Welang River Basin Flood Management and Master Plan

Baseline assessment Welang: balancing development, and flood resilience

Netherlands Enterprise Agency-Partners for Water
Water Resource Department of East Java Provincial Government

17 January 2022

Executive Summary

Flooding is increasingly a problem in the Welang catchment. Flooding mostly occurs in the downstream reach in and around the Kraton district, but also affects settlements in the midstream reach from Lawang to Sidogiri. Floods are mostly limited in depth and duration. In the Kraton district floods may be of combined fluvial and pluvial origin, while in the other areas they are mostly pluvial in origin.

The recent uptick in flood events is a result of man-induced changes in the catchment. Recent economic development has resulted in a strong urbanisation process throughout the catchment with large factories developing along the main transport corridors and irrigation channels. This urbanization process is not met with sufficient investments in stormwater drainage systems and leads to a push of agriculture further up the steep slopes of the Bromo and Arjuna mountains where steep slopes are planted with seasonal rainfed crops (resulting in higher run-off and excessive soil erosion). This development is managed insufficiently, and spatial plans mostly follow developments, and no adaptation requirements are in place for new agricultural developments on steep slopes (e.g., terracing).

Flood risk management is mostly focussed on post-disaster recovery and protection and, although individual departments have flood mitigation plans, in practice little coordination and effectively little prevention efforts are developed. Maintenance of existing flood protection infrastructure (e.g., maintenance dredging of rivers, cleaning of roadside drains, etc.) is limited and not effective.

Financially, the provincial and regional governments are increasingly thriving, but flooding may increasingly put a break on further economic development. Budgets have increased steadily, and more budget is available for support. This is a clear indication that poverty is reducing, and the economy is doing well. Flood events, especially pluvial events, lead frequently to severe congestion and hence have an economic effect. However, pluvial floods are perceived as nuisance.

The recent economic developments and the associated land cover changes, have significantly increased run-off and reduced infiltration and groundwater recharge. This has resulted in increased peak discharges during the rainy season, with much higher and faster flash-flood type discharge waves. In addition, in combination with much increased demand for groundwater for urban and rural purposes, groundwater tables in the mountains have significantly lowered, resulting in reduced discharges from springs and lower baseflows in the rivers especially during the dry season. Climate change may result in a shorter rainy season, but not to higher peak precipitation, and hence will likely lead to lower groundwater tables and baseflows, but not to higher peak discharge waves; which are only caused by land cover changes.

To address the immediate short-term fluvial flood risks in the downstream reach, protection measures need to be taken that lower peak water levels in and around Kraton (e.g., dredging, creation of a diversion channel). Fluvial flood risks can be lowered by aligning maintenance efforts by the various local and provincial departments involved.

In the medium-term, more efforts are needed to prevent a recurrence of both pluvial and fluvial flood risks. Measures need to be taken in the upstream reach to reduce run-off: terracing and the deployment of gully plugs in addition to the introduction of water sensitive agriculture practices.

These measures require strong guidance by the regional, provincial, and central governments. Spatial plans need to be drafted based on realistic estimates and the hydrological impacts should be evaluated. Land developments on steep hills should be restricted altogether to reduce run-off and prevent excessive soil erosion.

Table of Contents

1 Introduction

1.1 Project

The Welang River Basin Flood Management and Master Plan project is developed in close cooperation between Water Resource Department of the East Java Provincial Government and the Netherlands Ministry of Infrastructure and Water Management. The project is implemented under the Partners for Water Program, a program managed by the Netherlands Enterprise Agency (RVO), part of the Netherlands Ministry of Economic Affairs and Climate.

The Welang project supports the water management department of East Java Province in developing management strategies for both the entire watershed and for urgent issues. The project is subdivided in five Tasks, three of them leading to tangible deliverables: a baseline study, an Integrated River Basin Management Plan (IRBMP) and implementation plans for two high-priority problems. The two remaining tasks focus on interactive community involvement and training and capacity building.

This report is part of Task A, Flood Resilience Baseline and presents the results of the baseline assessment aiming at understanding the current and expected future flood hazards and the underlying mechanisms leading up to these flood hazards and is prepared under the coordination of Deltares with contributions from Wetlands International, The Water Agency and Witteveen+Bos.

1.2 This report

In this report the results of the flood resilience baseline assessment for the catchment are described. The underlying physical, socio-economic, and institutional contexts are assessed in detail in chapters 2, 3 and 4. In each of these chapters the findings of the past (before 2020), current (2020) and expected near future (after 2020) conditions on the ground are presented.

In chapter 5 the results of a detailed flood hazard analysis based on hydrological and hydraulic modelling are presented. This chapter describes the understanding of the past (2013), current (2020) and near future (2029) flood hazards, potential effects (risks) and the underlying drivers and causes. It provides insight in how changes in the environmental, socio-economic, and institutional contexts lead to observed and expected changes in flood hazards and risks.

In chapter 6 the identified key challenges, opportunities and needs with regards to flood resilience are provided. These challenges are presented in four main domains: 1) the downstream areas, 2) the upstream areas, 3) the midstream areas and 4) the governance. The identified key challenges, opportunities and needs inform the dialogue on how to improve flood resilience on the short-term and how to further improve and maintain high flood resilience in the long-term.

2 Physical Context

The Welang catchment is situated in East Java (see Figure 2.1). The sources of the river are on the slopes of the Bromo (south-east, 2,758m high) and Arjuna (south-west, 3,150m high) mountains and the river drains into the Madura Strait via the large Porong estuary. The size of the Welang catchment is about 518km^2 and the river is with a maximum width of about 25m near the river mouth, relatively small.

The northern area, downstream of the Surabaya-Probolinggo toll-road, is mostly flat with a maximum elevation of 10m+MSL and densely populated. The upstream slopes of the mountains are steep and sparsely populated; this is west of the Surabaya-Malang toll-road and south-east of the line Kota Pasuruan-Kota Malang. The mid-stream area is characterized by an undulating topography with numerous settlements dotted in the terrain.

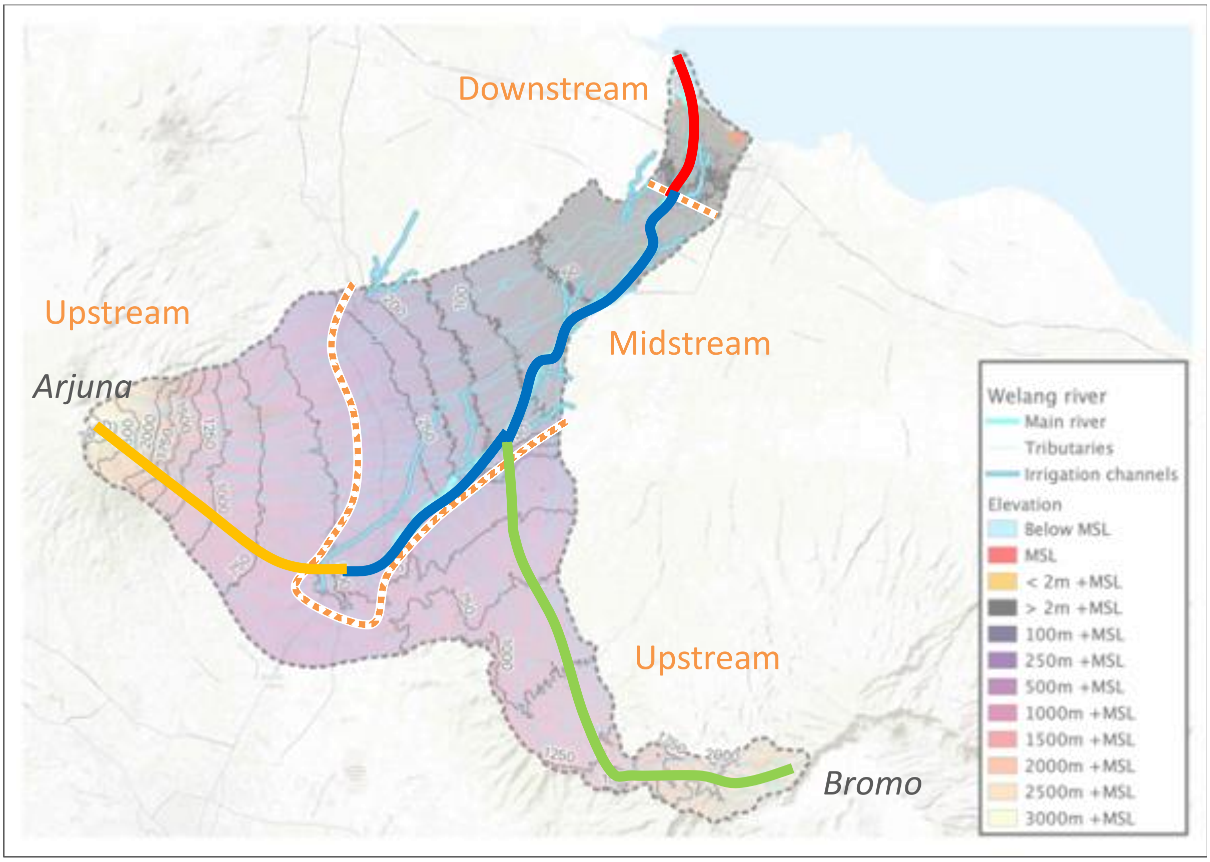


Figure 2.1 DAS Welang and its tributaries within the subdistricts

In rivers, three different sections can be distinguished (Figure 2.2). A steep upstream section where the sources of the river are found and where rapids and waterfalls are mostly present. A midstream section with gentle undulating terrain where the river runs in deeper valleys. And a downstream section (below 10m+MSL), north of the toll road, where the river flows through the lowland area where the city of Pasuruan has recently expanded into.

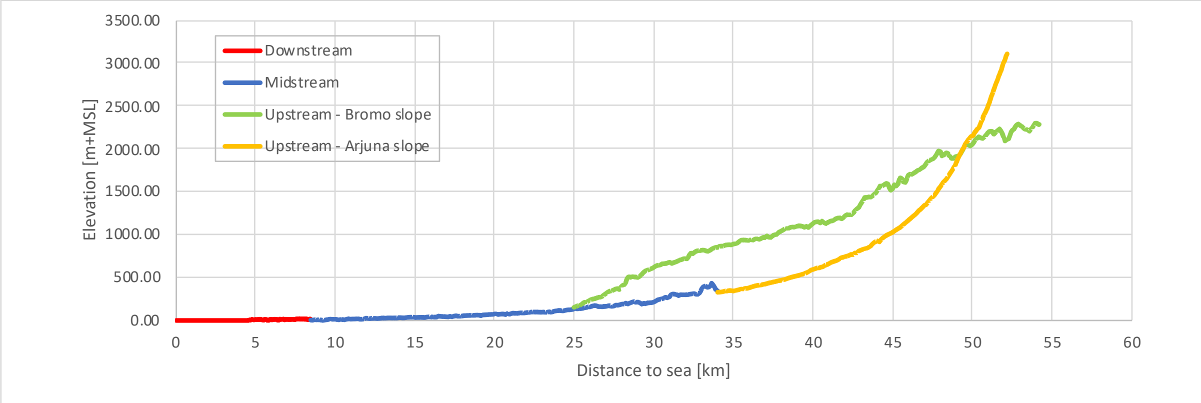


Figure 2.2 Three sections (downstream, mid-stream and upstream) can be clearly recognised in the terrain. Colours correspond with the sections in Figure 2.1.

2.1 Geology

2.1.1 Geology

The geological conditions are presented in Figure 2.3. The Welang stratigraphy comprises three underlying formations which are surficial deposit, sedimentary rocks, and volcanic rocks (Santosa and Suwarti, 1992). The surficial deposit is widely represented by river channels and beach deposits which are commonly situated in lowland coastal areas in north Java. In this area, the alluvial formation only covered the downstream end at the coast near Pasuruan.

The geology of the midstream and upstream areas is characterised by the Arjuna and Bromo volcanoes and is mostly volcanic in origin.

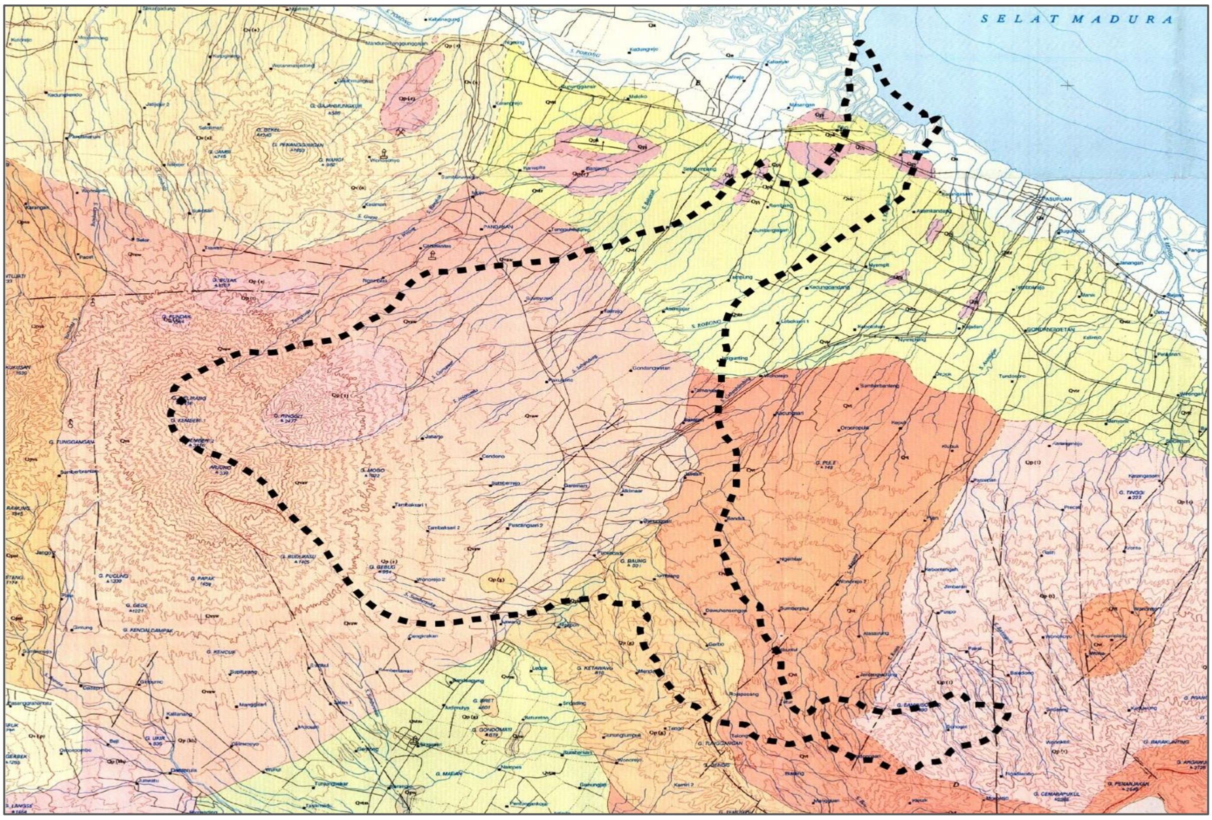


Figure 2.3 Geological map of DAS Welang

2.1.2 Soft soil and land subsidence

In total results of 28 CPT tests and 3 boreholes/SPT (with depths of 2 to 20m) (Figure 2.4) were available and used for the analysis. The data shows that the thickness of the soft soil varies along the downstream section of the Welang river (Figure 2.5). Near the toll-road the thickness of the soft soil is with about 1m very thin. Further towards the river mouth, the thickness of the soft soil layer increases to a maximum of about 10m. This is much less than what is found elsewhere along the north coast of Java where the thickness of the soft soil can reach 40-60m.

It is concluded that the risk of land subsidence is very limited, because the limited thickness of the soft soil. A small part of the downstream area (near the delta) is more susceptible to land subsidence due to alluvium deposit in this area. Land subsidence (due to e.g., groundwater abstraction) is likely very limited to a few mm per year, if present at all. Also, it is likely that land subsidence, if present, is mostly observable near the river mouth and is not significant in the urbanized area between the toll-road and the rail bridge. Towards the future, if the area downstream of the bridges is to be developed, land subsidence may increase there.

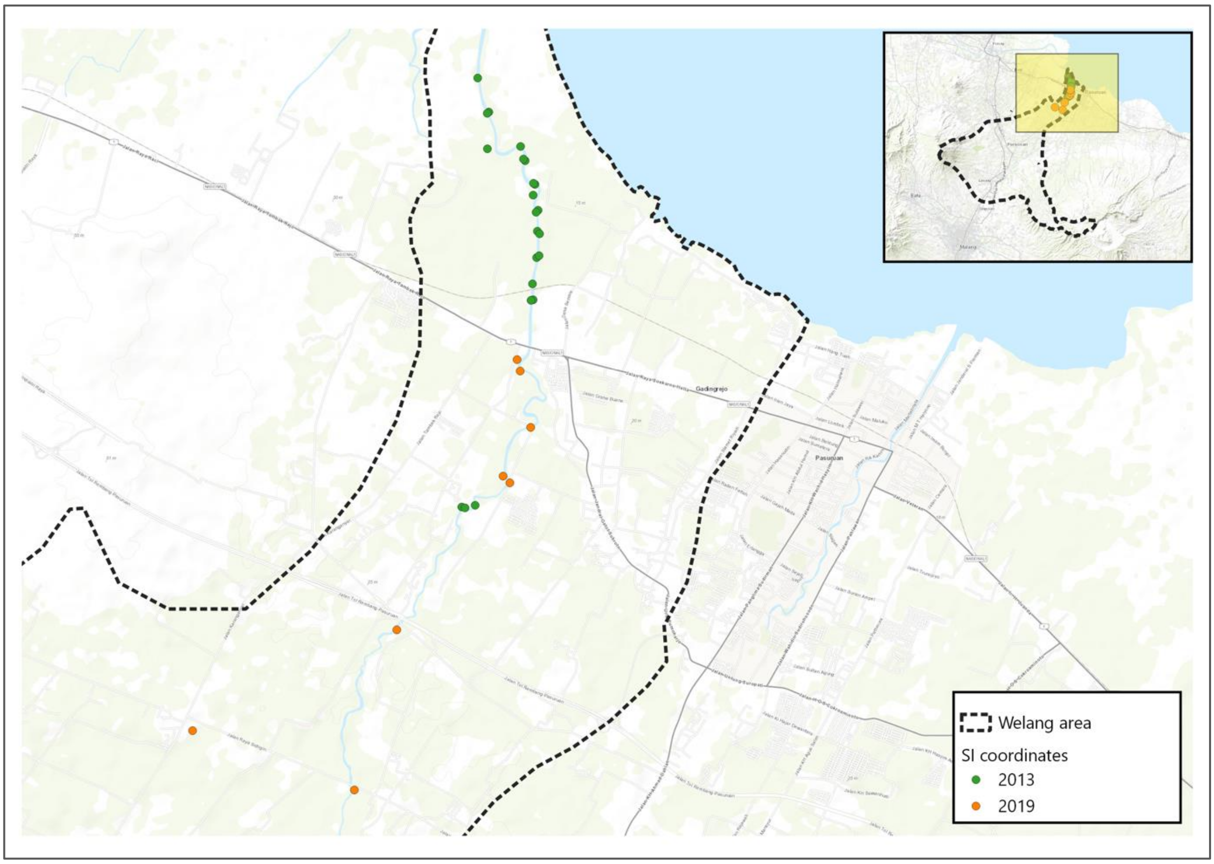


Figure 2.4. Available soil investigation data which were performed in 2013 (in green) and 2019 (in orange)

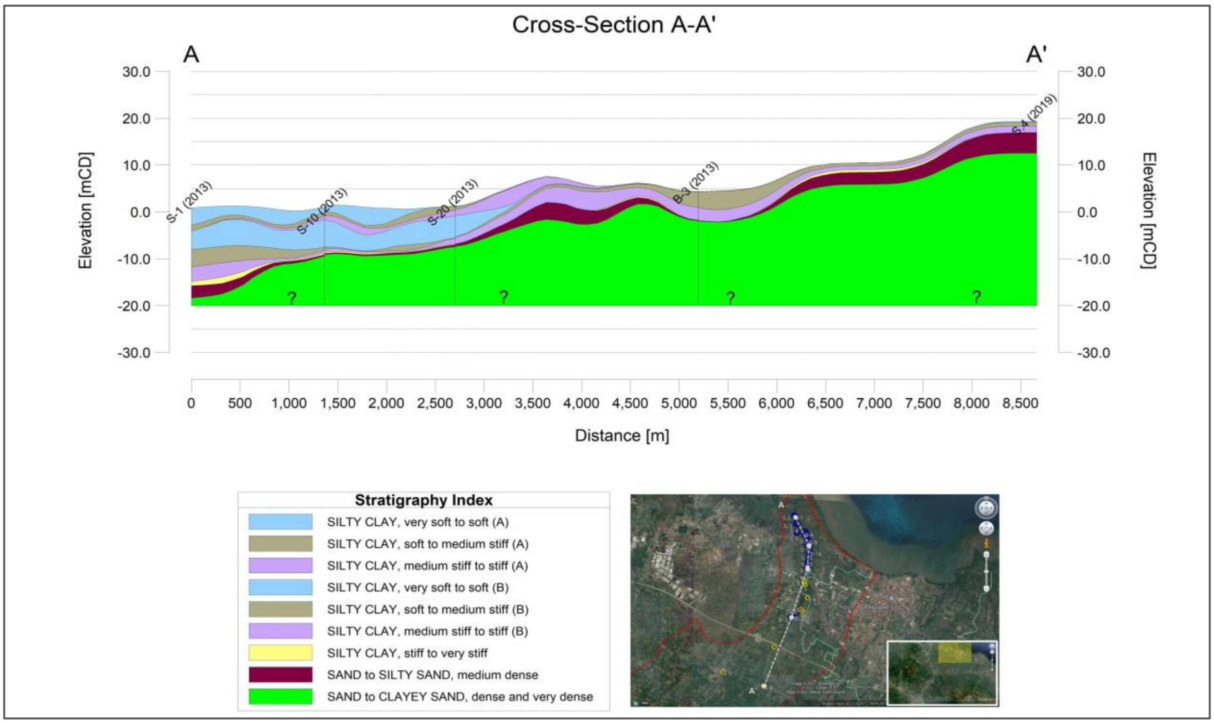


Figure 2.5. Select soil investigation result around Kali Welang in 2013 (source: xxxx)

2.1.3 Potential soil erosion

Estimations of potential soil erosion (Figure 2.6), indicate that the highest potential for soil erosion is along the steep slopes of the Arjuna and Bromo mountains. Especially the slopes above the Lawang and Tutur districts show very high potential soil erosion. This is also confirmed from visual observations which indicate a brown coloured river as far upstream as Lawang. This sediment may be transported downstream to the river mouth where it settles and reduces the discharge capacity of the river, potentially leading to higher water levels and flood hazards/risks.

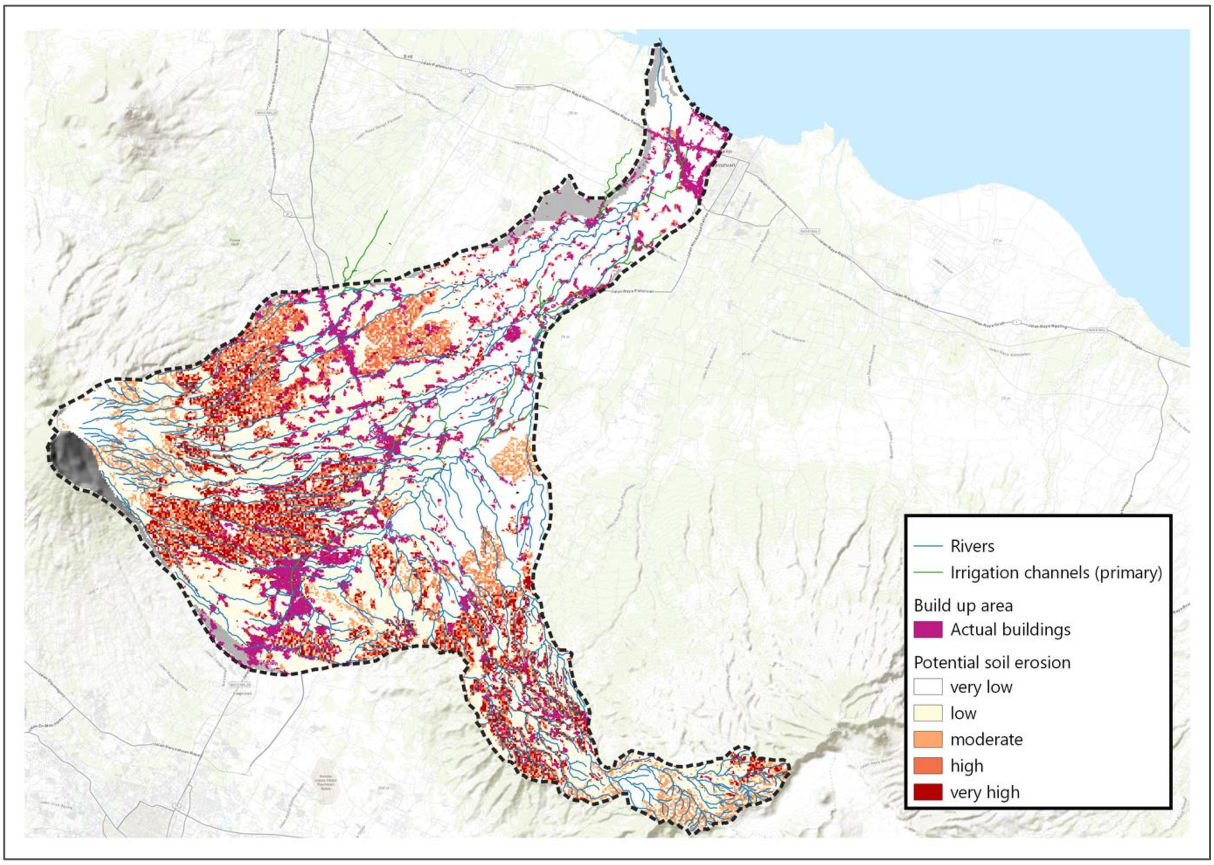


Figure 2.6. Potential soil erosion shows very high erosion near the foot of the mountains (source: original figure prepared for this publication)

2.2 Land development

2.2.1 Coastal development

The coastline of the Welang river has seen significant sedimentation at least since the 1970s (Figure 2.7). The land that arose from the sea before 2000, is currently used for fishponds. Whatever has sedimented since 2000 is currently covered in thriving mangroves.

The recent sedimentation and rapid development of the southern part of the Porong estuary has had major effects on the Welang river. Since the 1970s the Welang river has become some 2-3km longer.

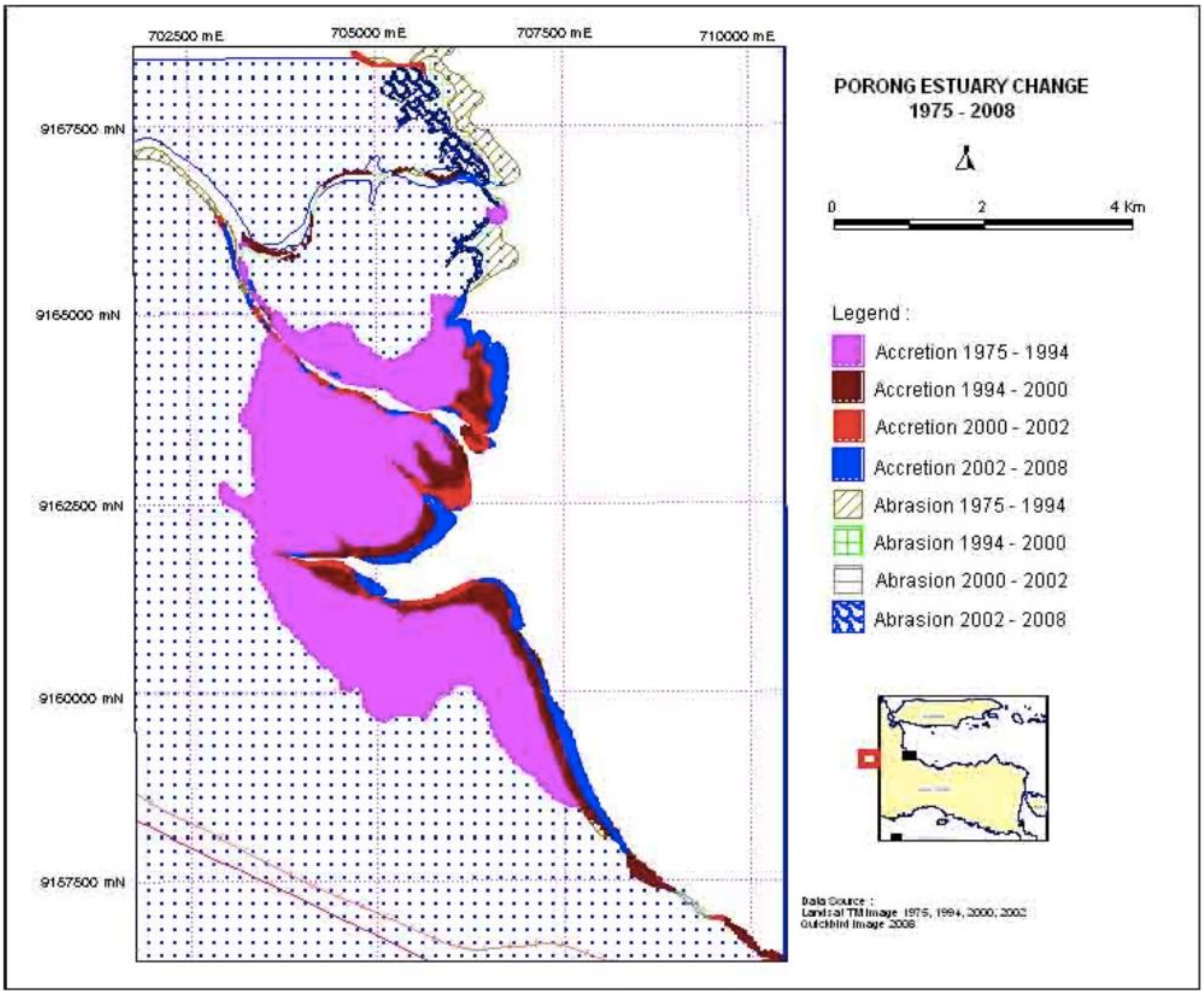


Figure 2.7. Coastal development of the Porong Estuary (Hernawan, 2008)

2.2.2 Land-cover

Current land-cover

In Figure 2.8 the current approximate land-cover is presented. Most land is cultivated or urbanised and only near the top of the mountains some forest cover is still present.

The upstream catchment is mostly covered by plantations and dry-agriculture (seasonal rainfed agriculture) and along the slopes leading to the Bromo mountain numerous small tourist settlements can be found. The results of the 2017 hydrological study indicate that most of the inland areas in the Welang watershed are categorized as 'somewhat critical land' (a reference to land vulnerable to soil erosion and landslides).

The midstream area is covered by irrigated agricultural land interspersed with villages. Two main transport arteries (Pasuruan – Malang and Surabaya – Malang) cut through the region and urban developments (housing areas and factories) are concentrated along these arteries.

In the downstream area, the development of the Kraton area as a suburb of Pasuruan city has turned once abundant rice-fields[1] into an urban network of small streets, dense low-cost housing complexes and big industrial warehouses. The region between the rail-bridge and the river mouth used to be

[1] Up to the late 1990s the Kraton area was still mostly covered in irrigated rice-fields and only along the provincial road a narrow strip of buildings (houses, "ruko's" and warehouses) could be found.

covered with fishponds, which are now only present at close distance to the coast and the remaining area is now used for rice cultivation. In this area a gas-metering plant was constructed in 2016.

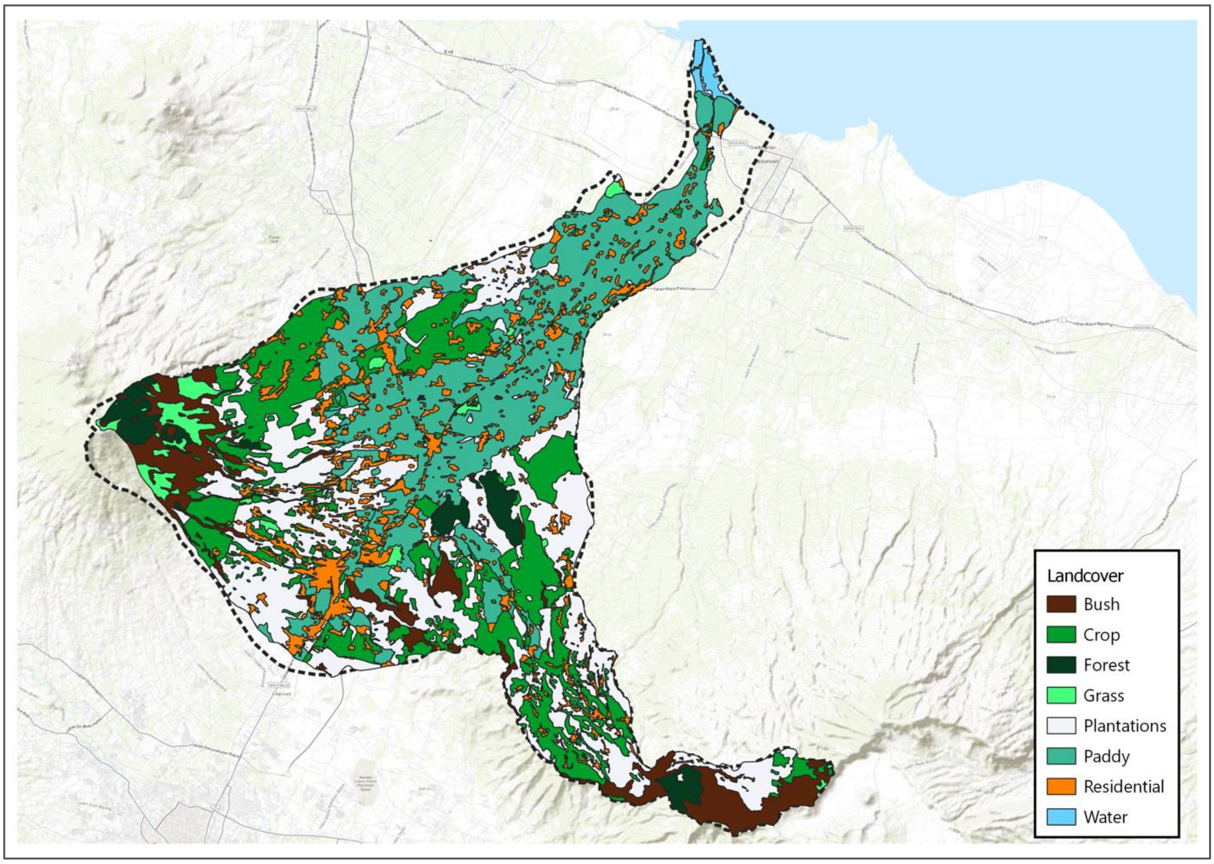


Figure 2.8. Land cover in the Welang Catchment

Historic land-cover

In Figure 2.9 the land cover changes since 2013 are provided. The figure shows that land for agricultural purposes and forested land cover have significantly reduced and made way for urban areas (artificial surfaces). This also shows urban areas encroaching on both existing agricultural land and the remaining forest cover and pushes agriculture further uphill into steep terrain with vulnerable soils. Especially the amount of land used for urban purposes (housing and industry) has increased significantly in recent years.

This urbanisation is also reflected in the number of villages with an 'urban' status from BPS[2]. The classification of villages to rural/urban follows a clear structure. There are 345 villages (desa/kelurahan) within the Welang Catchment. In 2010 96 villages in the catchment had the status 'urban', and in 2021 this number has increased to 152.

[2] The BPS classification based on a scoring system consisting of scores for population density, percentage of agricultural households, access to urban facilities, existence of additional facilities, percentage of built-up area, etc. Financial resources from national government to villages is dependent on the village status.

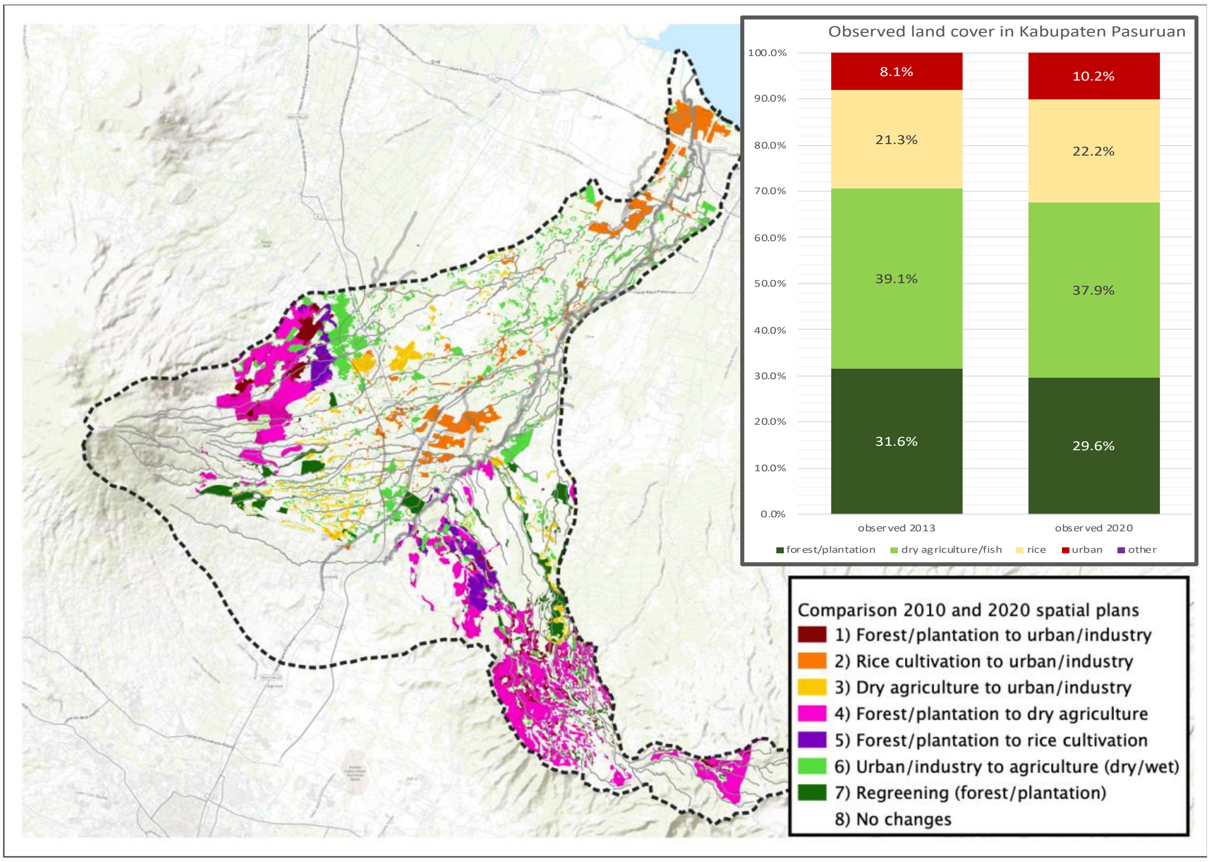


Figure 2.9. Comparing historic and current land cover, shows a steady decline in cultivated and forested area and a significant increase in artificial surfaces (paved urban) (sources: Author)

In the downstream area, the urban expansion of the city of Pasuruan has rapidly changed the landscape since the turn of the century. The urban development used to be focussed on the narrow stretch directly adjacent to the main roads but has now also expanded a bit further into the existing agricultural areas.

