to complete this step. It will ask a couple of questions, mostly an ‘Yes’ answer should do.

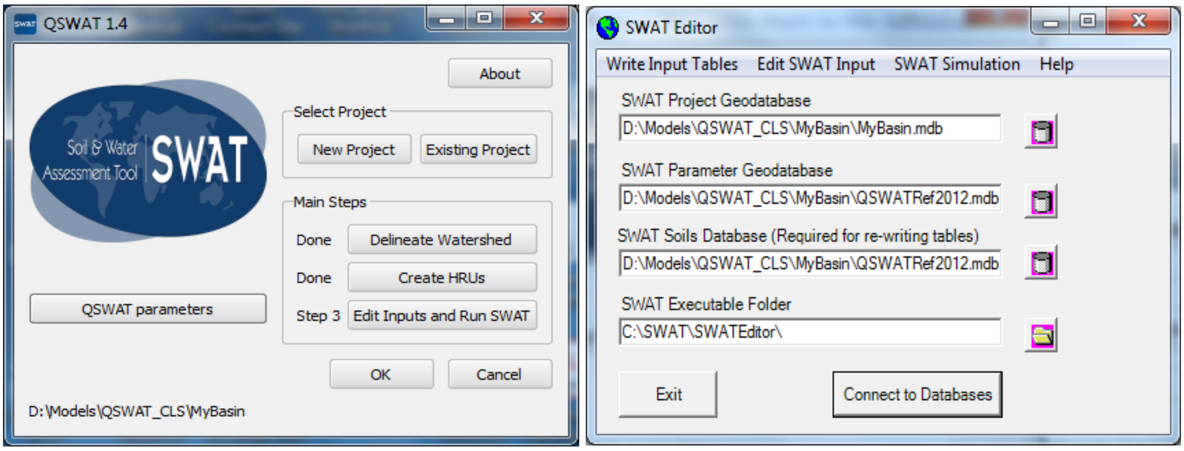
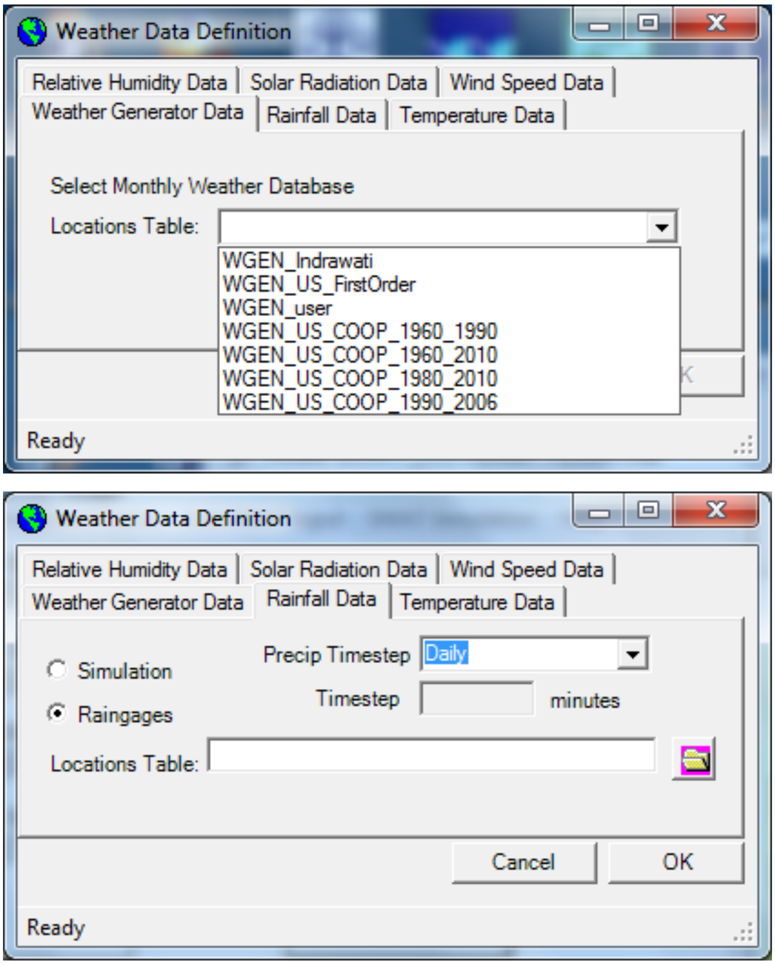


Figure 4.1a. Write weather data files: Before and after selecting 'Edit Inputs and Run SWAT' (left and right, respectively).



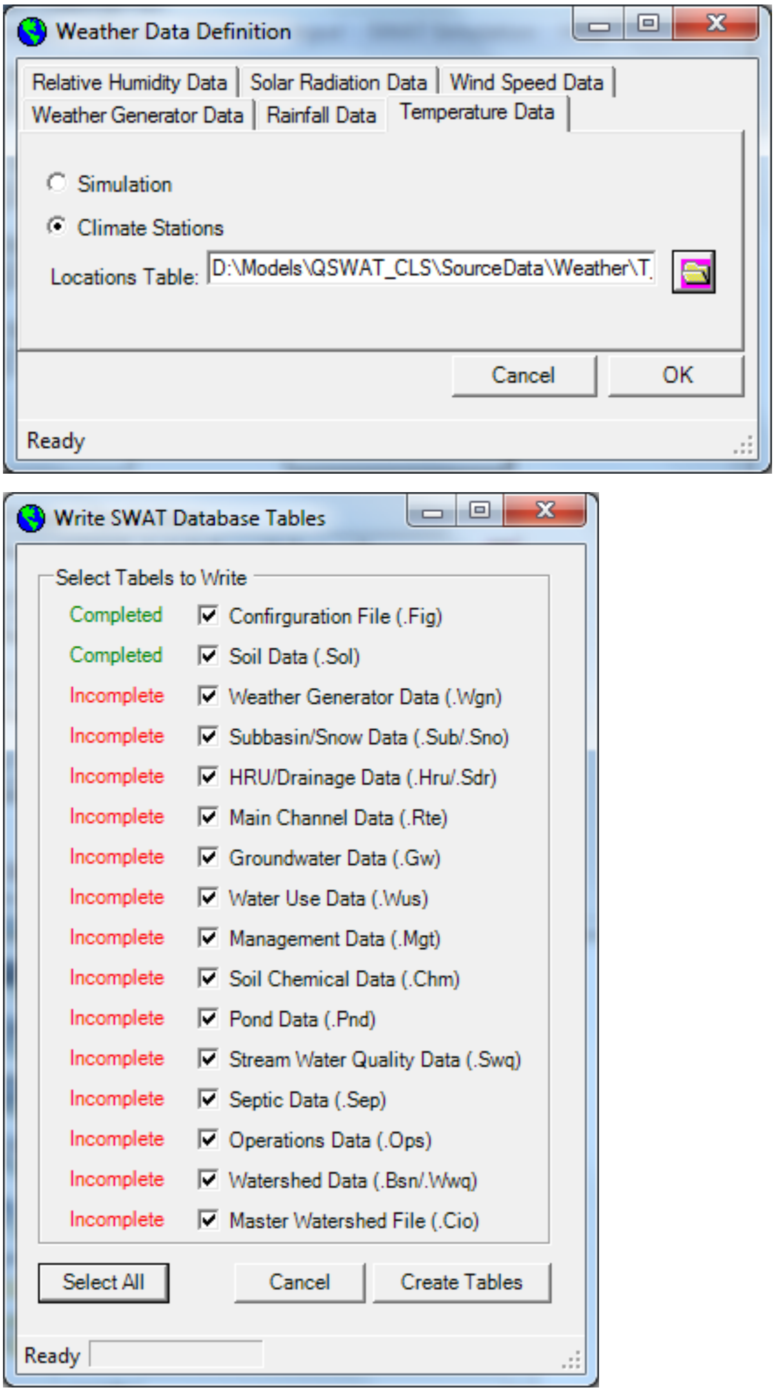


Figure 4.1b-f. Write weather data files in SWAT database table.

If you have missing values in any of the weather file (see Tab. 3.4.2), please see Box 4.1.

Box 4.1 Possible bug in writing weather data files by SWAT 2012 program
• If there are missing values in the weather time series files, e.g. precipitation, they are represented by -99.00 (see Tab. 3.4.2). It appears that SWAT 2012 program may make an error in writing weather data files in the SWAT database. Note that this may depend on the particular version of SWAT 2012 you are using.

- To check, browse to the TextInOut folder under your project folder (e.g. MyBasin/Scenarios/Dafault/TextInOut) [**If you do not have any missing values in the weather files, you do not need to do this step.**]
- Find the weather file(s), e.g. for precipitation pcp1.pcp.
- Open this file and check what it has for missing precipitation. If it has –099.0 (six character long), it is not good. It must be replaced by –99.0, which is five character long.
- Replace all –099.0 using the 'Replace' command in Notepad, for example. Do this for all weather files containing missing values.

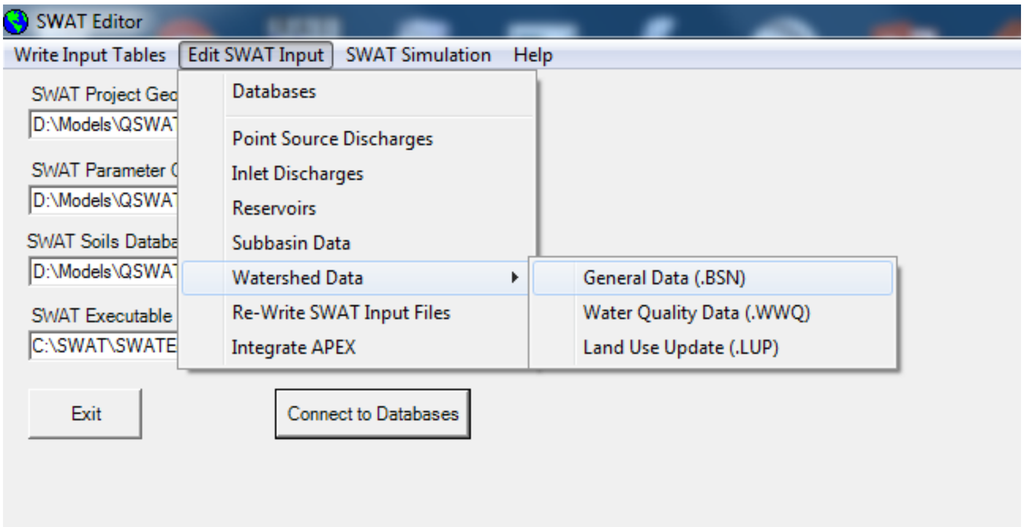
4.2 Edit input data and run simulation

Before selecting the SWAT simulation option, you may want to edit input parameters. In practice you probably use this option a lot, but for the first run I would recommend to run with the default parameters except one it our case. Remember, we only have precipitation and temperature data, which means we should select the PET option that needs only temperature data. In SWAT default, it has Penman-Monteith, which requires more input variables than temperature. The Hargreaves is the only option that requires only temperature.

Edit SWAT input to change PET method

To change the PET option

- Select 'Edit SWAT Input – Watershed Data – General Data'
- In the new form, click tab 'Edit Vales'.
- From the drop-down box for the PET Method, select Hargreaves.
- Select click Save Edits and close the form.
- Select 'Re-Write SWAT Input Files'
- Select .BSN and click Write Files. Close the file when done.