In the midstream region along the river and the provincial road, villages have developed rapidly to the expense of agricultural land since the late 1990s and early 2000s. Especially since the completion of the toll road, the corridor along this stretch has seen significant urbanisation.

However, the most dramatic changes can be found in the upstream region. Here numerous developments can be found, and large areas have been turned into residential areas or tourist retreats. Forests have been turned into agricultural land to grow vegetables or into plantations. Statistical data (BPS, 2020) also shows that landslides occurred in the Kecamatan where most vulnerable soils are found and where most land degradation has occurred recently.

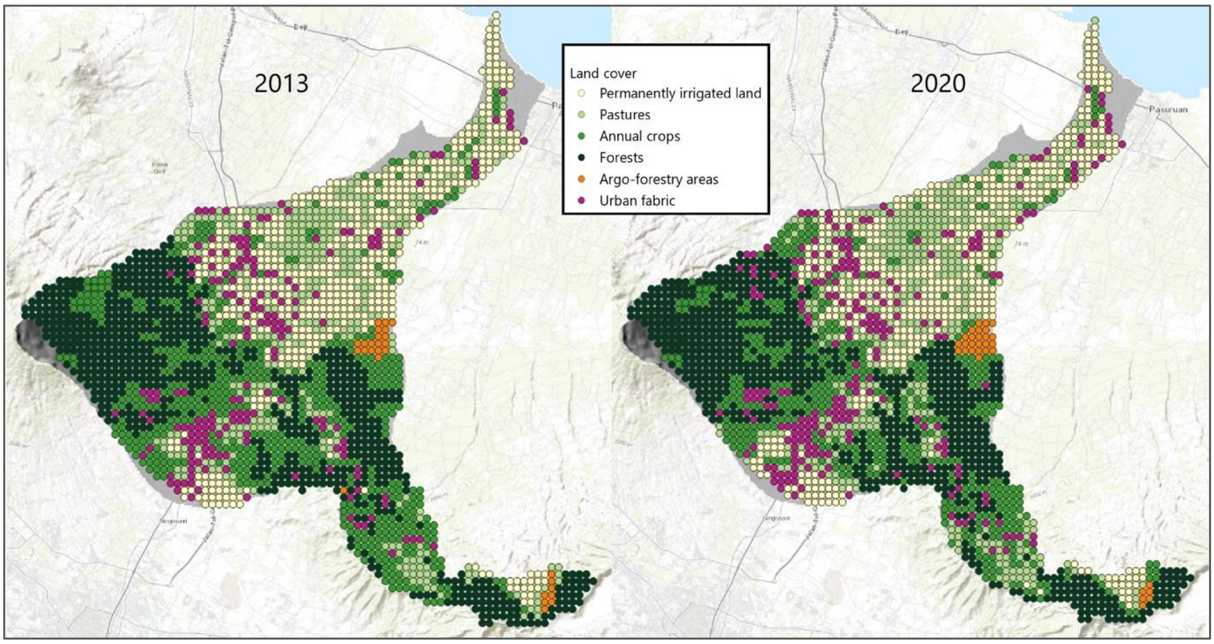


Figure 2.10. Estimated land cover in 2013 and 2020 shows increasing urbanization in the upstream region (original figure prepared for this publication)

2.3 Precipitation and climate change

2.3.1 Precipitation

In the Welang catchment precipitation observations are registered by BMKG and PUPR. Data for reliable observation stations was obtained through UPT for in total 14 stations in and near the catchment (Figure 2.11) and covers the period 1980-2019.

East Java is characterized by a humid tropical climate with two distinct seasons, a wet season from November to April and a dry season from May to October. This is also observed in the rainfall observations (Figure 2.13). Mean annual rainfall is about 2,000mm in the Welang catchment and typically there are about 100 rainy days, much less than the provincial average of 140 rainy days. During wet years total rainfall can reach about 3,200mm and during dry years only 1,400mm of rainfall is recorded.

The mountain slopes receive most rainfall (long term mean rainfall about 2,400mm/year) and typically have about 130 rainy days per year. Pasuruan city receives the least rainfall (long-term mean rainfall about 1,200mm/year) and typically has only about 80 rainy days per year.

There is a strong correlation with the ENSO (El Niño-Southern Oscillation) and IOD (Indian Ocean Dipole) cycles, with wet years associated with negative ENSO (La Niña) and dry years with positive ENSO (El Niño) (Figure 2.12). The number of days with rainfall is similarly correlated, with during La Niña 120 days of rainfall and during El Niño only 80 days, an average year has about 100 days with rainfall. During both strong negative ENSO and strong negative IOD there seems to be more rainfall during the dry season. Rainfall intensities are not influenced by either ENSO or IOD. The effect of ENSO on local rainfall is proportional to the average total rainfall during a neutral ENSO phase, i.e., rainfall during a strong negative ENSO phase is about 20-30% higher in both Pasuruan and Tutur relative to local rainfall in a neutral ENSO year.

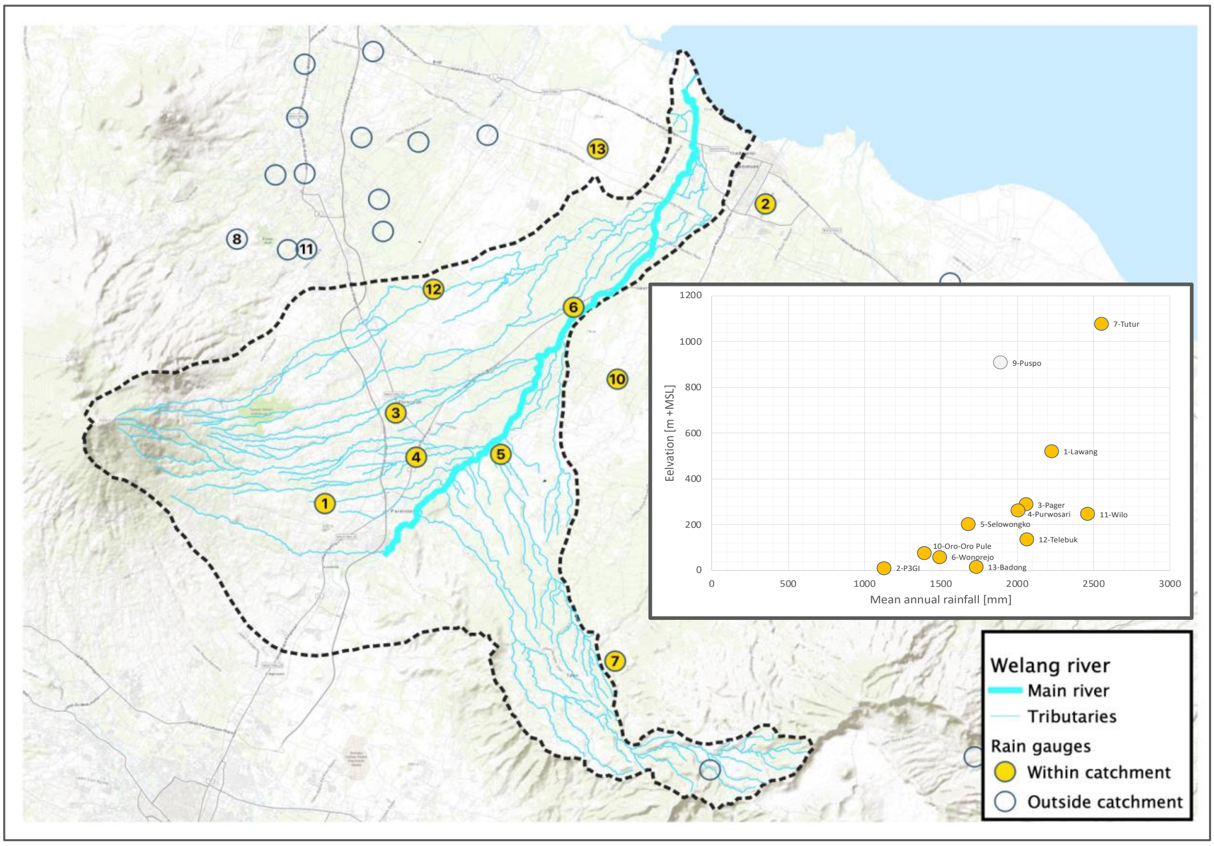


Figure 2.11. Rain gauges in the Welang catchment, insert graph shows the correlation between mean annual rainfall and the elevation of the rain gauges indicating more significantly more precipitation in the upstream region compared to the downstream region. (original figure prepared for this publication)

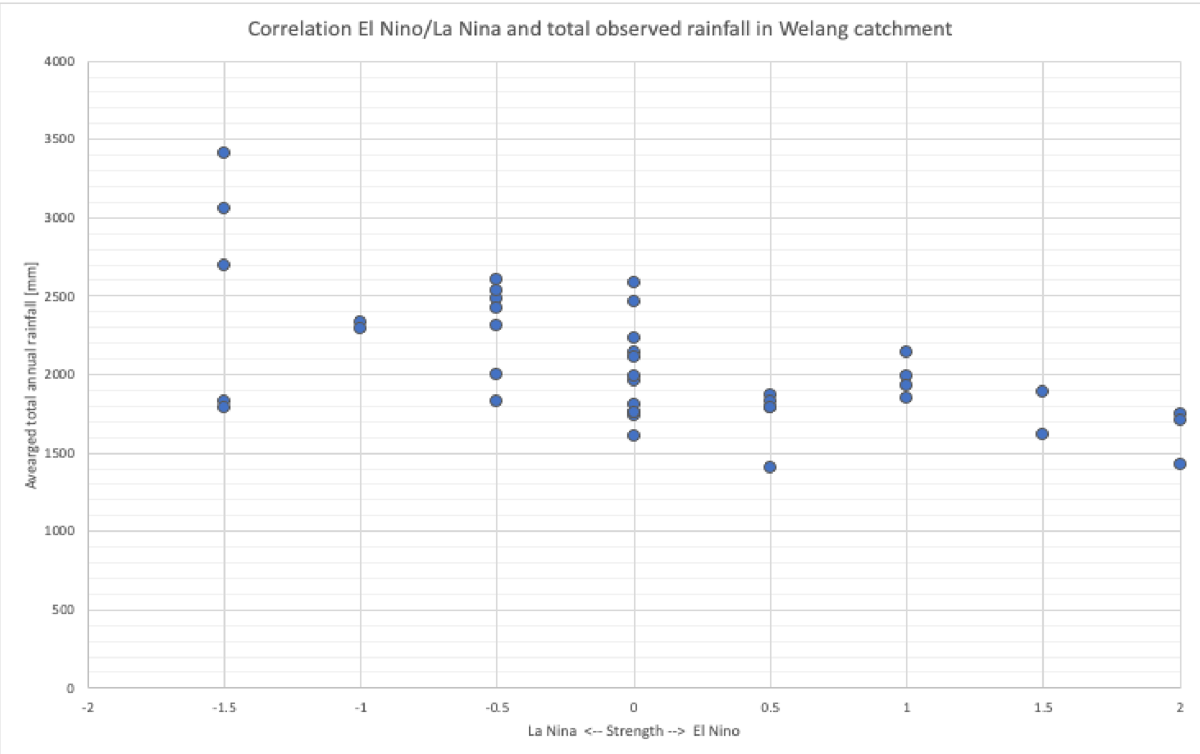


Figure 2.12. A correlation of rainfall data with ENSO classification shows higher total precipitation associated with strong negative ENSO phases (La Niña). (original figure prepared for this publication)

It is observed that the upstream mountain slopes receive about 2-3 times as much rainfall as the downstream urban areas (Figure 2.13). Observed peak rainfall intensities are also slightly higher in the mountains compared to the downstream region. While the total amount of rainfall has not significantly changed in the last 40 years, observations suggest that the number of days with rain has significantly reduced (Figure 2.14) since 1980. In both the downstream and upstream regions, the number of days with rainfall has in 40 years reduced with about 30-40 days. However, the number of days with heavy to extreme rainfall have increased significantly, with heavy to extreme rainfall more likely in the midstream and upstream regions.

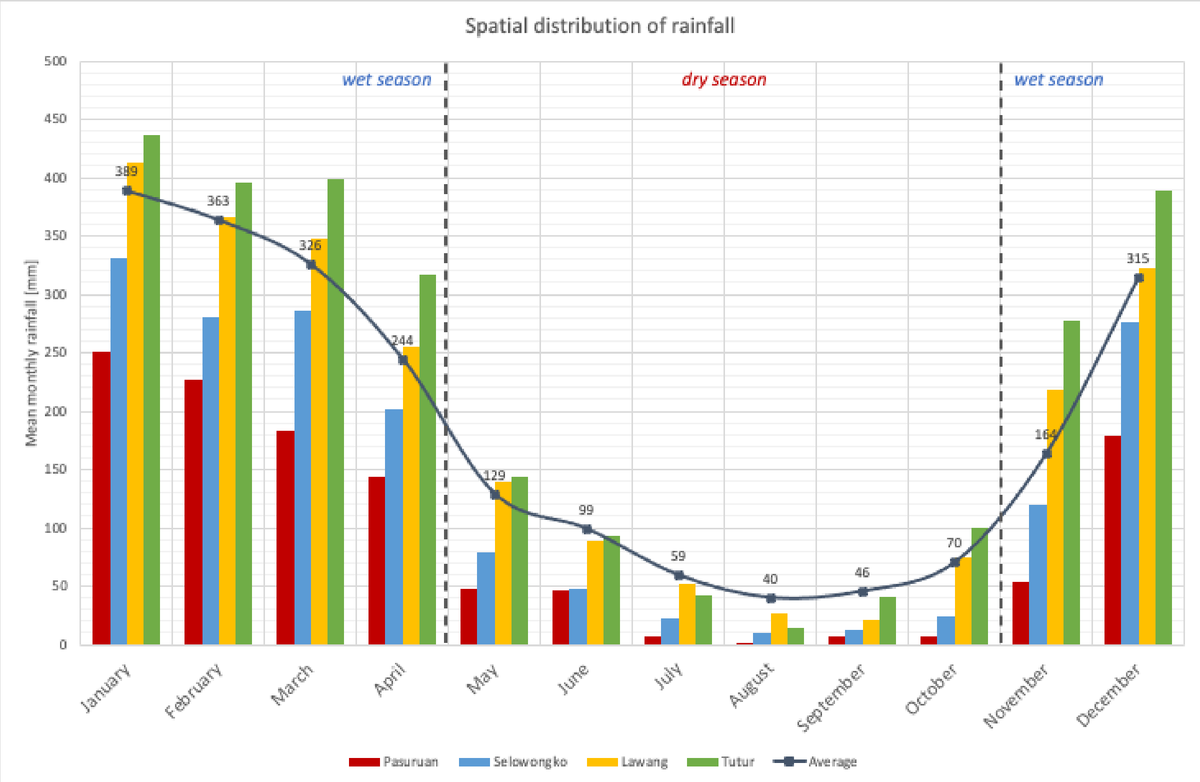


Figure 2.13. Mean monthly rainfall at different locations in the catchment shows significantly more rainfall in the upstream areas (data source: UPT)

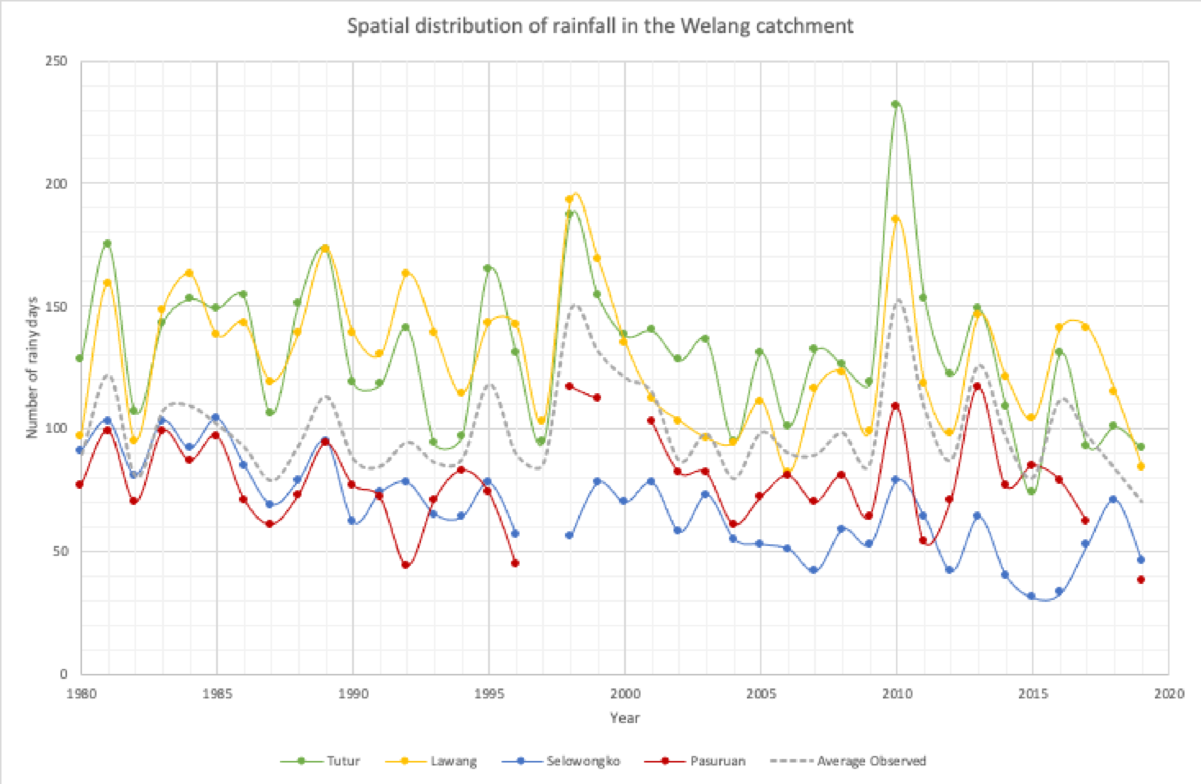


Figure 2.14. Number of days with rain at different locations in the catchment shows a downward trend and overall, more rainy days in the upstream regions (data source: UPT)

2.3.2 Climate change

Climate change may affect precipitation (patterns and intensities) and may therefore affect the river discharges. BMKG has conducted an extensive analysis of the effects of climate change in Indonesia[3]. The analysis shows that in the Welang catchment climate change may result in less total rainfall (Figure 2.15), less consecutive days with rainfall and more days without rainfall. The national analysis also shows that rainfall intensities during rainfall events are not expected to increase (Figure 2.16). These expectations are in line with the observations (1980-2019) from the rain gauges in the catchment (e.g., Figure 2.14).

It is expected that, although total rainfall may reduce, peak rainfall intensity (that result in design river discharges) may remain the same, although heavy and extreme rainfall events will likely occur more frequently; also a trend that is already observed. Reducing total rainfall and a further increase in number of days without rain, may lead to lower baseflows in the Welang river and its tributaries and potentially less infiltration to replenish groundwater and could therefore lead to more frequent droughts.

[3] https://www.bmkg.go.id/iklim/?p=proyeksi-perubahan-iklim&lang=ID

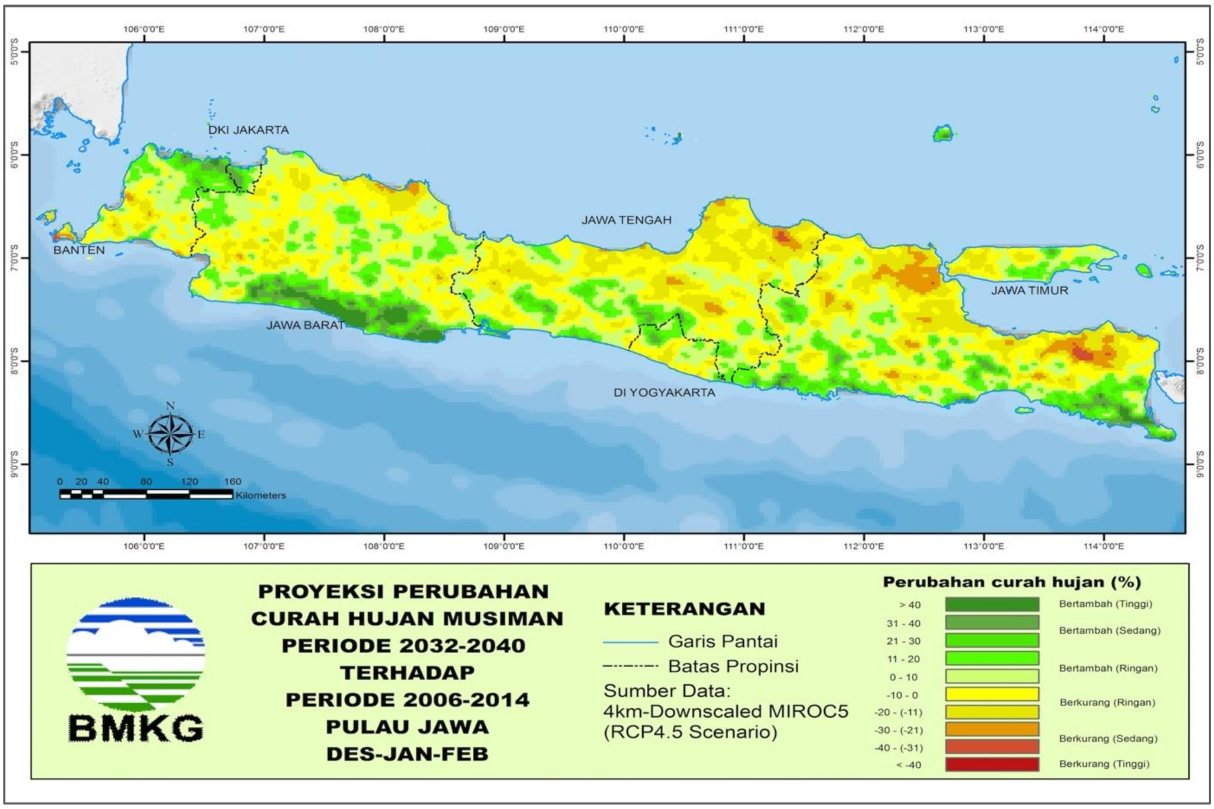


Figure 2.15. Expected changes in seasonal rainfall in Java shows less rainfall in the Welang catchment (source: BMKG)

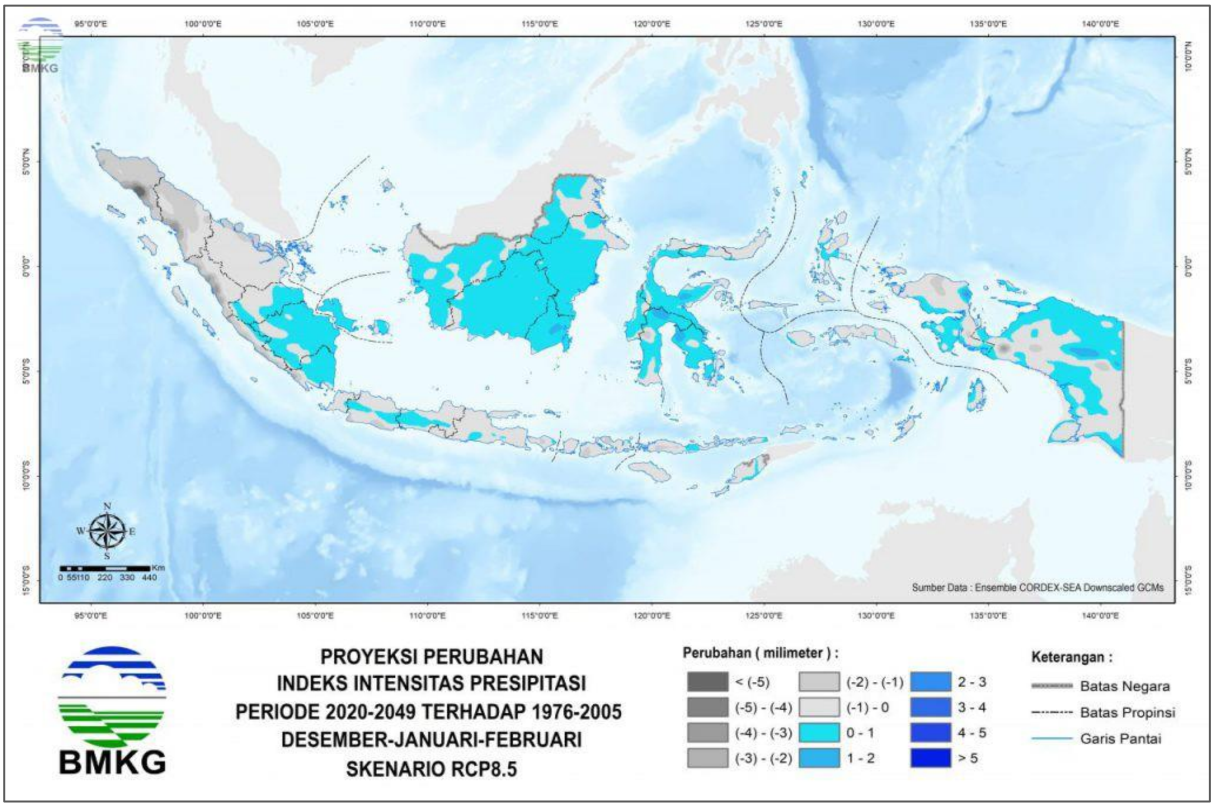


Figure 2.16. Expected changes in peak rainfall intensity (during rainy season) in Indonesia shows little change in peak rainfall intensity in the Welang catchment (source: BMKG)

2.4 Water Management

2.4.1 Irrigation, drainage, and wastewater management

Irrigation systems

In the catchment large irrigation systems are present (Figure 2.17). These systems receive water from the main river at inlets positioned just upstream of constructed weirs. It is unknown when these irrigation systems were constructed. Irrigation channels are mostly kept filled with water to allow for continuous irrigation. Specific primary, secondary and tertiary channels are defined, and maps are available at responsible agencies at provincial and regency level.

Several weirs are present in the Welang river. At these weirs water is diverted for irrigation purposes. The operation procedures of the weirs are unknown, and it is unknown how much water is diverted from the river.

Villages have developed along primary irrigation channels, with the large urbanized areas of Kraton and Purworedjo the best examples of the urbanization process.

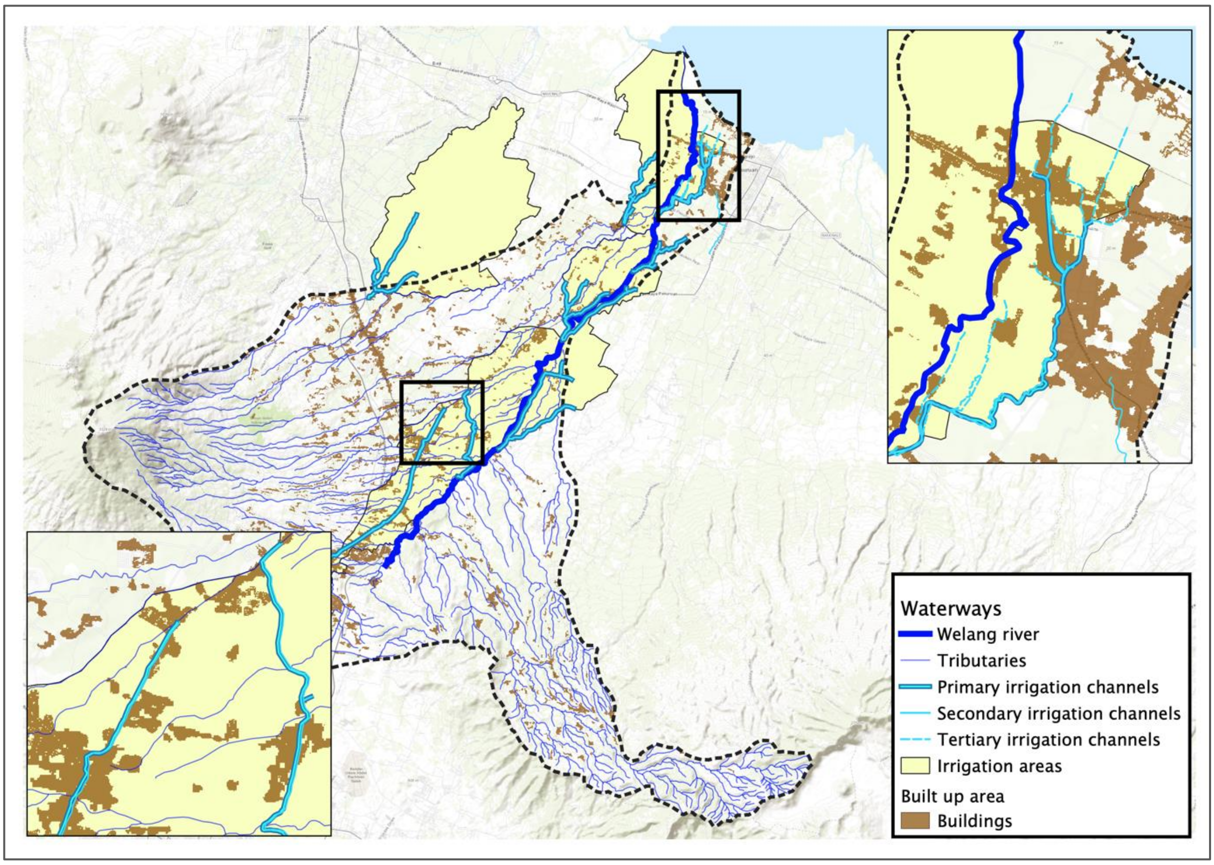


Figure 2.17. Existing irrigation systems in Welang catchment (source: TKP, 2021)

Drainage and wastewater management

Throughout the catchment, no specific (urban) drainage systems are present and stormwater from roads and buildings is drained via the irrigation systems. Around commercial markets irrigation channels are covered to allow for smooth passage by customers and at some locations, for instance in Lawang, shops have been built on top of the channels.

Furthermore, throughout the catchment no wastewater system is present and residential houses, factories, etc. dispose of their excess wastewater directly via the irrigation systems. Most houses presumably have septic tanks, and the larger factories are required to have on-site wastewater treatment plants (although this cannot be verified). However, it is expected that a significant amount of wastewater is disposed into the irrigation systems (Figure 2.18).

Figure 2.18. Domestic and industrial wastewater disposed directly into the Licin irrigation channels in Kraton (source: author)

Solid waste management

In the catchment, collection rates for municipal solid waste are low. Most solid waste remains uncollected, and people must find their own methods to dispose of solid waste. A significant amount of solid waste is openly burned along the roads and irrigation channels. However, the rest is disposed into the irrigation channels with bridges main locations for disposal into waterways.

Data (World Bank, 2021) suggests that most solid (and plastic) waste is disposed in waterways in the upstream and upper midstream areas, in Lawang and Purworedjo (Figure 2.19). This may suggest that a large fraction may be disposed in the local drainage channels and irrigation channels where it may lead to blockages, especially around commercial areas.

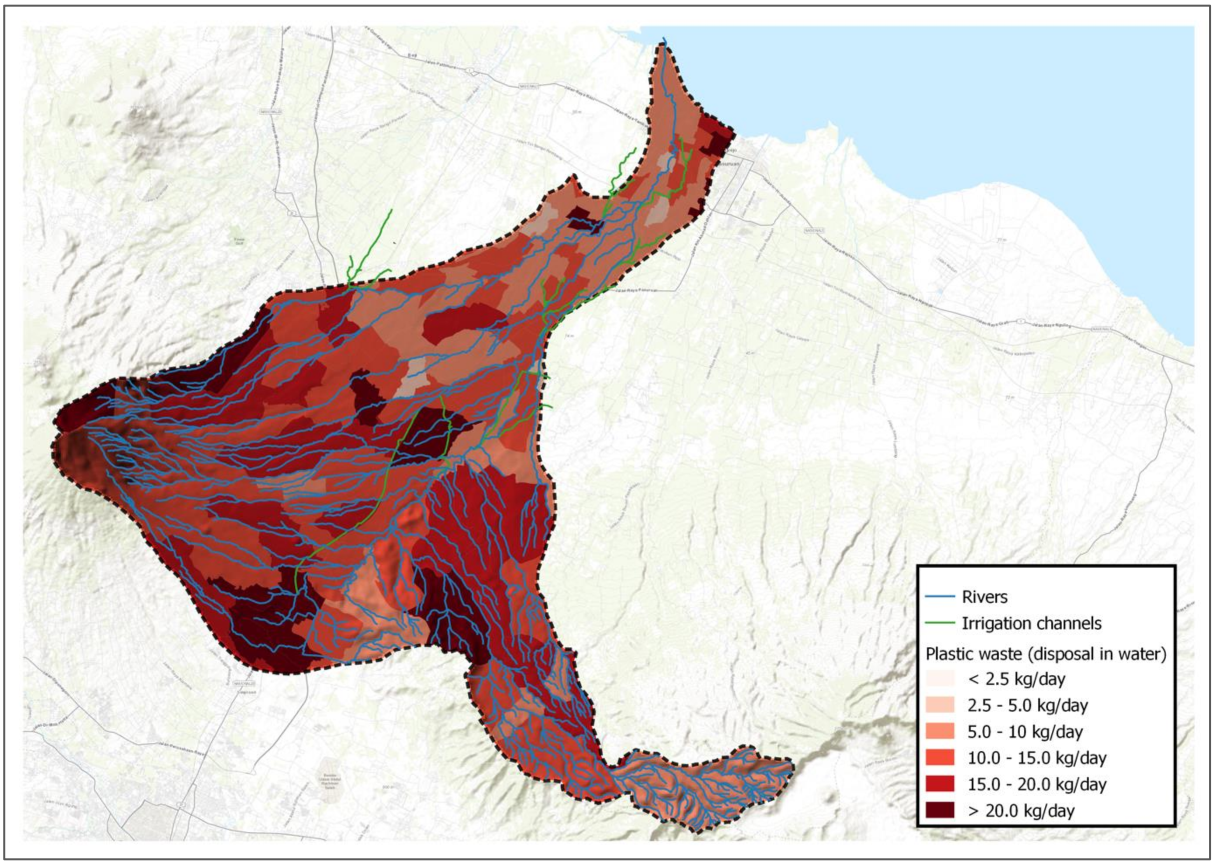


Figure 2.19. Plastic waste disposed directly into waterways (source: World Bank, 2021)

Conclusion

As such, the existing irrigation systems in the Welang catchment are in addition to irrigation, also used to discharge excess stormwater, wastewater, and solid waste. This means that there is significant pressure on the drainage capacity of the irrigation cum drainage systems in the area. Also, it is therefore very likely that the water quality in these irrigation systems is very low. What is concerning is that polluted water from irrigation channels is used to irrigate agricultural land to grow rice and other crops and that people use the channels to wash their dishes or a swim. It is likely that people, especially people in the rural areas, are exposed to high levels of pollutants.

2.4.2 Geohydrology

Groundwater systems

There are two aquifers in the region, one unconfined phreatic aquifer and one confined aquifer. The phreatic aquifer is located between 1-13m below ground level (bgl) and the confined aquifer between 20-190m below ground level.

Groundwater is generally used for water supply by both residents (for common household purposes) and industries (for industrial purposes). In total 241 known shallow and deep wells penetrate the phreatic and confined aquifers. The effect of groundwater abstraction is clearly visible in the iso-lines of the groundwater heads of both aquifers (Figure 2.20 and Figure 2.21).

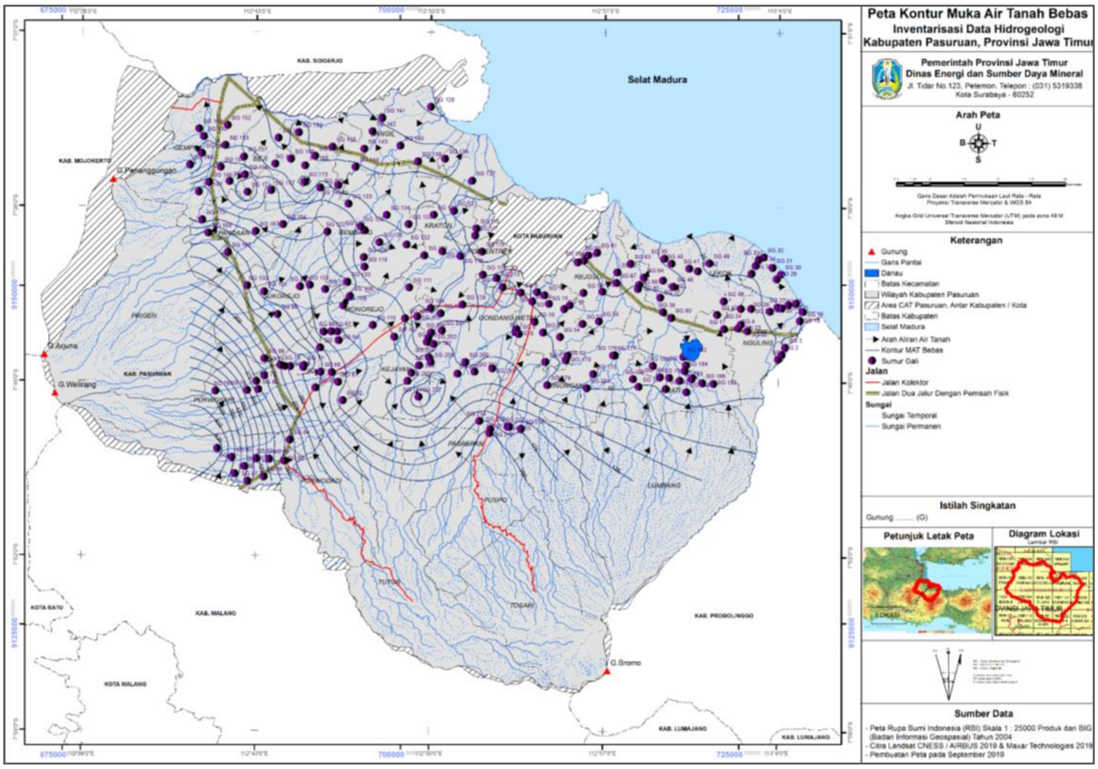


Figure 2.20 Groundwater contour of unconfined aquifer in the Pasuruan regency area (source [4])

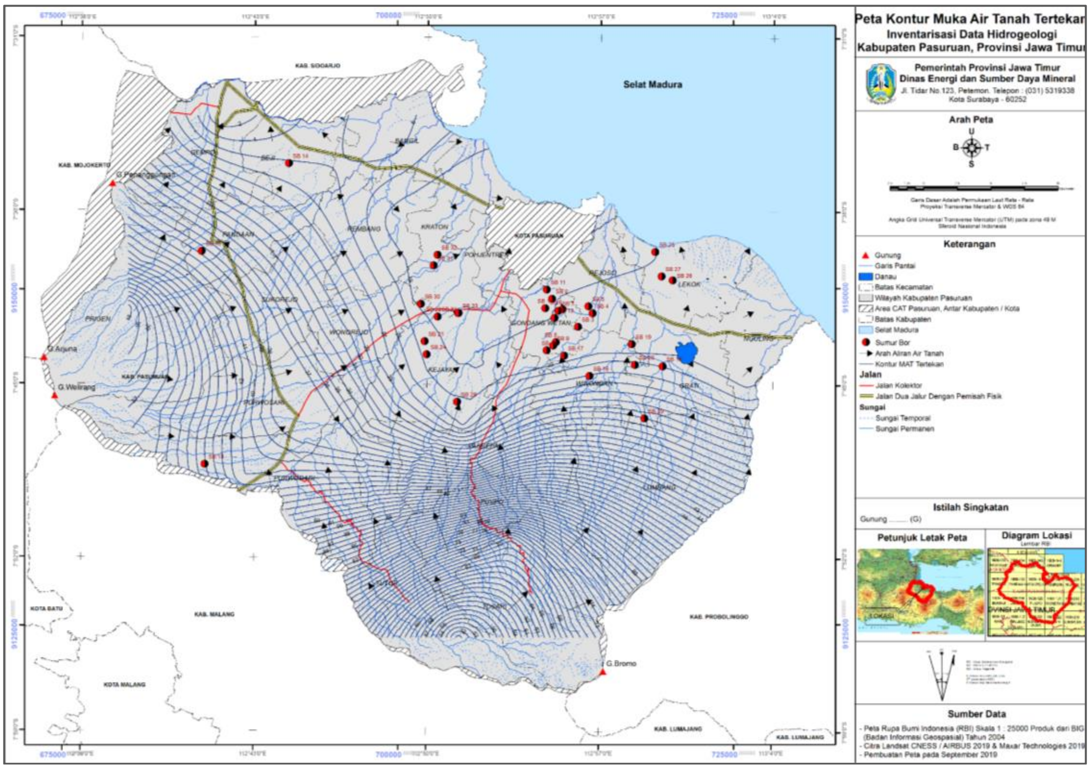


Figure 2.21 Groundwater contour of confined aquifer in the Pasuruan regency area (source [4])

Groundwater extraction

Groundwater abstraction wells are registered by East Java DESDM (Figure 2.22). Records for business licenses issued in 2019 and 2020 showed that licenses for individual wells allow extraction of 9.75 m^3/day

[4] CV Madani Callysta Saibuyun, 2020

up to 2160 m^3/day. Larger abstractions are taken from wells around 300m depth, while most smaller abstractions are taken from the shallow phreatic aquifer.

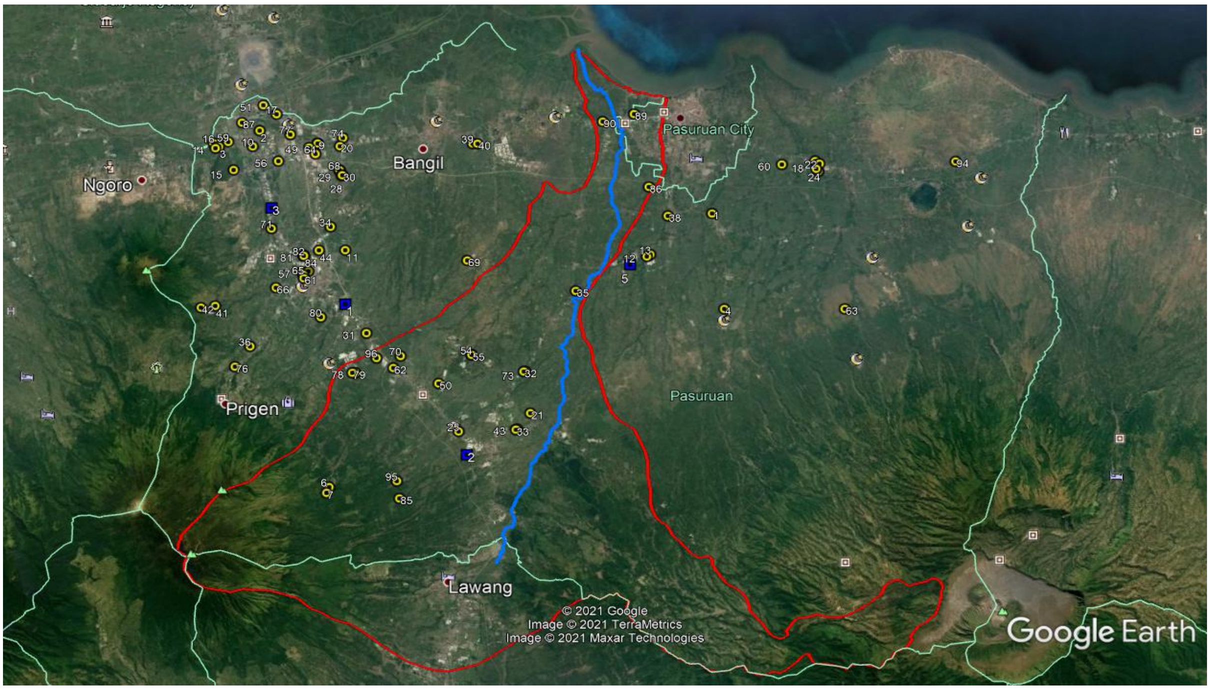


Figure 2.22. Location of extraction wells based on the permit records in 2019-2020 provided by DESDM

Based on the permit record, there are only three registered locations of extraction wells in Kraton area. These wells were installed at shallow depth (10-16 m) and allowable debit of 10 m3/day for each.

Groundwater monitoring

Groundwater tables are monitored by the East Java Mineral Resources and Energy Agency (Dinas Energi dan Sumberdaya Mineral, DESDM) (3 monitoring wells) and by private entities (6 monitoring wells) within Kabupaten Pasuruan (Figure 2.23). Monitoring data was obtained from the 6 private monitoring wells only. Wells are installed at depths between 86m and 130m. Both shallow (at 7 to 10m bgl) and deep (up to 50m bgl) water tables are measured. Monitoring data is available for up to 3 years only.

Figure 2.23 Monitoring wells present in Kabupaten Pasuruan area (symbols in blue and green indicated wells installed by private entities and government, respectively)

The groundwater level observations are presented (relative to the average level of the well) in Figure 2.24 for the three wells near the Welang catchment. Outliers were removed before the average groundwater levels were estimated.

The available data suggest that groundwater tables fluctuate but have not significantly lowered in the three-year observation period. These data alone are insufficient to conclude the overall trend of the groundwater heads for which longer time series of observations are required.

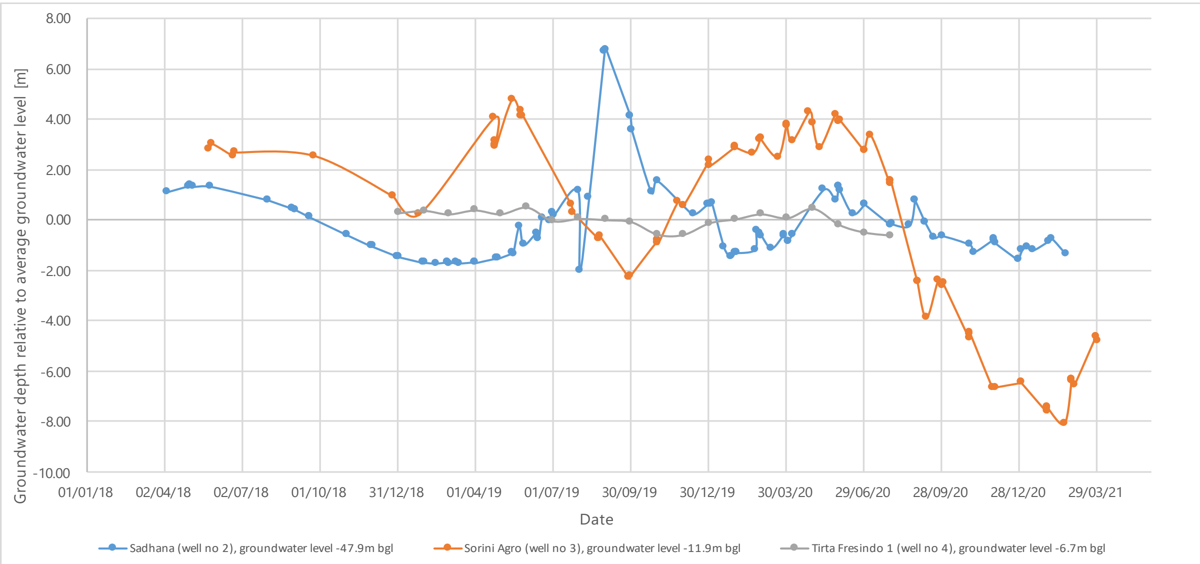


Figure 2.24 Groundwater levels relative to the average level over the observations

2.4.3 Water quality

Water quality in the Welang river is monitored monthly at 3 locations (Figure 2.25). Two monitoring stations are located in the upper midstream area and one station is located in the downstream region (at the same location as the Dompho automatic water level recorder).

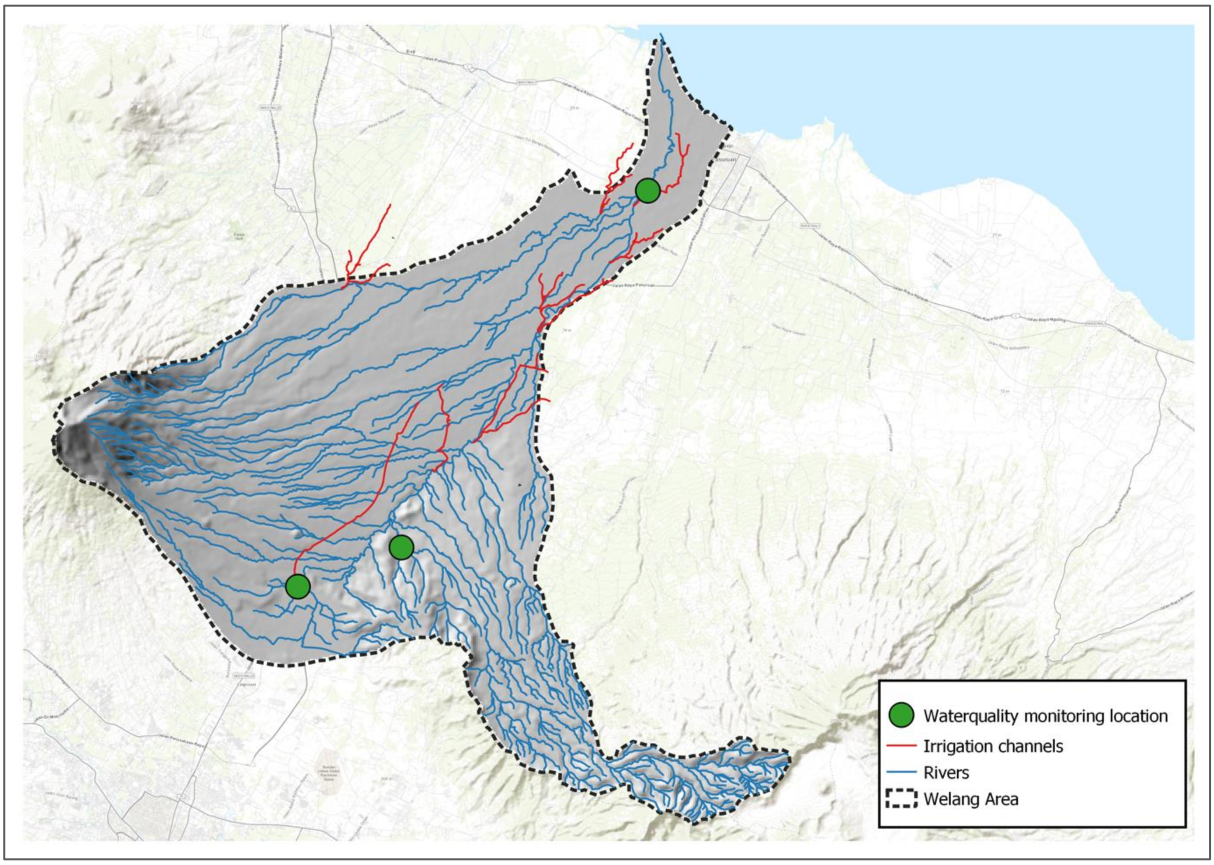


Figure 2.25. Location of water quality monitoring (source: Dinas Lingkuan Hidup)

Results are assessed following the NSF-WQI (National Sanitation foundation) and STORET (developed by the American Environmental Protection Agency, EPA) methods. A wide range of parameters is measured, and an assessment provides an overall water quality index.

Monitoring results show a steady decline in water quality from 2013 to 2020. Overall water quality is very poor. Water quality is worst in the upstream region, but the water quality in Dompho is also poor.

In the upstream region, measurements show high values for BOD, COD, DO and fecal coliform. These observations suggest high disposal rates of untreated household wastewater and solid waste in the area.

Water quality is only monitored in the main river, while most industries and settlements are located along the provincial road and irrigation channels. It is therefore expected that while solid waste may be disposed in the main river, most chemical pollutants are probably disposed in the irrigation systems.

Notes: red = heavily polluted, cream = moderate polluted, blue = lightly polluted, green = good/not polluted

Figure 2.26. Classification of water quality based on STORET method g (source: analysis)

2.5 Conclusion

The Welang river is a relatively short but steep river. After the streams have come down the very steep slopes of the Arjuna and Bromo mountains, the river runs through an undulated landscape where the river runs in relatively deep but narrow valleys. The terrain in the last 7.5km is flat, near sea level and densely populated.

Available rainfall observations cover the period 1980-2019 and show that average rainfall is about 2,000mm per year and has been fairly stable over the observation period. Rainfall predominantly falls during the wet season and most rainfall falls on the slopes of the Arjuna and Bromo mountains, with Tutur and Lawang receiving more than twice the amount of rain compared to Pasuruan. Due to climate change the number of rainy days has since 1980 steadily decreased and is expected to fall further. According to BMKG climate change is also expected to result in less total rainfall. However, no changes in peak rainfall intensity are expected.

The catchment used to be an agricultural powerhouse and the midstream and downstream regions used to be covered in irrigated rice-fields. Since the turn of the century land-cover has changed dramatically with ongoing large urban expansion of Pasuruan city in the downstream area and industrialisation/urbanisation along the provincial roads in the midstream area. More recently, in the upstream area forests are converted into plantations (horticulture) and new tourist settlements. This clearly shows a trend to land-uses associated with less retention capacity and more run-off.

At least since the 1970s the coastal zone has expanded rapidly and the Welang river is currently about 2km longer than about 50 years ago. The more recent coastal accretion is covered in flourishing mangroves. Sediment for the coastal accretion may have come from the Porong river to the North, but likely also from soil erosion in the upper midstream and lower upstream areas in the catchment where potential soil erosion is very high and land cover has been changed in recent years.

There is very little soft soil in the catchment; only in the coastal zone (5km) soft soil can be found. The layer is very thin and decreases with increasing distance to the sea. At the coast the soft soil layer is only 10m thick and near the toll-road there is no soft soil present. In this area no large groundwater abstractions are found. And it is concluded that land subsidence is likely very small if present at all.

The irrigation systems in practice function as combined systems for irrigation, stormwater drainage and discharge of wastewater. Channels are mostly full and so there is limited retention capacity in the system to store excess stormwater. In addition, a significant amount of solid waste is disposed in the channels and likely accumulates at bottlenecks (e.g., traditional markets in Lawang and Purwodadi); this reduces the discharge capacity and may lead to backwater effects upstream of these bottlenecks.

Furthermore, the water quality in the main river is poor and in the irrigation channels likely very poor; water quality is only monitored in the main river but deserves more attention in the irrigation channels.

3 Socio-economic Context

3.1 Population development

The population in the Weland catchment is concentrated along the main transport corridors from Malang to Surabaya and to Pasuruan (Figure 3.1). The main urbanized areas in the catchment are Pasuruan and Lawang. However, along the provincial roads, a continuous strip of houses and factories is present. While driving over the provincial road, one would get the false impression that the area is densely populated.

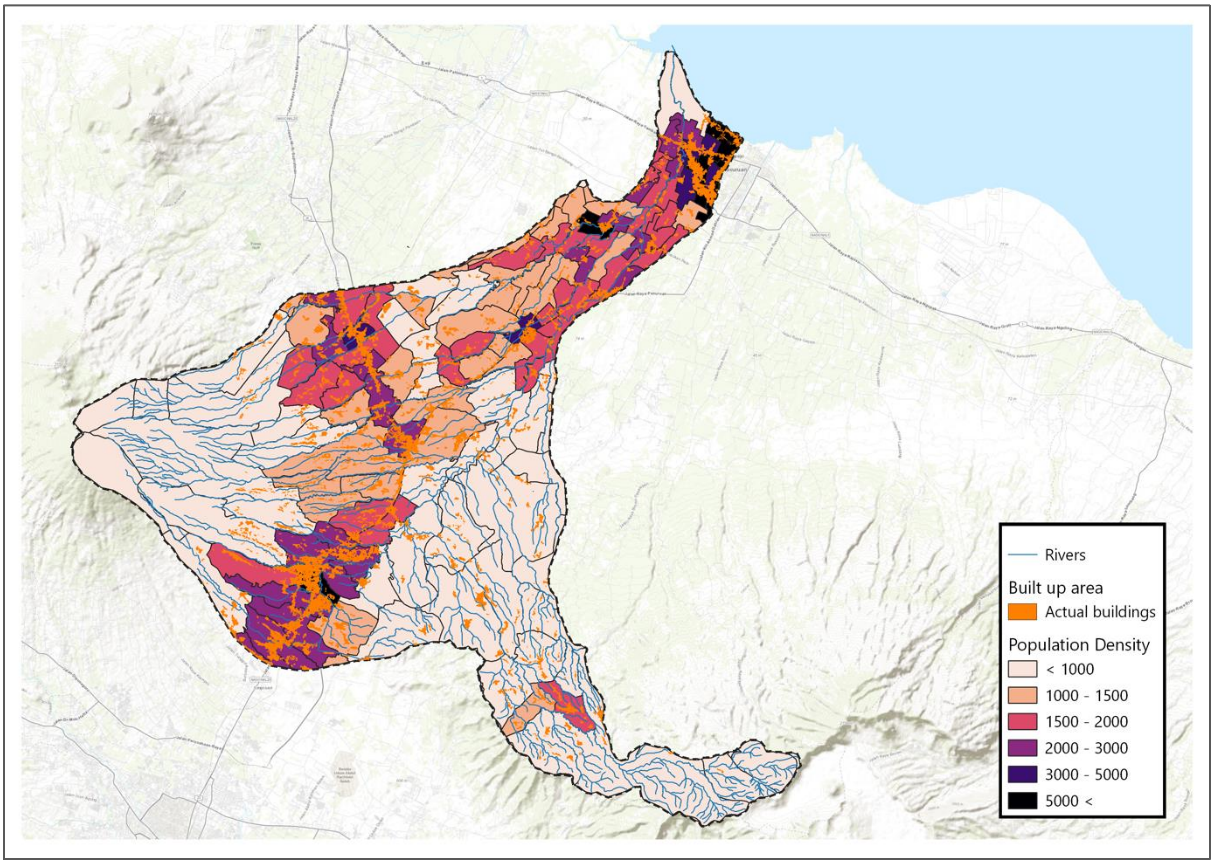


Figure 3.1. Population density shows concentration of people along main transport corridors (Source: BPS, 2019[5])

The population in the region, and specifically in kabupaten Pasuruan, has steadily increased over the past 40 years (Figure 3.2). On average the annual population growth rate was until the early 2000s about 1.6%. Since the mid 2000s the population growth is slowly reducing. It is expected that the population in the province will peak around 2033 (BPS, 2020). Since there are no regency specific projections yet, the population growth rates for the province are considered to make projections for the future population in the regency. The past population growth has likely concentrated in the villages (desa) along the transport corridors, although there is no data to confirm this.

[5] processed data from BPS, 2000-2020

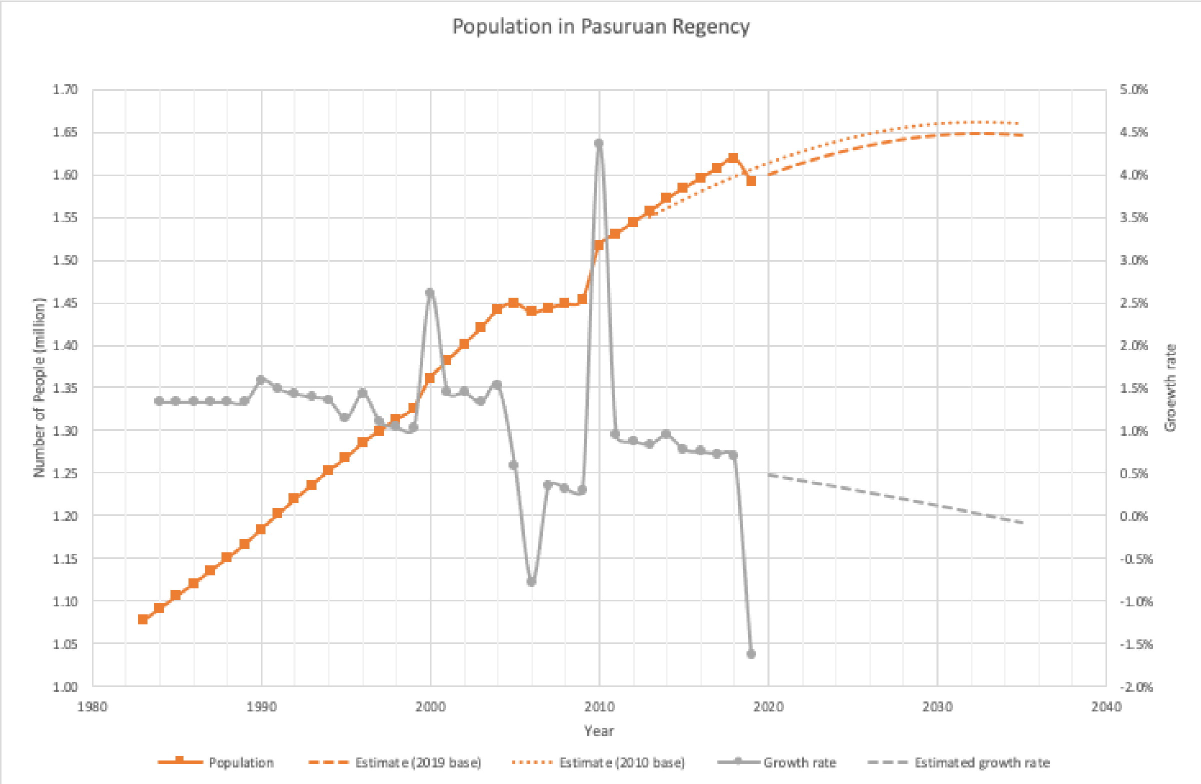


Figure 3.2. Population in Pasuruan Regency (source : Kemenko perekonomian 2014, BPS 2020, BPS 2010)

3.2 Economy

3.2.1 Economic development

Overall, in the three kabupaten/kota that cover the Welang catchment, the economy has grown significantly since 2010. The economic output of Kabupaten Pasuruan and Malang have each more than doubled in 10 years and are now worth respectively US$ 10.1 billion and US$ 7.2 billion. Kota Pasuruan was only established recently (was previously part of kabupaten Pasuruan), and the economic output is currently valued at US$ 0.6 billion.

The significant economic development of the region coincides with the completion of the toll road connecting Pasuruan with Surabaya and the rest of Java. Most industries, which account for over 60% of the economic output, are located along the provincial road connecting Pasuruan and Malang and around Purworedjo (where a main entrance to the toll road is located).

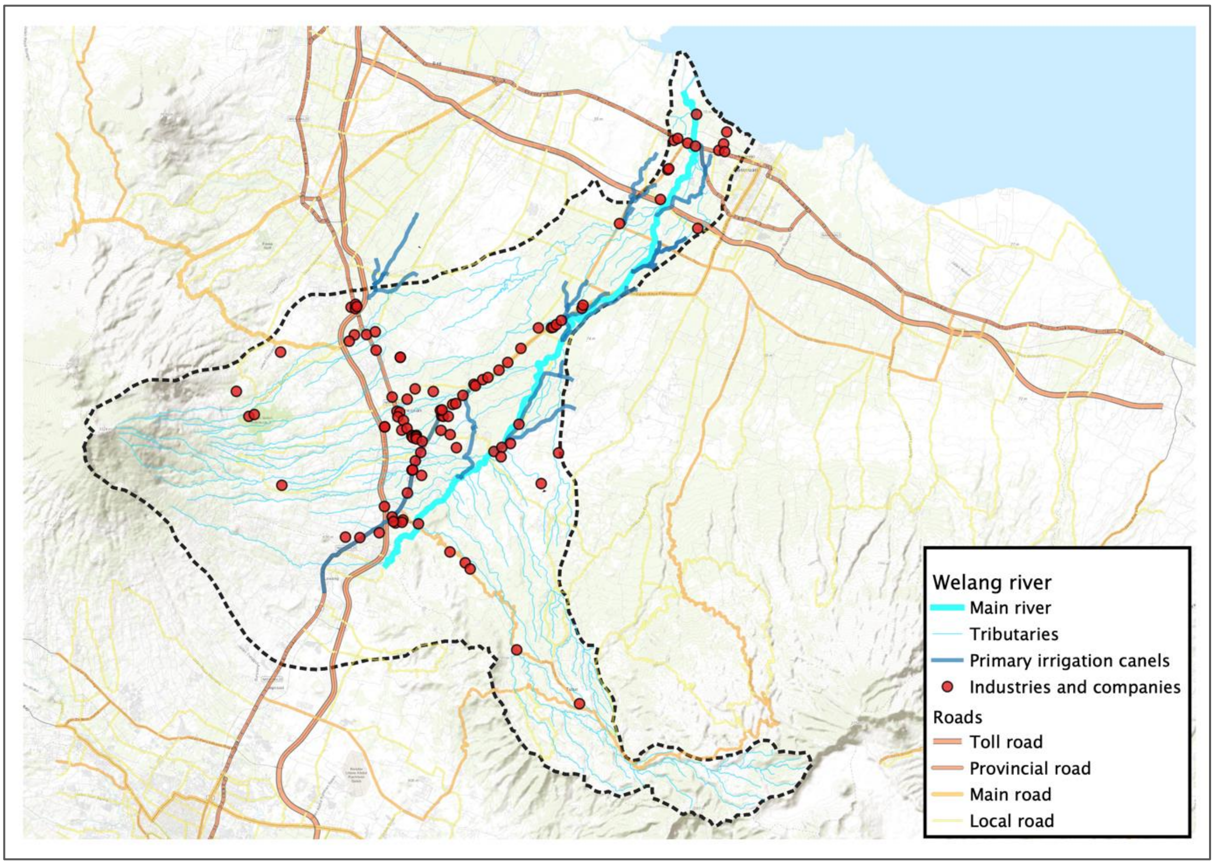


Figure 3.3. Distribution of industries and companies (Source: DLH Kabupaten Pasuruan, 2018)

3.2.2 Main economic sectors

The economy in the Welang catchment is diverse although the manufacturing sector contributes most (about 57%) to the economy in the catchment (Figure 3.4). The top 4 largest contributing sectors in the region is completed by the wholesale (12%), construction (10%), and the agricultural (7%) sectors. This division has not changed in the last 10 years and these sectors combined generate a steady 86.6% of GDRP in Kabupaten Pasuruan.

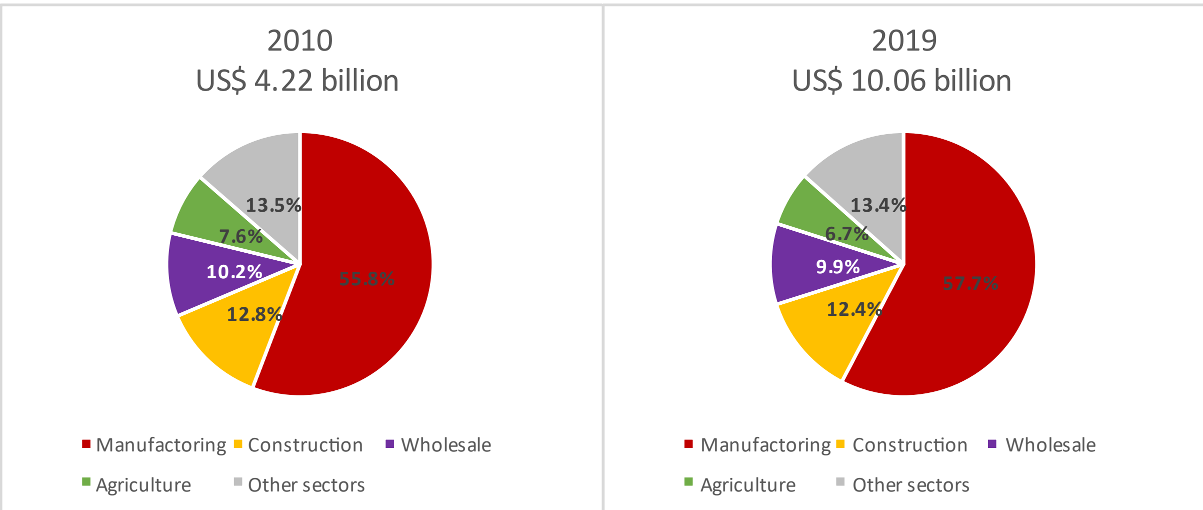


Figure 3.4. Contribution of top4 economic sectors to GDRP in 2010 and 2019 (source: BPS 2020)

In Kabupaten Pasuruan (the regency covering most of the catchment), the economic sectors that have grown most in absolute terms in the past decade are the manufacturing, construction, and wholesale sectors, while the tourist industry, the financial, the health and the transport and storage sectors have shown the largest relative growth. These sectors drive urbanisation and land conversion to paved surfaces. Although the output of the agricultural sector has doubled, this sector is one of the sectors showing the smallest relative growth.

Since 2010 output from the agricultural sectors doubled (206%), while the output of urban based sectors increased with 241% in line with the overall growth of the regional economy (Table 3.1). This highlights the increasing importance of the urban based sectors. Interestingly, over the same period, output of sectors associated with public infrastructure and public services increased with 204%.

Sector	Agriculture, Forestry, and Fishing	Mining and Quarrying	Manufacturing	Electricity and Gas	Water Supply, Sewerage, Waste Management and Remediaton Activities	Construction	Wholesale and Retail Trade	Transportation and Storage	Accomodation and Food Service Activities	Information and Communication	Financial and Insurance Activities	Real Estate Activities	Business Activities	Public Administration and Defence, Compulsory Social Security	Education	Human Health and Social Work Activities	Other Service Activities	total
2010	322	30	2,354	56	2	540	431	24	131	122	28	31	4	58	28	5	53	4,219
2019	670	55	5,803	86	3	1,251	993	67	403	264	82	71	11	120	71	15	99	10,063
absolute change	348	26	3,449	30	1	711	562	44	272	142	54	40	7	61	43	10	46	5,844
relative change	208%	186%	246%	154%	188%	232%	230%	285%	307%	217%	291%	228%	253%	205%	254%	286%	187%	239%

Table 3.1. GDRP for Kabupaten Pasuruan, values in million US$ unless stated otherwise. (source: BPS 2020)

In the higher midstream and upstream areas (e.g., kecamatan Tutur, Purworedjo and Purwodadi), the primary economic sectors are traditional farming of seasonal crops (e.g., potatoes, cabbage and carrots)[6] and more recently the production of ornamental plants and Chrysanthemum[7].

In the midstream areas several manufacturing factories have recently been developed and now form the industrial backbone for the larger urbanized centres in Kabupaten Pasuruan (e.g., kecamatan Kejayan and Purwodadi). The recent rapid urbanisation has led to a boom for the construction sector in this area.

The urbanized area of Pasuruan (Kota Pasuruan and Kabupaten Pasuruan, around Kraton) has rapidly urbanised in recent years. Main economic sectors in the urban area centre around wholesale, manufacturing, and transport/storage and in the city itself financial and communication services.

Although, near the coast in the downstream area, a significant number of fishponds are present. And interspersed with the recently urbanized areas around Kraton, irrigated rice cultivation completes the agricultural economic sector here. However, the agricultural sector does not provide a significant contribution to GDRP of Kota Pasuruan and the sector seems to struggle.

[6] Maroeto, et al, 2017. GIS utilisation in indentification of critical land distribution in uphill area of Welang Watershed. Conference paper at: https://www.researchgate.net/publication/324674863

[7] Pratomo and Andri, 2013.Socio-Economic Aspect and Potency of Chrysant Flower Agribusiness on Pasuruan District, East Java.J. Hort. Indonesia 4(2):70-76. Agustus 2013

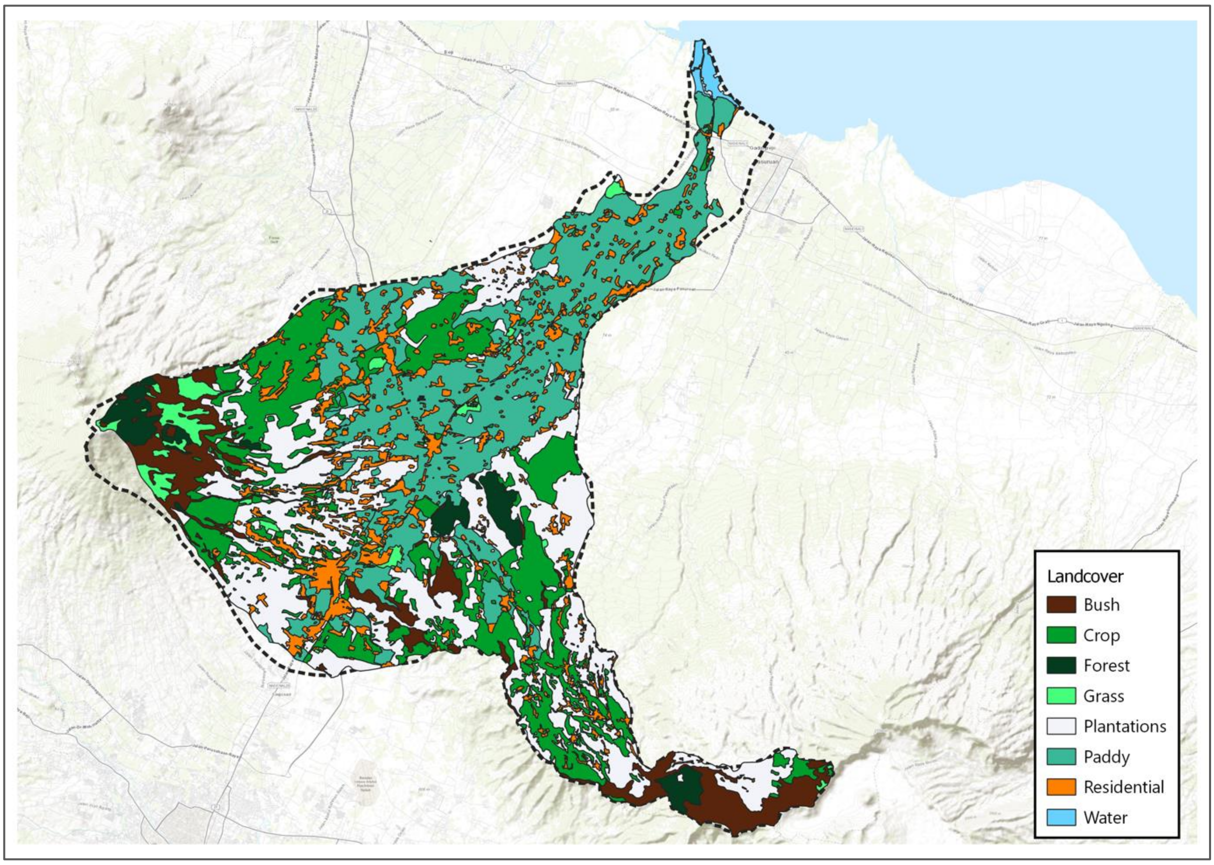


Figure 3.5. Landuse map of welang Watershed (Source: UPT PUSDA Pasuruan 2020)

3.3 Socio-economic stakeholders

The socio-economic landscape in the Welang catchment is broad and covers individual farmers, small and large private landowners and developers and small, medium, and large companies. The recent rapid economic and physical development in the catchment has significantly changed the socio-economic landscape. In return, the socio-economic stakeholders shape the development in the region and are in effect the drivers for the recent changes in flood hazards and risks.