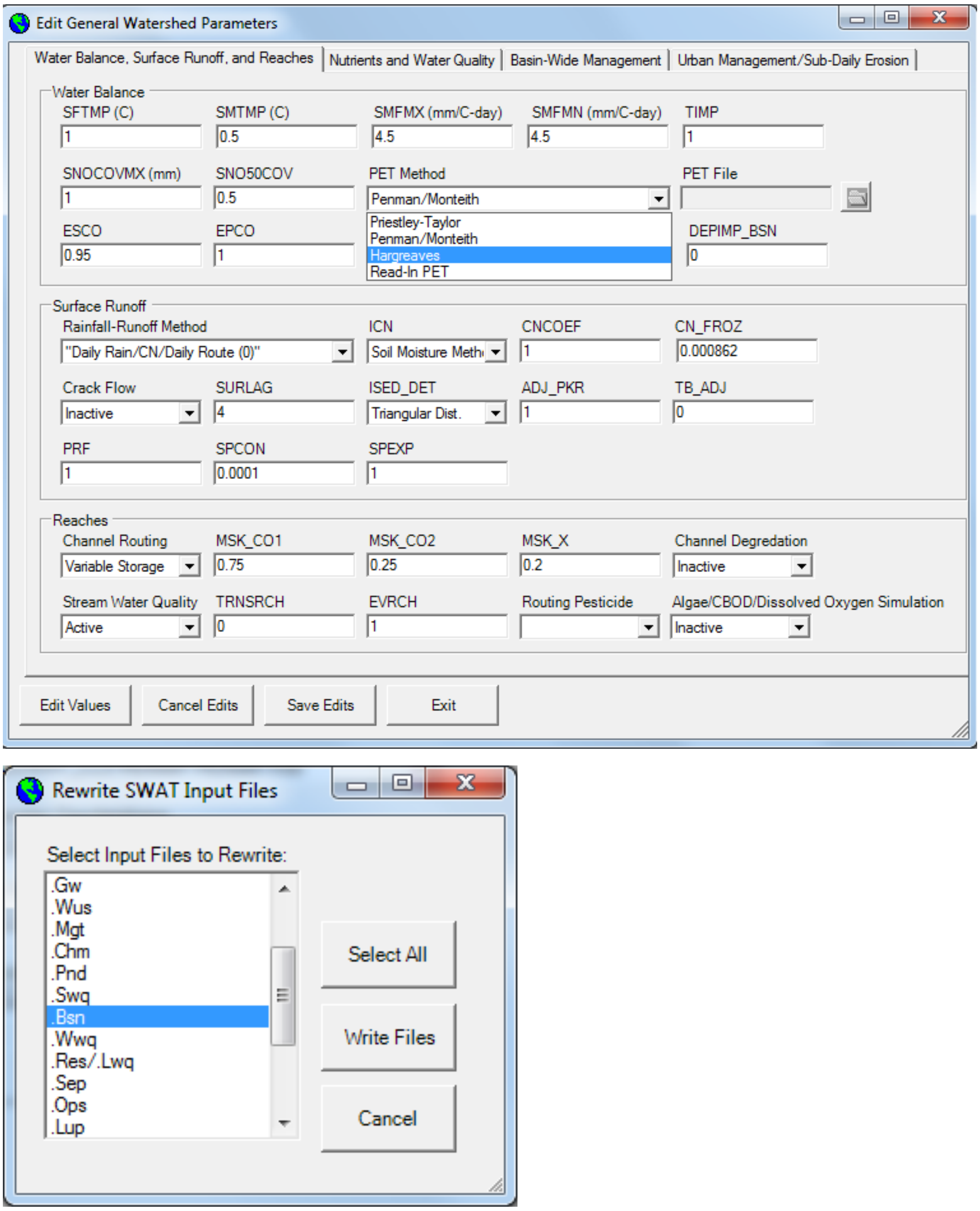


Figure 4.2a-c. SWAT Edit Input Data example.

Run SWAT

- Select from the menu ‘SWAT Simulation – Run SWAT’
- In the new form, specify selections and click tab ‘Setup SWAT Run’
- The Select ‘Run SWAT’. When the run is completed, close this form.

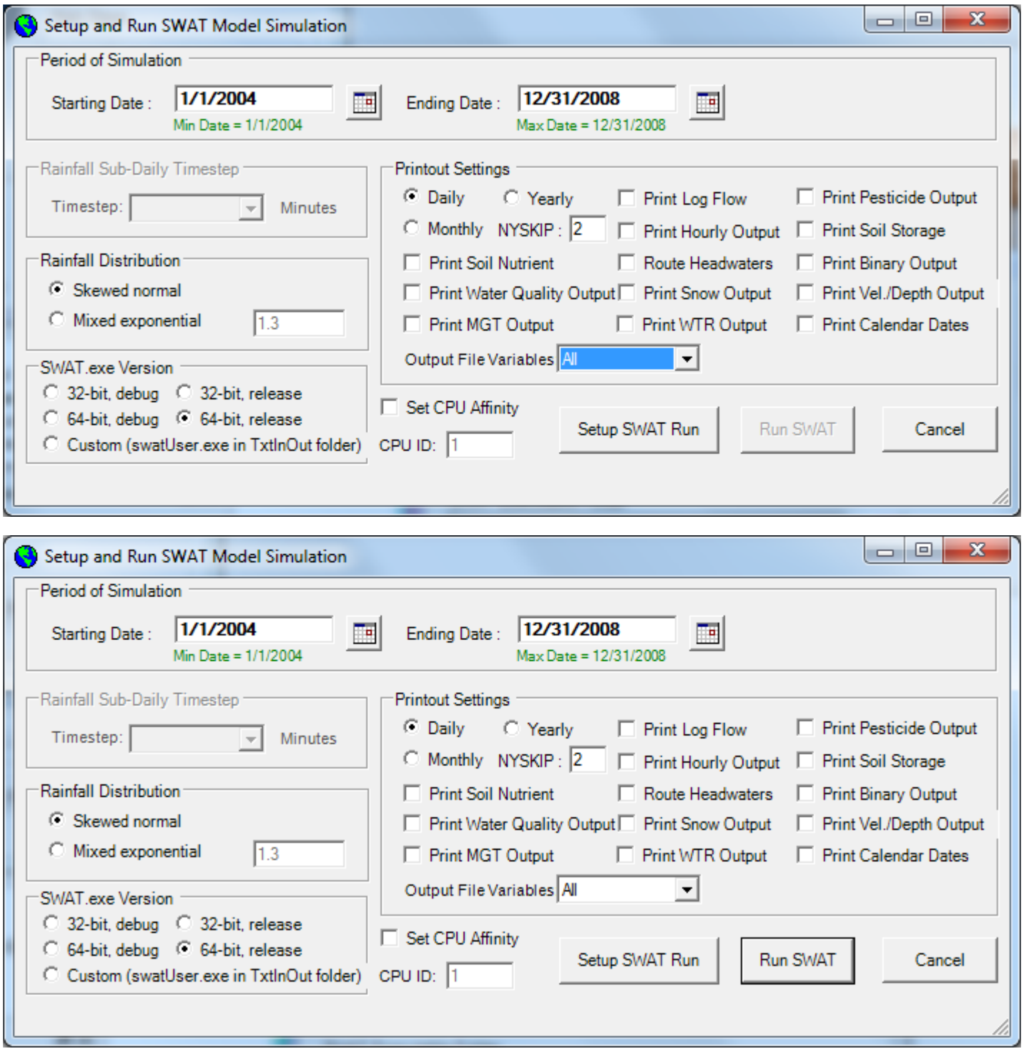
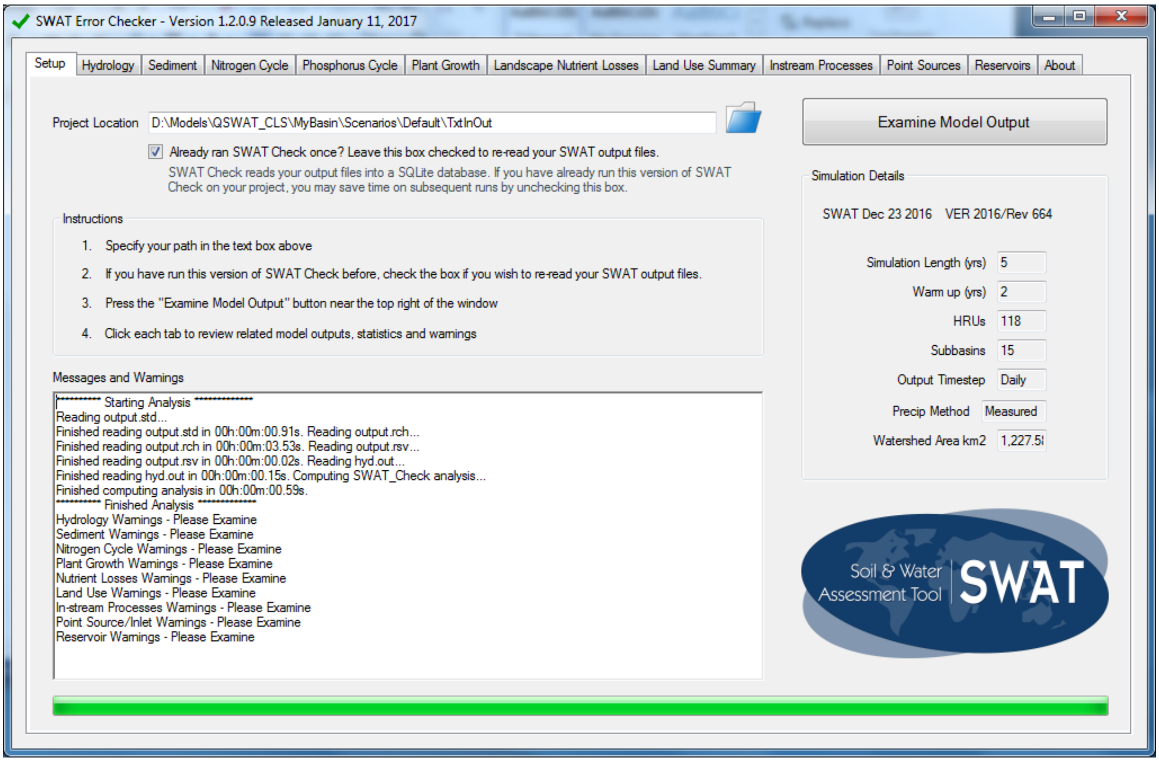
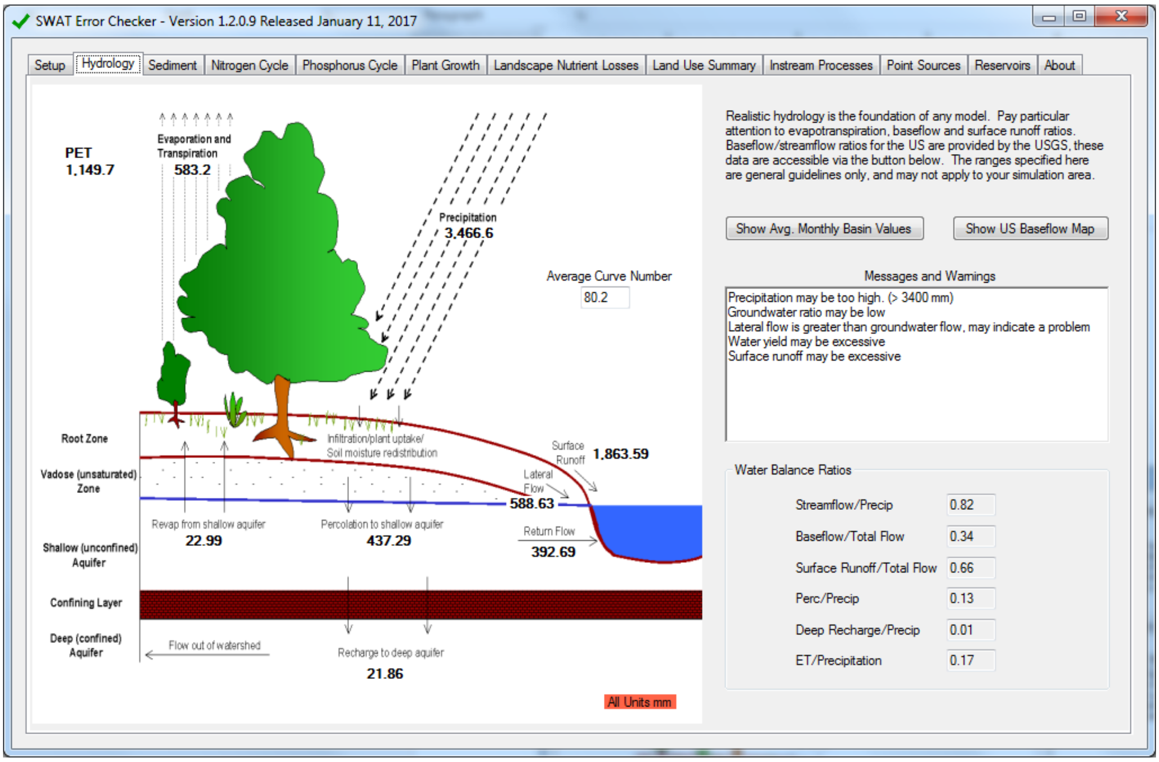


Figure 4.2d-e. SWAT Run Simulation setup.

Read SWAT outputs

- Once the run simulation is complete, from the main menu, select ‘SWAT Simulation – Read SWAT Output’
- In the new form, click the tab ‘Run SwatCheck’.
- In the new form, click the tab ‘Examine Model Output’. When complete, check the second tab ‘Hydrology’ to view summary of hydrological output.
- Click the tab ‘Show Avg. Monthly Basin Values’ to see the monthly average output table.
- Observe the output and see if they makes sense to you!


SWAT Error Checker - Version 1.2.0.9 Released January 11, 2017
Setup
Hydrology
Sediment
Nitrogen Cycle
Phosphorus Cycle
Plant Growth
Landscape Nutrient Losses
Land Use Summary
Instream Processes
Point Sources
Reservoirs
About
Project Location
D:\Models\QSWAT_CLS\MyBasin\Scenarios\Default\TxtInOut
Examine Model Output
Already ran SWAT Check once? Leave this box checked to re-read your SWAT output files.
SWAT Check reads your output files into a SQLite database. If you have already run this version of SWAT Check on your project, you may save time on subsequent runs by unchecking this box.
Instructions
1. Specify your path in the text box above
2. If you have run this version of SWAT Check before, check the box if you wish to re-read your SWAT output files.
3. Press the "Examine Model Output" button near the top right of the window
4. Click each tab to review related model outputs, statistics and warnings
Messages and Warnings
********** Starting Analysis **************
Reading output.std...
Finished reading output.std in 00h:00m:00.91s. Reading output.rch...
Finished reading output.rch in 00h:00m:03.53s. Reading output.rsv...
Finished reading output.rsv in 00h:00m:00.02s. Reading hyd.out...
Finished reading hyd.out in 00h:00m:00.15s. Computing SWAT_Check analysis...
Finished computing analysis in 00h:00m:00.59s.
********** Finished Analysis **************
Hydrology Warnings - Please Examine
Sediment Warnings - Please Examine
Nitrogen Cycle Warnings - Please Examine
Plant Growth Warnings - Please Examine
Nutrient Losses Warnings - Please Examine
Land Use Warnings - Please Examine
In-stream Processes Warnings - Please Examine
Point Source/Inlet Warnings - Please Examine
Reservoir Warnings - Please Examine
Simulation Details
SWAT Dec 23 2016 VER 2016/Rev 664
Simulation Length (yrs) 5
Warm up (yrs) 2
HRUs 118
Subbasins 15
Output Timestep Daily
Precip Method Measured
Watershed Area km2 1,227.5
Soil & Water Assessment Tool
SWAT


SWAT Error Checker - Version 1.2.0.9 Released January 11, 2017
Setup
Hydrology
Sediment
Nitrogen Cycle
Phosphorus Cycle
Plant Growth
Landscape Nutrient Losses
Land Use Summary
Instream Processes
Point Sources
Reservoirs
About
PET
1,149.7
Evaporation and Transpiration
583.2
Precipitation
3,466.6
Average Curve Number
80.2
Root Zone
Vadose (unsaturated) Zone
Shallow (unconfined) Aquifer
Confining Layer
Deep (confined) Aquifer
Infiltration/plant uptake/ Soil moisture redistribution
Surface Runoff
1,863.59
Lateral Flow
588.63
Revap from shallow aquifer
22.99
Percolation to shallow aquifer
437.29
Return Flow
392.69
Flow out of watershed
Recharge to deep aquifer
21.86
All Units mm
Realistic hydrology is the foundation of any model. Pay particular attention to evapotranspiration, baseflow and surface runoff ratios. Baseflow/streamflow ratios for the US are provided by the USGS, these data are accessible via the button below. The ranges specified here are general guidelines only, and may not apply to your simulation area.
Show Avg. Monthly Basin Values
Show US Baseflow Map
Messages and Warnings
Precipitation may be too high. (> 3400 mm)
Groundwater ratio may be low
Lateral flow is greater than groundwater flow, may indicate a problem
Water yield may be excessive
Surface runoff may be excessive
Water Balance Ratios
Streamflow/Precip 0.82
Baseflow/Total Flow 0.34
Surface Runoff/Total Flow 0.66
Perc/Precip 0.13
Deep Recharge/Precip 0.01
ET/Precipitation 0.17

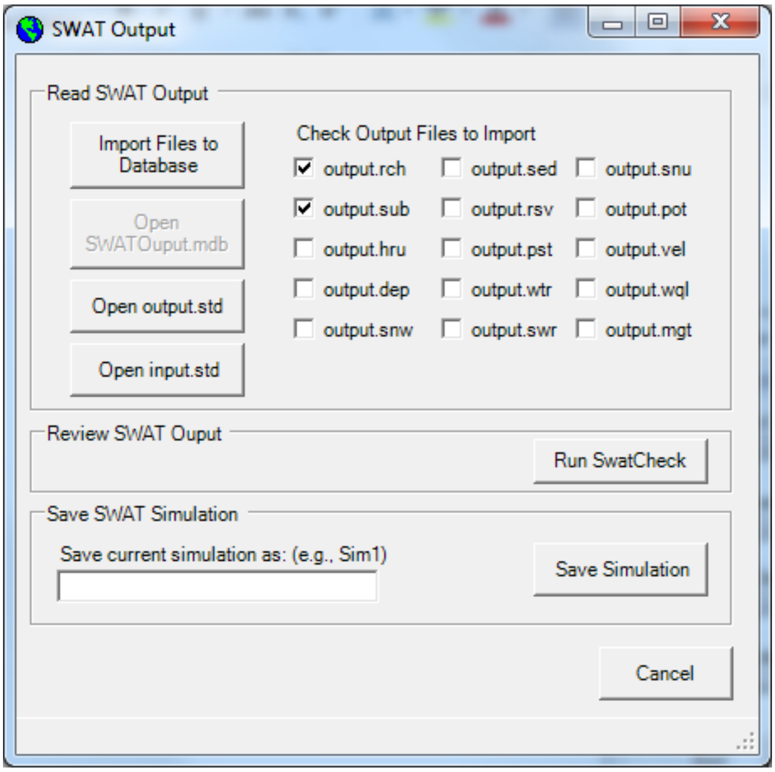
Average Monthly Basin Values

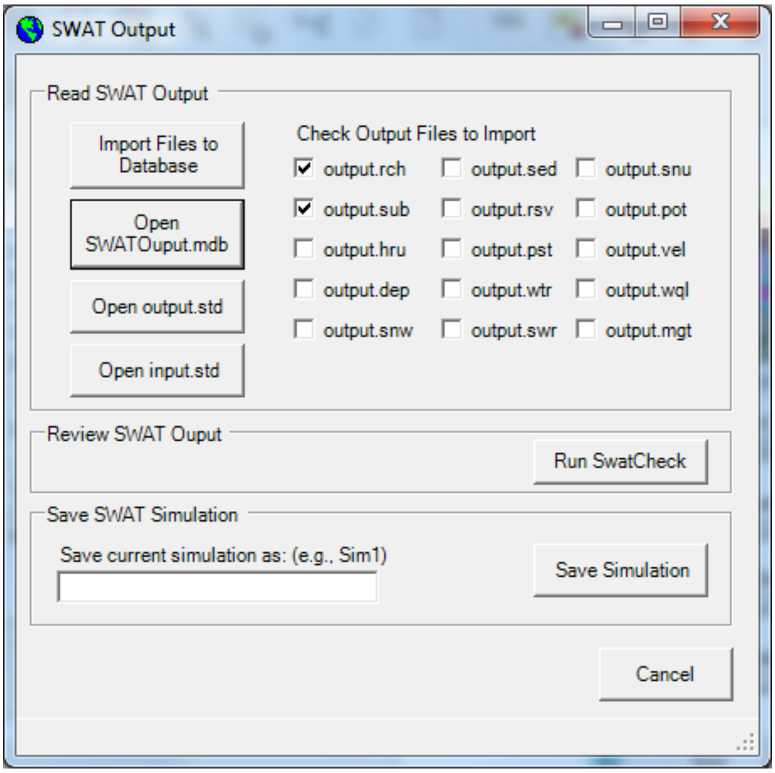
Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (MM)	PET (MM)
1	1.46	0.00	0.01	0.33	5.72	5.40	0.01	58.44
2	27.86	0.00	7.00	5.24	14.10	9.28	9.91	69.95
3	698.45	0.00	659.53	10.25	671.66	22.76	964.32	106.07
4	92.94	0.00	16.37	18.16	36.07	47.77	22.19	129.00
5	153.30	0.00	31.05	33.24	66.15	79.72	33.46	132.62
6	500.70	0.00	217.44	94.22	321.68	91.53	153.29	121.60
7	767.88	0.00	384.40	154.30	583.51	94.31	220.52	116.61
8	760.31	0.00	379.81	155.18	623.19	85.33	208.99	109.33
9	378.42	0.00	145.93	93.98	344.17	70.87	110.85	93.52
10	67.85	0.00	21.17	20.30	129.22	43.69	21.74	90.62
11	5.50	0.00	0.31	0.97	48.65	20.15	0.42	68.14
12	12.61	0.00	0.75	2.58	22.98	12.57	1.01	55.37

Figure 4.2f-h. Read and examine SWAT output. **(Note that the results shown here are just for the demonstration of QSWAT model building and simulation steps. It is not meant to use these values for any other purposes.)**

Save outputs to the database

- In the 'SWAT Output' form, click the check boxes for the outputs you want to save, e.g. Output.rch and Output.sub, and click Import Files to Database.
- Then click the tab Open SWAToutput.mdb to view the outputs in MS Access tables. You can also export (or copy paste) these tables to MS Excel.





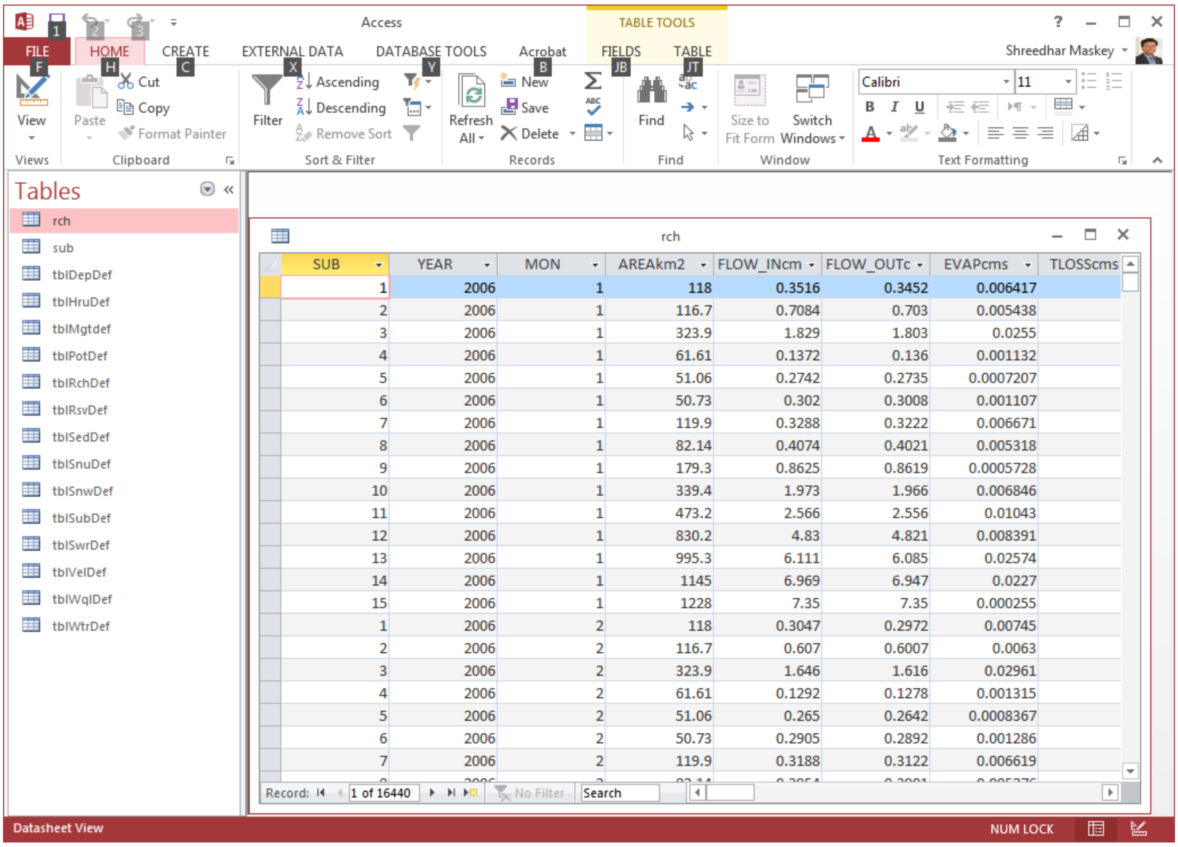


Figure 4.2i-k. Save output to SWAT database and view output tables. **(Note that the results shown here are just for the demonstration of QSWAT model building and simulation steps. They are not meant to be used for any other purposes.**

C

Python code nearest distance

```
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from collections import Counter

#%%
CurrentRes=pd.read_excel('total current reservoirs.xlsx', header=0)
streams =pd.read_csv("streampoints_buffer.csv", header=0)

#%%
CurrentRes['New Res ID']=np.zeros(len(CurrentRes))
CurrentRes['Dist']=np.zeros(len(CurrentRes))

for i in range(len(CurrentRes)):
    #Finding closest coordinate for irrigation reservoirs
    DisMat = np.sqrt((CurrentRes['lat'][i] - streams["ycoord"])**2 +
        (CurrentRes['long'][i] - streams["xcoord"])**2)

    #finding index of min distance
    res_i = DisMat.idxmin()

    #finding coord of min distance
    DistPond=DisMat[res_i]*105 #degrees to km around lat ~20 degrees north

    CurrentRes['New Res ID'][i]=res_i
    CurrentRes['Dist'][i]=DistPond      #in km

CurrentRes=CurrentRes.sort_values(by=['Dist'])


CurrentRes['lat_stream'] = np.zeros(len(CurrentRes))
CurrentRes['long_stream'] = np.zeros(len(CurrentRes))

for i in range(len(CurrentRes)):
    streams_tmp=streams[streams.index == CurrentRes['New Res ID'].iloc[i]]
    CurrentRes['lat_stream'][i] = streams_tmp['ycoord']
    CurrentRes['long_stream'][i] = streams_tmp['xcoord']

CurrentRes.head()

#%%
CurrentRes.to_csv(r'distance_reservoirs_to_stream.csv', index = False)
```

Listing C.1: Python code nearest distance method for calculating distance between current reservoir and nearest stream location.