Insight in the socio-economic landscape is currently limited to NGO's and CBO's and basically only provides information on the communities in the catchment. Little is known about other stakeholders, such as the large industry (Danone, Cargill, Indofood, pharmaceutical industries, etc.), the farmers (paddy farmers, subsistence farmers, shrimp farmers, small and big plantation owners, etc.), construction industry (cement factories, brickmakers, stone crushers, etc.), the tourism sector and the landowners (especially individuals or companies who own significant amounts of land).

To anticipate on and effectively mitigate potential future flood hazards, it is important to have insight in the complete socio-economic landscape and the (level of) organisation of the various socio-economic stakeholders. Currently there is only very limited insight in the socio-economic landscape, and it is highly recommended to improve this.

No	Socio-economic stakeholders	National	Province	District	NGO/CBO	Private	Direct FM	Indirect FM	Role	Prevention	Mitigation	Emergency	Recovery
1	**CBO/NGOs**				**x**		**x**			**x**	**x**	**x**	**x**
a	Si Hijau				x		x		Conduct reforestration and awarenes raising	x			
b	FKPS				x		x		Channeling aspirations from the locals on waste and environmental health to the local gov	x			
c	DESTANA				x		x		Lead the disaster management activities from prevention to rehab and reconstruction at v	x	x	x	x
d	KMPS				x		x		Conduct flood minitoring , prevent and control effort in community scale	x	x		
2	**Private Sector**					**x**		**x**	Provide CSR for for critical land rehab purpose and any other relavant purpose for flood prevention and managament	**x**			
a	Otsuka					x		x		x			
b	Danone					x		x		x			
c	PG Kedawoeng					x		x		x			

Table 3.2. Identified socio-economic stakeholders and their roles related to water resources management and flood (risk) management

Sectoral forum

Two existing sectoral forums have been identified which are active in Kabupaten Pasuruan:

- Forum DAS work closely with local NGOs and the private sectors to support rehabilitation initiatives in the upstream area.
- Forum PRB Kabupaten Pasuruan has been established in 2013 by BPBD and aims to build synergy and collaboration in disaster management. Up until now, most of activities conducted by the forum are related to emergency response and post disaster activities.

Community-based organisations (CBOs)

In the area several community-based organisations (CBOs) are active. These CBOs are mostly initiated by regional government agencies:

- Masyarakat Peduli Sungai (MPS) are established at village level for community participation, participatory mapping and planning, and flood control. Since 2016 through Dinas PU initiatives in total 15 MPS have been established in villages in East Java province. So far only 1 has been established in the Welang catchment
- Desa Tangguh Bencana (DESTANA) is a community group/village level forum initiated by BPBD. The aim is to build disaster resilience through community preparedness capacity building programs. Each group consists of 30 members per village. There are currently two Destana active in villages in the downstream region of Welang Watershed (in Sidogiri and Tambak Rejo)
- Other CBO such as KTH (Agroforestry community groups), LMDH (forest village), Gapoktan (agriculture Community groups), HIPPA (water user community) are strategic organisations to raise awareness and implement community-based flood management initiatives

Community based organisations and groups can play an active role in addressing various environmental problems. For instance, in the region tourism groups have been initiated to promote a more tourist friendly environment. Each community group has internal regulations that stipulate sanctions and fines for river pollution. As a result, the river at these locations is now supposedly cleaner.

3.4 Socio-economic impacts: Poverty and Health

Prosperity and health are often adversely affected by floods. Floods affect poor populations more and often contribute to the poverty trap. Flood prone land is often cheapest and so poor people are pushed towards these areas. With regular exposure to floods, assets are often damaged, and a disproportionate part of poor people’s income is used to cover damage expenses. In addition, flood events are often followed by outbreaks of water borne diseases such as diarrhoea.

3.4.1 Poverty

Poverty in East Java and the Welang catchment in specific has significantly reduced since 2001. In 2001 the poverty rate in Kabupaten Pasuruan was about 20.9% and stands currently (2020), despite the significant population growth, at about 9.5%. The current rate is slightly higher than the rate in 2019 (8.7%). In absolute terms, the number of economically marginalized people has halved in 20 years from about 290,000 in 2001 to about 150,000 in 2020.

Like elsewhere, the Covid pandemic has resulted in an increase of poverty rates and poverty has increased with up to 6% in the individual kabupaten in the catchment. However, the longer-term effects of this recent increase in poverty are not yet known.

Pre-Covid, East Java province had in 2019 with 10.4% a higher poverty rate than the national average of 9.2%. The poverty rate in the kabupaten in the Welang catchment are with about 9% each (Kabupaten Pasuruan 8.7% and Kabupaten Malang 9.5%) slightly lower than the provincial average, Kota Pasuruan has a significantly lower poverty rate with 6.5% in 2019.

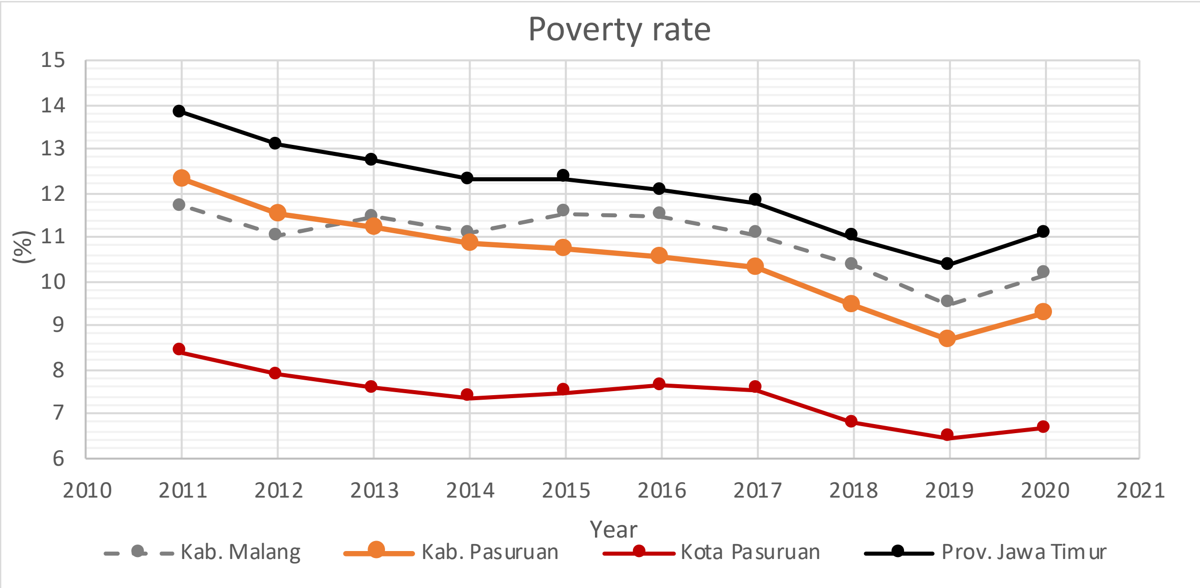


Figure 3.6. Poverty rate in the regencies and province (source: BPS 2021)

Also taking into consideration the poverty line (Figure 3.7) it becomes clear that people in Kota Pasuruan are much better off; likely a result of the availability of higher paying jobs in factories. Kota Pasuruan has a higher poverty line and a much lower poverty rate. However, this is a narrow economic definition of poverty and does not consider the fact that rural populations often have access to land and are often able to grow their own food and sometimes timber and are less exposed to environmental pollution.

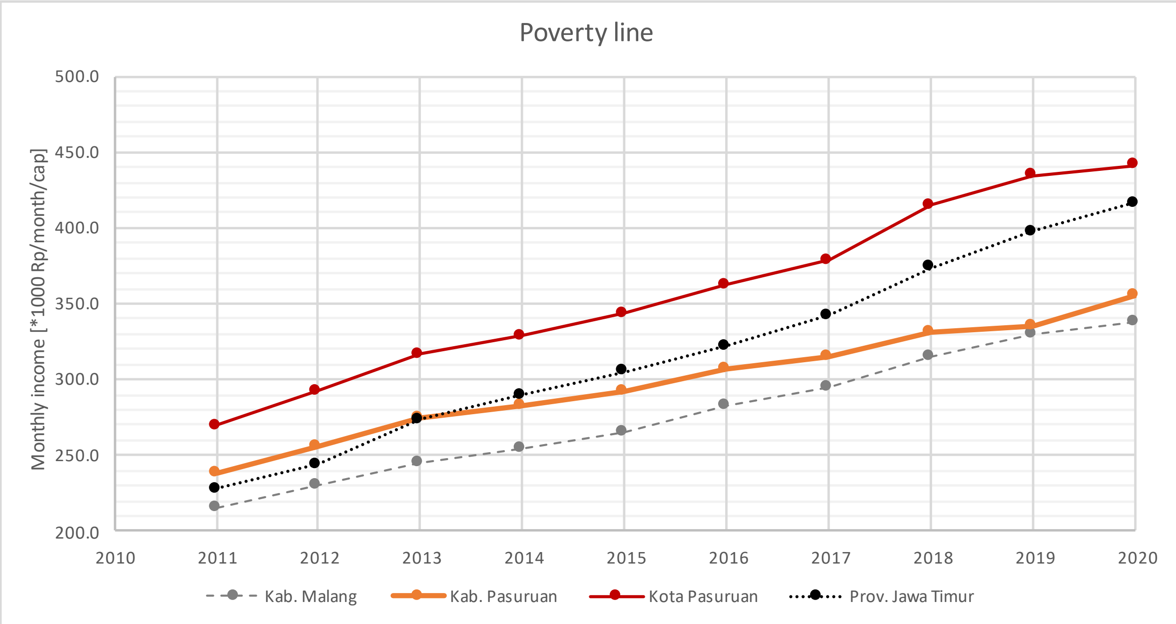


Figure 3.7. Poverty line for the regencies and the average for the province (source: BPS, 2021)

The spatial distribution of poverty is visualised in Figure 3.8. The data is obtained from PerGub XX/2020 and are not in line with the official poverty rate published by BPS for the kabupaten; the poverty rate according to the data is almost 17%. Poverty rates are highest in the agricultural villages in the lower midstream and downstream regions. Along the main roads and in the upstream region, poverty rates are much lower.

Based on the current data, it is not possible to estimate the impact of flood events and flood hazards on poor population groups.

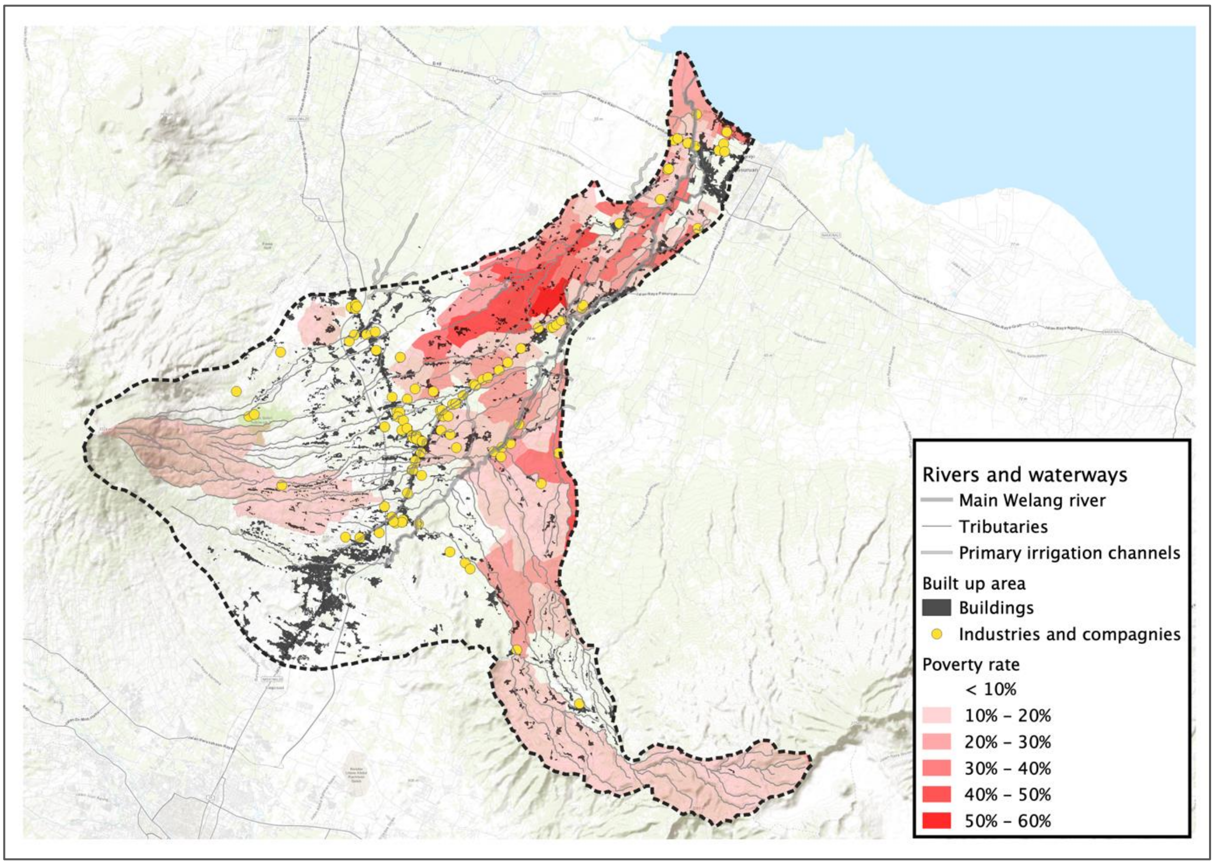


Figure 3.8 Desa poverty rate Kabupaten Pasuruan (Source: poverty data PerGub xx/2020, location of industry and companies DLH)

3.4.2 Health impacts of floods

Flooding may lead to diseases such as diarrhoea, malaria, etc. The pathogens that can cause these diseases thrive in water, especially polluted water. Most people come frequently into contact with open water, either directly (e.g., because they bathe in the river or irrigation channels) or indirectly (e.g., because dishes from roadside food stalls are cleaned in the open irrigation channels along the main roads).

An initial assessment of reported cases in 2015[8] (disaggregated to village level) shows that diarrhoea cases are most prevalent in villages along the irrigation channels and where high amounts of solid waste are disposed in the environment (either disposal in public spaces or directly into waterways). A more detailed assessment can be conducted when number of daily cases at village level can be compared to flood events.

[8] Total number of cases for 2015 was reported at kecamatan level. To show the number of cases at village level, a uniform rate within the kecamatan was assumed.

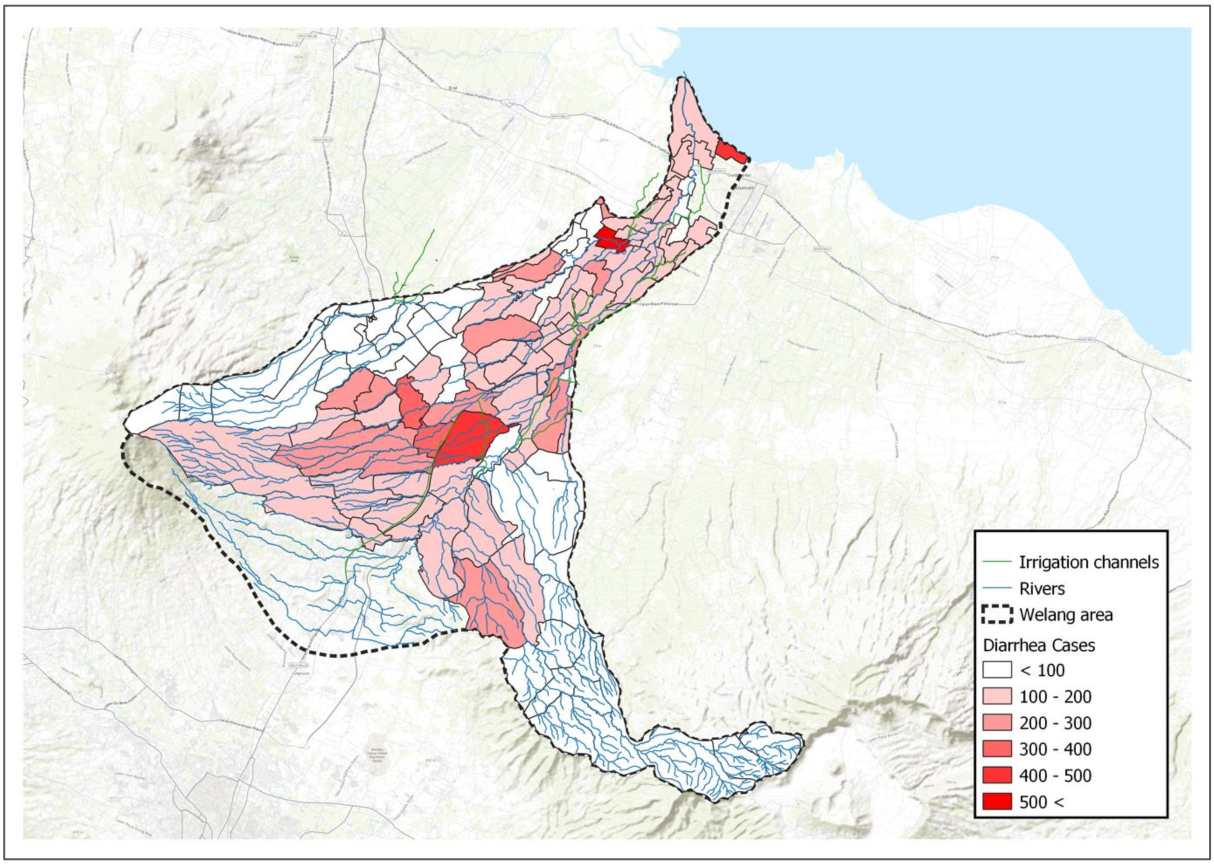


Figure 3.9. Number of diarrhoea cases in Pasuruan regency in 2015 (data at kecamatan level obtained from Dinas Kesehatan, disaggregation to village level by author)

3.5 Conclusion

The economic shift from primarily an agricultural powerhouse to an economy based on industries, manufacturing is well under way. This economic shift has resulted in rapid urbanization along the Pasuruan – Malang corridor, mostly along the provincial road and irrigation channels. More recently the tourism sector has started to develop along the slopes of the Arjuna and Bromo mountains where it drives land-conversion and deforestation.

While these physical developments are visible and have obviously resulted in significant changes in the socio-economic landscape, very little is currently known about the socio-economic stakeholders in the Welang catchment. Insight is limited to communities only, through NGO's and CBO's. It is unknown who the biggest water users and polluters are, it is also unknown to what extend the various farmers are organised and how landownership is distributed. This makes it almost impossible to anticipate on potential future developments in the catchment and to effectively influence the socio-economic development in the region. It also poses a major risk to future hazards (e.g., flood, drought, landslides, etc.) and potentially food security.

Despite strong population growth, poverty in the catchment has significantly reduced in both relative and absolute terms. This is likely driven by the development of the industrial and manufacturing sectors. The total number of people below the poverty line stands currently at about 150,000 in Kabupaten Pasuruan, significantly lower than in 2001 when 290,000 people lived below the poverty line. However, with a rate of 9.3% poverty remains high in Kabupaten Pasuruan.

The economic development and reduced poverty have enabled people to buy properties and construct new houses and has resulted in a demand for commercial developments. The urbanization trend clearly follows the trends of the population growth and economic development. Social and financial assistance by the regional government has also significantly increased in recent years. This is another key indicator that poverty is reducing, and the economy is improving.

In addition, it was found that the spatial distribution of cases of water-borne diseases (e.g., diarrhoea) largely corresponds with the spatial distribution of reported flood events. This suggests that there may be causal link. Unfortunately, detailed information to further assess the health effects of flooding was not available.

This also shows that addressing flood hazards sustainably and long-term, will have many additional benefits beyond avoiding nuisance and damages to properties. Reducing flood hazards and risks will contribute to poverty alleviation and reduces costs associated with water-borne diseases. And it may have additional benefits in sectors that were not covered in this analysis.

4 Institutional Context

A clear legal and institutional framework is a prerequisite for effective flood prevention and management. The legal framework regulates and determines the duties, responsibilities, and authorities in various aspects of flood prevention and mitigation, as well as regulates funding, monitoring and evaluation mechanisms and coordination and cooperation mechanisms between institutions. The legal framework also regulates the mechanism of prohibition and sanctions in flood prevention and mitigation efforts. The institutional framework follows and refers to the legal framework and determines how the division of tasks in flood prevention and mitigation efforts is carried out, as well as how these various institutions work together and coordinate. This section will discuss the legal framework and institutional framework, as well as their relation to the planning and implementation of flood prevention and management efforts in the Welang River.

4.1 Legal framework

In the existing laws and regulations, the rules and principles are provided that influence the flow of water from when it falls from the sky as precipitation to the sea. In Table 4.1 an overview of the main laws and regulations is provided. Two main categories can be distinguished:

1. Laws and regulations that govern land cover, land conservation and development in general:
   - spatial planning (e.g., the 2007 spatial planning law, UU 26.2007)
   - forestry (e.g., the 1999 law on forestry, UU 41/1999)
   - protection (e.g., the 2009 law on environmental protection and management, UU 32/2009)
   - development (e.g., the national development planning system, UU 25/2004)
2. Laws and regulations that govern the flow and utilization of water:
   - water resources management (e.g., the 2019 law on water resources management, UU 17/2019)

In addition, there are laws and regulations which establish responsibilities:

1. under normal conditions, between national, provincial, and regional governments (e.g., the 2014 local government law, UU23/2014)
2. during disasters (e.g., the 2007 disaster management law, UU24/2007)

law/regulation number	law	presidential/ministerial regulation	regional regulation	governor decree	content
Land cover					
UU 26/2007	x				Spatial Planning
UU 41/1999	x				Forestry
UU 32/2009	x				Environmental Protection and Management
Flow and utilization of water					
UU 17/2019	x				Water Resource Management
PP 37/2012		x			Watershed Management
PerMen PUPR 4/2015		x			criteria and designation of river basin
PerMen PUPR 10/2015		x			Procedures for Compiling Water Resources Strategic Management Plan
Perda 5/2011			x		Water Resource Management in EJP
Perda 16/2018			x		River Management
Pergub 12/2013				x	Policy and Strategy for Water Resource Management in EJP (JAKPROV PSDA)
Pergub 392/2013				x	water resources management patterns of Welang Rejoso River Basin
Pergub 37/2018				x	Implementing Regulation of Perda 16/2018 on River Management
SK Gub 188/2018				x	development of coordination team of Water Resource Management of Welang Rejos River Basin (TKPSDA)
Responsibilities (normal conditions)					
UU 23/2014	x				Local government
Disaster conditions					
UU 24/2007	x				Disaster Management
Perda 3/2010			x		Disaster Management in East Java

Table 4.1. Main prevailing laws and regulations related to water management and flood resilience

Land cover and regional development

Land development is regulated through a series of national laws and regulations.

The spatial planning law regulates the zoning of land (Figure 4.1). Spatial plans are being made by all government levels (national, islands, provincial, and regional/city/district) and the plans of lower governments must accommodate the plans from the higher governments. The spatial plan consists of two parts, a structural plan (which shows the spatial structural organisation of communities through settlements, industrial areas, connecting infrastructure, etc.) and a detailed plan (which provides the classification of land into zones that e.g., allow development within certain limits or demand conservation of existing land-cover). Spatial plans have a lifetime of 20 years and can be evaluated and updated every 5 years. They are based on the existing land-cover/land-use and include (infrastructural) plans from all government agencies.

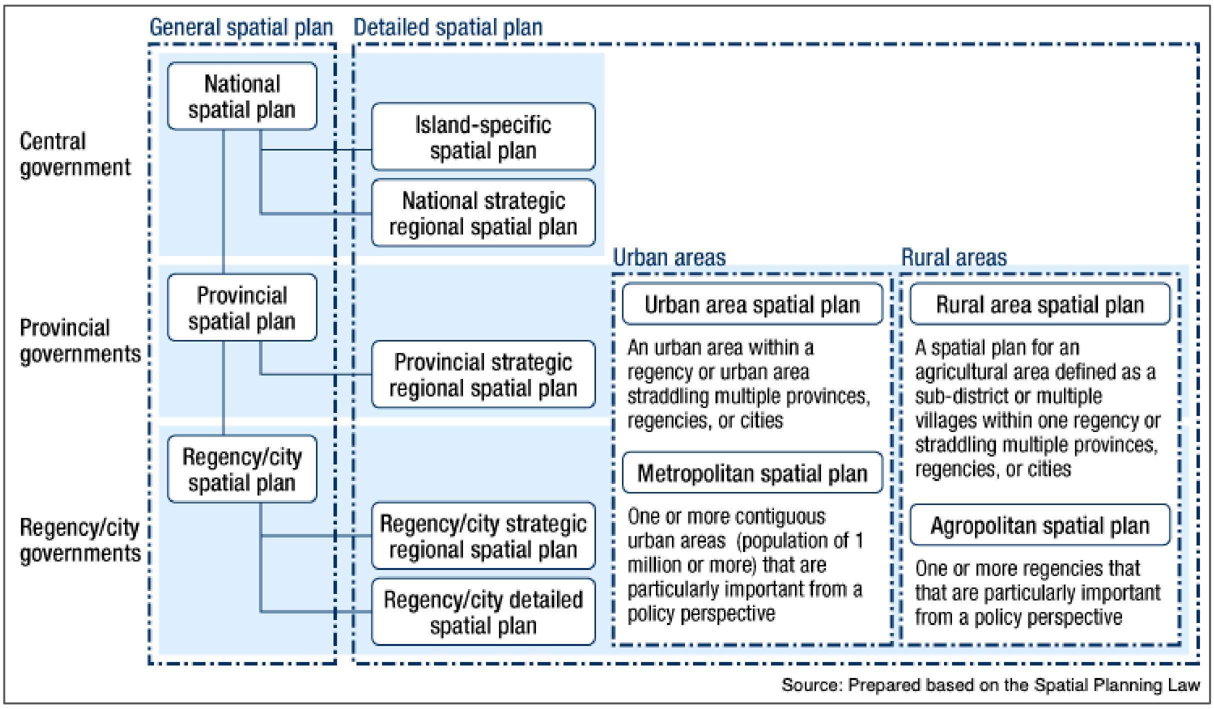


Figure 4.1. Spatial planning process in Indonesia (source: MILT [9])

The national law on forestry stipulates that at least 30% of a catchment needs to remain forest, but leaves it open as to whether it can be natural forest or production forest. Also the spatial planning law stipulates that 30% of a catchment needs to remain forest and in addition the spatial planning law states that 30% of urban areas need to remain green public space (RTH) (which includes parks, green lanes along roads and cemeteries).

Through the environmental protection and management law (UU 32/2009) sustainable development is ensured. The law requires all plans, including spatial plans, to be verified for environmental impacts. A strategic environmental assessment (KLHS) is mandatory for spatial plans.

National and regional development is managed through the development law (UU 25/2004). Currently the existing development regulations do not demand that other plans need to be aligned and form the foundation for sustainable development, it merely states that other plans should be 'considered'. Although in coordination initiatives such as through TKPSDA plans and programs are discussed, agreed changes are not formalized and included in the relevant plans and programs. The development regulations do not provide guidance on the integration of all related plans and programs and related plans only need to be considered when drafting the development plans, not 'used as-is'. This leads to further institutional stove-piping and likely to inefficiencies and reduces the effectiveness of individual plans and programs.

Looking specifically at the individual regulations, it becomes clear that although the same terms are used in the various laws and regulations, the definitions thereof and practical implications are often different. For instance, in both Public Works (PUPR) and Environment and Forestry (KLHK) regulations, the term 'green open space' (RTH) is used. The definitions are however different, while in the KLHK definition the coastal zone is included in RTH, in the regulation from PUPR it is not. In addition, in the PUPR regulation greens along riverbanks and roads are not considered 'green open space', while the spatial planning law states different (see above).

[9] https://www.mlit.go.jp/kokudokeikaku/international/spw/general/indonesia/index_e.html

Flow and utilization of water

Water is primarily regulated as a resource by the water resources management law (UU 17/2019). The law distinguishes between surface water/water on land (over-land flow) and in the ground as groundwater. While management of surface water/overland-flow is assigned to the ministry of Public Works and Public Housing (PUPR), groundwater is managed by the ministry of energy and mining (ESDM).

Multiple national, provincial, and regional regulations are in place that further specify tasks and mandates for various agencies and departments. The existing regulations further recognize river systems and irrigation systems and assign the management of (parts of) these systems to specific agencies and departments. Drainage systems are not specifically recognized as systems; individual drains are in general part of the road infrastructure and are managed accordingly, with primary drains formally considered as part of the main river system and managed by PU-SDA.

As required by the water resources law, through a Governor Decree (SK Gub 188/2018) the Regional Water Resources Coordination Team (TKPSDA) is established in East Java province and is tasked with the coordination of water management plans, designs, synchronisation of programs and activities (such as monitoring), strategic issues, etc. and reports directly to the Governor. This team is a platform to align initiatives, plans and projects related to water management. The Water Resources Law (UU 17/2019) states that the integrated water resources management plan forms a reference plan for the development plans and spatial plans.

The Ministry for the Environment and Forests is not directly involved in or responsible for water resources management. However, the task of water conservation of the ministry affects water resources management and vice versa. Therefore, forest management is also organised according to catchments in the same way as water resources management is. Following the forestry law (UU 41/1999) conservation plans are developed which form reference plans based on which the development plans and spatial plans are drafted. In addition, the ministry for the environment and forestry is responsible for water quality monitoring.

Normal responsibilities

Under normal conditions, responsibilities for the execution of tasks are divided between the national, provincial, and regional governments. The national law on local government (UU 23/2014) regulates the division.

The law states that the authorities are divided following a simple rule: in principle everything (except areas, systems of national strategic importance) is managed by local governments, unless a system crosses borders, then the authority is scaled upwards. E.g.:

- when a catchment is within a regional border, the authority lies solemnly with the regional authority
- when a catchment crosses a regional border, but not a provincial border, the authority lies with the provincial government
- when a catchment crosses a provincial or national border, the authority lies with the national government

The same rules apply for all other systems and water resources infrastructures.

The responsibility of the Welang river follows from the ministerial regulation (Permen PUPR 14/2015) and is assigned to the provincial government. As such, the primary authority for the main river (not the smaller tributaries) and the primary and secondary irrigation systems lies with the provincial Government, in this case the East Java Province, while the responsibility of all tertiary systems lies with the kabupaten/kota. The national government does not have direct responsibility in the Welang catchment.

In the regulations (PerMen PUPR 28/PRT/M/2015) the physical river boundaries are defined. PU-SDA can only implement measures within these physical boundaries. In the regulations, distinction is made between rural and urban areas, although it is unclear how this classification is applied in the Welang catchment, i.e., which areas are considered urban/rural. While in rural areas the boundary of the main river is defined as 100m to each side from the river centreline, in urban areas it is 50m.

Disaster conditions

During disasters, the national disaster management agency (BNPB) takes responsibility for the immediate response: rapid assessment on losses and damages, etc. The focus under these conditions is to contain the disaster as much as possible.

BNPB also has responsibilities pre-disaster and post-disaster. In the pre-disaster phase, the agency has the authority to identify and analyse disaster risks and is responsible to install early warning systems. BNPB is also required to educate and train communities in preparedness. Post-disaster the agency is responsible for the immediate rehabilitation and reconstruction.

The regional disaster agency (BPBD) is tasked with coordinating physical and non-physical efforts to prevent disasters. In the Welang catchment, BPBD coordinates the execution of the efforts between the provincial and regional government agencies. The disaster management agency is by law (UU 24/2007) required to draft a Disaster Management Plan (RPB) which forms one of the reference plans for the development plans and spatial plans.

4.2 Institutional stakeholders

The framework of institutional stakeholders (Table 4.2) related to flood risk management refers to the existing structure of formal organisations active in flood risk management, either directly or indirectly. In this section the various stakeholders are introduced and is discussed how tasks are divided and collaboration, planning and coordination in flood prevention and mitigation efforts and arranged. At the end of the section existing problems and challenges, are discussed and suggestions are provided how these could be addressed.

No	Institutional Stakeholder	National	Province	District	Role	Direct FM	indirect FM	Prevention	Protection	Emergency	Recovery
1	**Planning and Development Coordination (Bappen**	x	x	x	**Coordination of development initiatives and evaluation of strategic environmental assessments (KLHS)**		x	-	x		
a	Planning agency of East Java Province (EJP)		x				x	-	x		
b	Planning agency of Malang District			x			x	-	x		
c	Planning agency of Pasuruan District			x			x	-	x		
d	Planning agency of Pasuruan City			x			x	-	x		
2	**Public Works and Housing**	x	x	x	**development and maintenance of public infrastructure**	x	-	-	x		-
a	BBWS Brantas Sampean	x			construction of flood mitigation measures in the Welang river	x			x		
b	Public works and water resource (Dinas PUSDA) EJP, implemented by UPT PSDA Pasuruan)		-		Flood monitoring , hydrological monitoring		-	-			
			x		Flood control infrastructure along main river (construction and maintenance)	x			x		
			x		Primary and secondary irigation development and maintenance	x			x		
c	Public works and water resource (Dinas PUSDA)		x		Construction and maintenance of stormwater drains	x			x		
d	Water Resource of Pasuruan Regency			x	Flood control, irigation network construction and maintenance	x			x		
				-	Social/community awareness		-	-			
e	Irrigation Agency of Malang Regency			x	Flood control, irigation maintenance, drink and waste water management	x			x		
f	Housing Agency, Pasuruan City			x	Housing reconstruction	x					-
g	Housing Agency, Pasuruan Regency			x	Housing reconstruction	x					-
h	Public works and Bina Marga, Pasuruan Regency			x	Construction of Drainage	x			x		
i	Public works of Pasuruan City			x	Drainage construction and maintenance, flood control	x			x		
j	Cipta Karya Malang Regency			x	Construction of drainage, Drinking and watewater management	x			x		
3	**Environment and Forestry**	x	x	x	**Management of (production) forests, solid waste, pollution control**	x		x			
a	BPDASHL Brantas Sampean	x			Watershed Control and Protected Forests	x		x			
b	BBKSDA Jawa Timur			x	Management of the Gunung Baung conservation forest	x		x			
c	Balai Taman Nasional Bromo Tengger Semeru	x			Management of the Bromo Tengger Semeru National Park	x		x			
d	Environmental Agency, EJP		x		Environmental management, solid waste and B3 management, polution control		x	x			
			x		Capacity strenthening and legal awareness on environmental protection		x	x			
e	Environmental Agency, Malang Regency			x	Control of Pollution and Environmental Damage		x	x			
f	Environmental Agency, Pasuruan District			x	Waste management, polution control and environmental management		x	x			
g	Environmental Agency, pasuruan City			x	Waste management, polution control, green open space management		x	x			
h	Forestry Agency, EJP through CDK wilayah Lumajang		x		Land rehabilitation and forest conservation, Community development in forest buffer areas, watershed management and social forestry	x		x			
i	Management of Tahura R Soeryo (UPT)		x		Planning, implemention, and monitoring of Tahura R Soeryo forest conservation area	x		x			
4	Spatial Planning and Land Management (ATR/BPN)	x	x	x	drafting and approval of spatial plans and collection of land taxes		x	x			-
5	Disaster Management Authority (BNPB/BPBD)	-	-	-	Prevention and preparedness program		-	-			
		x	x	x	Emergency response	x				x	
		-	-	-	Rehabilitation and reconstruction		-				-
6	Agriculture	x	x	x	Agricultural commodity insurance		x	x			
		-	-	-	Maintenance of tertiary irrigation channels	-		x			
7	Health Agency		x	x	Disaster cluster handles rapid health assessment and emergency response		x			x	
8	Villages, Development of Disadvantaged Regions, and Tr		x	x	oversees the use of village funds, community empowerment program		x	x	-		
9	Social Affairs		x	x	social empowerment and social protection		x	x		-	
10	Tourism		x	x	Tourism destination development		x	x			
11	Energy and Mineral Resources		x	x	Licensing of groundwater abstraction wells and mining		x	x			
12	Industry and Trade (Maland regency)			x	Solid Waste Management		x	x			
13	Marine Affairs and Fisheries		x		Coastal monitoring and degradation control		x	x			
14	Finance	x	x	x	Budgeting		x	x			
15	Home Affairs	x			Regulations		x	x	x	x	x
16	Perhutani KPH Pasuruan (SoE)	x			Plantation and production forest concessions		x	x			
17	Parliament (DPR/DPRD)	x	x	x	Budgeting		x	x			
		x	x	x	Establish laws		x	x	x	x	x
18	**Multistakeholder forum**	x	x				x	x			
a	TKPSDA	x			Discuss the pola and water resouce plans, and monitor implementation		x	x	x		
b	Forum DAS		x		Conduct reforestration and private sector monitoring on rehabilitation		x	x			
c	Forum PRB	x	x		Strengthen coordination and collaboration in disaster risk reduction		x	x			

Table 4.2. Institutional stakeholders and their formal roles related to water resources management and flood (risk) management

4.2.1 National level institutions

Within the Welang catchment, the national government as the owner of national forests and conservation areas and of state-owned enterprises involved in plantations, has an impact on flood risks in the catchment. In addition, currently the Ministry of Public Works and Housing is temporarily tasked with the implementation of flood mitigation measures in the river that have been proposed as part of the Presidential Decree on the economic development of East Java (PP 80/2019).