D

Google Earth Engine Code

```
//Import Maharashtra area (var table) and reservoir locations to be analyzed
var table = ee.FeatureCollection("users/jentejanssen/Maharastra");
var reservoirs = ee.FeatureCollection("users/jentejanssen/
    Current_reservoir_locations_Ghatanji")

//Clip image to region of interest (Maharashtra area)
var clipToCol = function(image){
  return image.clip(table);
}

//Import Copernicus Land Cover Data and clip to region of interest
var landcover = ee.ImageCollection("COPERNICUS/Landcover/100m/Proba-V/Global").map(
    clipToCol).mosaic()

//Specify band colors for different classification types
var sldXml =
  '<RasterSymbolizer>' +
  '  <ColorMap type="intervals" extended="false" >' +
  '    <ColorMapEntry quantity="0" color="#282828" label="Unknown. No or not enough
    satellite data available."/>' +
  '    <ColorMapEntry quantity="20" color="#FFBB22" label="Shrubs. Woody perennial
    plants with persistent and woody stems and without any defined main stem being less
     than 5 m tall. The shrub foliage can be either evergreen or deciduous."/>' +
  '    <ColorMapEntry quantity="30" color="#FFFF4C" label="Herbaceous vegetation.
    Plants without persistent stem or shoots above ground and lacking definite firm
    structure. Tree and shrub cover is less than 10 %."/>' +
  '    <ColorMapEntry quantity="40" color="#F096FF" label="Cultivated and managed
    vegetation / agriculture. Lands covered with temporary crops followed by harvest
    and a bare soil period (e.g., single and multiple cropping systems). Note that
    perennial woody crops will be classified as the appropriate forest or shrub land
    cover type."/>' +
  '    <ColorMapEntry quantity="50" color="#FA0000" label="Urban / built up. Land
    covered by buildings and other man-made structures."/>' +
  '    <ColorMapEntry quantity="60" color="#B4B4B4" label="Bare / sparse vegetation.
    Lands with exposed soil, sand, or rocks and never has more than 10 % vegetated
    cover during any time of the year."/>' +
  '    <ColorMapEntry quantity="70" color="#F0F0F0" label="Snow and ice. Lands under
    snow or ice cover throughout the year."/>' +
  '    <ColorMapEntry quantity="80" color="#0032C8" label="Permanent water bodies.
    Lakes, reservoirs, and rivers. Can be either fresh or salt-water bodies."/>' +
  '    <ColorMapEntry quantity="90" color="#0096A0" label="Herbaceous wetland. Lands
    with a permanent mixture of water and herbaceous or woody vegetation. The
    vegetation can be present in either salt, brackish, or fresh water."/>' +
  '    <ColorMapEntry quantity="100" color="#FAE6A0" label="Moss and lichen."/>' +
  '    <ColorMapEntry quantity="111" color="#58481F" label="Closed forest, evergreen
    needle leaf. Tree canopy >70 %, almost all needle leaf trees remain green all year.
     Canopy is never without green foliage."/>' +
  '    <ColorMapEntry quantity="112" color="#009900" label="Closed forest, evergreen
    broad leaf. Tree canopy >70 %, almost all broadleaf trees remain green year round.
    Canopy is never without green foliage."/>' +
```

```
'    <ColorMapEntry quantity="113" color="#70663E" label="Closed forest, deciduous needle leaf. Tree canopy >70 %, consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off periods."/>' +
'    <ColorMapEntry quantity="114" color="#00CC00" label="Closed forest, deciduous broad leaf. Tree canopy >70 %, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods."/>' +
'    <ColorMapEntry quantity="115" color="#4E751F" label="Closed forest, mixed."/>' +
'    <ColorMapEntry quantity="116" color="#007800" label="Closed forest, not matching any of the other definitions."/>' +
'    <ColorMapEntry quantity="121" color="#666000" label="Open forest, evergreen needle leaf. Top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, almost all needle leaf trees remain green all year. Canopy is never without green foliage."/>' +
'    <ColorMapEntry quantity="122" color="#8DB400" label="Open forest, evergreen broad leaf. Top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, almost all broadleaf trees remain green year round. Canopy is never without green foliage."/>' +
'    <ColorMapEntry quantity="123" color="#8D7400" label="Open forest, deciduous needle leaf. Top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, consists of seasonal needle leaf tree communities with an annual cycle of leaf-on and leaf-off periods."/>' +
'    <ColorMapEntry quantity="124" color="#A0DC00" label="Open forest, deciduous broad leaf. Top layer- trees 15-70 % and second layer- mixed of shrubs and grassland, consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf-off periods."/>' +
'    <ColorMapEntry quantity="125" color="#929900" label="Open forest, mixed."/>' +
'    <ColorMapEntry quantity="126" color="#648C00" label="Open forest, not matching any of the other definitions."/>' +
'    <ColorMapEntry quantity="200" color="#000080" label="Oceans, seas. Can be either fresh or salt-water bodies."/>' +
'  </ColorMap>' +
'</RasterSymbolizer>'

//Import layers to map and zoom to region of interest (reservoir locations)
Map.centerObject(reservoirs, 10)
Map.addLayer(landcover.select('discrete_classification').sldStyle(sldXml), null, "Land Cover")
Map.addLayer(reservoirs.draw({color: 'blue', pointRadius: 1}), {}, "reservoirs")

//Reduce land cover table to reservoir locations only and add the land cover data to the reservoir table
var landcoverWithClassification = landcover
  .reduceRegions({
    collection: reservoirs,
    reducer: ee.Reducer.mode().setOutputs(['crop-coverfraction']),
    scale: 1
  });

print(landcoverWithClassification)

//Export table to drive
Export.table.toDrive({
    collection: landcoverWithClassification,
    description: 'landcoverWithClassificationGhatanjiCurrent',
    fileFormat: 'CSV',
});
```

Listing D.1: Google Earth Engine code for obtaining land cover per reservoir location.

E

Python code for analysing GEE output data

```python
import pandas as pd
import matplotlib.pyplot as plt
import itertools

df = pd.read_csv("landcoverWithClassificationHinganghat.csv", header = 0) #read in csv file, output from GEE with land cover fraction per reservoir location

df['.geo'] = df['.geo'].map(lambda x: x.lstrip('{"type":"Point","coordinates":[').rstrip(']}'))
df[['X', 'Y']]= df['.geo'].str.split(",", expand=True).astype(float)

#Drop series of columns which contains all 0's.
landuse = df.drop(['INLET', 'PTSOURCE','RES', 'system:index', 'bare-coverfraction-stddev','grass-coverfraction-stddev', 'forest_type',
                   'crops-coverfraction-stddev', 'data-density-indicator','discrete_classification',
                   'discrete_classification-proba','moss-coverfraction', 'moss-coverfraction-stddev',
                   'shrub-coverfraction-stddev', 'snow-coverfraction', 'tree-coverfraction-stddev', '.geo'], axis = 1)

#Define for which land cover fraction a reservoir location is a suitable location. Fractions can be adjusted accordingly.
def check(landuse):
    if (landuse['urban-coverfraction']>50):
        return 'Not Suitable (urban fraction too large)'
    elif (landuse['crops-coverfraction']<40):
        return 'Not suitable (cropfraction too little)'
    elif (landuse['crops-coverfraction']>40):
        return 'Suitable'

landuse['Suitability'] = landuse.apply(check, axis = 1)

#Create visable plot
groups = landuse.groupby("Suitability")

colors = itertools.cycle(["r", "b", "g"])
plt.figure(figsize=(10,7))
for name, group in groups:
    plt.plot(group["X"], group["Y"], marker="o", markersize = 3, linestyle="", color=next(colors), label=name)
plt.legend(loc='upper left', fontsize = 10)
plt.title('Suitability reservoir locations based on land cover fraction', fontsize = 16)
plt.xlabel('Longitude', fontsize = 12)
plt.ylabel('Latitude', fontsize = 12)
plt.savefig("Resercoir location suitability.png")
```

Listing E.1: Python code running the output data of GEE to estimate which locations are sufficient as a reservoir location with respect to land cover fraction.

F

Model delivered to Solidaridad

Calculate distance to nearest stream and give streamnetwork coordinates of nearest stream

With this code the distance from a potential reservoir location to the nearest stream is calculated. This model is developped for the project "Water Efficiency in Sustainable Cotton-based production systems in Maharashtra, India" carried out by Solidaridad.

For this code several datasets regarding the streamnetwork of a region are necessary. These files are provided to Solidaridad as well and can be found on [add link].

! Make sure the latitude longitude coordinates are in decimals and not DMS or GPS coordinates !

In [ ]:
```
import numpy as np
import pandas as pd
```

Step 1 - choose region

First choose the region in which the potential reservoir is located. To activate the file, remove the # in front of the streamnetwork of the area.

For example: if the potential location is in Yavatmal, the code is first:

```
#streamnetwork = pd.read_csv("Streampoints_Yavatmal.csv", header=0)     #Yavatmal
```

To activate it remove only the first #:

```
streamnetwork = pd.read_csv("Streampoints_Yavatmal.csv", header=0)     #Yavatmal
```

In [ ]:
```
# streamnetwork = pd.read_csv("Streampoints_Wardha.csv", header=0)         #Wardha
# streamnetwork = pd.read_csv("Streampoints_Nagpur.csv", header=0)        #Nagpur
# streamnetwork = pd.read_csv("Streampoints_Yavatmal.csv", header=0)      #Yavatmal
# streamnetwork = pd.read_csv("Streampoints_Amravati.csv", header=0)     #Amravati
```

In [ ]:
```
reservoir = pd.DataFrame(columns=['latitude', 'longitude'])
```

Step 2 - add potential locations coordinates

Here add the latitude (x coordinate) and the longitude (y coordinate) to the model.

For example:

```
reservoir.loc[0] =  [78.612563,             #x/latitude coordinate
                     20.554911]            #y/longitude coordinate
```

!Make sure to use a . and not a , as decimal separator!

In [ ]:
```
reservoir.loc[0] =  [latitude,             #x/latitude coordinate
                     longitude]             #y/longitude coordinate
```

Step 3 - Run the model

Do not change anything in this step. In the code below the model calculates the distance to the nearest stream.

```
In [ ]: reservoir['Dist[m]'] = np.zeros(len(reservoir))
        reservoir['latitude stream'] = np.zeros(len(reservoir))
        reservoir['longitude stream'] = np.zeros(len(reservoir))

        for i in range(len(reservoir)):
            #Finding closest coordinate for irrigation reservoirs
            DisMat = np.sqrt((reservoir['longitude'][i] - streamnetwork["ycoord"])**2 +
                             (reservoir['latitude'][i] - streamnetwork["xcoord"])**2)
            #finding index of min distance
            res_i = DisMat.idxmin()
            #finding coord of min distance
            DistPond=DisMat[res_i]*105000 #degrees to m around lat ~20 degrees north

            reservoir['Dist[m]'][i]=DistPond      #in m
            reservoir['latitude stream'][i] = streamnetwork["xcoord"][i] #latitude coordinate of close
        st streamnetwork
            reservoir['longitude stream'][i] = streamnetwork["ycoord"][i] #longitude coordinate of clo
        sest streamnetwork
```

Step 4 - Show output

This last step shows the model output. This output includes the coordinates of the potential location, distance to nearest stream and coordinates of the nearest stream.

```
In [ ]: reservoir
```

Step 5 - Optional

Export the file to your own computer. This step is optional, but useful if you want to store the data.

You can change the name of your file to anything in between the `' '` as long as you put .csv behind it (the name including .csv should turn red, make sure it is between `' '`). Do not change `, index = False, header=True` .