- Ministry of Public Works and Housing:
    - BBWS Brantas Sampean
      Although water resources management in the Welang catchment is not a regular responsibility of BBWS Brantas, through the Presidential Decree on the acceleration of the economic development of East Java (PerPres 80/2019) BBWS Brantas is now tasked with the construction of flood mitigation measures in the Welang river (see section 4.3.4 for more details on these plans).
- Environment and Forestry Ministry:
    - BPDASHL Brantas Sampean
      The Brantas Pekalen Watershed and Protected Forest Management Center is a Technical Implementation Unit under and responsible to the Directorate General of Watershed Control and Protected Forests.
    - BBKSDA Jawa Timur
      East Java Natural Resources Conservation Center (established in 2007, under the Environment and Forestry Ministry) manages the Gunung Baung conservation forest in Purwodadi district.
    - Balai Taman Nasional Bromo Tengger Semeru
      The National Park Center of Bromo Tengger Semeru is a Technical Implementation Unit under the Directorate General of Natural Resources and Ecosystem Conservation (KSDAE) in charge of managing the Bromo Tengger Semeru National Park.
- Ministry of State-owned enterprises:
    - Perhutani KPH Pasuruan
      Perum Perhutani Forest Management Unit (KPH) Pasuruan, controls production forests in and around Pasuruan regency covering a total area of about 320km2. The production forests under control of Perhutani KPH Pasuruan are all in the upstream region on the slopes of the Bromo and Arjuna mountains. In these production forests pine trees and teak trees are grown for timber production.

These ministries have direct impact on land-use or water management and their projects and programs directly affect water discharges and flood hazards. In addition, there are stakeholders that have an indirect effect on the developments that affect discharges and flood hazards.

- Ministry of Planning (Bappenas)
    - Responsible for the national development planning related to water resources management, implemented through a five-year plan (RPJMN) in collaboration with relevant ministries
    - In addition, Bappenas allocates and approves projects funded through the national DAK funds and, in collaboration with the Ministry of Finance, may approve international loans to fund for specific projects
- Ministry of Finance
    - The ministry of Finance is responsible to draft and provide the national budget (APBN) which includes budgets for APBD and for projects funded through DAK
- Ministry of Home Affairs
    - The ministry of Home Affairs is responsible for orderliness and development of water resources at the provincial and district levels and can clarify regulations and mandates
- National Parliament (DPR)
    - The parliament develops and approves laws that affect water resources management and indirectly affect activities that affect water management
    - A commission is responsible to approve the APBN budgets (see budgetary analysis in section 4.4)

4.2.2 Institutes at provincial and regency level

Any issues, projects, programs, and initiatives related to water resources and flood hazards in the Welang river catchment are discussed and managed through the Water Resources Management Coordination Team (Tim Koordinasi Sumber Daya Air, TKPSDA) Welang Rejoso. This coordination team has been established in 2013 with the aim to build synergies in water resource management. TKPSDA has the task to discuss the design of water resources management plans (pola and rencana SDA), program designs and activity plans, proposes a water allocation plan, a hydrological, hydrometeorological and hydrogeological information system management plan, and a plan for the utilization of human, financial, institutional resources. The team reports directly to the governor.

Currently there are 25 agencies listed as member, however representatives of neither the scientific community nor research centres are part of TKPSDA. TKPSDA meets regularly to discuss a selection of priority issues in water resource management in the Welang catchment, including concerning flood events and hazards. The coordination team has indicated that ideally the team would meet at least four times a year (as also required through Permen PUPR 17/2017), however, budget constraints limit the number of times the team comes together to two times a year.

Looking at the individual agencies and their capacities to fully execute the tasks under their responsibility, it becomes clear that most agencies require more (permanent) staff and budget. For example, UPT PSDA Pasuruan currently does not have sufficient budget to recruit sufficient operational staff and the secretariate of TKPSDA remains without dedicated staff and can only meet twice a year. Monitoring of boundaries and critical embankments as well as regular maintenance are not performed to requirements. Complicating factor within the agencies is regular changes in staff and leadership due to among others job-rotation, which hinders capacity building at institutional level.

In addition, specific tasks and responsibilities are highly regulated, but budgets to meet the responsibilities are insufficient. For instance, solid waste management is the responsibility of DLH, but DLH needs more capacity and budget to collect it and there is currently no formal sanitary landfill in the area. Therefore, solid waste mostly remains uncollected and often ends up in drains and rivers where it accumulates and causes problems. UPT PSDA and PUSDA do not have the capacity to remove waste from the rivers and drains and when they do, they must pay DLH to dispose of the collected waste, for which they do not have budget.

River systems, to prevent fluvial flooding

The management of rivers within a catchment is regulated in the water resources law. All main/primary rivers/waterways/drains within a river basin are managed by one agency following the “one river one management” policy. In the Welang catchment that means that river management falls under the provincial responsibility and this task is assigned to Dinas PUSDA. Dinas PUSDA is therefore tasked with maintaining river retaining works, cleaning of the river, dredging, etc.

Drainage systems, to prevent pluvial flooding

Drainage systems are not specifically recognized in the prevailing regulations, only individual drains are recognized. The maintenance and construction of drains follows the owner of the road along which the drain is positioned. For instance, a drain adjacent to the provincial road in Kraton is to be maintained by Dinas PUSDA (province), while a drain along a local road in Kraton is to be maintained by Dinas SDA (kabupaten Pasuruan). The drain itself is constructed by the agency which funds and builds the road as part of the road construction.

Primary drains are part of the main river system and therefore, in the Welang catchment, fall under the authority of the provincial government.

Irrigation systems

In the Welang catchment, maintenance of primary and secondary irrigation channels is the responsibility of Dinas PUSDA (province). Maintenance of the tertiary irrigation channels is the responsibility of the agriculture department (Dinas Pertanian, kabupaten).

Note that Dinas PUSDA only since 2018 is tasked with managing irrigation systems (in line with Permen PUPR 14/2015). Until 2018, management of irrigation systems was a task from the irrigation department (also under PUPR). The structure of Dinas PUSDA requires community participation, while that was not a requirement for the irrigation department which was more focused on maintenance of existing infrastructure only.

4.2.3 Conclusion

Flood protection is the responsibility of Public Works, with currently BBWS Brantas Sampean, through the Presidential Decree on the acceleration of the economic development of East Java (PerPres 80/2019), tasked with the construction of flood mitigation measures in the Welang river. Dinas PU at East java province is normally responsible for the development and maintenance of protection works along the main river and primary irrigation channels. The Public Works agencies are the only agencies who have direct influence on flood risk management. Public Works does not have the mandate to initiate or implement preventive measures.

Large development plans (and associated funds, see section 4.4) are approved and managed through Bappenas. Bappenas therefore holds a central role in approval of mitigating measures, focusing mostly on physical measures. Traditionally Bappenas and Public Works have a strong relation, with Public Works implementing the plans drafted and approved by Bappenas.

Most other involved ministries and their agencies can initiate (and adjust) projects to prevent (future) flood events and therefore can improve long-term flood resilience. The ministries of Spatial Planning and Land Management (ATR/BPN) and Environment and Forestry (KLHK) and their agencies are best positioned to provide significant meaningful impact on flood resilience with relatively little effort, while the ministry of Agriculture and its agencies can provide significant meaningful impact, but that would require significant effort because of the unorganized nature of the agricultural sector.

BNPB has a direct role in emergency response, while the health agencies provide medical relief for affected populations.

Budget constraints are mostly mentioned as the limiting factor to allow for frequent and efficient coordination between the institutional stakeholders. However, the absence of legal requirements to align programs and plans and to seek endorsement/approval from other agencies, means coordination efforts are largely dependent on the initiative of individual decision makers.

4.3 Development framework

Regional visions determine regional development policies. In this section the existing visions, programs, plans and designs as well as awareness raising campaigns related to flood resilience in the Welang catchment are presented.

4.3.1 Long-term and medium-term development plans

The provincial and regional governments regularly prepare development plans that guide development efforts in the regions. Long-term (RPJPD) plans have a planning horizon of 20 years, while medium-term (RPJMD) plans have a planning horizon of 5 years.

East Java Province

East Java Province aims to become a leading agribusiness centre, globally competitive and sustainable, that contributes to a prosperous and virtuous province (RPJPD 2005-2025, Province East Java). The long- and medium-term development plans for kabupaten Pasuruan and Malang resonate the rural ambitions for the region, while the development plans for Kota Pasuruan show an ambition to become a competitive trading centre with a strong industrial sector.

Key aspects of the region in general and the words that are associated with the region or frequently used in the development plans are:

- good governance: high quality, innovative, clean, effective, and accountable and democratic governance
- public awareness and participation in development and preservation of the environment and environmentally sound spatial planning and development with good harmony between ecological, social, economic, and cultural spaces and values
- village and family centred rural- and agricultural-based economic development with sufficient space for tourism and the creative industries and in balance with religious values and local wisdom and with special attention for vulnerable groups

Kabupaten Pasuruan

In their vision Pasuruan regency has a less clear vision compared to the province. The central theme in the development plan from Pasuruan regency is to support local initiatives and to develop basic infrastructure and services to promote economic growth. The regency wants to improve the coverage and quality of water supply systems and sanitation services and aims to reduce environmental pollution.

The regency primarily aims to support tourism development in the upper mid-stream and upstream regions and promote economic development along the main infrastructure arteries. On the slopes of the Bromo mountain, in Tutur, the regency would like to develop a web of tourist villages connected through new roads and bridges and with attractions such as off-road activities. In addition, the government wants to promote the batik industry in this area.

Kota Pasuruan

Kota Pasuruan envisions to further develop as a trading centre and would like the modus to shift from land-based transportation to sea-based transportation. In addition, the city administration recognizes the potential of the flourishing mangrove areas as an eco-tourism destination.

Pasuruan city is well-known as a religious centre and the city administration has identified religious tourism as an opportunity to increase GDRP and the well-fare of local communities. Specific opportunities identified focus on its rich religious heritage: tombs of religious leaders and ancient buildings around mosques.

Programs mentioned in the RPJMD

Figure 4.2From the provincial and district medium-term development plans in total 43 agencies have been identified with in total 122 programs related to flood prevention in the Welang catchment (Figure 4.2). Most are to be implemented through public works and water resources (32 programs), followed by the field of environment and forestry (29 programs) and the field of disaster management (26 programs), this is in line with 3 regimes that explained in legal framework.

No	Institutional Stakeholder	Role: Prevention	Role: Protection	Role: Emergency	Role: Recovery	Prevention	Preparedness	Protection (structural)	Protection (non-structural)	Emergency Response	Rehabilitation Reconstruction	total
1	**Planning and Development Coordination**	-	x									**2**
a	Planning agency of East Java Province (EJP)	-	x			1						1
b	Planning agency of Malang District	-	x			1						1
c	Planning agency of Pasuruan District	-	x									0
d	Planning agency of Pasuruan City	-	x									0
2	**Public Works and Housing**	-	x		-							**32**
a	BBWS Brantas Sampean		x					1				1
b	Public works and water resource (Dinas PUSDA) EJP,	-	x					1				1
c	Public works and water resource (Dinas PUSDA)		x									0
d	Water Resources and spatial planning, Pasuruan	-	x			6		3	1			10
e	Irrigation Agency of Malang Regency		x			1		3				4
f	Housing Agency, Pasuruan City				-	2						2
g	Housing Agency, Pasuruan Regency				-						1	1
h	Public works and Bina Marga, Pasuruan Regency		x					2				2
i	Public works of Pasuruan City		x			3		5				8
j	Cipta Karya Malang Regency		x			1		1	1			3
3	**Environment and Forestry**	x										**27**
a	BPDASHL Brantas Sampean	x				1						1
b	BBKSDA Jawa Timur	x				1						1
c	Balai Taman Nasional Bromo Tengger Semeru	x										0
d	Environmental Agency, EJP	x				3			1			4
e	Environmental Agency, Malang Regency	x				4						4
f	Environmental Agency, Pasuruan District	x				3						3
g	Envoronmental Agency, pasuruan City	x				10						10
h	Forestry Agency, EJP through CDK wilayah Lumajang	x				4						4
i	Management of Tahura R Soeryo (UPT)	x										0
4	**Spatial Planning and Land Management**	x			-							**0**
5	**Disaster Management Authority (BNPB/BPBD) ***	-		x	-							**20**
a	Disaster Management agency, EJP Province	-		x	-				1	1	1	3
b	Disaster Management agency, Malang Regency	-		x	-		1		2	2	1	6
c	Disaster Management agency, Pasuruan Regency	-		x	-	1	2			3	1	7
d	Disaster Management agency, Pasuruan City	-		x	-				2	1	1	4
6	**Agriculture**	x							1			**1**
7	**Health**			x							1	**1**
8	**Villages, Development of Disadvantaged**			x								**6**
a	Community Development Agency, EJP Province	x	-						1			1
b	Community Development Agency, Malang Regency	x							1			1
c	Community Development Agency, Pasuruan Regency	x							4			4
9	**Social Affairs**	x										**4**
a	Social Agency, EJP Province	x		-					1			1
b	Social Agency, Malang Regency	x									1	1
c	Social Agency, Pasuruan City	x								1		1
d	Social Agency, Pasuruan Regency	x					1					1
10	**Tourism**	x										**9**
a	Tourism Agency, EJP Province	x					1					1
b	Tourism Agency, Malang Regency	x							1			1
c	Tourism Agency, Pasuruan City	x							3			3
d	Tourism Agency, Pasuruan Regency	x							4			4
11	**Energy and Mineral Resources (Jawa Timur)**	x				1		2				**3**
12	**Industry and Trade (Malang regency)**	x				1						**1**
13	**Marine Affairs and Fisheries (Jawa Timur)**	x				1						**1**
14	**Finance**	x										**0**
15	**Home Affairs**	x	x	x	x							**6**
a	Admistrative Bureau, Pasuruan City	x	x	x	x				4			4
b	Subdistrict authority, Pasuruan City	x	x	x	x	1						1
c	Satpol PP, Pasuruan City	x	x	x	x		1					1
16	**Perhutani KPH Pasuruan (SoE)**	x				1						**1**
17	**Parliament (DPR/DPRD)**	x										**0**
18	**Multistakeholder forum**	x										**8**
a	TKPSDA	x	x									0
b	Forum DAS	x				1			1			2
c	Forum PRB	x				1	1	1	1	1	1	6
	Total					46	6	18	29	8	7	**122**
	National government					2	0	1	0	0	0	3
	Provincial government					11	1	3	5	1	2	23
	Kabupaten Pasuruan					11	2	6	13	2	3	37
	Kota Pasuruan					17	3	5	7	4	1	37
	Kabupaten Malang					8	1	4	5	2	2	22

* not a ministry, but reports directly to the President
** budgets (ABPN/DAK)
*** approving projects funded through national budgets

Figure 4.2. Flood related programs for Welang catchment identified from RPJMDs

4.3.2 Water resources strategic & integrated river basin management plans

The water resources strategic plan and the integrated river basin management plan are drafted under the leadership of Dinas PU (province). Other agencies and institutes contribute to the plans.

The water resources strategic plan mentions the strong need for improved data collection and data management (both hydrological and water quality data). The plan also mentions a demand for faster responses to flood management and flood control and it states that irrigation performance needs to be improved to provide sufficient water for the agricultural backbone of the region.

The strategic plan mentions that the biggest driver for the increased flood pressures is the rapid land-cover changes and the loss of forest cover in the province. The strategic plan resulted in a draft 5-year integrated river basin management plan (2016-2035) to reduce floods in 30 flood-prone rivers the province. However, the plan has not been approved yet.

At regency level, BPBD Kabupaten Pasuruan prepared flood contingency plans for the Welang catchment. The document outlines vulnerable areas for flooding and includes detailed standard operating procedures for emergency response.

Looking at the underlying data and information used by Dinas PU and BPBD to assess flood hazards and risks, it becomes clear that the agencies use different basic datasets. While public works (PUPR) is generally considered the expert on hydrology and is the agency who owns the national hydrological framework, BPBD uses their own experts to estimate flood hazards.

4.3.3 Spatial plans and spatial zonation

Spatial plans (structural spatial plan, RTRW)

The government agencies involved have structural spatial plans in place that indicate the types of measures planned and the locations where measures are considered.

The government of East Java province has a strong emphasis on prevention. Improved coordination, awareness-raising and early warning and evacuation of identified flood-prone areas are key proposals mentioned in the spatial plan. In addition, several structural measures are identified to reduce flood hazards in the downstream region:

1. construction of retaining walls and embankments along the river
2. river dredging and creation of riverbanks
3. construction of both open and closed channels or tunnels
4. regulation of flow velocity and surface water discharge from upstream areas

In addition, in the spatial plan the plans from the regional government of Kabupaten Pasuruan are mentioned. The list of planned structural measures is extensive but lacks specificity. Structural measures seem mostly heavy in terms of required investments and seem rather destructive to the environment (e.g., normalization of channels and construction of dams, weirs, etc.). However, the regional government puts significant emphasis on the development of new drainage systems to separate stormwater discharge from irrigation. Specifically better coordination and synchronization of programs and plans between the regional and provincial government is specifically mentioned as a non-structural measure.

In relation to the spatial plan in Kabupaten Pasuruan, BPBD Kabupaten Pasuruan has conducted a flood risk assessment and has prepared a Disaster Management Plan (RPB). Integration of the RPB with the spatial plan (RTRW) and medium-term development plan (RPJMD) has been initiated, but so far not all recommendations have been included. BPBD is also not able to further follow up on these aspects.

The provincial forestry department supports farmers to carry out participatory mapping of forests and agricultural areas along the borders of the forests. Primary aim is to empower the farmers and get the farmers involved in the spatial planning process. It is unclear to what extent the results of these efforts have contributed to the establishment of the current spatial plan.

Spatial zonation (detailed spatial plan, RTRD)

The spatial zonation allows for ample urbanisation and development throughout the catchment (Figure 4.3 and Figure 4.4) and especially in the upper mid-stream and upstream regions; note that these areas receive most rainfall and cover most vulnerable soils. There are barely any limitations on where existing land-cover can be converted, and this will mean that in practice land conversion will mostly follow similar trends as in the recent past. Based on an extrapolation of recent spatial developments, a potential future land cover map was created. This shows that the areas covered by urban areas is expected to increase further (Figure 4.4), mostly at the expense of agricultural land. In addition, it is expected that natural forest cover will further reduce, and unprotected natural forests may be converted to production forests; while permitted, retention capacity of production forests is much smaller compared to natural forests. The total forest coverage will probably remain about 30%.

While the current detailed zonation provides ample space for development (Figure 4.3), it also means that actual spatial developments are highly unpredictable. Therefore, government agencies cannot accurately anticipate on expected developments. For instance, PUSDA cannot anticipate expected requirements for drainage needs because it is unclear where new houses/industries will be developed. Also, the road managers at kabupaten level cannot anticipate the development of a road network that will provide sufficient capacity in e.g., 5 years from now. Note that the space reserved for additional urbanization (residential or industrial uses) is more than 4,000ha in the area governed by Kabupaten Pasuruan alone, while the total area currently used for those purposes in the entire catchment is about 6,000ha.

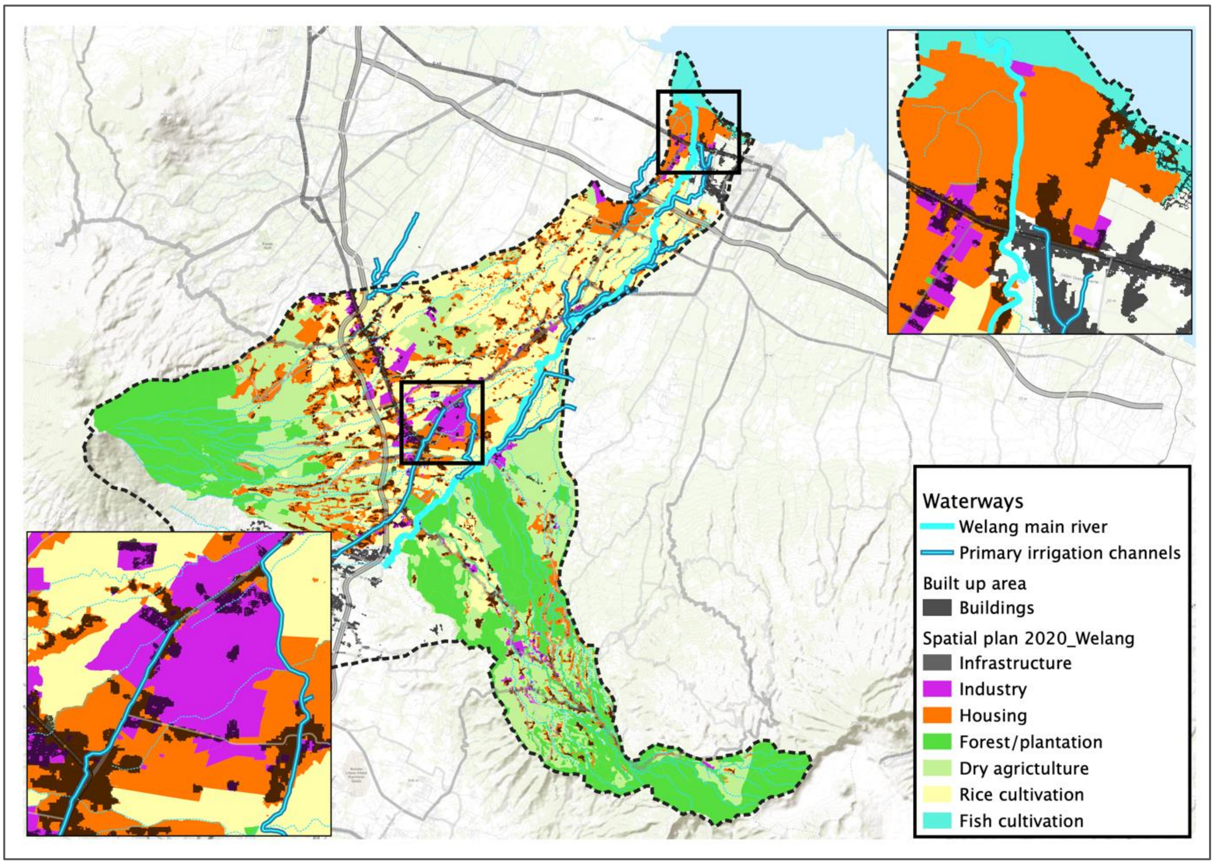


Figure 4.3. Recent (2020) spatial plan for Kabupaten Pasuruan.

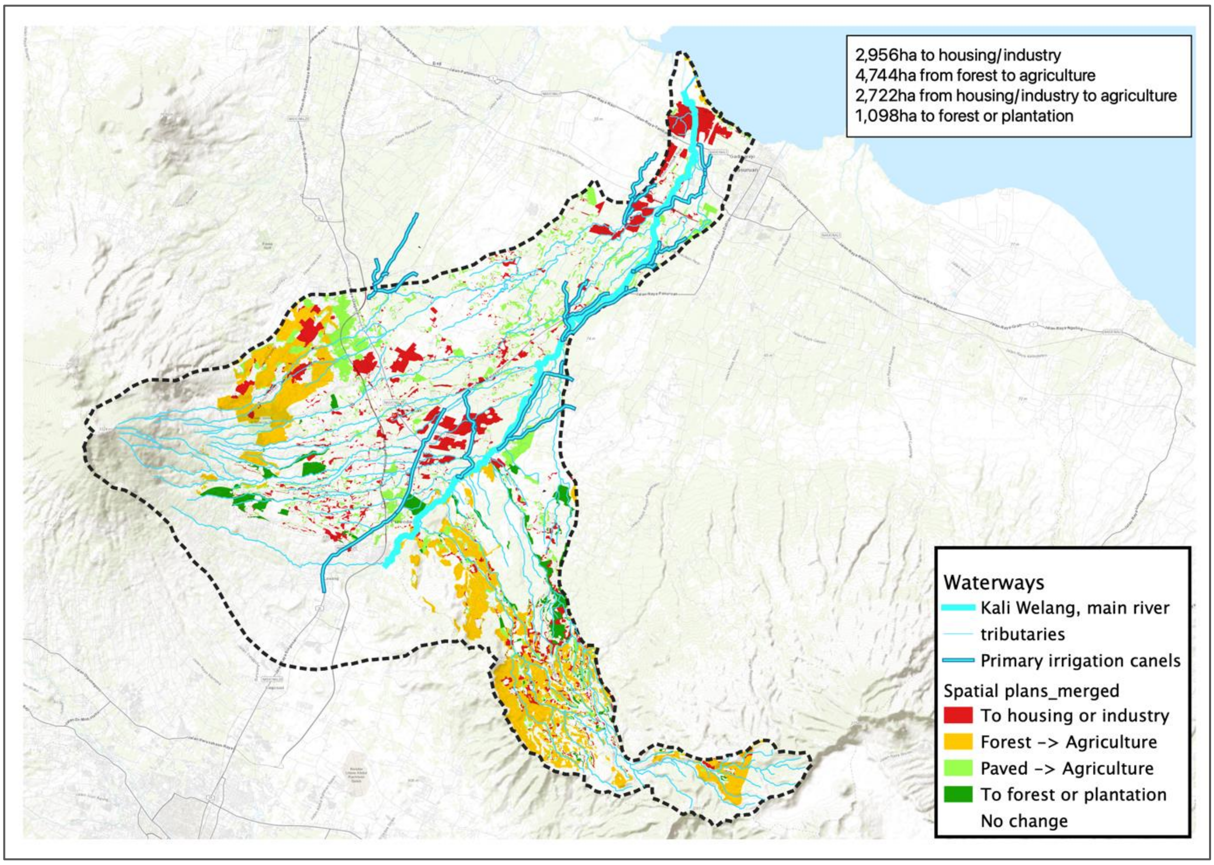


Figure 4.4. Changes between 2010 and 2020 spatial plan for Kabupaten Pasuruan shows significant changes in the entire catchment.

4.3.4 Specific plans and designs

UPT PSDA is responsible to draft specific plans and designs with regards to flood protection in the Welang river catchment. The river basin management plan is the designated plan to present all relevant plans from the various institutes and agencies involved in flood resilience and to show how the plans interact with each other and together effectively reduce flood hazards and flood risks and increase flood resilience. The current plan (drafted in 2016-2035) is still in draft and so not formalized and endorsed.

However, in the plan several projects have been identified and described (this list is extracted directly from the draft river basin management plan):

- Prevention
  - Non-physical measures:
    - Prepare flood zone
    - Awareness of EWS and flood prevention
    - Coordination upstream downstream for flood prevention
  - Physical measures:
    - Infrastructure development & rehabilitation:
      - Elevation of the surface of the main highway get flooded
      - Normalization / improvement of river channels that regularly flooding
      - Repair of the estuaries of the K. Welang
      - Construction of Check Dams in the tributaries of Order 3, Order 4 in the upstream domain
      - Operation & maintenance and monitoring of rivers
- Protection
  - Non-physical measures:

    - Prepare flood forecast
    - Determination of evacuation routes and evacuation locations
  - Physical measures:
    - Emergency rehabilitation embankments
    - Preparation of evacuation facilities and locations
- Recovery
  - Non-physical measures:
    - Socialization to the community related to recovery efforts due to floods and water damage
  - Physical measures:
    - Rehabilitation & reconstruction of environmental conditions, public facilities, social facilities, housing and settlements and river infrastructure

In addition, UPT PSDA is responsible to plan and carry out regular works related to operation and maintenance. UPT PSDA has identified and proposed activities such as flood monitoring, post-flood river cleaning, institutional development of floodgate management, etc. The proposed activities have all been approved.

Two NGOs (Si Hijau and FKPS) are currently active in the Welang catchment. FKPS is involved in waste management activities, while Si Hijau is working on re-greening (planting of trees) in the upstream region.

4.3.5 Awareness, social protection, and insurance

Some agencies have social policies and programs in place to raise awareness and/or protect vulnerable communities:

- BPBD
  - in terms of prevention and preparedness, there are at least 18 programs including disaster response villages, early warning systems and evacuation signs.
- Dinas Lingkungan Hidup
  - has programs related to waste management and pollution control. They manage waste bank programs with local CSOs and the private sector. In 74% of the household associations waste banks (privately managed by volunteers) have been established.
- Agricultural agency (*Dinas Pertanian)*
  - in collaboration with PUSDA and HIPPA carries out several activities to raise awareness within communities on water use and climate change and flood hazards
  - in collaboration with HIPPA maintains tertiary irrigation channels
  - in Kabupaten Pasuruan has an agricultural insurance program which currently covers 1,500ha of rice fields. It is unclear what damages the insurance covers
  - In collaboration with CDK: through community forests, agroforestry, wana farma and water resources conservation activities, awareness is raised within communities. All activities are carried out on community land, in forest buffer areas
  - In collaboration with Pesantren: a similar approach is followed with similar projects within the villages where these pesantren are based
- Social department (*Dinas Sosial*)
  - has several programs related to flood control in the Welang River. They include natural disaster preparedness programs through the establishment of disaster preparedness villages and post-disaster social rehabilitation programs
- Village agency (*Dinas Pemberdayaan Masyarakat*)
  - Several activities related to river conservation, revegetation, flood control and management, waste management and education-awareness raising program can be addressed and designated to be funded by Dana Desa/village fund through musrembang process.
- FKPS (NGO)

- runs several programs in waste management through early childhood education programs in schools (*sekolah adiwiyata*)
- in addition, they have developed an app (Susur Kali) to allow children to learn about the river from upstream to downstream through field investigation near their houses. The app allows participants to update each other on flooding occurrence
- manages the Adus Kali program, a series of activities to educate and build awareness at community level

4.4 Budgetary framework: budgets and expenses

All projects and programs in Indonesia are dependent for funding through the national (APBN) and regional (Anggaran Pendapatan dan Belanja Daerah, APBD) budgets. In Indonesia the national budget (APBN) is managed by the Ministry of Finance and must be approved by the National Parliament (DPR). The APBN is financed through national taxes, income from natural resources (oil and gas) and loans and grants.

At provincial and district level, the local budget (APBD) consists of budget provided by national government supplemented with locally collected taxes and levies that are not transferred to the national level. Provinces transfer part of their APBD budget to regencies through grants and redistribution schemes. In addition, NGOs can fund specific projects directly after approval by Bappeda.

In addition, villages have their own source of funding directly from the national government for small village projects. The regencies have no control over or influence on how villages spend this money.

The fiscal decentralization law (UU 33-2004) regulates the flow of funds. Figure 4.5 provides a simplified schematic of the budgeting and financing structure.

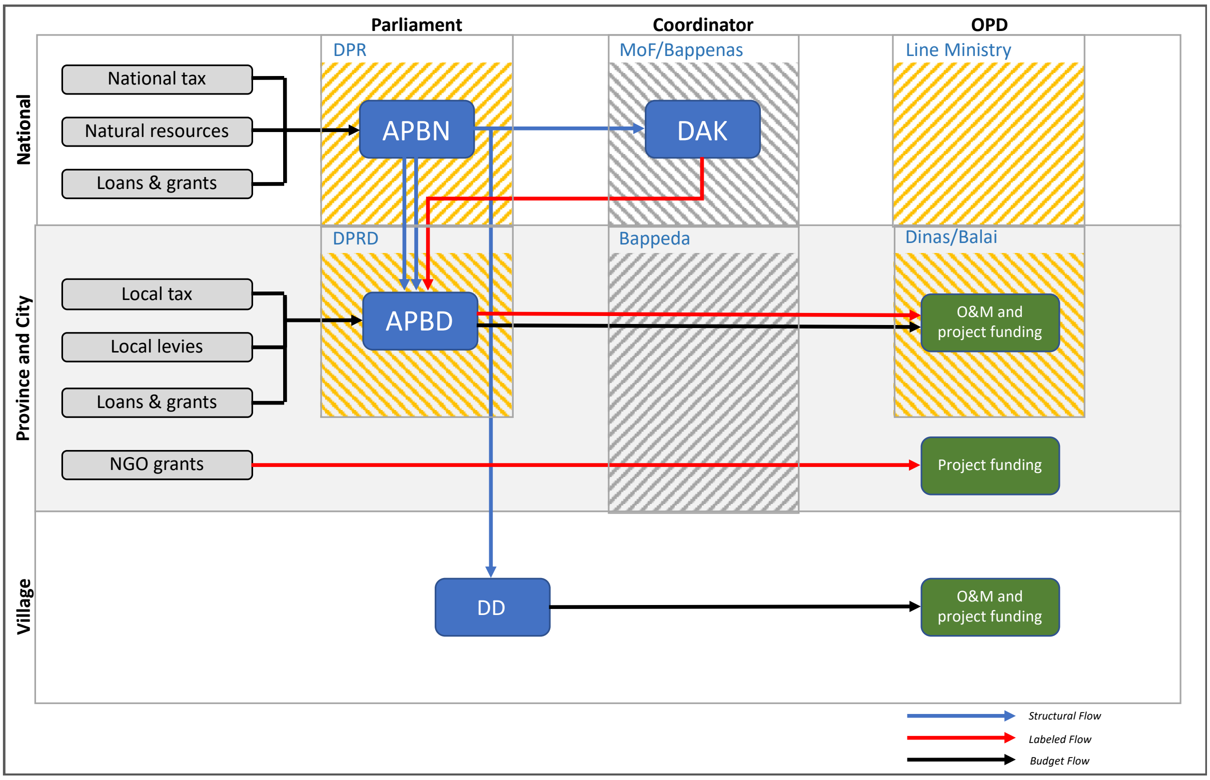


Figure 4.5. Simplified schematic for regular flow of funds and budgets (source: Deltares, 2018)

4.4.1 APBD: Kabupaten Pasuruan

The budget of a regency consists of budget provided by the national government, complemented with local taxes and levies that are not transferred to the national government and grants from other governments (e.g., other kabupaten/kota or the province).

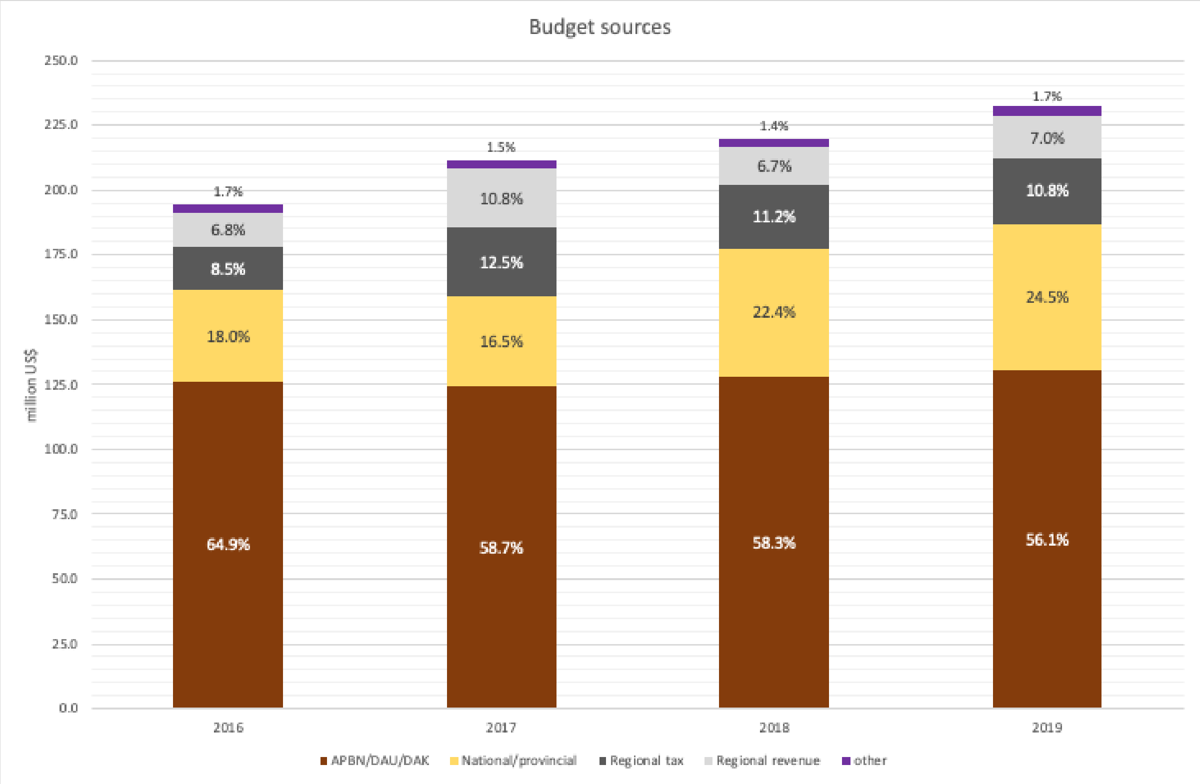


Figure 4.6. Budget sources for Kabupaten Pasuruan (source: BPS, 2020)

Figure 4.6 shows that the flow of funds from APBN is rather constant. Over the recent years, the contribution from the provincial government has almost doubled. In addition, the locally generated funds now contribute almost 20% to the regional budget. However, the local income from taxes and levees fluctuate significantly.

APBN: national budget

In Indonesia, regional budgets are provided largely by funds from the central government. Funding from the national government is very stable and the national government provides Kabupaten Pasuruan with about US$ 125 million per year. The national government distributes APBN to the regions via the following funds:

- ABPN, tax: accounts for about 15% of the contribution from APBN
- APBN, non-tax: accounts for about 65% of the contribution from APBN
- DAU, public allocation fund: accounts for about 20% of the contribution from APBN
- DAK, special allocation fund: Kabupaten Pasuruan has not received any DAK funds recently

Other funds from national and provincial governments: grants and autonomy funds

The budget breakdown for Kabupaten Pasuruan also shows that grants and autonomy funds are increasingly an important source of funding. These funds are provided by the provincial government. It is unclear to what extent these funds are labelled for specific purposes.

The significant increase of grants and autonomy funds for Kabupaten Pasuruan is important. The relative importance of these sources also shows that the regency is more reliant on funding from the provincial government and that the provincial government can indirectly influence policy at regency level.

PAD: regional taxes and revenues

PAD, in the form of taxes, levies and other regional revenues contributed 17.8% in Kabupaten Pasuruan in 2019, while these sources accounted for 15.3% in 2016. In 2017 regional revenues in Kabupaten Pasuruan were very high, it is unknown what caused this outlier.

The recent relative and absolute increase in local revenues and taxes shows that local revenues and taxes are becoming a more important source of local budgets and underscore that the local economy is increasing and poverty is reducing. The regional government should use these funds to further support the economy and reduce poverty.

DD: Dana Desa

4.4.2 APBD: East Java Province

The provincial budget consists of distributed funds from the national government and local taxes and revenues. The East Java province obtains about 55% of its budget from local taxes and revenues and the rest is received through allocation funds from the national government (DAK and DAU). The provincial budget in general is stable and there is little variation in importance of specific sources.

Regional taxes and revenues are slowly increasing in East Java province. This again is a clear indication that poverty is reducing, and more people and businesses are contributing to the government budget.