The file will be stored in the folder where the code is stored.

```
In [ ]: reservoir.to_csv ('potential reservoir data.csv', index = False, header=True)
```

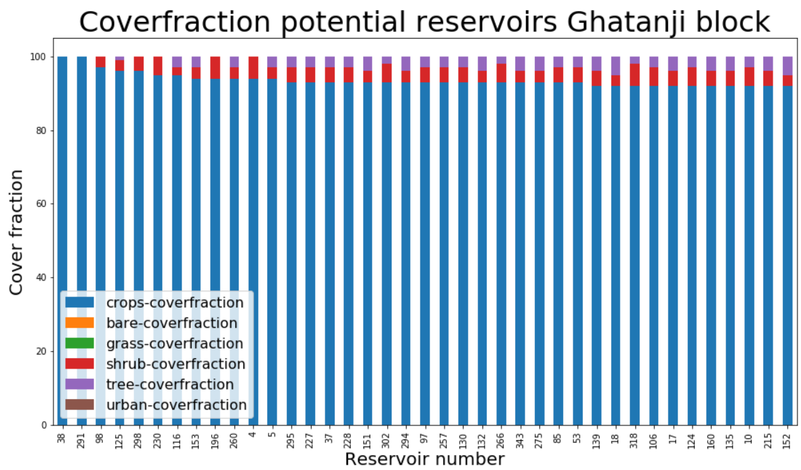
Step 6

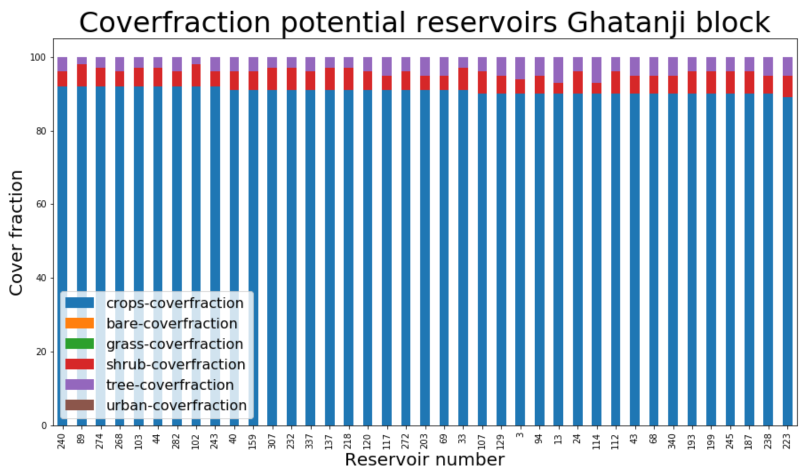
Set the model back to its original values in step 1 and step 2 for the next user.

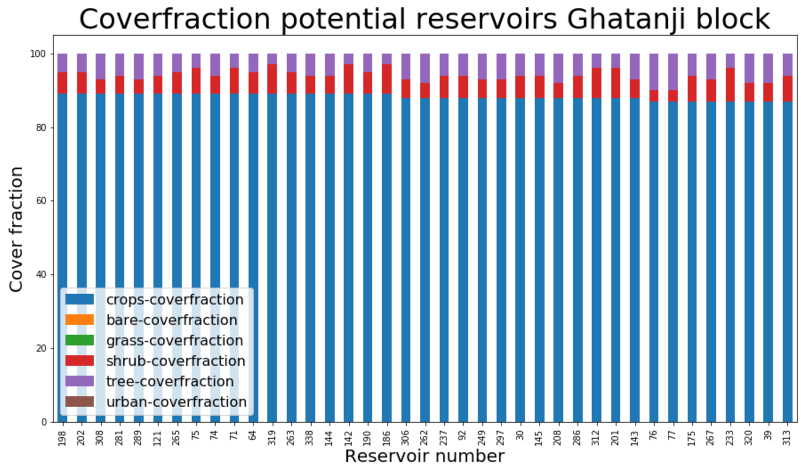
G

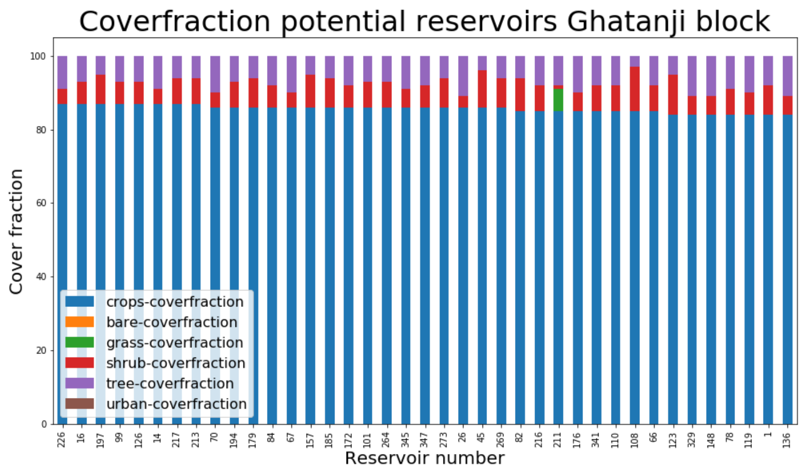
GEE: land cover classification results

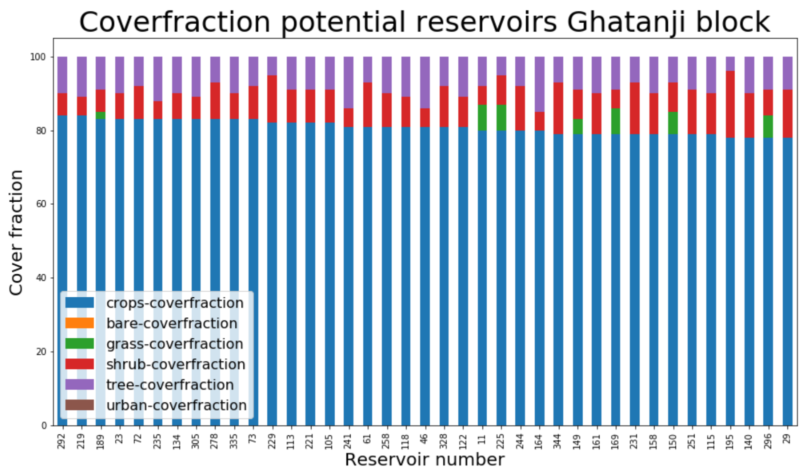
G.1. Ghatanji block land cover results

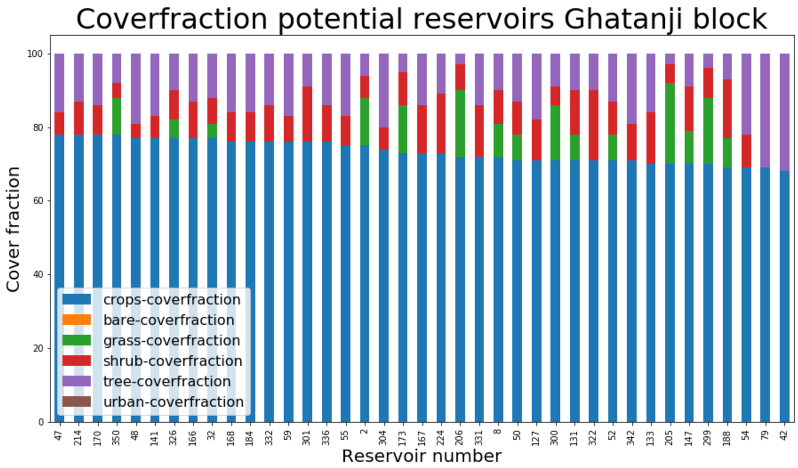


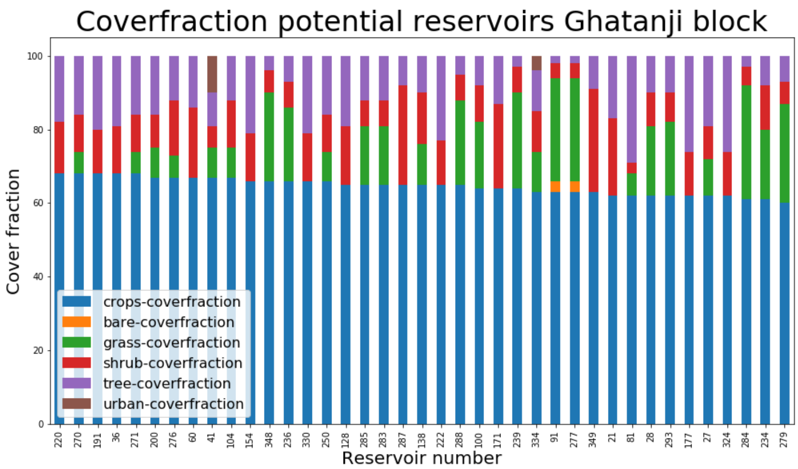


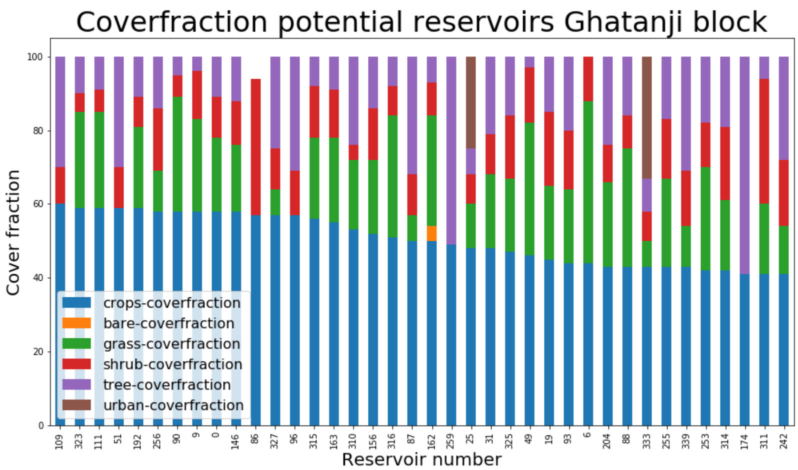

Coverfraction potential reservoirs Ghatanji block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
198 202 308 281 289 121 265 75 74 71 64 319 263 338 144 142 190 186 306 262 237 92 249 297 30 145 208 286 312 201 143 76 77 175 267 233 320 39 313


Coverfraction potential reservoirs Ghatanji block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
226 16 197 99 126 14 217 213 70 194 179 84 67 157 185 172 101 264 345 347 273 26 45 269 82 216 211 176 341 110 108 66 123 329 148 78 119 1 136

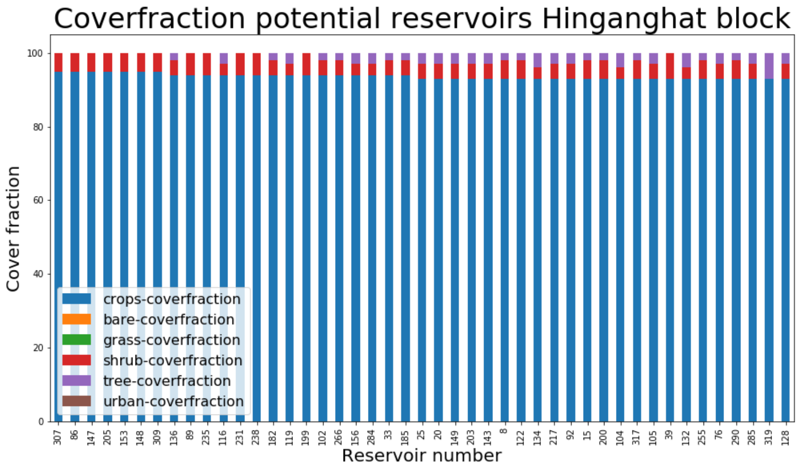

Coverfraction potential reservoirs Ghatanji block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
292 219 189 23 72 235 134 305 278 335 73 229 113 221 105 241 61 258 118 46 328 122 11 225 244 164 344 149 161 169 231 158 150 251 115 195 140 296 29

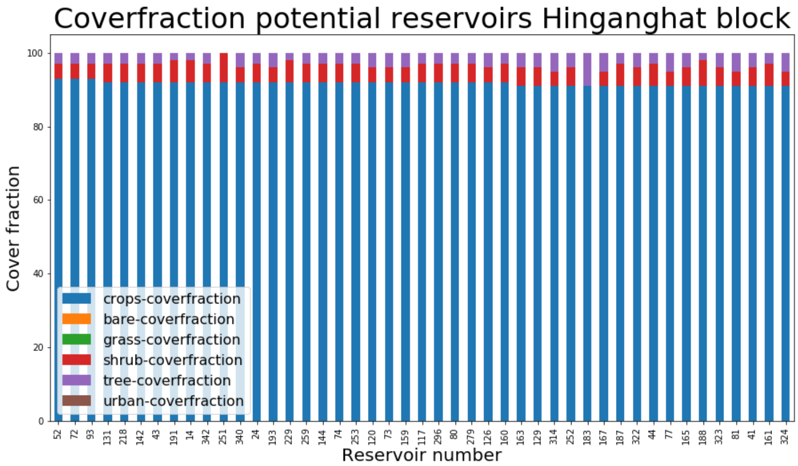

Coverfraction potential reservoirs Ghatanji block
Cover fraction
0
20
40
60
80
100
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
47 214 170 350 48 141 326 166 32 168 184 332 59 301 336 55 2 304 173 167 224 206 331 8 50 127 300 131 322 52 342 133 205 147 299 188 54 79 42
Reservoir number

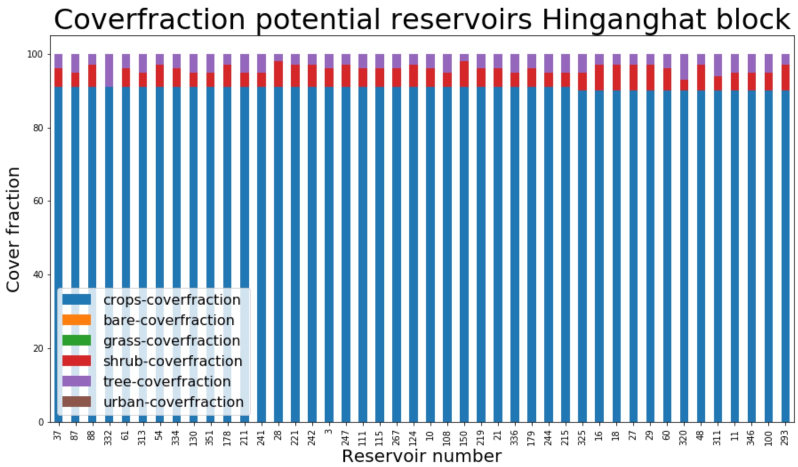

Coverfraction potential reservoirs Ghatanji block
Cover fraction
0
20
40
60
80
100
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
220 270 191 36 271 200 276 60 41 104 154 348 236 330 250 128 285 283 287 138 222 288 100 171 239 334 91 277 349 21 81 28 293 177 27 324 284 234 279
Reservoir number

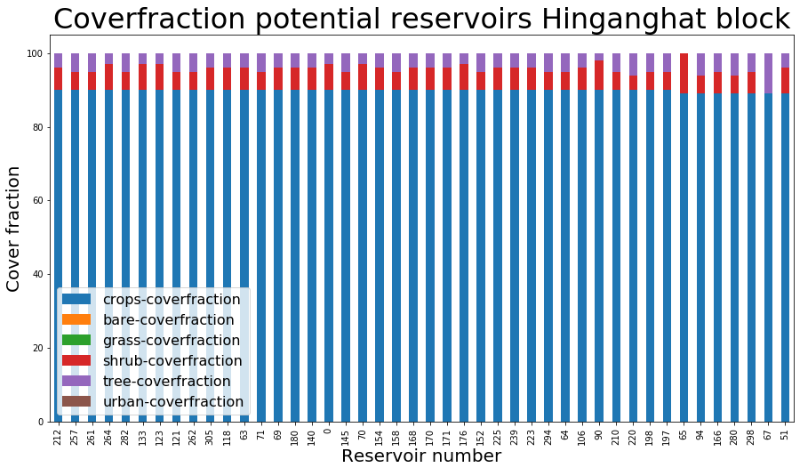

Coverfraction potential reservoirs Ghatanji block
Cover fraction
0
20
40
60
80
100
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
109 323 111 51 192 256 90 9 0 146 86 327 96 315 163 310 156 316 87 162 259 25 31 325 49 19 93 6 204 88 333 255 339 253 314 174 311 242
Reservoir number

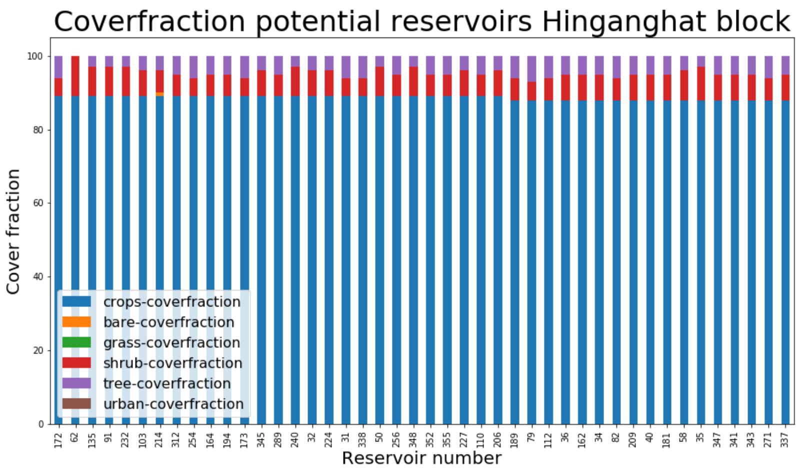
G.2. Hinganghat block land cover results

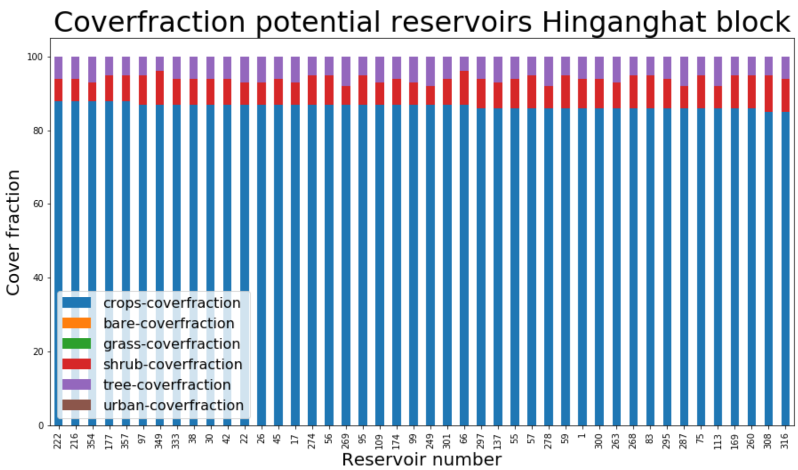


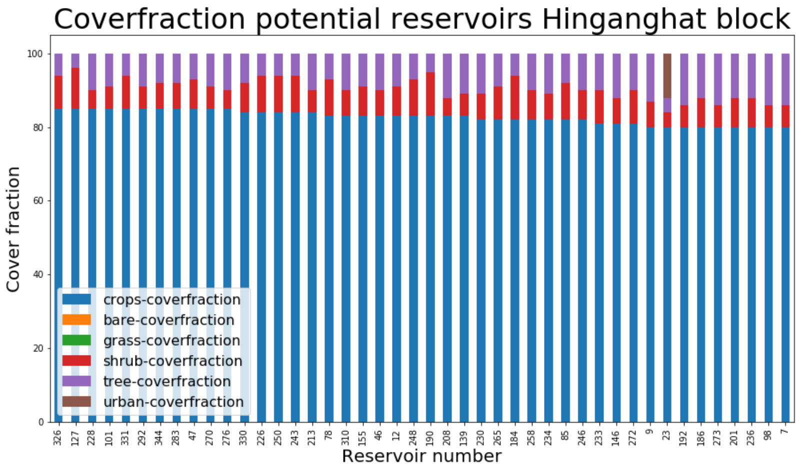


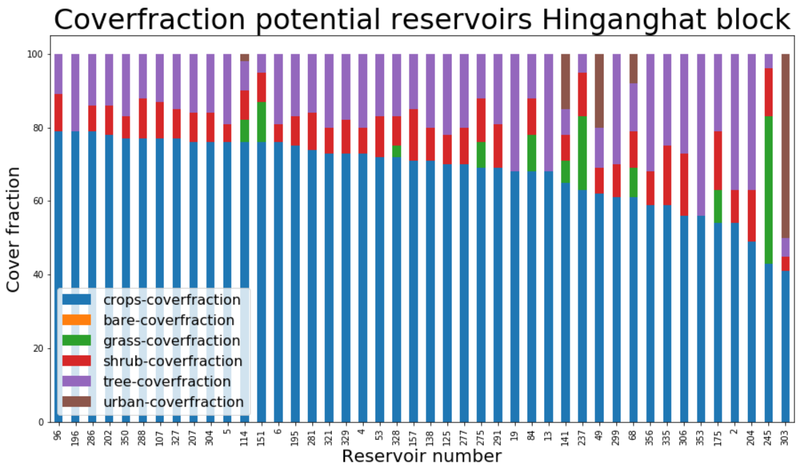



Coverfraction potential reservoirs Hinganghat block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
212 257 261 264 282 133 123 121 262 305 118 63 71 69 180 140 0 145 70 154 158 168 170 171 176 152 225 239 223 294 64 106 90 210 220 198 197 65 94 166 280 298 67 51


Coverfraction potential reservoirs Hinganghat block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
172 62 135 91 232 103 214 312 254 164 194 173 345 289 240 32 224 31 338 50 256 348 352 355 227 110 206 189 79 112 36 162 34 82 209 40 181 58 35 347 341 343 271 337


Coverfraction potential reservoirs Hinganghat block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction
0
20
40
60
80
100
222 216 354 177 357 97 349 333 38 30 42 22 26 45 17 274 56 269 95 109 174 99 249 301 66 297 137 55 57 278 59 1 300 263 268 83 295 287 75 113 169 260 308 316


Coverfraction potential reservoirs Hinganghat block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction

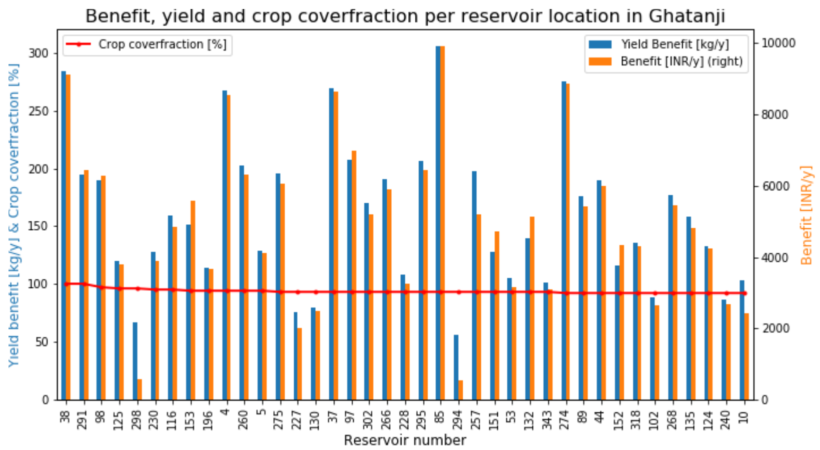

Coverfraction potential reservoirs Hinganghat block
Cover fraction
Reservoir number
crops-coverfraction
bare-coverfraction
grass-coverfraction
shrub-coverfraction
tree-coverfraction
urban-coverfraction

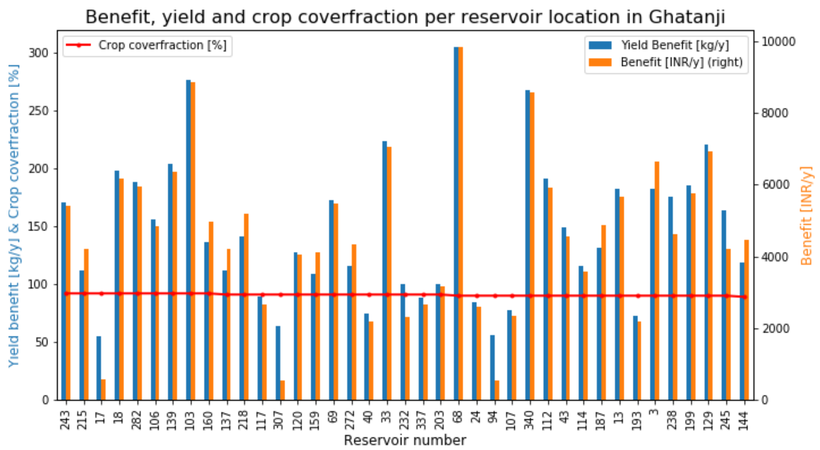
H

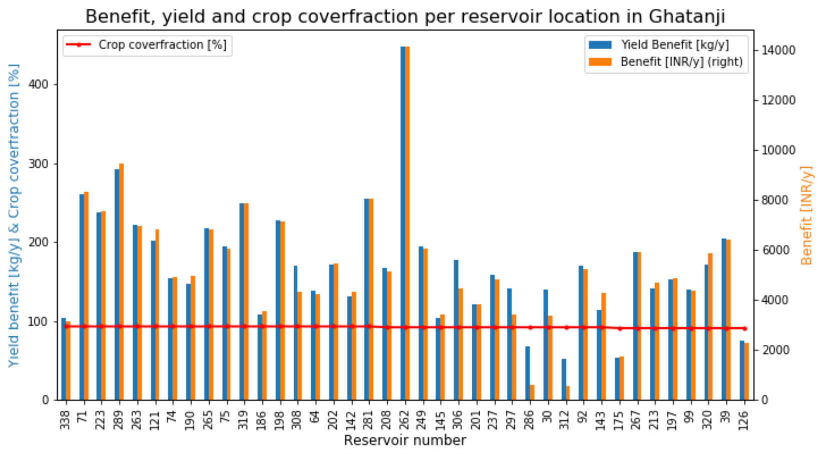
Socio-hydrological model results

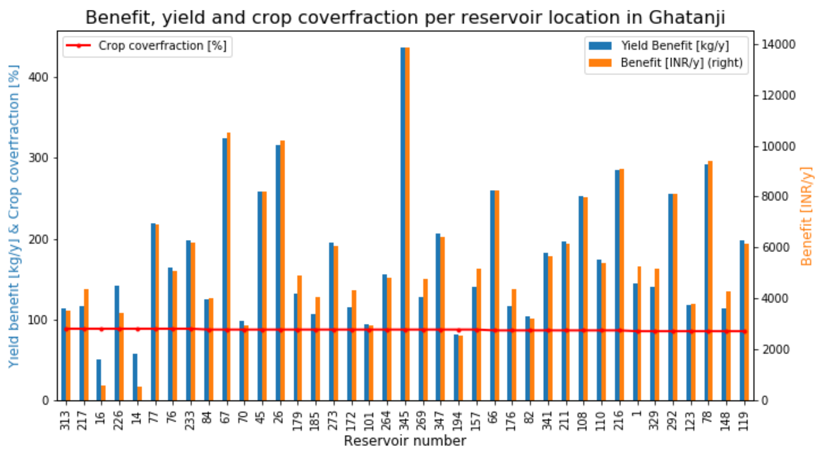
H.1. Socio-hydrological results Ghatanji block