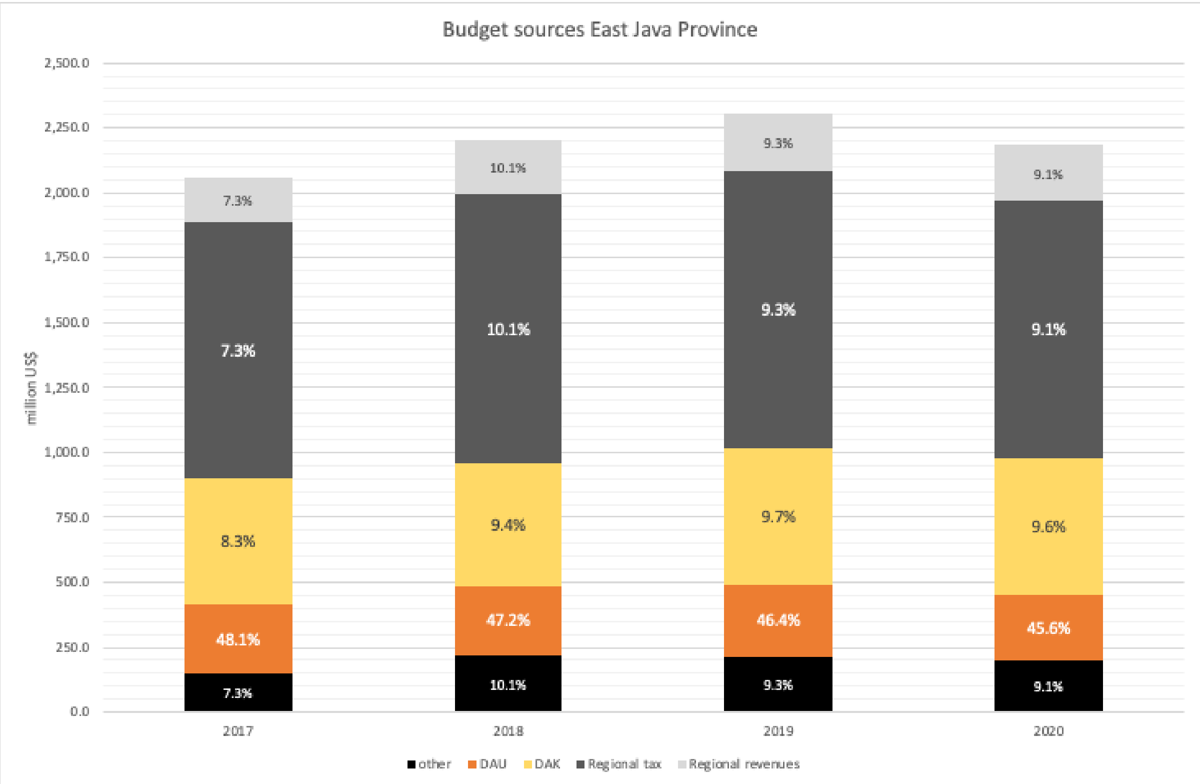


Figure 4.7. Budget sources for East Java province (source: BPS, 2021)

Investments in water management are considered of strategic national importance to achieve goals defined in the long- and medium-term national development plans and programs. Therefore, the national government plays a key role in channelling funds from the central government to implement strategic projects. Through the Special Allocation Fund (DAK), the central government funds water resources management projects that are then executed by the National River Basin Authority (BBWS Brantas) or the Watershed and Protected Forest Management Center (BPDAS LH Brantas Sampean).

BBWS Brantas and BPDAS LH Brantas Sampean fall under the authority of the provincial government. DAK funds are project-based and are therefore labelled. These funds are requested from the national government and are subject to approval by Bappenas. Interestingly DAK funding in East Java province is stable and has not fluctuated much in recent years.

Requested and approved budgets related to Welang Catchment

DAK funding worth US$ 6.9 million is approved for BBWS Brantas projects in the Welang Catchment. These funds are specifically for the implementation of protection works along the Welang river in the downstream region. Proposed works are related to river normalization and construction of new and heightening of existing river embankments in and around the Kraton area.

For the planning period 2019-2024, the provincial water resources department (UPT PSDA) estimated operation and maintenance costs for monitoring and repairs of works along the main Welang river and in irrigation systems within the Welang catchment at US$ 4.5 million, or about US$ 750,000 per year.

Although the proposed activities have been approved, the budget for these activities has not been made available. In effect, available budget is barely sufficient to cover regular expenses related to operational personnel.

4.4.3 Expenses: Kabupaten Pasuruan

Until very recently, Kabupaten Pasuruan had a budget deficit. Only in 2019 the expenses were in line with the available funds.

Regular expenses for personnel and goods and services are stable and account for about 60% of the total expenses from the regency (Figure 4.8). The data does not provide insight in the type of goods and services, which likely includes maintenance.

Kabupaten Pasuruan has significantly reduced capital expenses in the recent years (from about US$ 57.8 million in 2016 to US$ 30.8 million in 2019) (Figure 4.8). This suggests that in recent years less investments have been made in infrastructure.

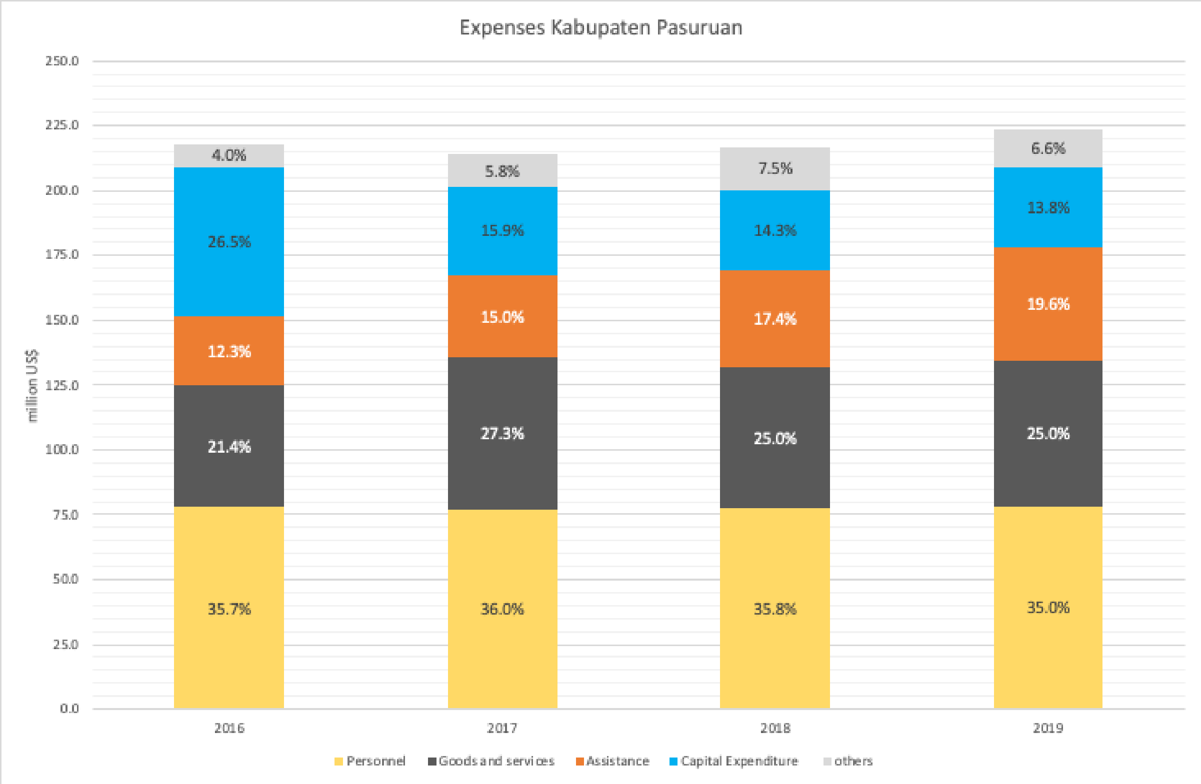


Figure 4.8. Expenses by Kabupaten Pasuruan province (source: BPS, 2020)

Social and financial assistance by the regional government of Kabupaten Pasuruan has significantly increased in recent years (Figure 4.9). This is another sign that the economy in region overall increased and poverty declined. The total assistance provided by the regional government of Kabupaten Pasuruan reached a total about US$ 43.8 million in 2019, up from US$ 26.7 million in 2016.

At provincial level, financial assistance has reduced in recent years. However, the total reduction of the expenses for financial assistance by the provincial government is much smaller than the absolute increase of these expenses at Kabupaten Pasuruan.

The regional government has increasingly more means that could be used to stimulate flood resilience at root (household/business) level. For instance, the government could decide to subsidise rainwater collection. It is unknown what this assistance is provided for now and how the government decides what to provide assistance for.

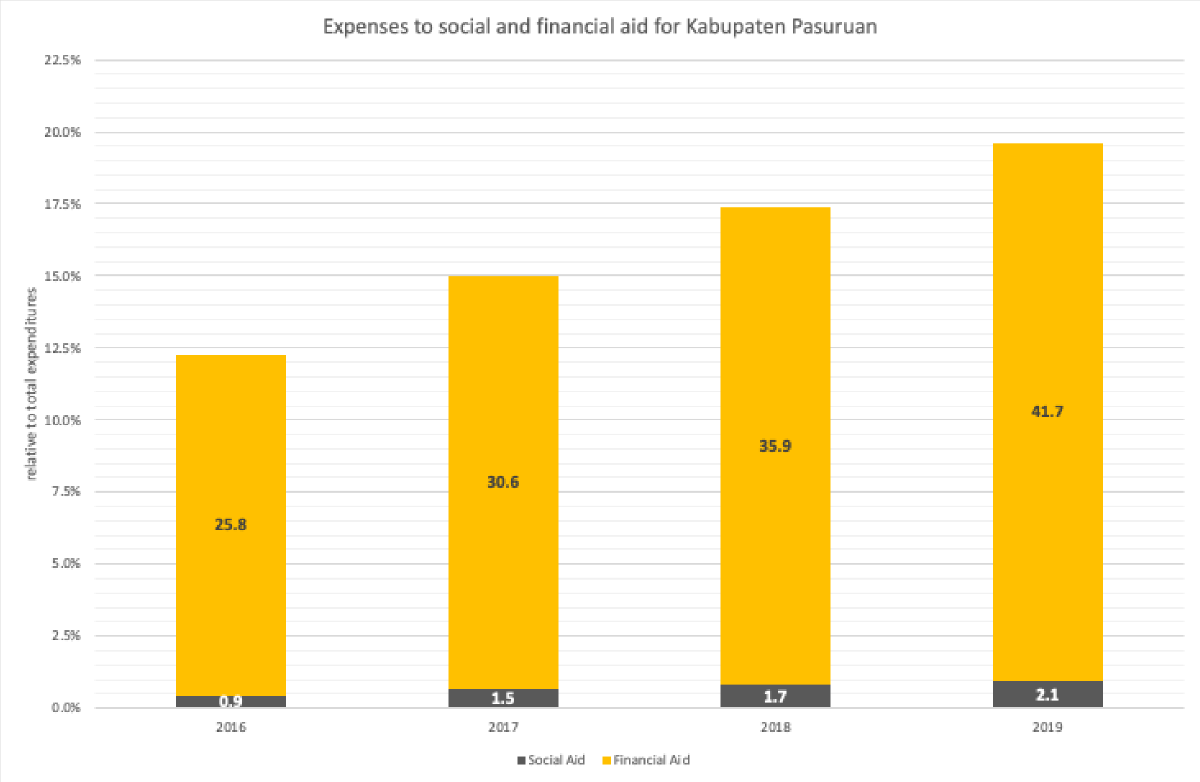


Figure 4.9. Expenses on social and financial assistance by Kabupaten Pasuruan (labels in million US$) (source: BPS, 2021)

4.4.4 Expenses: East Java Province

Expenses for personnel and goods and services by the East Java Provincial government have increased from US$ 830.8 million in 2017 to US$ 951.3 million in 2020 (Figure 4.10). The increase is mostly in goods and services. The data does not provide insight in the type of goods and services, which may include maintenance.

Last year the province had unforeseen expenses of US 70.1 million. These are likely expenses related to COVID-19. Otherwise, other costs are stable and only account for about 4% of the total expenses.

Also, distribution of funds from the provincial government to the regencies is stable and about 20% of the available funds are distributed to the regional governments.

However, East Java provincial government has, similarly to Kabupaten Pasuruan, significantly reduced capital expenses in the recent years (from about US$ 213.1 million in 2017 to US$ 131.3 million in 2020) (Figure 4.10). This suggests that in recent years less investments have been made in infrastructure in the province in general.

On the other hand, the available financial data shows that recently the provincial government has increased the use of grants to regional governments. Expenditures from grants increased from about US$ 443.1 million in 2017 to about US$ 637.2 million in 2020 (Figure 4.10).

These grants are directly distributed to the regional governments but could be based on projects proposed by the regional governments. In 2019 grants accounted for 10.6% of the total budget of the regional government of Kabupaten Pasuruan, up from 8.5% in 2016, which shows that grants are increasingly important for regional governments. However, this form of funding is uncertain for the regional government and allocation may be subjective. For the provincial government they form a mechanism to excerpt influence developments in the region.

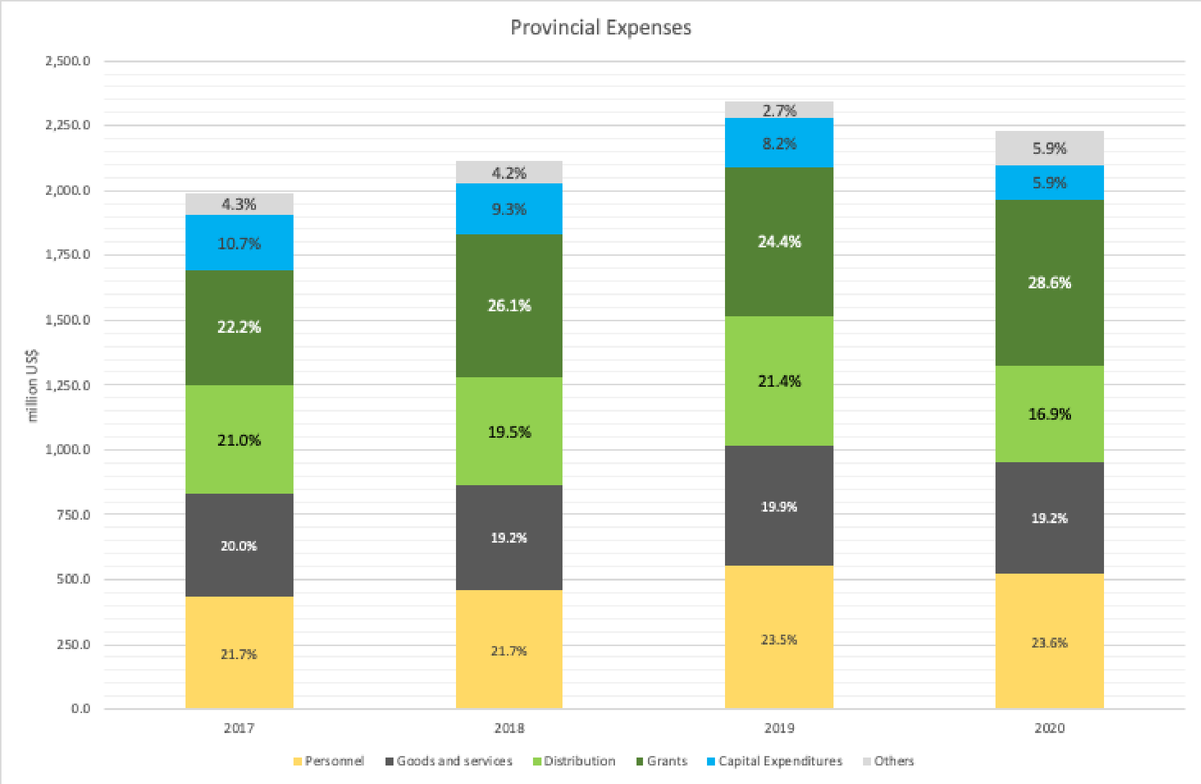


Figure 4.10. Expenses by East Java provincial government (source: BPS, 2021)

4.5 Conclusion

The Welang region and the economy are developing rapidly which has resulted in reduced poverty and improved living standards. For the governments this means that more funds are available to provide support to the population and to work on improving existing infrastructure and facilities. The regional governments are increasingly less reliable on the national government for funding, although the national government still provides about 60% of the regional budget.

Local budgets have increased significantly in the last years and reflect the recent strengthening of the economy and the reduction in poverty. Although distributed funds from the central government account for about 55% of the available regional budget, Kabupaten Pasuruan relies increasingly less on the central government for funding. **Local revenues have recently increased significantly and increasingly grants from the provincial government form an important source of funding for the regional government.** This points to an opportunity for the provincial government to indirectly influence developments in the regencies.

Visions and plans are prepared, but largely in a sectoral manner and synchronization needs to be improved. Drafting of plans and visions is done by all government agencies. However, this is mostly a parallel process, is mostly conducted within a department and based mostly on data from the specific department. In some cases, planning is a linear process, like in the drafting of the development plans and spatial plans where the underlying plans are only 'considered'; In practice however, a significant number of details are not absorbed into the development/spatial plans. Consequently, most plans need to be aligned and consolidated. This leads to significant inefficiencies for the government. Ideally, plans should be drafted as an iterative process where each plan forms an integral part of the more holistic development plan.

A gap analysis, where the various plans are compared and gaps are quantified, was not within the scope of this assignment, but is recommended as a first step to align (vertically and horizontally) plans and visions. For instance, it seems that the spatial plan is highly ambitious, and some aspects may be unrealistic. As an example, the total area reserved for new urbanization (for residential use or industrial use) in the new spatial plan is more than 4,000ha, while the current area used for housing and industries is about 6,000ha and the total population is expected to peak soon. Also, in the spatial plan the area north of Kraton is designated for residential purposes, while the provincial government plans to revitalize the irrigation systems (which are currently also used for drainage) leading into this area from the Licin and Grinting weirs.

Although laws and regulations are clear in terms of mandates related to action, mandates on data acquisition require clarification. For instance, while BNPB is responsible to identify and analyse disasters, there are no laws or regulations that determine who is responsible to provide the hazard maps. Therefore, BNPB has a method to determine flood hazards that is inconsistent with the one used by PUPR. Therefore, multiple flood hazard maps exist which often contradict each other.

Authorities between provinces and regencies and between various agencies are divided along administrative lines only. In practice this leads to situations where the responsible authority is not the affected one when things go wrong. For instance, the environmental agency is responsible for the collection of solid waste, but uncollected waste ends up in rivers where the water agency must remove it and subsequently must pay the environmental agency to dispose of it. Another example can be found in the management of the drainage system, where the provincial government is responsible to maintain drains along the provincial road, but when these are clogged or too small and cause flooding along the adjacent roads, it is the regional administration who is affected.

Government agencies are structurally in need for more budget and more (permanent) staff. For instance, while collaboration on water issues is arranged via TKPSDA, this body lacks permanent dedicated staff and lacks budget to hold frequent meetings and verify implementation of agreed plans. A complicating additional factor is that smooth transfer of knowledge and expertise when staff is rotated is often undervalued, and therefore no long-term capacity is developed within the government at institutional level. While individual staff is trained and promoted on a regular basis, the gained knowledge and skills leave the institutes when staff members are rotated elsewhere.

In addition, maintenance of existing infrastructure and development of new infrastructure is done by the same teams. Therefore, these tasks are competing for (human and financial) resources. It would be better to decouple these and have specific departments within the agencies that focus on the maintenance task and the development task only. To secure maintenance, these departments could be assigned an annual budget based on past performance and local levees/taxes can be adjusted to meet the financial needs. Development budgets could be secured through investment funds from Bappenas/Bappeda.

River Basin Management Plans contain ideas and ambitions, but are weak on concrete, feasible actions. The list of proposed flood protection measures in the river basin management plans (Pola) mainly contains general ideas but is not specific in terms of neither the flood reduction aims nor the geographic location where measures are required. More importantly, the underlying analyses do not generally show flood hazards let alone flood risks now and towards the future. In addition, an objective consideration of priorities based on a general set of guiding principles on accepted flood protection levels is not possible. Currently there is no agreement on what an acceptable level of flood risk is.

While urbanization requires more investment in infrastructure and more regular maintenance, actual budgets are low. Looking at the budgets and expenses from the provincial and regional governments, it becomes clear that at both levels, governments are investing less in infrastructure and budgets for maintenance are low. This despite the recent economic development and despite the rapid urbanization in the Welang catchment. In addition, this seems to be in contradiction with the specific plans mentioned in the spatial plan which show, especially from the regional government, an ambition for new stormwater drainage systems throughout the catchment.

Flood resilience is high on the agenda of many agencies, but coordination of initiatives and accountability can be improved. There are many more agencies with plans to invest in flood resilience than would be expected from a narrow interpretation from the prevailing laws and regulations on water resources management. Currently, most projects are funded by the initiating agency through single source funding and so goals and aims of these projects are narrowly defined based on the goals and aims of the initiating agency. Consistent alignment of plans and the introduction of basket-funding (through which an aligned project plan can contribute to the goals and aims of multiple agencies and be funded by multiple agencies) could significantly improve flood resilience within the catchment at lower costs while at the same time allow individual agencies to spend more on permanent staff. The provincial government could use grants to regional governments to stimulate basket-funding initiatives and a neutral agency (e.g, Bappeda or Bappenas) could facilitate an open discussion to align plans and budgets and hold participating stakeholders accountable.

The current approach is heavy on (expensive) infrastructural protection measures and could be rebalanced towards (cheaper) non-physical prevention initiatives. The current practice of sectoral planning leads to projects (often infrastructural) that mainly focus on the goals of the executing agency/department while they may have unwanted effects on the goals of other agencies/departments – which are insufficiently taken into consideration. While plans and designs for flood protection measures may be expected to mitigate the current flood problems targeted, it is expected that they might not be sufficient to provide sustainable long-term protection. This is partly because the impacts of other planned developments within the catchment are not considered in the plans/designs (often unknown to other agencies/departments) and partly because a very narrow definition of flooding (fluvial only) is followed. While environmental impact assessments are required for most projects and for some plans, the results rarely lead to adjustments of designs and plans, especially plans from other agencies/departments. The current practice of sectoral planning is a result of decentralised and sectoral agendas and targets. Paradoxically, individual policy targets are rarely met, and the practice results in ever bigger challenges that require ever bigger investments. While developments may always lead to changes in flood hazards and risks, an evaluation of the hydrological impact of development plans may lead to small adjustments to flood prevention and mitigation plans and designs which can provide longer flood protection.

5 Flood Analysis

5.1 Introduction

Three different primary flood mechanisms are distinguished:

1. **Coastal flooding**: where water from the sea inundates low-lying coastal areas. This is caused by a discrepancy between high sea water levels resulting from high tide and/or storm surge and coastal protection levels.
2. **Fluvial flooding**: where high discharges in rivers or streams exceed the local discharge capacity leading to overflow of channels. This is caused by a misalignment of high discharges originating from upstream sources and local discharge capacity of the river/stream/channel.
3. **Pluvial flooding**: where local rainfall cannot drain to a river or stream and causes local ponding. This is caused by a misalignment of peak rainfall and the available storage/discharge capacity in the local drainage system.

The effects of climate change to rainfall in Indonesia and the Welang catchment specifically, are not well understood. There is significant uncertainty, and the global models are not in agreement. It could be that more total rainfall and higher rainfall intensities are to be expected and/or more prolonged droughts. However, considering that the global models are not in agreement, these changes are likely relatively small and may not have a significant impact on flood hazards/risks in the catchment. Climate change in relation to rainfall is therefore not considered in this assessment.

Global climate change is already leading to rising sea levels. In Indonesia current estimates still assume a long-term trend of 8mm/yr. This may have an effect of flood hazards (especially coastal and fluvial) in the downstream reach of rivers.

5.2 Recent Flood Events

										observed rainfall					
date	rainy season	dry season	affected people	tide	river	precipitation	downstream	midstream	upstream	WONOREJO	WONOREJO (+/- 2days)	TUTUR	TUTUR (+/- 2days)	LAWANG	LAWANG (+/- 2days)
03/02/2004	x		27,501				x			N/A	N/A	N/A	N/A	N/A	N/A
13/01/2005	x		1		x					N/A	N/A	N/A	N/A	N/A	N/A
14/03/2005	x		N/A		x					N/A	N/A	N/A	N/A	N/A	N/A
31/12/2005	x		N/A		x	x				N/A	N/A	N/A	N/A	N/A	N/A
06/01/2007	x		N/A		x					0	0	0	0	0	0
25/02/2007	x		N/A		x		x			26	26	60	60	10	40
27/03/2007	x		N/A		x					9	41	0	6	20	20
30/01/2008	x		2,247		x	x				**117**	**117**	28	35	24	44
19/01/2009	x		3,500	x		x				0	8	0	4	10	10
07/01/2010	x		7		x	x				0	**100**	16	41	2	56
09/01/2010	x		2,056		x	x	x			**100**	**100**	15	41	3	38
11/05/2010		x	N/A		x	x	x		x	0	**85**	7	69	3	70
06/12/2010	x		1	x		x	x			**166**	**166**	8	36	56	56
05/03/2011	x		N/A		x					7	72	3	57	3	65
26/12/2011	x		12,931				x			30	30	70	70	25	36
03/06/2013		x	N/A				x			27	60	12	12	30	70
09/06/2013		x	4,000				x			0	4	21	21	20	27
24/07/2013		x	N/A	x						0	0	0	13	0	31
25/11/2013	x		N/A		x	x	x			36	36	12	60	5	**102**
25/11/2013	x		2,205	x	x	x				36	36	12	60	5	**102**
11/12/2013	x		10,901			x				6	12	17	30	6	**89**
13/12/2013	x		3,591			x	x			0	36	15	70	0	**101**
17/12/2013	x		3,325		x	x			x	10	29	10	25	19	**101**
18/12/2013	x		3,278		x	x				0	10	17	25	9	21
03/01/2014	x		3,000			x	x			0	36	0	20	0	**75**
04/01/2014	x		N/A			x				0	36	20	41	75	**75**
28/01/2014	x		21,535			x				13	28	21	48	11	45
22/02/2014	x		12,235	x	x	x	x			0	56	0	41	25	31
17/03/2014	x		1,450		x	x				70	70	5	25	70	70
22/04/2014		x	N/A			x				0	22	0	24	0	**77**
23/04/2014		x	270			x				0	22	20	30	45	45
27/12/2014	x		N/A				x			60	60	**115**	**115**	15	90
19/01/2015	x		3,580		x					12	37	17	23	17	30
02/02/2015	x		6,500				x			2	42	0	70	14	**141**
05/02/2015	x		5,536		x					0	42	**85**	**85**	65	65
10/02/2015	x		2,565		x					20	60	24	27	16	52
01/03/2015	x		N/A				x			9	67	60	60	27	**89**
03/04/2015	x		N/A						x	0	0	**180**	**180**	7	7
21/02/2016	x		14,021				x			N/A	N/A	N/A	N/A	N/A	N/A
30/06/2016		x	58,706				x			N/A	N/A	N/A	N/A	N/A	N/A
05/01/2017	x		250						x	N/A	N/A	N/A	N/A	N/A	N/A
11/01/2017	x		27,500				x			N/A	N/A	N/A	N/A	N/A	N/A
30/01/2017	x		10,000				x	x		N/A	N/A	N/A	N/A	N/A	N/A
28/02/2017	x		N/A				x			N/A	N/A	N/A	N/A	N/A	N/A
21/11/2017	x		N/A				x			N/A	N/A	N/A	N/A	N/A	N/A

Table 5.1. Reported flood events (source: DIBI database (BNPB), PU-SDA)

Historic flood events in Indonesia are registered by BPBD in the national DIBI database. Unfortunately, the DIBI database register is not very accurate. For example, the registered dates of flood events are often not representing the actual date when flood events occurred. This makes reconstructing the conditions surrounding historic flood events difficult. Moreover, the direct causes leading up to the flood events cannot be accurately identified. However, general trends can be identified from the list of reported flood events (Table 5.1).

In general, flood events tend to occur mostly during the rainy season and mostly during the months December and January. But flood events also happen during the dry season, albeit that these do not happen as frequently, they tend to happen once per 3-4 years.

Flood events mostly affect the desa/kelurahan in the downstream reach of the river, although desa/kelurahan in the midstream reach are sometimes affected during the rainy season.

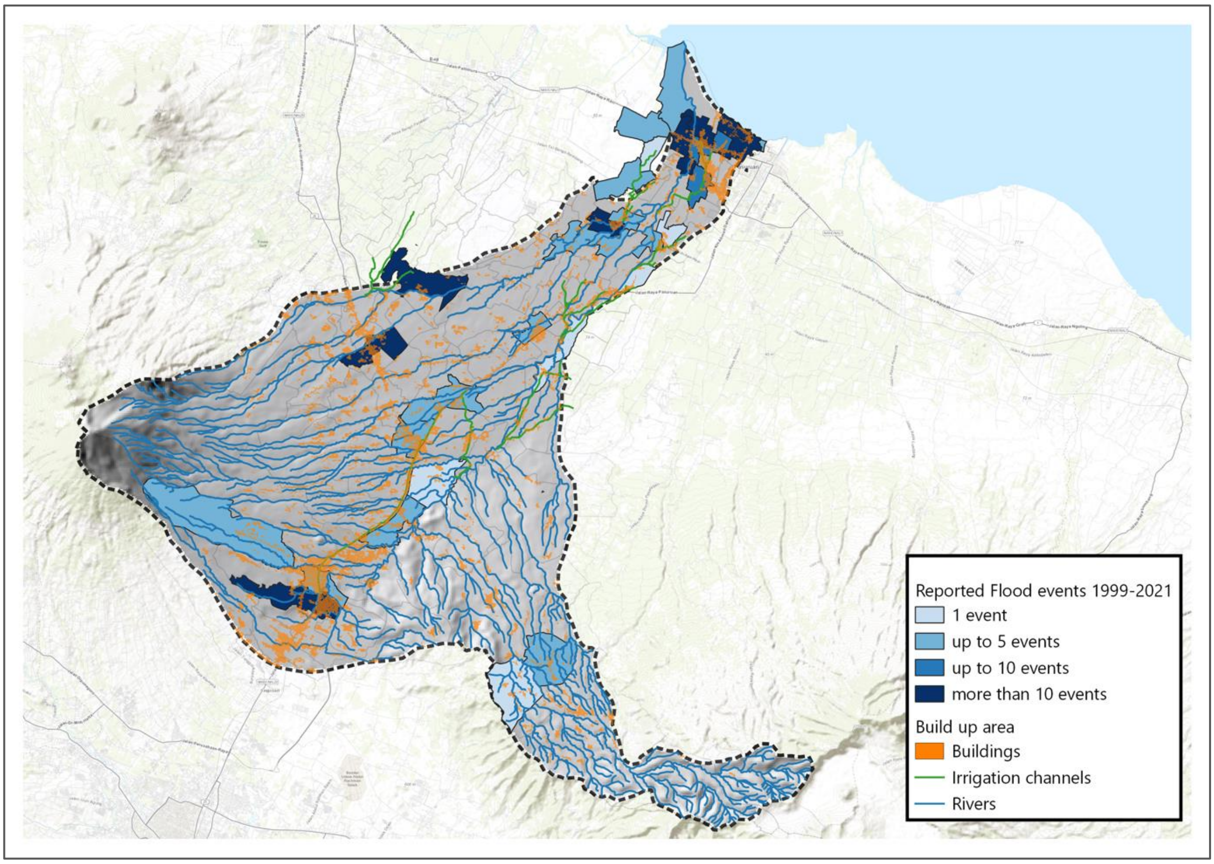


Figure 5.1. Reported flood events between 1999 and 2021 (source: BNPB DIBI-database 1999-2015, BPBD 2016-2021).

Most often high precipitation is mentioned as the main cause of flooding, often in combination with high water levels in the river. A few times high tides were mentioned as an additional cause; indicating that high spring tide may lead to backwater effects in the downstream reach and may reduce retention capacities in the drainage system in and around the Kraton subdistrict.

Residents indicated that flooding in the downstream reach used to be frequent and quite extensive although shallow (maximum inundation levels about 20-30cm) and never lasted more than a few hours (mostly less than 3-4hrs); another indication that tidal influence affects flooding in this area. Since the very recent completion of the upgrade of the embankments, flooding in this area has not re-occurred.

It was reported that in the upstream region, on the slopes of the Bromo mountain, in recent years landslides have occurred in the rainy season. In addition, in this region during the dry season droughts have been reported.

5.3 Coastal Flood Hazards

Coastal flooding is currently not considered a main flood mechanism in the Welang catchment. The low-lying coastal zone is the narrow strip between the railway and the sea. While this area is low-lying, it is mainly used for aquaculture near the sea – which requires frequent inundation with seawater – and towards the railway land is mostly irrigated and used for rice cultivation.

Elevations in the catchment are well above MSL. Only in the coastal zone, the fishponds are just above MSL. However, the digital elevation model is inaccurate in these areas[10] and fishponds are normally supposed to be below MSL. Fishponds rely on frequent flushing with fresh seawater and are therefore normally below MSL.

Land subsidence is very limited in the coastal zone and no large urbanization (which may result in more groundwater abstraction) is expected in this zone. Towards the future, it is therefore not expected that coastal flooding will become a significant flood hazard.

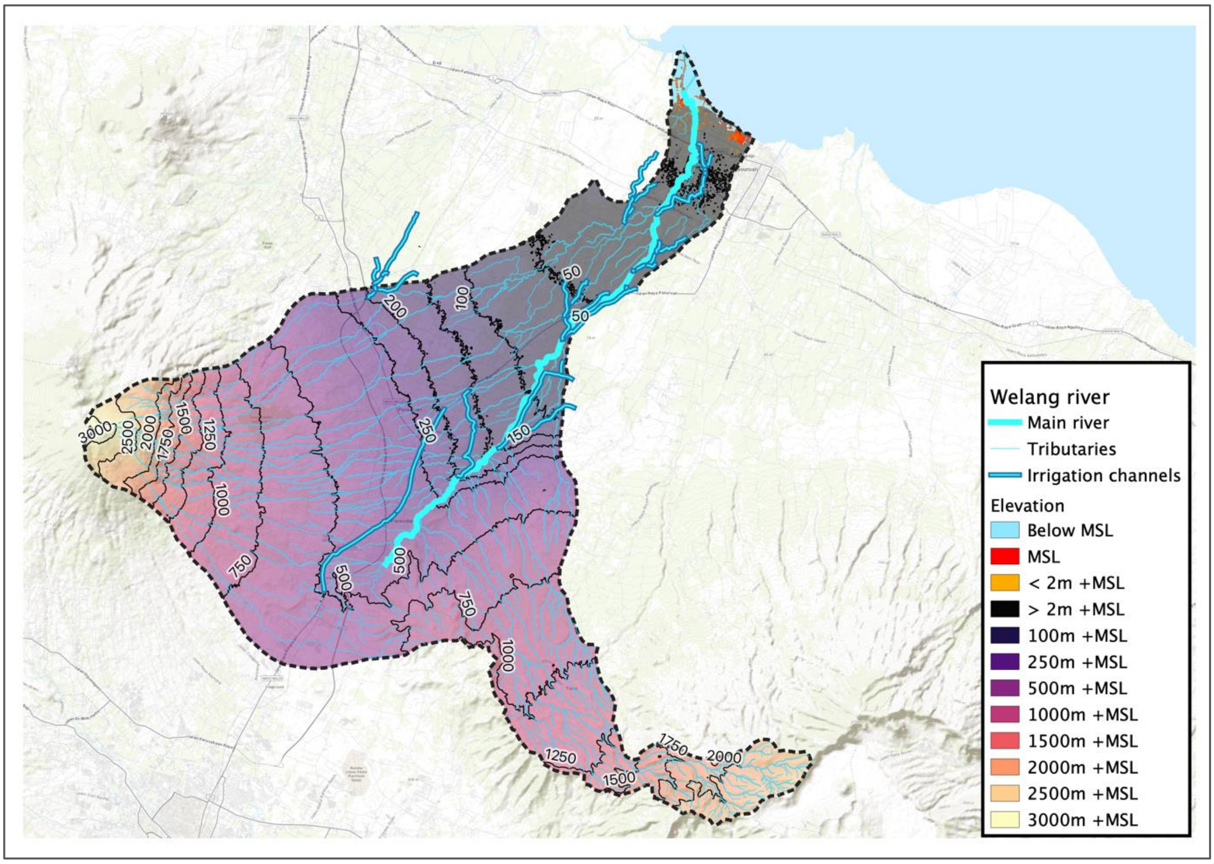


Figure 5.2. Terrain elevations are well above MSL and only the fishponds are within the potential coastal flood zone.

5.4 Fluvial Flood Hazards

Fluvial flood hazards used to be a main cause along the downstream Welang river in Kraton. However, the recent improvements of the embankments[11] have significantly reduced the hazard in Kraton and reportedly no floods have occurred since. Towards the future, under further upstream land conversion, fluvial flood hazards may become a problem once again.

[10] The DEMNAS DEM is derived from the TERRASAR-X products which generally have large data-gaps in the coastal zone because there is no reflection on inundated areas such as fishponds.

[11] Design and construction height of embankments are unknown

5.4.1 Flood hazards

To assess current (2020) fluvial flood hazards, and the historic (2013) and potential future (2029) developments thereof, hydrological and hydraulic models were developed as part of this project (Appendix A). A wflow hydrological model was prepared to assess the effects of the rapidly changing land cover (see sections 2.2 and 4.3) (Figure 5.3 and Figure 5.4) to peak river discharges. Subsequently a hydraulic model (prepared with SOBEK) was used to assess expected peak water levels in the river under discharges with various return periods (1, 10, 25 and 100 years) for recent past (2013), current (2020) and potential future (2029) conditions.