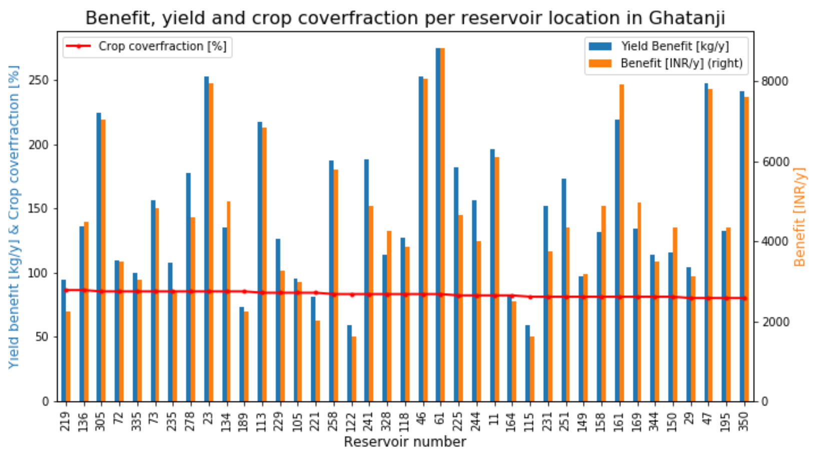
Benefit, yield and crop coverfraction per reservoir. The crop coverfraction is not related to the increase in yield or benefit. The increase in yield as well as benefit are correlated to each other. Made by author



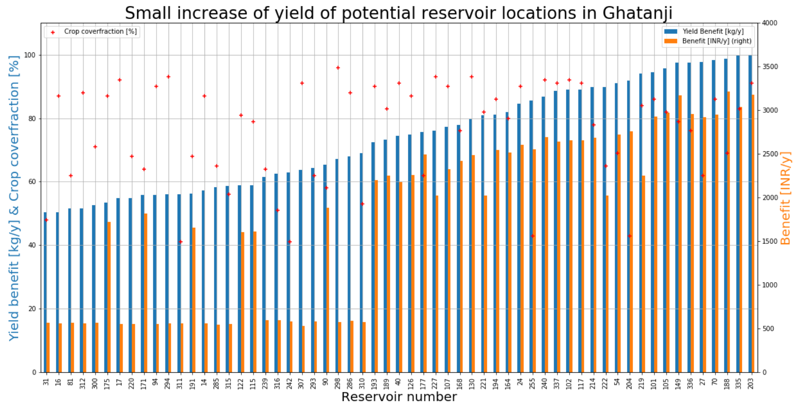


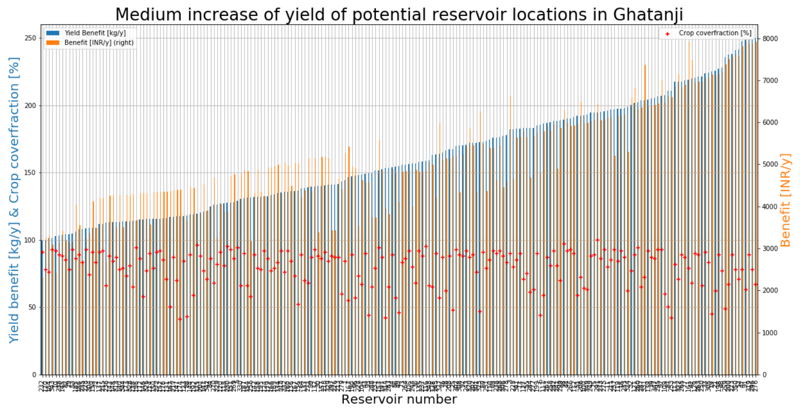

Benefit, yield and crop coverfraction per reservoir location in Ghatanji
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
0 100 200 300 400
0 2000 4000 6000 8000 10000 12000 14000
338 71 223 289 263 121 74 190 265 75 319 186 198 308 64 202 142 281 208 262 249 145 306 201 237 297 286 30 312 92 143 175 267 213 197 99 320 39 126
Reservoir number

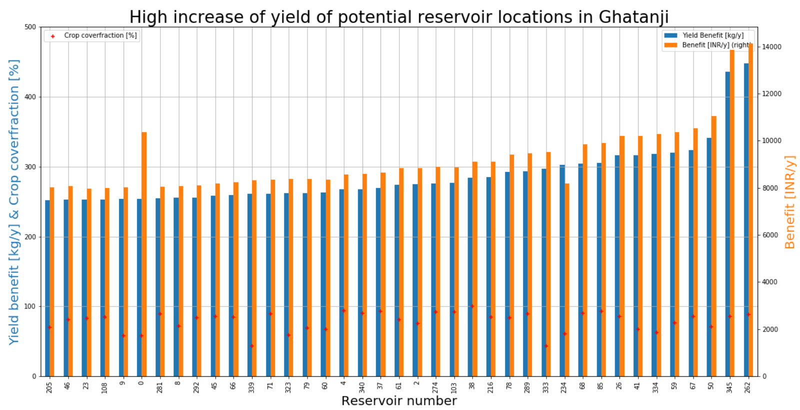

Benefit, yield and crop coverfraction per reservoir location in Ghatanji
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
0 100 200 300 400
0 2000 4000 6000 8000 10000 12000 14000
313 217 16 226 14 77 76 233 84 67 70 45 26 179 185 273 172 101 264 345 269 347 194 157 66 176 82 341 211 108 110 216 1 329 292 123 78 148 119
Reservoir number


Benefit, yield and crop coverfraction per reservoir location in Ghatanji
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
0 50 100 150 200 250
0 2000 4000 6000 8000
219 136 305 72 335 73 235 278 23 134 189 113 229 105 221 258 122 241 328 118 46 61 225 244 11 164 115 231 251 149 158 161 169 344 150 29 47 195 350
Reservoir number

Reservoirs separated into small, medium and high increase in yield. Benefit and yield are closely correlated. Crop cover fraction is not related to yield and/or benefit. Made by author.

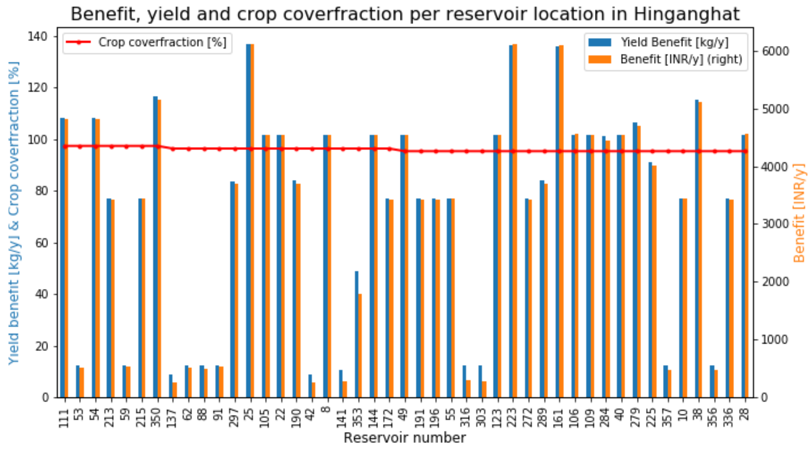

Small increase of yield of potential reservoir locations in Ghatanji
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

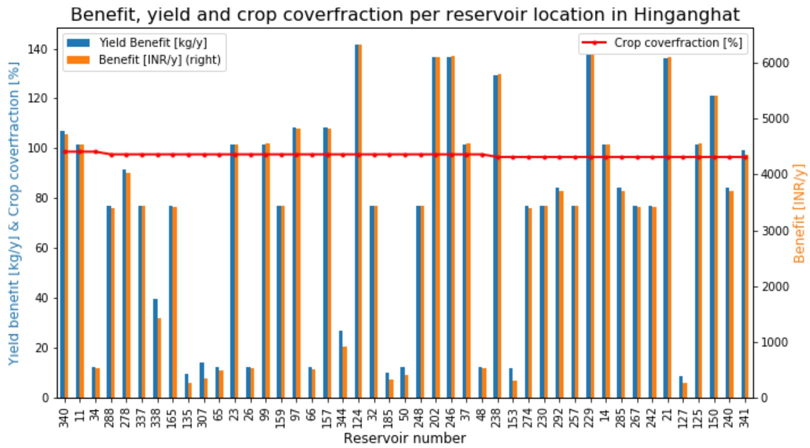

Medium increase of yield of potential reservoir locations in Ghatanji
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Crop coverfraction [%]
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

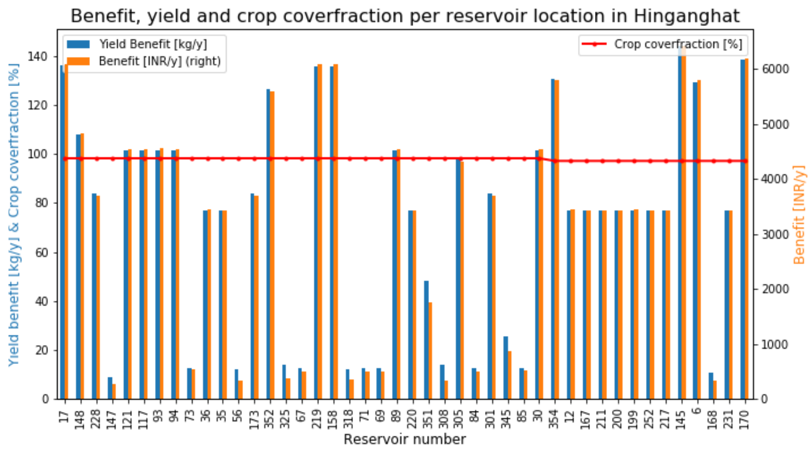

High increase of yield of potential reservoir locations in Ghatanji
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

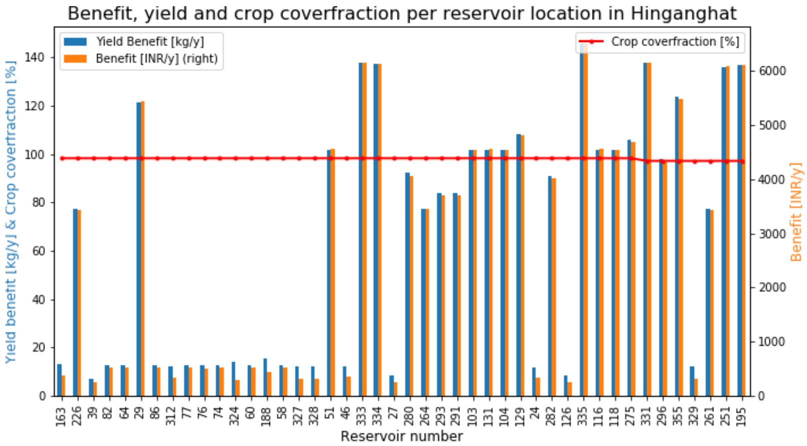
H.2. Socio-hydrological results Hinganghat block

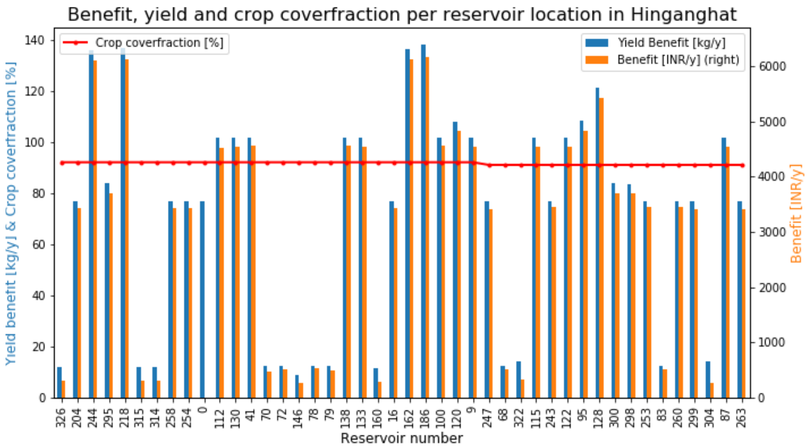
Benefit, yield and crop coverfraction per reservoir. The crop coverfraction is not related to the increase in yield or benefit. The increase in yield as well as benefit are correlated to each other. Made by author.

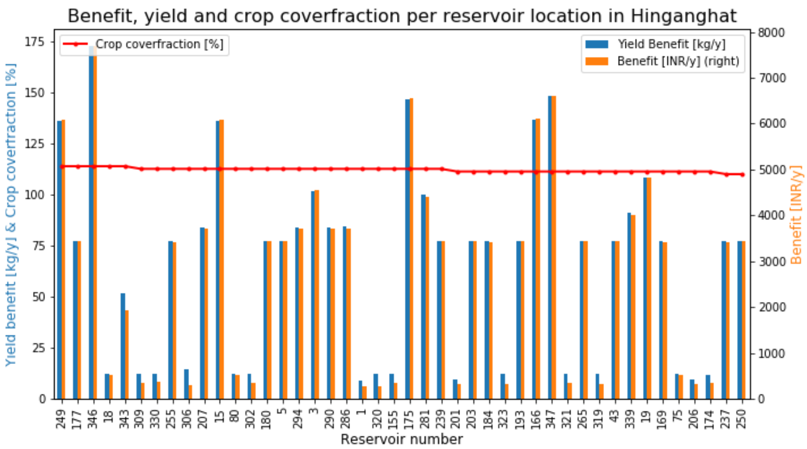


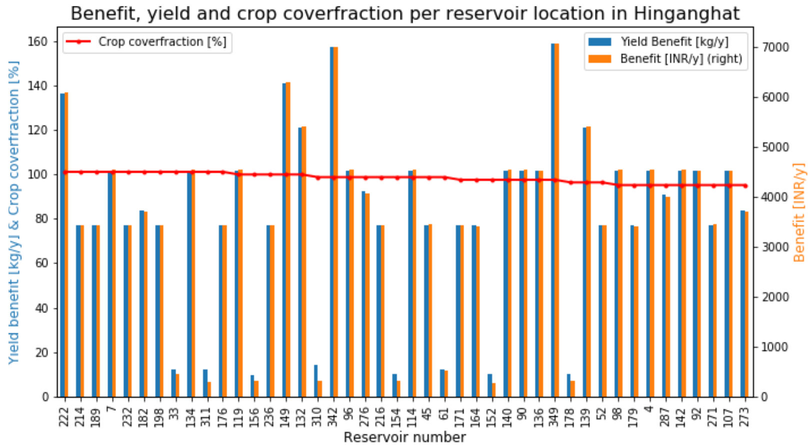


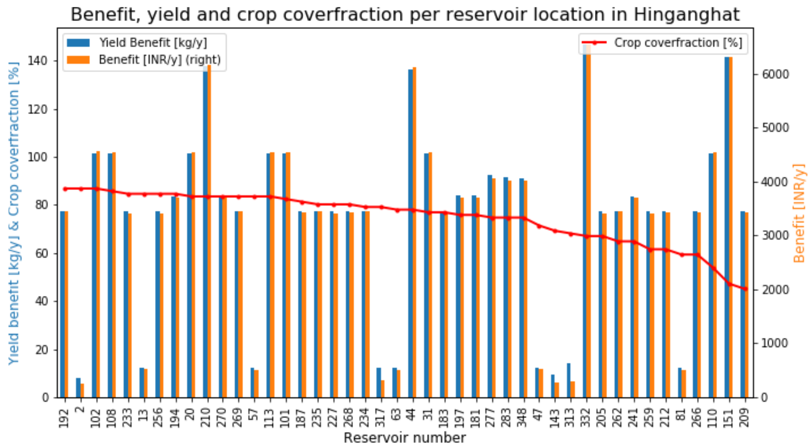



Benefit, yield and crop coverfraction per reservoir location in Hinganghat
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Crop coverfraction [%]
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

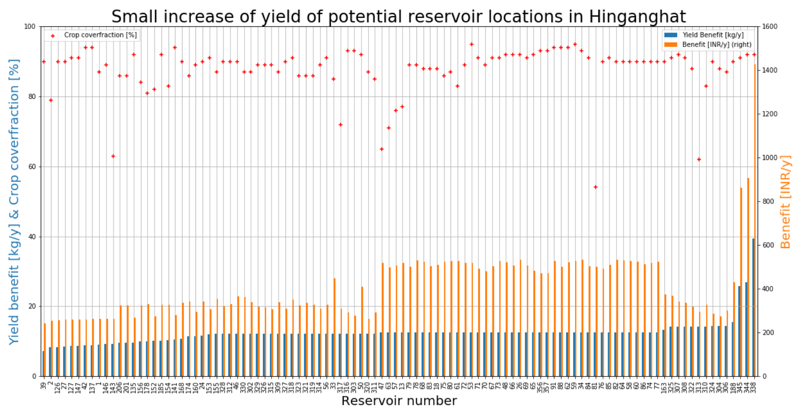

Benefit, yield and crop coverfraction per reservoir location in Hinganghat
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

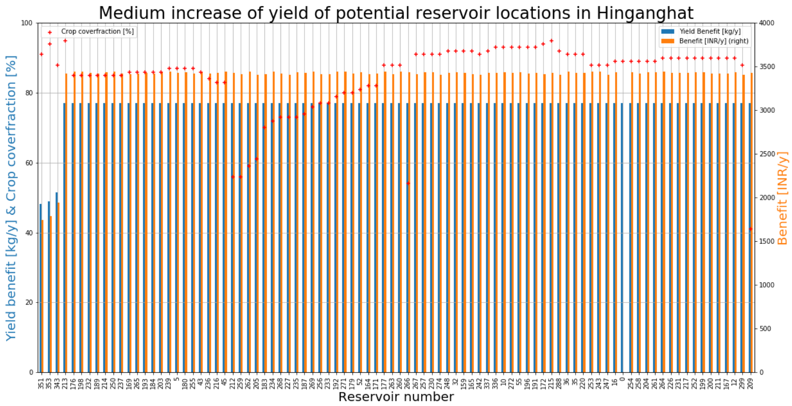

Benefit, yield and crop coverfraction per reservoir location in Hinganghat
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

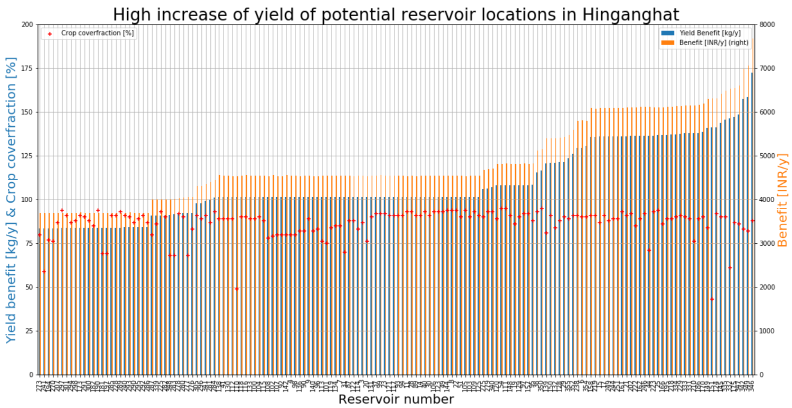




Reservoirs separated into small, medium and high increase in yield. Benefit and yield are closely correlated. Crop coverfraction is not related to yield and/or benefit. Made by author.




Medium increase of yield of potential reservoir locations in Hinganghat
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number


High increase of yield of potential reservoir locations in Hinganghat
Crop coverfraction [%]
Yield Benefit [kg/y]
Benefit [INR/y] (right)
Yield benefit [kg/y] & Crop coverfraction [%]
Benefit [INR/y]
Reservoir number

Locations constructed by Solidaridad

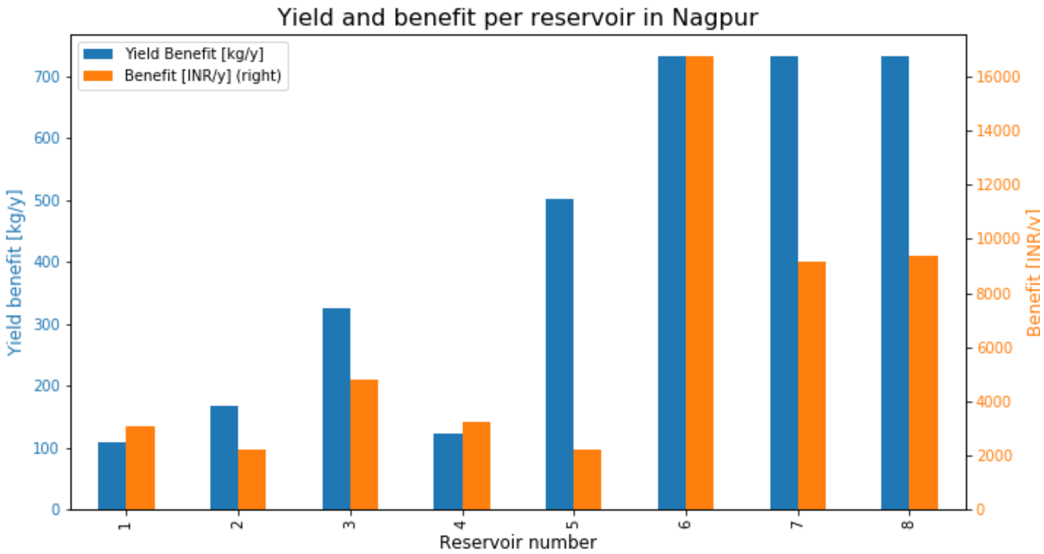


Figure I.1: Yield and benefit of each reservoir constructed by solidaridad in the Nagpur district. Made by author.

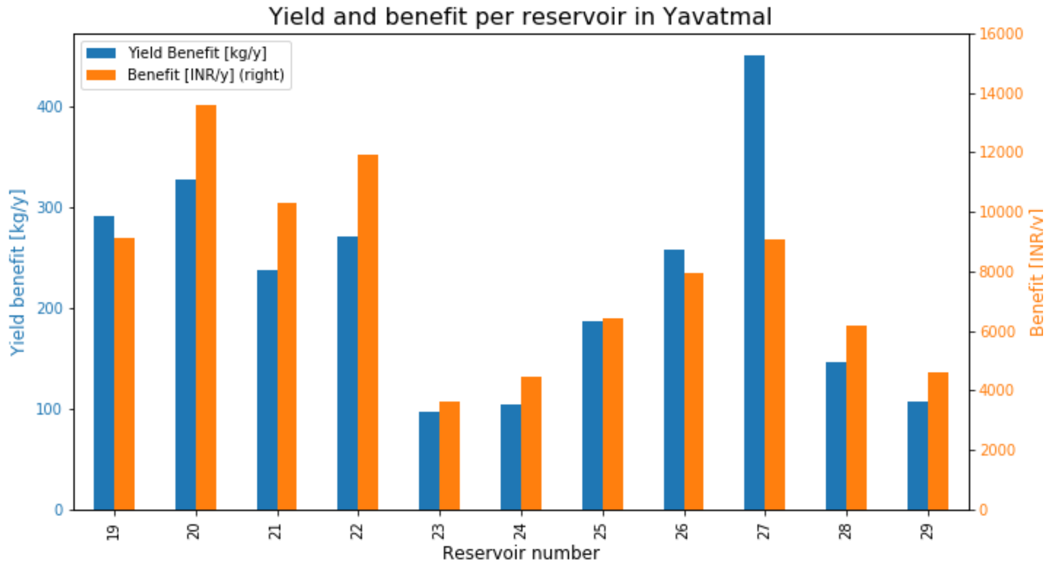


Figure I.2: Yield and benefit of each reservoir constructed by solidaridad in the Nagpur district. Made by author.

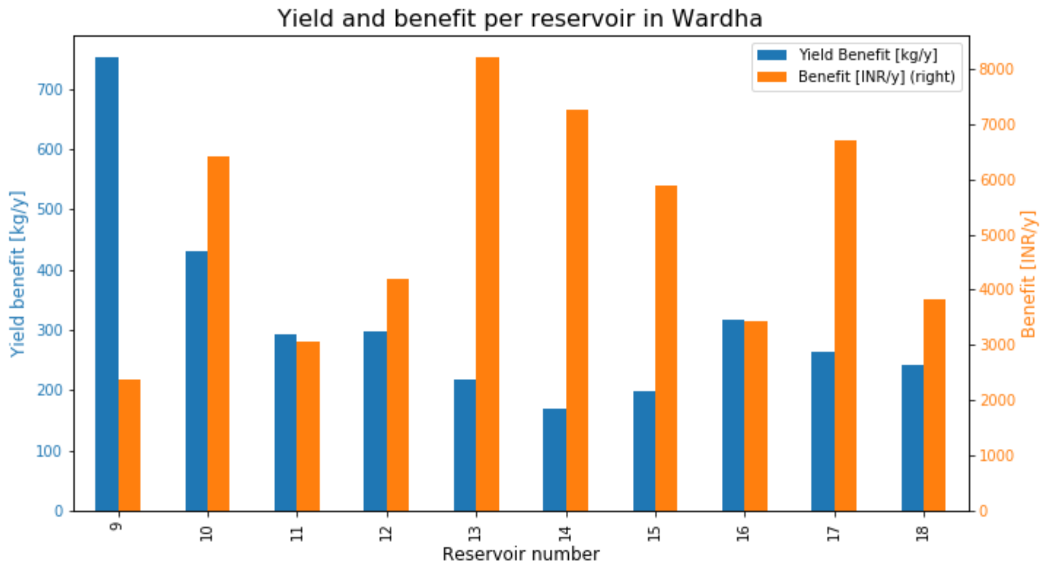


Figure I.3: Yield and benefit of each reservoir constructed by solidaridad in the Wardha district. Made by author.