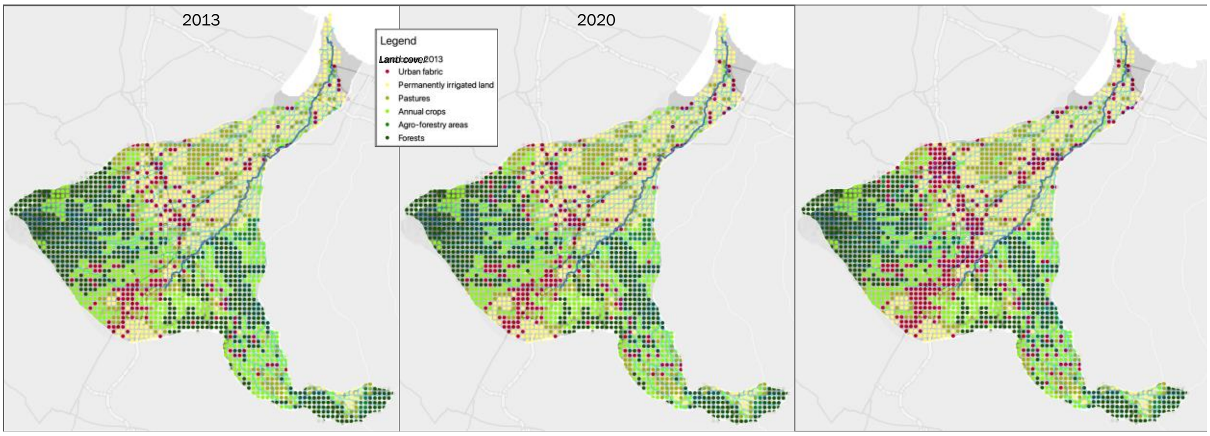


Figure 5.3. Estimated land-cover in 2013, 2020 and 2029 shows significant land conversion in the upper midstream and upstream areas.

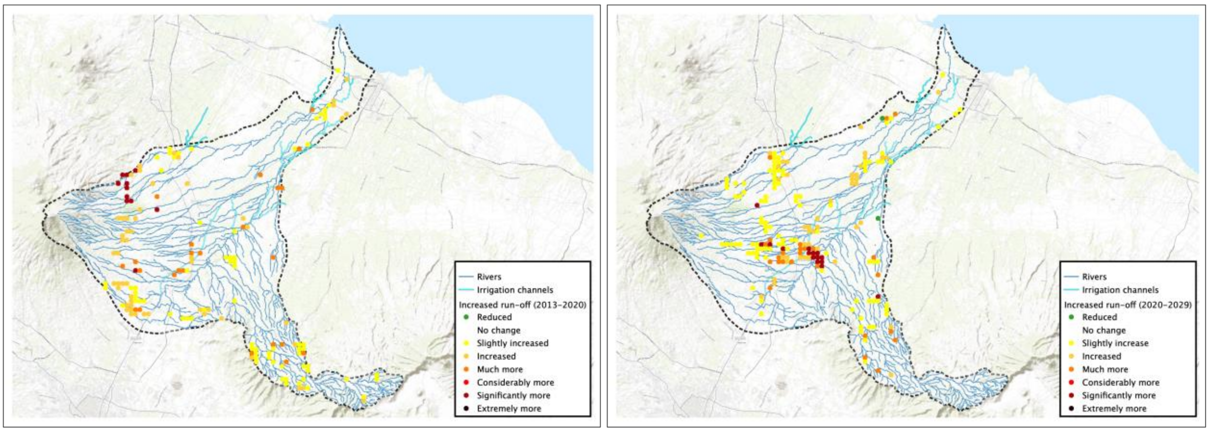


Figure 5.4. Estimated land degradation from 2013 to, 2020 (left) and from 2020 to 2029 (right) shows most land degradation occurs in the upper midstream and upstream areas while they may be perceived as minor changes.

The relative changes can be used to show trends and expectations, although the models have their limitations:

- The base-flow of the rivers is underestimated[12] in the hydrological model and simulated discharge timeseries do not correspond to the observed discharges[13]. However, the values of simulated high discharges do match with the observed values of high discharges. Therefore,

[12] During the dry season, the baseflow in the river originates from the numerous springs and groundwater flows in the catchment. This flow was not included in this version of the model.

[13] Rainfall patterns used in the model have been derived from global datasets in combination with local observations. While the long-term pattern of rainy season and dry season is correctly represented in the models, the actual rainfall pattern seems incorrect. This is a result of the limited number of rainfall stations in the catchment in combination with a significant number of inconsistencies in the rainfall data.

although the timeseries cannot be used to validate historic flood events, the models can be used to estimate peak discharges and compare the probability of high discharges due to various (environmental) changes in the catchment.

- Vertical referencing of water levels, tidal levels and cross-sections seem to be inconsistent, which results in significant uncertainties with regards to the simulated absolute water levels in the hydraulic model. Adding to these uncertainties is the limited number of observations of water levels at peak discharges (available rating curves are based on observations under normal discharges only), which specifically results in uncertainty of absolute high-water levels. Therefore, simulated water levels can only be relatively compared.

The wflow simulations show that peak discharges have significantly increased since 2013 and are expected to further increase towards 2029 due to rapidly changing land cover. Peak discharges have already increased with about 10% since 2013 (green line in Figure 5.5) and are expected to increase another 10% towards 2029 (dark blue line in Figure 5.5).

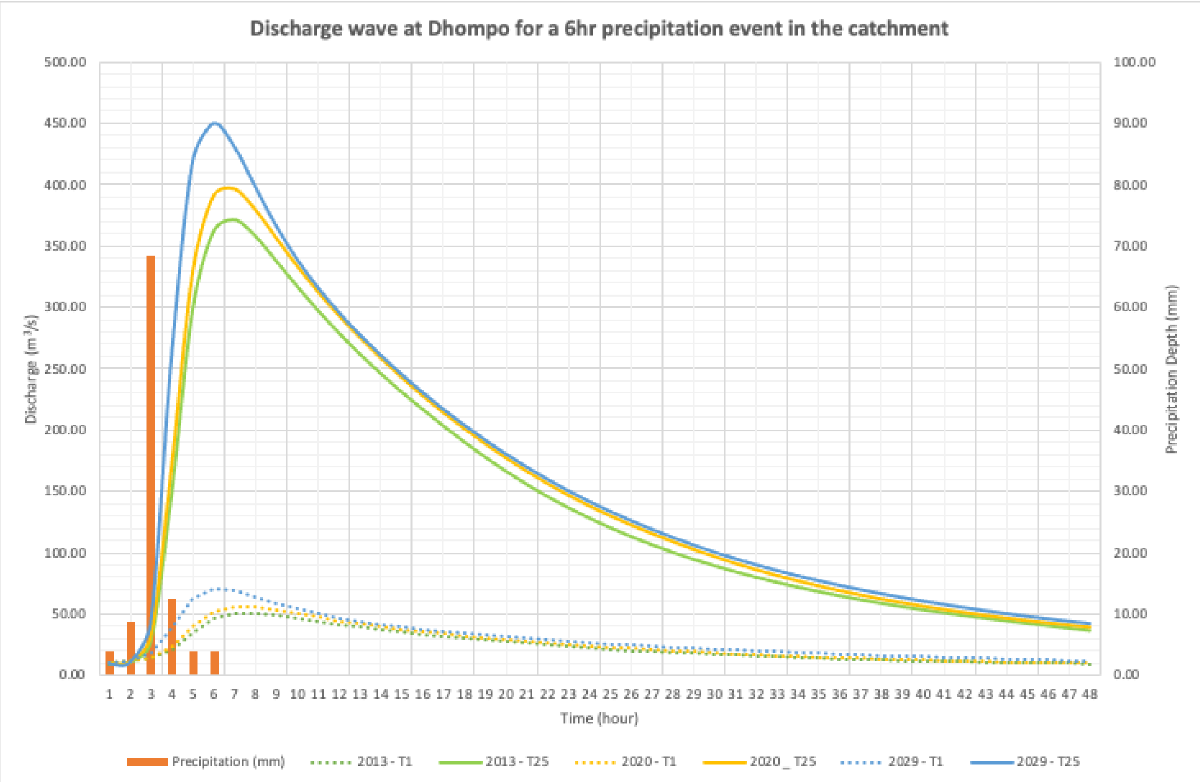


Figure 5.5. Discharge waves have significantly changed due to upstream land-conversion.

These higher peak discharges (from the same hypothetical rainfall) translate into higher peak water levels. From 2013 to 2020 peak water levels have increased with about 10cm in the midstream reach, and with up to 20cm in the downstream reach (green line in Figure 5.6). Towards 2029 water levels are expected to increase with an additional 25-50cm (dark blue line in Figure 5.6).

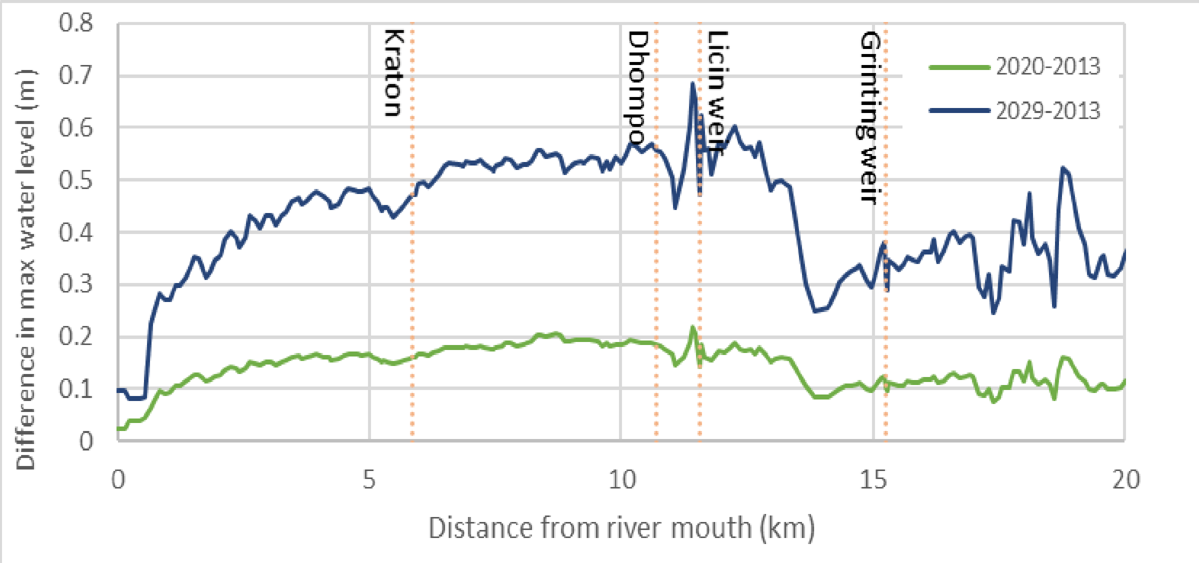


Figure 5.6. Relative changes to water levels of the Welang river show significant water level increases.

While it is unknown what the current embankment levels along the lower reach of the Welang river are and how much freeboard is available, Figure 5.6 shows that the region between the Licin weir and the provincial road in Kraton is the area which has seen and will see the largest increase in water levels.

Between the Licin weir and Dhompo the embankment is not strengthened yet. Peak water levels are already near the terrain and may soon become higher than the natural embankments. The embankments at Kraton have been strengthened at the start of 2021, however, it is unknown what design levels have been assumed and therefore it is unknown when overtopping may be expected again. If the remaining freeboard is currently less than about 40cm, then overtopping may be expected again before 2029, unless additional measures are implemented.

5.4.2 Causes of Fluvial Flooding

In Table 5.2 an overview is provided of the identified drivers and pressures that have led to the existing fluvial flood hazards. Without adjustment of the enabling mechanisms, it is expected that the drivers and pressures will continue.

Enabling mechanism	location of driver: downstream	midstream	upstream	Physical environment: Driver	Pressure	State
most remaining (production) forest is unprotected			x	deforestation leads to soil erosion and higher sediment load	downstream sedimentation leads to reduced discharge capacity	Fluvial flooding
no regulations to limit soil exposure at construction sites and on agricultural land			x	inadequate land management leads to soil erosion and higher sediment load	downstream sedimentation leads to reduced discharge capacity	Fluvial flooding
spatial plan does not have enough protection mechanisms for vulnerable land	x	x		urbanisation leads to increased run-off	higher peak discharge leads to higher maximum water level	Fluvial flooding
spatial plan does not have regulations to limit impact of urbanization	x	x		urbanisation leads to increased run-off	higher peak discharge leads to higher maximum water level	Fluvial flooding
most remaining forest is unprotected			x	deforestation leads to increased run-off	higher peak discharge leads to higher maximum water level	Fluvial flooding
under prevailing regulations open water is not protected		x	x	reduced retention capacity	higher peak discharge leads to higher maximum water level	Fluvial flooding
spatial plan does recognises too narrow width of river	x			encroachment	Reduced discharged capacity leads to higher water level	Fluvial flooding
unclear land ownership status	x			encroachment	Reduced discharged capacity leads to higher water level	Fluvial flooding
spatial plan allows land conversion in irrigation schemes	x	x		urbanisation of irrigated agricultural land	Reduced water demand leads to high flow of water through irrigation channels	Fluvial flooding
spatial plan does recognises too narrow width of river		x		encroachment	reduced protection	Fluvial flooding
unclear land ownership status		x		encroachment	reduced protection	Fluvial flooding

Table 5.2. Overview of identified drivers, pressures and enabling mechanisms for fluvial flood hazards and risks.

The main identified drivers are land conversion (deforestation and urbanisation) and encroachment of the rivers. These developments lead to higher run-off and more soil erosion. Higher run-off has a direct impact on the peak discharge of the river, while soil erosion (which leads to sedimentation in the downstream reach) and encroachment results in reduced discharge capacities of the river.

Effect of land cover changes

Recently in the upper-midstream and upstream regions of the catchment, land cover has changed significantly. Forest and agricultural land have been converted to make space for urbanisation and industrialization and for tourist accommodation. Consequently, the number of buildings and roads has increased in these areas.

This has resulted in increased run-off in these areas. Increased run-off leads to increased peak river discharges (Figure 5.5) and higher peak water levels (Figure 5.6).

In terms of increased peak run-off, these have been most severe in the upper Welang river at Lawang (+8.2%) and in the Kali Sumber Pinang at Sidogiri (+6.9%), followed by the confluence point at Purworedjo (+3.0%).

While the increased run-off originates in the upstream region, the combined increased peak discharge mostly affects the areas in the downstream

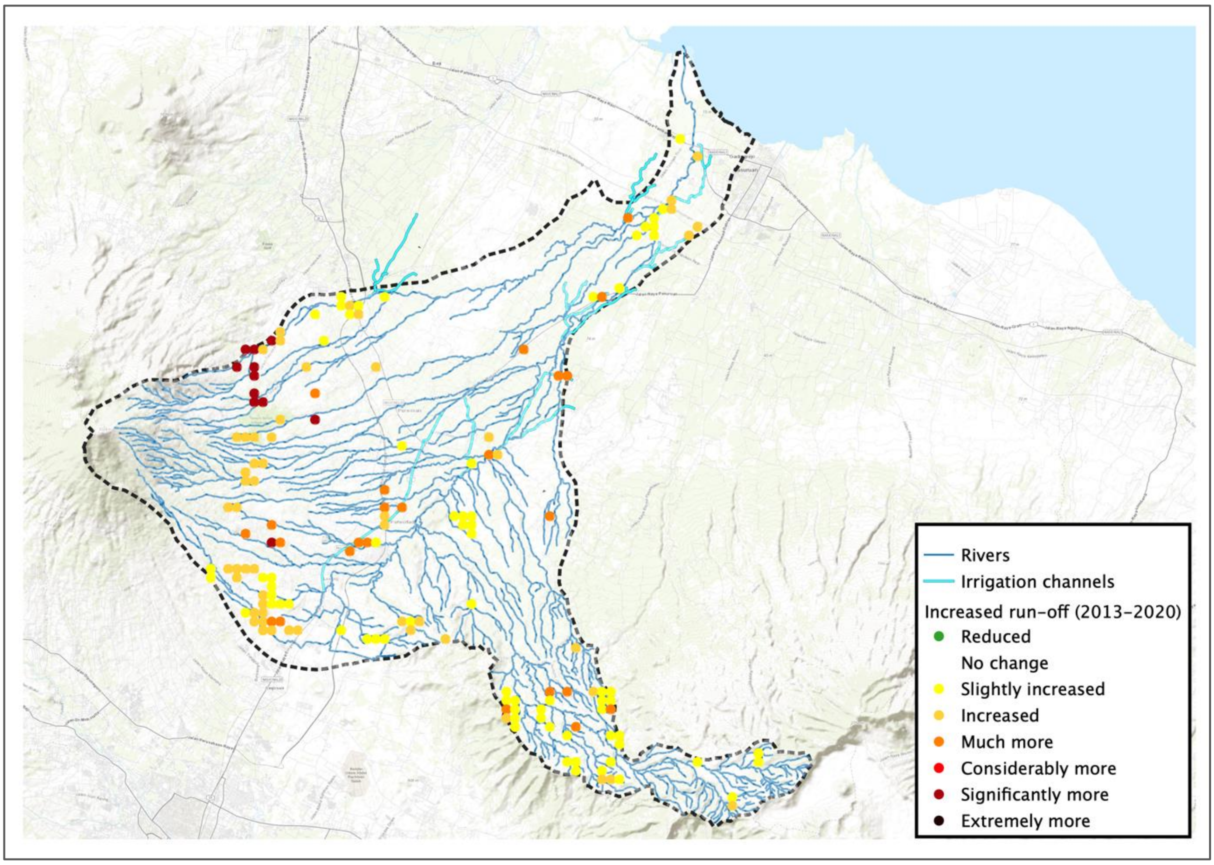


Figure 5.7. Land cover changes between 2013 and 2020 have resulted in increased run-off from upper-midstream and lower-upstream regions.

Table 5.3. Estimated past (2013), current (2020) and potential future (2029) peak river discharges (in m^3/s) at different locations along the Welang river.

	2013	2020	2029	2020/ 2013	2029/ 2020	2029/ 2013
Lawang	123.3	133.4	147.5	108%	111%	120%
Purwosari	205.1	221.4	261.0	108%	118%	127%
Grinting	265.4	284.4	313.9	107%	110%	118%
Dhompo	370.7	396.5	449.7	107%	113%	121%
Rivermouth	382.1	412.0	454.1	108%	110%	119%
Sumberpinang	101.5	108.6	130.4	107%	120%	128%

It is estimated that the changes in land cover in the past decade have resulted in peak discharges which are now about 10% higher (Figure 5.5) compared to 2013 conditions (Table 5.3). Observed discharges in 2006 and 2013 confirm that this trend has been going on for some time.

Considering the various existing government plans and the economic development trends, it is expected that in the next 10 years, land conversion in these areas will continue. This will lead to even higher peak discharges (Table 5.3). It is estimated that peak discharges of about 300m^3/s, which used to have a return period of about 12-15years in 2013, will likely occur on average once every 7 years towards 2029 (Figure 5.8).

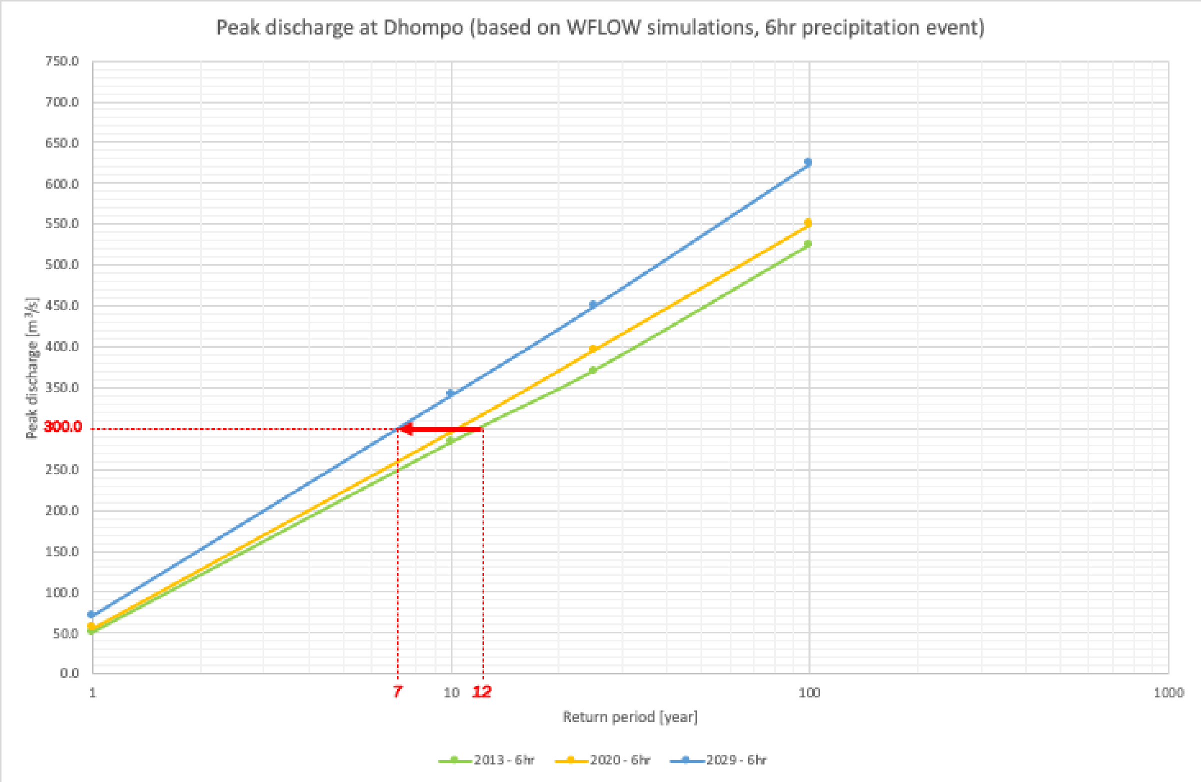


Figure 5.8. Return periods of peak discharges at Dhompo monitoring station for past (2013), current (2020) and future (2029) land cover conditions.

Figure 5.6 shows that flooding in the downstream region (up until at least the Licin weir) may occur frequently again if land conversion continues and no preventive measures are implemented.

Effect of encroachment and soil erosion

Land cover changes in the upper midstream and upstream regions have occurred in areas with vulnerable soils (see Figure 2.6). This has led to more soil erosion upstream, which washes off and ends up in the river. High sediment loads in the river are transported downstream and settle once river currents have reduced.

Most sediment is deposited near the river mouth where it increases bed levels and thus reduces the discharge capacity (see Figure 5.9). While water levels close to the sea are sea-dominated, further upstream near Kraton backwater effects, caused by the reduced discharge capacity, lead to higher water levels.

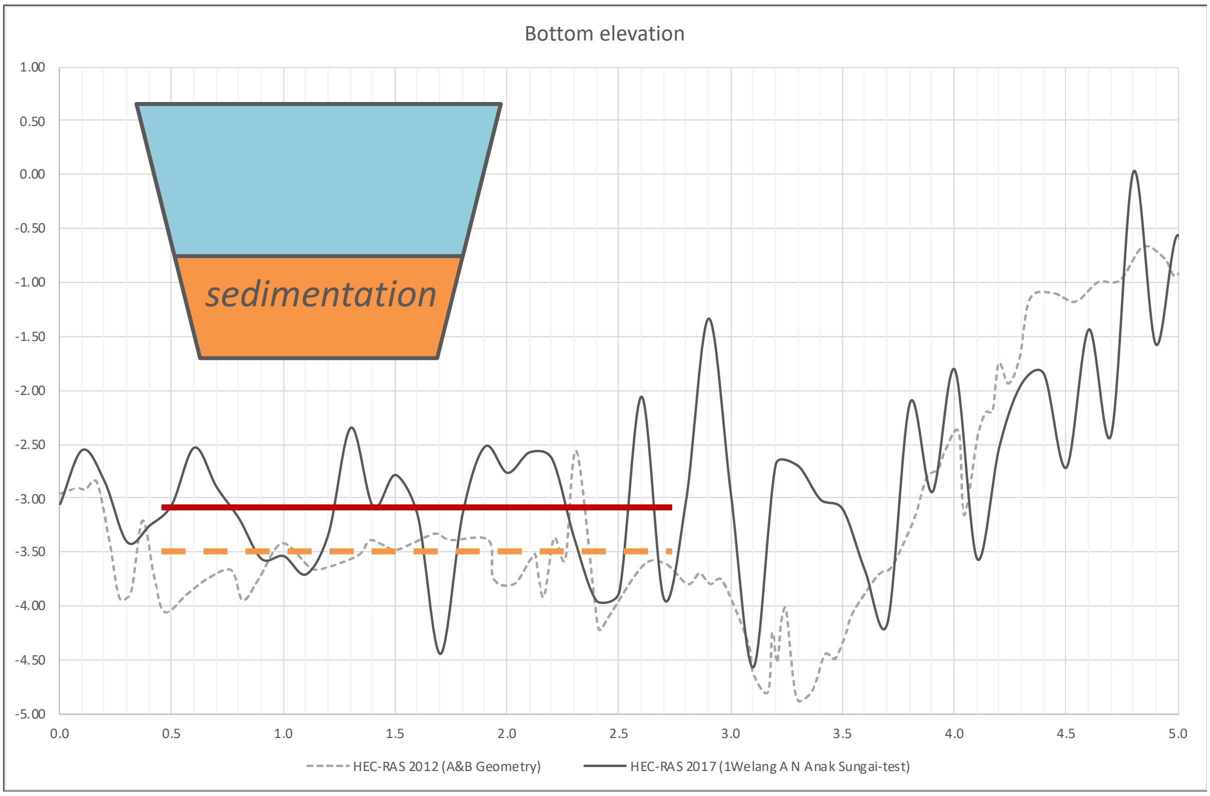


Figure 5.9. Upstream erosion leads to downstream sedimentation and increased bed levels in the river as is visible from the surveys in 2012 and 2017.

In addition, the river width between the toll-road and the railway bridge has been fixed in recent years. Reportedly, the river used to have a wider profile. But with the development of the area, roads have been built along the river and were subsequently widened to the expense of the river. In addition, recently embankments have been erected. All these developments have likely slowly encroached the river and resulted in a slightly narrower river profile in and around the Kraton area.

These two developments (sedimentation and encroachment) have resulted in higher water levels in the Kraton area and may have backwater effects further upstream towards Dhompo[14].

It is expected that sediment loads will remain high towards the future, considering the existing government plans and economic developments in the catchment. This will result in ongoing sedimentation near the river mouth and hence will keep water levels in and around Kraton high.

5.4.3 Conclusion

The recent increases in fluvial flooding in the Kraton area are caused by upstream land conversion and have been exacerbated by downstream sedimentation and encroachment in the Kraton area itself. The recent heightening of the embankments in Kraton, have likely significantly reduced the current likelihood of fluvial flooding in Kraton.

It is expected that land conversion in the upper midstream and upstream areas will continue, considering the current socio-economic developments in the catchment and the various (spatial) development plans of the involved governments and agencies. If not mitigated, this will result in a further increase of peak discharges in the river. In addition, this will lead to continuous sedimentation in the downstream reach of the river, which leads to further heightening of water levels downstream from the Griting weir and

[14] Note that this backwater effect may have changed the relationship between discharges and water levels.

especially in and around the Kraton area. It is therefore expected that in the near future the likelihood of fluvial flooding will increase again, with the areas around the Licin weir and between Dhompo and the provincial road likely to see overtopping.

5.5 Pluvial Flood Hazards

Pluvial flood events are under-recognized in the Welang catchment. In general, pluvial flooding only occurs during high precipitation and only results in floods with limited depth. The impression these type of flood events leave behind is not dramatic.

However, pluvial flooding is very common in Indonesia, and in the Welang catchment as well. Pluvial flooding mostly shows as local ponding and results in heavy traffic and local inundation of houses and shops. Depending on river water levels, pluvial floods may only last a few hours at most. However, with climate change, more frequent and more intense precipitation events might be expected[15] which may lead to more pluvial flooding.

In the Welang catchment, the areas suspected of being affected by pluvial flooding are the urbanized villages in the midstream and downstream region (Figure 5.10). Especially the areas with higher population densities, such as Lawang, Purwodadi, Purworedjo and Kraton, are frequently affected by pluvial flooding. During high intensity precipitation traffic in these regions comes to a standstill because the roads are inundated and function as rivers. In the downstream reach, pluvial flooding may be exaggerated when coinciding with peak river discharges.

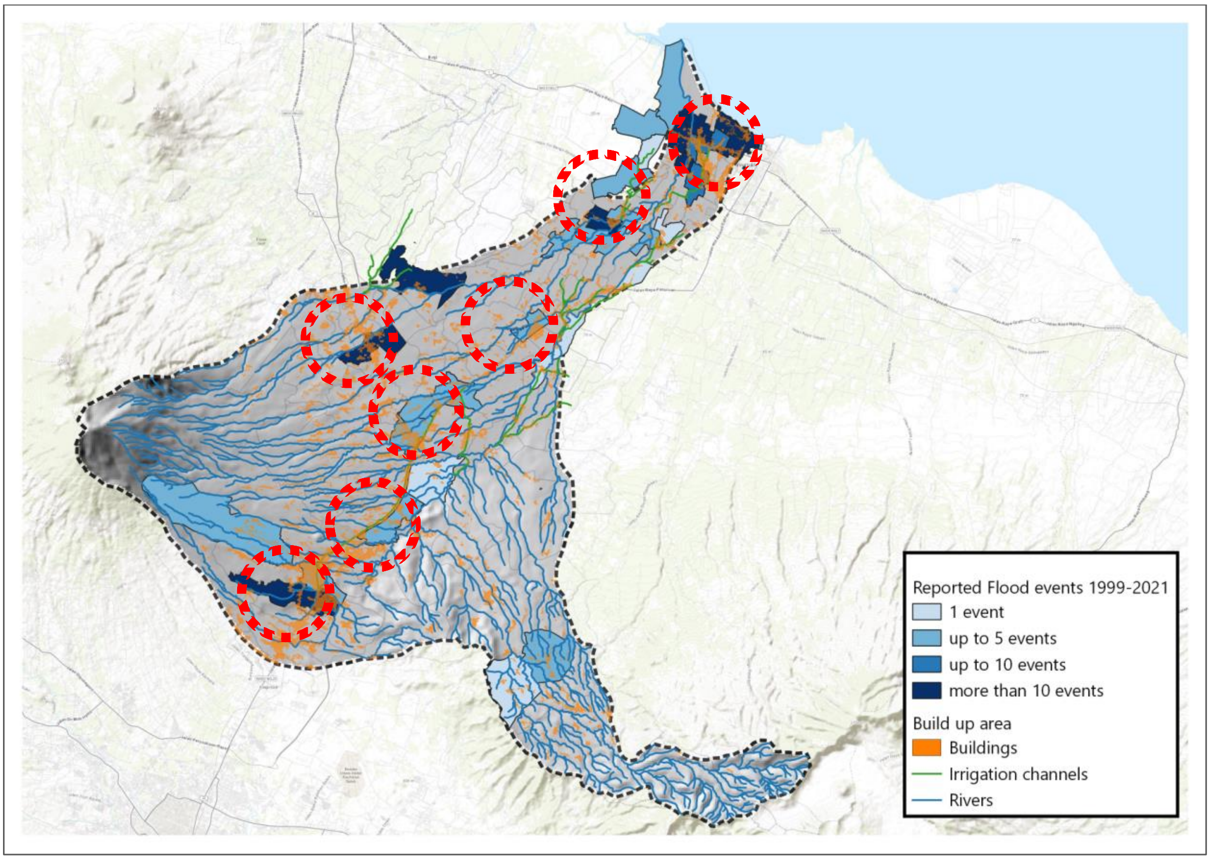


Figure 5.10. Pluvial flooding suspected in urbanized areas.

[15] Climate change effects in terms of changes in rainfall (patterns, volumes and intensities) are highly uncertain and the climate models are not in agreement

5.5.1 Causes of Pluvial Flooding

In Table 5.4 and overview is provided of the identified drivers and pressures that have led to the existing pluvial flood hazards. It is expected that the drivers and pressures will continue if the enabling mechanisms are not adjusted.

	location of driver			Physical environment		
Enabling mechanism	downstream	midstream	upstream	Driver	Pressure	State
spatial plan does not protect existing open water	x			urbanisation of open water	reduced retention capacity	Pluvial flooding
insufficient investment in (urban) drainage	x	x		irrigation channels are also used for drainage of stormwater	higher water levels in irrigation channels during rainfall	Pluvial flooding
insufficient investment in waste water collection and transport	x	x		irrigation channels are also used for drainage of waste water	higher water levels in irrigation channels	Pluvial flooding
insufficient investment in (urban) drainage	x	x		absence of urban drainage	rainwater is forced to flow overland	Pluvial flooding
innadequante and insufficient collection of solid waste	x	x		accumulation of uncollected waste in urban drains	rainwater is forced to flow overland	Pluvial flooding
inadequate and insufficient regular cleaning of roads	x	x		accumulation of sediment in urban drains	rainwater is forced to flow overland	Pluvial flooding
inadequate design of urban drainage system	x	x		absence of an outlet of the urban drainage system	rainwater is forced to flow overland	Pluvial flooding

Table 5.4. Overview of identified drivers, pressures and enabling mechanisms for pluvial flood hazards and risks.

The identified main drivers for pluvial flooding are the absence of designated stormwater drainage systems and the accumulation of uncollected solid waste. The absence of designated stormwater drainage systems forces excess rainwater to find alternative pathways to flow to rivers and streams. Where stormwater does manage to flow into channels within the urban areas, the high amount of accumulated solid waste significantly reduces discharge capacities of these channels, leading to higher water levels and more overland flow.

Designated stormwater systems

Within the catchment, designated stormwater drainage systems are not available. While in the catchment and specifically in the Kraton area, roadside drains have been constructed, these channels are connected to the irrigation channels. Throughout the catchment irrigation channels are also used to collect and transport stormwater and roadside drains are connected to the irrigation system.

Throughout the catchment, the primary and secondary irrigation channels double as stormwater drainage channels. Irrigation channels are designed to bring-in a constant flow of water to allow year-round farming. These systems have a large inlet channel in the upstream part of the irrigation scheme, and then slowly the channels divide and become smaller and narrower and mostly end in agricultural land downstream. This means that further downstream in the irrigation systems, discharge capacities reduce significantly.

The discharge capacity in the existing irrigation/drainage network decreases further downstream into the network (Figure 5.11). In irrigation systems water levels are often close to or above terrain level and so storage capacity (before channels overtop) is very limited. This is amplified by accumulation of sediment and solid waste, which further reduces storage and discharge capacities. This means that at locations where under normal conditions water levels are close to terrain levels (such as along Jl. Gatot Subroto in Pasuruan), flooding is a frequent occurrence during rainfall events,

Figure 5.11. Irrigation channels are also used to discharge stormwater, although discharge capacities reduce due to combined decreased channel width/depth and accumulated solid waste trapped near outflows (gates)

Drainage systems are designed to collect stormwater from an area in small channels and then bring it to bigger channels until it can be discharged into a river or stream downstream of the drainage catchment. In drainage systems, discharge capacities increase further downstream into the system.

Most reported flood events in the catchment occur along the primary irrigation channels in the downstream and midstream regions (Figure 5.12).

It is expected that urban areas will further develop and urbanize, considering the socio-economic developments. At the same time, the government budgets from recent years suggest that little budget is allocated for investment in new stormwater drainage systems. It is therefore expected that in the coming years pluvial flooding will become more frequent, more widespread, and more extensive, although it will not per se result in deeper floods.

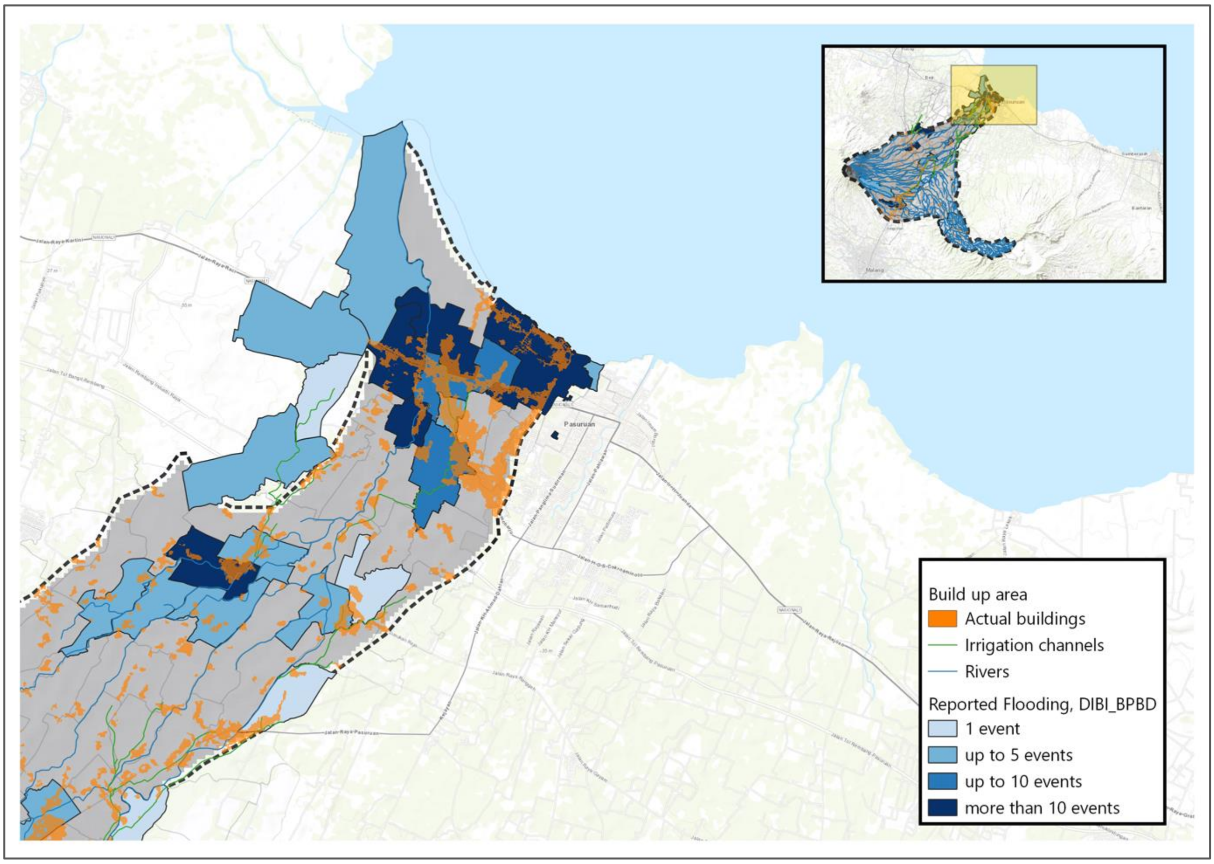


Figure 5.12. Reported flood events in and around the Kraton area have mainly occurred along the irrigation channels.

Accumulation of solid waste

Throughout the catchment solid waste remains largely uncollected. While in the urban areas collection is easier and therefore more likely, large amounts of solid waste are observed along the streets and in the various channels and waterways in the urban areas. Especially around commercial centres (e.g., traditional markets) large quantities of solid waste are observed.

During rainfall events, waste washes off and flows into drains and channels. Near bottlenecks (e.g., around sluice gates) waste accumulates and significantly reduces the discharge capacity of the drains and channels (Figure 5.13). This will result in higher water levels in the connected drains and will therefore result in flooding further upstream in the drainage catchment.

Figure 5.13. Solid waste accumulates in channels and drains.

Towards the future it is expected that solid waste collection in the urban areas will improve, and that the accumulation of solid waste will reduce. There are multiple initiatives at regional and national level to significantly increase the collection rates of solid waste. The national government has the ambition to increase solid waste collection to 70% in Indonesia in 2024, currently it stands at just over 40%.

5.5.2 Conclusion

The recent rapid urbanisation and economic development has not been accompanied by investments in new urban drainage systems; another sign that government plans are not aligned. As a result, irrigation channels now double as drainage channels. In combination with high accumulation of uncollected solid waste (resulting from low collection rates), this increasingly leads to pluvial flooding in the urban centres of Lawang, Purwodadi, Purworedjo and Kraton.

Considering the socio-economic developments, plans and available budgets, it is expected that pluvial flooding may further increase into the near future. Collection of solid waste is expected to improve, and that may result in a reduction of accumulated solid waste in the various waterways throughout the catchment. However, the continuing urbanisation and the lack of funds to develop a designated urban drainage system, it is expected that extent of pluvial flooding will increase.

5.6 Conclusion

Of the three types of flood hazards, only fluvial and pluvial flooding occurs. It is also not expected that coastal flooding will become a significant hazard into the future.

Fluvial flooding is the most significant and likely results in the biggest damages (although this could not be quantified) and affects Kraton, Sidogiri and the areas around Licin and Griting weirs. Irrigation channels may also contribute to fluvial flooding, although this could not be quantified, and may affect Lawang, Purworedjo and the Pasuruan/Kraton areas.

Although pluvial floods could not be quantified, it is suspected that it is a widespread problem and affects all urbanized areas: Lawang, Purwodadi, Purworedjo, Sukoredjo, Wonoredjo, Sidogiri, and Pasuruan/Kraton.

Fluvial flooding may result in the most significant direct damages, and pluvial floods are expected to cause the most nuisance; traffic frequently comes to a standstill on main roads and commercial centres in the urbanized areas. In addition, it was shown that there seems to be a correlation between the number of cases of water-borne diseases (such as diarrhoea) and the frequency of reported flood events, and floods may contribute to the poverty-trap as it seems there is some correlation between the poverty rate and the flood frequency. Floods therefore also have a large indirect impact that should be taken into consideration and deserves more attention.

While fluvial floods affect the downstream and lower midstream reaches, the drivers that lead to higher water levels in this area are found elsewhere. Recent rapid urbanization and land-cover changes associated with agricultural and tourism developments in the upper midstream and upstream reaches (the areas which receive most rainfall), have resulted in increased run-off and hence significantly higher peak discharges. These spatial developments have also resulted in more exposed soils in the vulnerable areas along the mountain slopes and have therefore led to more soil erosion. Sediments settle in the river mouth and lead to reduced discharge capacity in the downstream reach of the river.

Although pluvial floods could not be quantified and the extent remains unknown for now, pluvial flooding is expected to be widespread. The drivers for pluvial flooding are mostly found in the large number of discontinuities in the de facto drainage network. In addition, drains are often blocked – including entrances to drains and drainage outlets to rivers and streams – with accumulated sediment and uncollected solid waste.

It is expected that both fluvial and pluvial flooding will increase into the future, and existing regulations and planning practices and government budgets are not sufficient to guide developments and investments to avoid this trend. The new spatial plan allows for significant development (urbanization and deforestation) in the upper-midstream and upstream reaches of the catchment and is therefore expected to accommodate developments that result in higher run-off and higher discharges and more flooding into the future. In addition, sectoral plans are not integrated and anticipating and the large numbers of (in)direct stakeholders – which are not all part of the TKPSDA team – leads to inefficiencies in planning and coordination to which the high turn-over of staff and leadership within government agencies, does not contribute. Within the regulations there are several inconsistencies in required protection levels and the urban drainage system is not as such recognized.

Other related hazards, such as landslides and droughts are expected to increase when the existing planning practices remain in place. Recently landslides and droughts have been reported in the upstream reach and the locations largely coincide with areas that have seen changes in landcover. Expected future spatial developments may therefore lead to more landslide and drought events. And since the baseflow of the river is likely strongly influenced by groundwater, any changes that result in a reduction of infiltration – note that land cover changes result in higher run-off – are expected to affect the baseflow of the river during the dry season.

6 Groundwater Resources

6.1 Introduction

As described in Chapter 5, the recent changes in land cover have resulted in a significant increase in run-off especially in the upper midstream and upstream reaches of the catchment. Since total annual precipitation has remained constant (see section 2.3), this increase in run-off must be balanced by a reduction in infiltration. Reduced infiltration may lead to reduced groundwater heads and reduced discharges at springs.

In this chapter the effects of past changes and expected future changes in land cover and groundwater demand associated with economic development, are evaluated.

6.2 Recent Drought Events

Recent drought events have been reported in the Welang catchment and the wider Pasuruan regency. These events are registered by BPBD in the national DIBI database.

In total 3 recent[16] drought events have been recorded in the DIBI database:

1. July 2008, unknown which areas were affected.
2. June 2012, Kecematan Gempol and Kecematan Lumbang (both around the border between upstream and midstream regions).
3. September 2013, Kec. Lekok, Kec. Puspo, Kec. Lumbang, Kec. Grati and Kec. Winongan (all kecematan around the border between upstream and midstream regions).

During all drought events reduced discharges from springs was reported. To mitigate the effects of the droughts, water trucks were mobilized to distribute water during each of the reported drought events.

In general, drought events tend to occur into the dry season (months June to October) and tend to last several weeks to months. The drought affected areas are near the foot of the mountains at the border between the upstream and midstream area and coincide with the areas where most springs are found. Not surprisingly, groundwater heads are above surface level around the areas where springs can be found, in the transition area from upstream to midstream, at the foot of the mountains (Figure 6.1).

[16] Note that available data from the DIBI database only covers the period 1999-2017

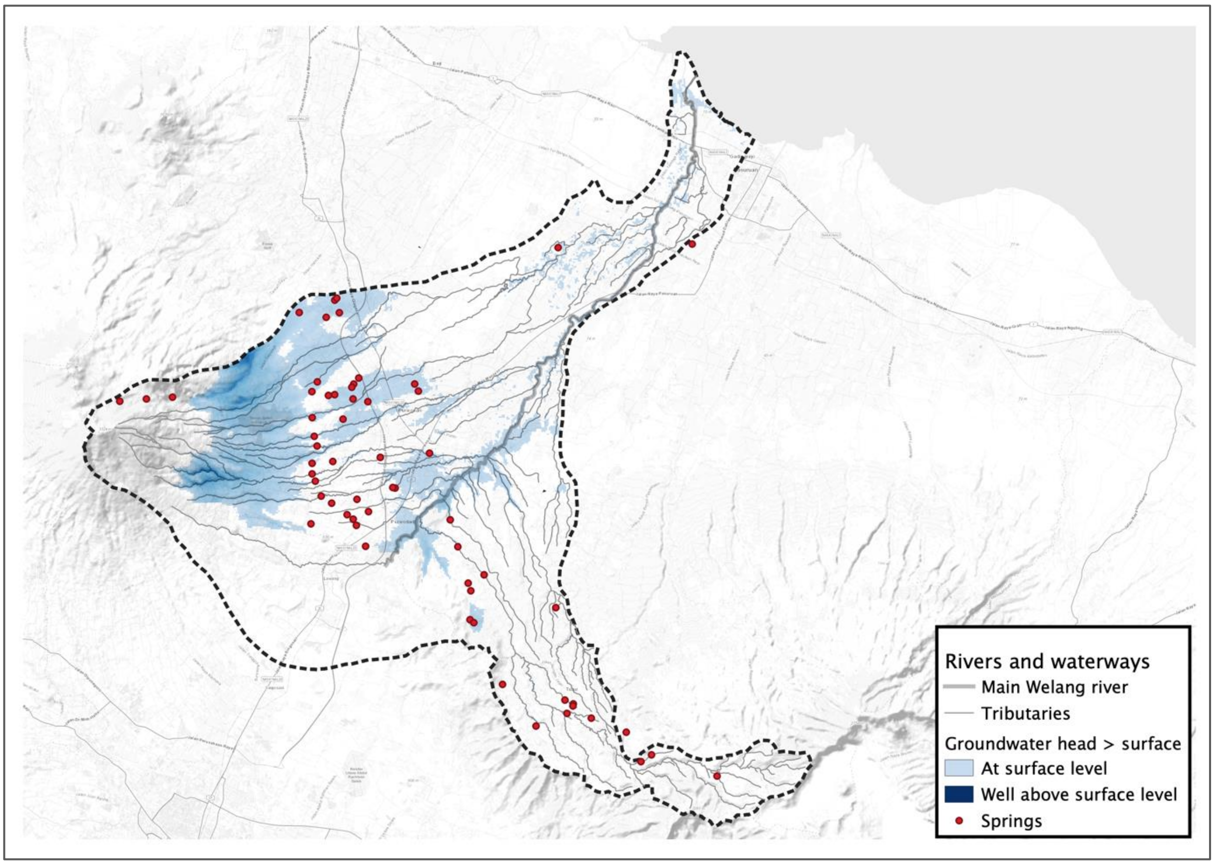


Figure 6.1. Springs are found in areas where groundwater heads are above surface level and mostly in the transition zone from upstream to midstream. Note that the model and digital elevation data are too coarse to identify springs along the steep Bromo slopes around Tutur.

Note that no droughts were reported in the upper upstream reaches, where recently large land conversions have been observed and where land was converted to for agricultural purposes. It is reported that the area is well-known for using groundwater-pumps to provide water for agriculture.

Figure 6.2. Sprinklers installed to water crops on steep slopes of the Bromo mountain (upstream reach)

6.3 Groundwater Levels and Recharge

To assess the impacts of land cover changes and economic developments on groundwater recharge and groundwater levels, a groundwater model was developed. The groundwater model (ModFlow) was coupled with the hydrological model (WFLOW) and uses the same hydrological boundary conditions as are used for the hydrological assessment (see section 5.4). A complete description of the model is provided in Appendix B.

To assess changes in groundwater heads and recharges, a representative precipitation timeseries was created. This timeseries was used to estimate groundwater heads and recharge for the 2013, 2020 and 2029 land cover conditions.

In addition, effects of increased groundwater abstractions for urban (residential and industrial) purposes associated with increased urban areas as well as potential changes in the duration of the dry season, were evaluated. Note that (deep) groundwater abstraction for agricultural purposes have not been included and may further decrease groundwater heads in the upstream reach of the catchment.

Available geological data and data on groundwater levels is limited, especially in the upstream reaches. The individual model results for groundwater heads are rough indications only, although trends are deemed reliable. Trends have been verified against available observation data of e.g., the Umbulan spring and observed groundwater heads in the midstream reach.

It was found that groundwater heads are lowest in the months October-November (Figure 6.3). This coincides with the transition from the dry-season to the rainy season. Groundwater levels are highest around February-April, at the peak of the rainy season.

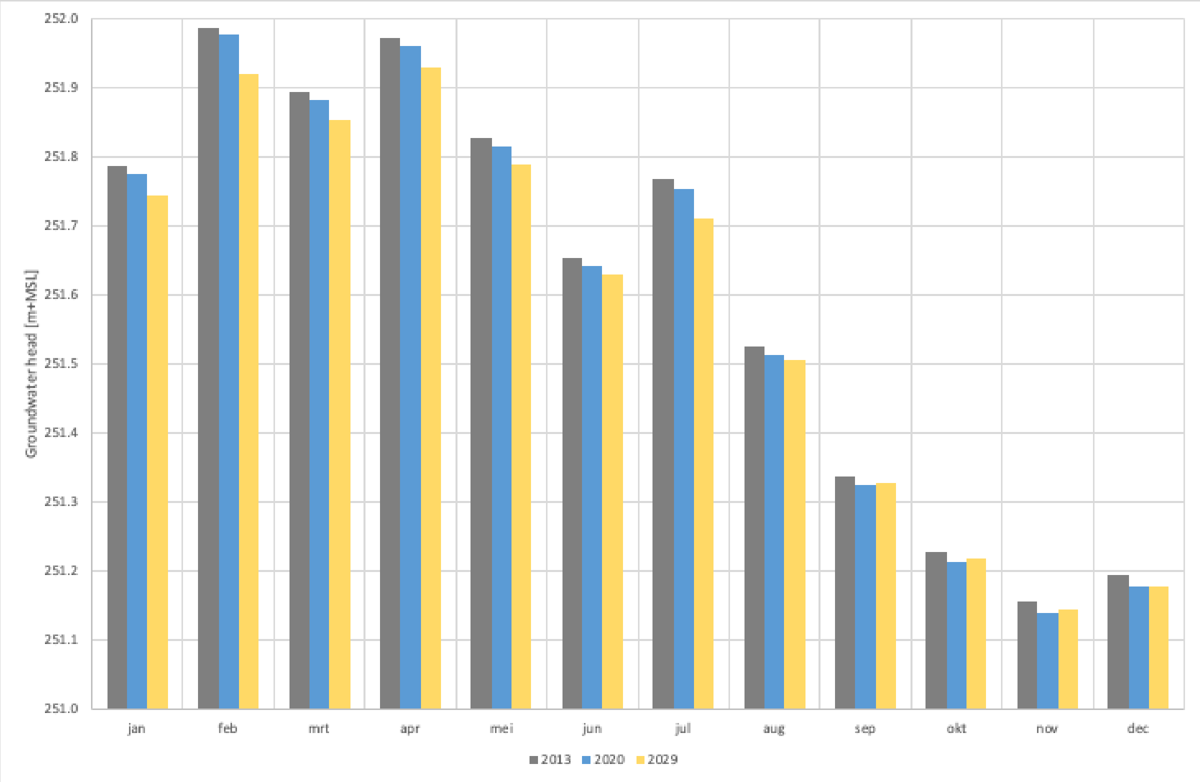


Figure 6.3. Groundwater levels fluctuate with the seasons and are decreasing due to land cover changes (example around Tutur extracted from simulation results)

It was found that groundwater heads have significantly lowered (up to about 20-30m) in the upstream reach from 2013 to 2020, especially at higher elevations. Changes in groundwater heads in the midstream reach are less pronounced (Figure 6.3). Most notable, it was found that groundwater heads in the area where cartesian springs are present, have lowered. This is an indication that spring discharges in this region may have started to decrease. This is corroborated by the reported reduction of spring discharges.

When accounting for potential reduced precipitation and increased groundwater abstraction rates for urban needs (not accounting for groundwater abstraction for agriculture) groundwater heads in the upper midstream are slightly lower again.

Looking at where changes in groundwater recharge are most pronounced, it becomes clear that there is a clear correlation with areas where land cover changes occur.

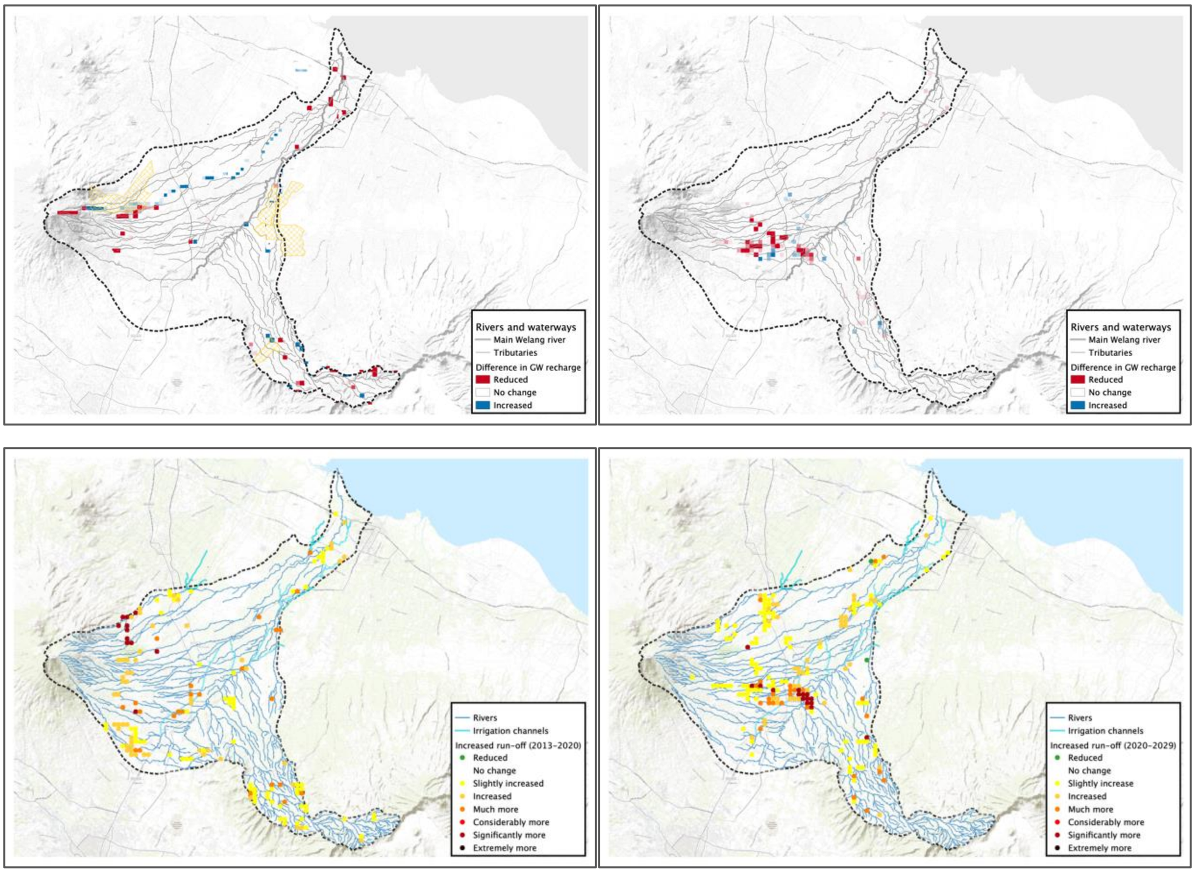


Figure 6.4. Reduced recharge due to land cover changes in the areas. Note that along rivers groundwater recharge increases, this is a consequence of reducing groundwater heads (figures based on simulation results)

6.4 Conclusion

It is concluded that recent changes in land cover in the upstream areas have affected groundwater recharge and groundwater levels in the upstream and upper midstream reach in the Welang catchment and the wider Pasuruan groundwater catchment. Reductions in recharge rates coincide with areas where land cover has changed.

Reduced recharge rates since 2013 have resulted in lower groundwater heads. The highest reductions in groundwater heads can be found in the upstream reaches, with reduced heads all the way to the upper midstream reach. The most profound changes are visible through reduced discharges at cartesian springs. At cartesian springs, groundwater finds its way to the surface and the discharge is directly related to the head relative to surface level.

Looking towards 2029, it becomes clear that further land conversion along the steep slopes of the Arjuna and Bromo mountains, will further reduce groundwater recharge and will therefore further reduce groundwater heads and spring discharges.

It is concluded that it is very likely that discharges of springs will further reduce and some may dry up. With agriculture in the upper midstream and lower upstream reaches dependent on water from springs, water stress will likely increase. Considering that groundwater abstraction for agricultural purposes is a common practice in the region, pressures on groundwater resources may further increase into the future.

In combination with increasing groundwater abstraction for urban (residential and industrial) purposes and potential longer dry seasons associated with climate change, groundwater resources may significantly reduce into the future.

7 Key Challenges, Opportunities and Needs

Looking at the historic and potential future flood hazards and the physical, socio-economic, and institutional contexts, we can identify the key challenges the region faces and opportunities that may arise. These key challenges and the opportunities can be arranged according to four domains:

1. The downstream river corridor: where until recently fluvial flooding occurred frequently and where in the future fluvial flooding may reoccur.
2. The upstream mountain slopes: where rapid land clearing and conversion in areas receiving most rainfall, significantly affects peak discharges which in the downstream area lead to fluvial flooding and reduces groundwater resources which lead to lower discharges of springs in the dry-season.
3. The midstream and downstream urbanised areas: where drainage systems are ineffective and increasingly frequent pluvial flooding leads to serious disruptions to public life and affects the economy, public health and likely contributes to the poverty trap.
4. The governance: where the activities of all stakeholders in the catchment – which may affect the physical or socio-economic context – are managed and guided through a complex arrangement of regulations, plans and budgets and where stakeholders are held accountable.

In this section the key challenges in each of these domains are elaborated on and identified opportunities and recommendations to explore to improve flood resilience in the catchment are provided.

In general, there are challenges with regards to existing flood hazards and risks which require investments in physical mitigation and protection measures, but there are also challenges with regards to future potential flood hazards that can be avoided through improvements in coordination, accountability, and the regulatory framework.

7.1 Downstream river corridor: accommodating discharge capacity in densely populated urban areas

Peak discharge waves have heightened and shortened significantly resulting from upstream land conversions in recent years. At the same time, the discharge capacity of the downstream river has been reduced. The width of the river has been reduced to about 50m in the downstream urban area, while the formal width of the river in the midstream area is 100m. Furthermore, suspended sediments from upstream soil erosion settle near the river mouth. This has resulted in much higher peak water levels in the now densely populated area in the downstream reach of the river.

Fluvial flooding used to be a frequent problem in and around the Kraton area and affected the population along this stretch of the river. The recent heightening of the embankments along the downstream reach of the Welang river has significantly reduced the probability of fluvial flooding in this area. However, the railway bridge is still often affected and inundates during combined high discharges and high spring tide. To further reduce water levels, alternatives to shorten the river in the downstream reach could be explored.

Towards the future, under the current socio-economic conditions and with the current development plans and regulations, it is expected that the peak discharges will further increase, and sedimentation will continue leading to higher water levels in the downstream reach. This may in the future lead to renewed fluvial flooding.

To avoid future fluvial flooding, the discharge capacity in the downstream reach needs to be increased. This can be achieved through a combination of the adoption of a required minimum river profile (minimum depth and width) in the downstream reach (to be monitored and actively maintained, e.g., through regular dredging). In addition, upstream land conversions need to be managed and guided to avoid downstream flood problems; this requires an upstream-downstream integrated approach.

7.2 Upstream area: water sensitive development

In recent years land in the upstream region has been converted to accommodate the increasing numbers of tourists. Settlements and new tourist areas have developed higher up on the slopes of both the Arjuna and Bromo. This has also led to a conversion of land from forest and plantations to agricultural land for cultivation of seasonal crops.

From a hydrological perspective, this development has resulted in much higher run-off, reduced groundwater recharge and likely more soil erosion. This was already identified in the last draft IWRBMP and is now quantified. It was found that since the area receives most rainfall, even perceived small developments have significant impacts on run-off, river discharges and groundwater recharge and groundwater heads. Downstream this is increasingly leading to flood problems:

- higher run-off results in a steeper discharge curve and higher water levels in the downstream reach,
- sediments settle in the downstream reach of the river, reducing the discharge capacity and further increasing the water levels.

These developments have also contributed to the recent reported drought problems in the catchment. The drought problems are mostly found downstream of regions where land has been converted. When runoff increases, less water is available to infiltrate and recharge groundwater resources, and groundwater tables drop. In the long-term this leads to droughts. Discharges of springs have reduced as a result of recent land cover changes. This will be further exacerbated by climate change which is expected to result in less rainy days.

Towards the future, it is expected that the land conversion will continue and pressures on water resources will increase. The spatial plans and regional development plans clearly show an ambition to further develop the upstream region into a tourist hotspot and main entry point for the mountains and more industrialisation in the upper midstream and upstream regions. Under the current conditions it is expected that run-off will further increase, and more soil will erode leading to more flood problems in the downstream reach and more droughts in the upstream region. The government plans to promote water heavy industries (like batik) in the upper midstream and upstream regions, which in combination with the absence of piped water supply and longer dry periods may put more pressure on groundwater resources and will lead to further reducing spring discharges and lower base flows in the river in the dry season and therefore droughts in the wider catchment.

Integrated approach is required to address downstream flood hazards and droughts. To reduce the downstream flood pressure and improve groundwater resources, run-off and soil erosion from upstream sources need to be reduced urgently. This requires an integrated upstream-downstream approach, which could be achieved through a combination of improved water sensitive land-management, where through the application of terracing and planting of appropriate crops and conservation run-off and exposed soils are reduced, and the application of measures to reduce the flow in gullies and streams (e.g., gully plugs). In addition, the development of settlement ponds for suspended sediment at strategic locations in the midstream reach (e.g., near brickmaking communities) can reduce the flow of sediment downstream.

Hydrological evaluation of plans is needed to avoid future flood and drought problems. In addition, to avoid an increase in downstream flood pressures towards the future, land conversions need to be managed and guided. This can be achieved through the adoption of regulations and hydrological checks (where the impact of government plans, including a spatial plan drafted based on needs-assessments, is evaluated with a hydrological model), run-off and soil erosion from future developments in the midstream and upstream areas can be avoided and the impact on downstream flood risks and droughts in the wider catchment minimized.

7.3 Midstream and downstream areas: untangling integrated water resources systems

In the past decades numerous agricultural land-plots (often in irrigation schemes) have been changed to develop residential houses or industrial estates. This has focused along the main infrastructural arteries (where roads and irrigation channels often run in parallel) in the midstream and downstream areas where existing residential areas have expanded, and new industrial estates have been developed along the provincial roads. Although the total converted land is significant, the developments have been mostly initiated on an individual basis by individual citizens or businesses and only a few developments have been initiated by real estate developers (in the lower housing segment only).

In the catchment, primary drainage systems – even in Pasuruan – are absent, and stormwater is drained via the irrigation systems instead. Only in the more densely populated urbanised area around Pasuruan stormwater drains have been constructed along roads. And larger real estate developers have constructed small scale stormwater drainage systems, although only on the land-plot they developed. The small private developments (residential houses and businesses) have relied on existing public infrastructure (mostly irrigation channels).

Around the commercial centres in the catchment, the absence of access to drainage systems results in frequent flooding. In the commercial centres the irrigation channels have been covered to allow for easy passage and market trade, but at the expense of stormwater drainage capacity.

There are no central wastewater collection systems in the catchment. Although the larger factories are required to have on-site wastewater treatment facilities and all others are required to have sceptic tanks, most excess wastewater is discharged via public infrastructure. In practice, a significant amount of wastewater flows into the irrigation channels.

Solid waste collection coverage is very low in the catchment and most solid waste is treated on an individual basis. Throughout the catchment large amounts of solid waste are disposed in or adjacent to rivers and waterways including irrigation/drainage channels. Solid waste is often transported in rivers and waterways and accumulates at bottlenecks, e.g., just before culverts or gates. Accumulated waste significantly reduces the discharge capacity locally and hence leads to higher water levels upstream of the bottlenecks.

As a result, the irrigation systems now double as stormwater and wastewater drainage systems and are clogged with solid waste, which frequently leads to overland flow of stormwater during rainfall throughout the catchment. Irrigation systems are normally filled with water and are designed to allow for irrigation of agricultural land, meaning that water levels are often near or above the terrain. Irrigation systems are not designed to discharge stormwater and, although in undulating terrain combination of irrigation and drainage functions is sometimes possible, combination often leads to overland flow during rainfall.

In addition, the integration of these systems may result in very poor water quality in these systems. The water quality is monitored at several locations in the main rivers, but not in the irrigation system. Pollution of the irrigation channels may therefore remain undetected. It is unknown what the effect is when polluted water is used for irrigation. However, considering that water from irrigation channels is often used to wash dishes at informal food stalls and that children play in irrigation channels, it is likely that the exposure of the population to various pollutants is very high.

There are currently no concrete or approved plans to develop urban drainage systems or wastewater collection and treatment facilities, improvement of collection and management of solid waste is however high priority. Therefore, towards the future, the pluvial flood problems will likely worsen. It is expected that ongoing small scale private developments will continue and as a result the pressures on the irrigation systems will increase leading to more pluvial flooding: more often, affecting more locations and probably with larger magnitude.

To reduce pluvial flooding, storage and discharge capacities within urban areas need to be increased. On the short-term this means:

- opening covered channels to allow stormwater to enter the channels,
- regularly removing accumulated solid waste from channels, and
- lowering the base flow of irrigation channels to create space for stormwater.

In addition, especially in the downstream densely populated area around Kraton, a review and redesign – starting with the development of master plans – of the existing water management systems is required with the aim to create separate systems for irrigation, stormwater drainage and wastewater collection, transport, and treatment. This will undoubtedly take time to establish but will provide benefits for all stakeholders: clean and sufficient water for downstream agriculture and aquaculture, no hindrance from pluvial flooding and no smelly drains.

Furthermore, to avoid future problems:

- land conversions need to be managed and guided more strongly, which will allow to anticipate on expected developments and sufficient storage and drainage capacity can be secured in advance,
- water quality monitoring may be extended to the irrigation channels to find polluters and to address pollution at the source,
- the (operation of) existing irrigation schemes may be evaluated, potentially leading to recommendations to adjust the systems based on current and expected future water demands and to apply proper operating and maintenance practices, and
- in the more densely urbanised areas in the midstream region, the development of a separate stormwater drainage system with sufficient storage and drainage capacity – based on new master plans – should be considered.

7.4 Governance: integrating and aligning visions, plans, budgets, and revenues

Various government agencies are actively working on flood resilience. It was found that in total 43 agencies have planned in total 60 programs to improve flood resilience. In addition, a regional multi-stakeholder platform to align plans, balance interests and manage water resources is active.

However, plans from different agencies are in practice rarely aligned and hydrological effects of development plans in general are not verified. Proposed flood resilience plans are based on the existing current condition only and likely insufficient under future planned conditions. A clear example is the spatial plan, which shows a significant proposed increase in paved area to the expense of agricultural and forest cover, but there are no plans to mitigate the effects on the hydrology. Similarly, while social agency (Dinas Sosial) has flood related plans, the effect of the recent heightening of the embankments in the downstream reach on poverty reduction has not been assessed.

In addition, available data suggests that the government agencies do not have access to sufficient funds leading to a suboptimal level of public services including solid waste management and infrastructure. Although a significant number of projects and measures is proposed only a small number is approved and may be implemented in reduced form, mostly due to budgetary constraints. Although budgets are increasing and the administrations in the region generate more local revenues, capital investments have reduced significantly in the last few years. In addition, the budgets for goods and services (including regular maintenance) have remained constant, despite the significant economic development and rapid urbanization and despite the already dilapidated state of public infrastructure in the catchment.

While non-structural measures and alignment of plans and projects are often more effective and efficient, approved projects, which are currently mostly funded through DAK and implemented by BBWS Brantas, are mostly structural in nature. In addition, approved projects are mostly designed and implemented by a single (often national) agency (mostly BBWS Brantas or BPDAS LH Brantas Sampean) only and so serve the goals of the implementing agency only, while the maintenance burden falls on the local government. While pooling of funding sources can lead to wider involvement of stakeholders and agencies and optimize secondary goals (e.g., poverty reduction or agricultural reform), so-called basket-funding has so far not been applied, despite numerous agencies having plans related to flood resilience.

Furthermore, although a regional multi-stakeholder platform to balance interests and manage water resources is active, in practice TKPSDA does not have sufficient funds to hire permanent staff or to verify agreed modifications to plans. In addition, local communities are rarely involved in the design of measures and measures are found only within the jurisdiction of the implementing agency. For instance, critical embankments are raised in an area with brickmakers who rely on frequent inundation of land, while a more suitable location for an embankment could be found outside the 200m river zone (BBWS jurisdiction).

In addition, authorities between the national, provincial, and regional government and between various agencies are divided along administrative lines only. In practice this leads to situations where the responsible authority is not the affected one when things go awry. For instance, the environmental agency is responsible for the collection of solid waste, but uncollected waste ends up in rivers where the water agency must remove it and subsequently must pay the environmental agency to dispose of it. Another example can be found in the management of the drainage system, where the provincial government is responsible to maintain drains along the provincial road, but when these are clogged or too small and cause flooding along the adjacent roads, it is the regional administration who is affected.

Therefore, in the short term, additional budget is required to invest and bring flood resilience to an acceptable level. Required funding is likely significant and so this is a significant challenge for the entire government. If funds for investments cannot be mobilized from local sources, a request at national level through DAK or via Bappenas to international financing institutes could be made. Funds might be obtained through the upcoming national fund for flood resilience managed by Bappenas. In addition, budgets for agencies may need to be increased to allow for more effective governance; this will likely reduce required investment costs in the medium to long-term.

While the prevailing regulations and plans do not have an impact on the current flood hazards and risks, it is by far the largest driver for future flood hazards and risks. To reduce future flood hazards and risks, changes in governance can be both more cost effective and a source of funding. Through multi-directional alignment of plans and basket-funding of measures, goals of multiple agencies can be reached through single projects, e.g., poverty can be alleviated, and flood hazards reduced through re-greening initiatives in the upstream region. In addition, when the true cost of proposed development plans become clear, local revenues can be brought in line with expected costs, e.g., through increasing levees for permits or the creation of a land development agency with a monopoly on land conversion for certain destinations (e.g., commercial use), revenues can be generated to pay for the development of new drainage systems.

Appendix A Hydrologic and hydraulic modelling

Approach

Introduction

In this project two models namely WFLOW SBM and SOBEK are used. WFLOW SBM is used to get the upstream boundary conditions for hydraulic modeling using SOBEK.

WFLOW is a distributed hydrological model already applied for the whole of Indonesia in the Joint Cooperation Program, consisting of multiple Indonesian agencies, using cells of 0.5x0.5km. The WFLOW model can be fed with global databases on land use, soil type, elevation, etc. More detailed local data can be used if available. WFLOW is an open source distributed hydrological model available on GitHub.

A WFLOW SBM model requires three main types of inputs:

- static data, such as a Digital Elevation Model (DEM), land use and soil data;
- dynamic data, such as precipitation, potential evapotranspiration and air temperature; and
- model parameters such as soil hydraulic conductivity or surface roughness.

In order to fit the Welang Basin model time resolution (daily and hourly) and space resolution (0.004167° - ~500 meters), most of the data available were first pre-processed using a combination of resampling or downscaling techniques.

Gridded static data, such as Digital Elevation Model (DEM), soil and land use usually have a finer resolution than the wflow model. In order to keep the level of details from the original datasets, both model schematization derived from the DEM (catchment delineation, river network and characteristics or slope and flow direction) or model parameters derived using pedo-transfer functions from soil and land use data, were first computed from the original fine resolution of the corresponding datasets before being resampled and aggregated to the wflow model resolution of ~500 meters (Figure 7-1).

Gridded dynamic data, such as precipitation or temperature have, on the contrary, usually has a coarser resolution than the wflow model. In order to better capture local rainfall patterns or temperature variability, the dynamic data can be downscaled using either global long-term climatology or elevation maps.

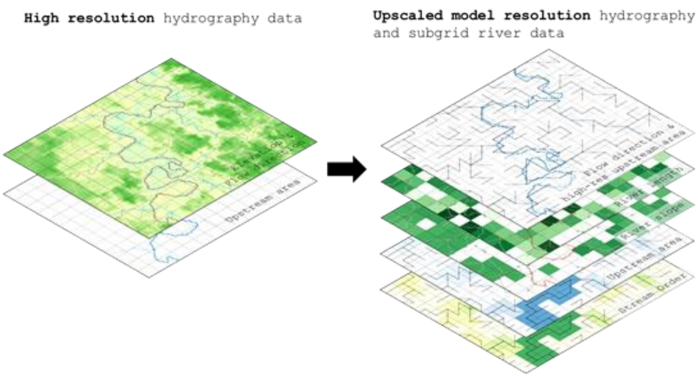


Figure 7-1 From high to detailed upscaled hydrography data

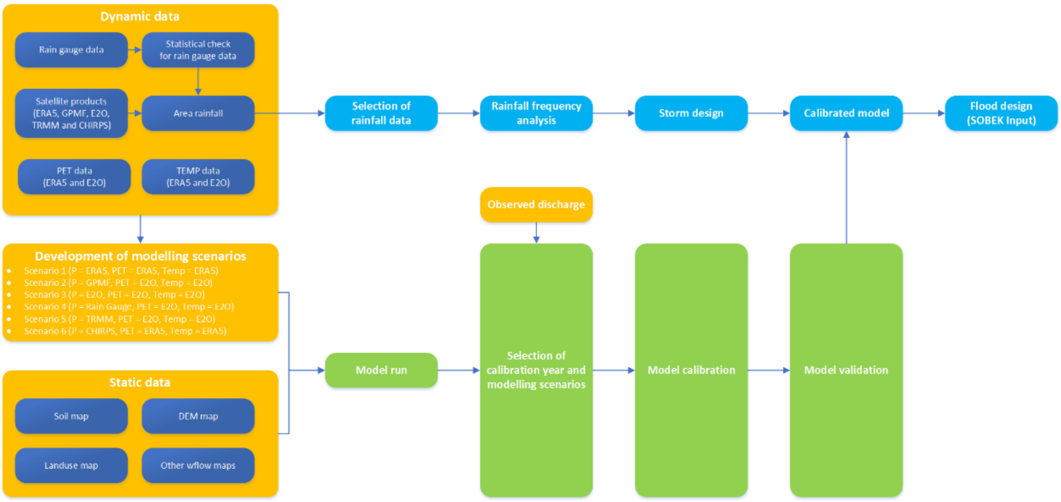


Figure 7-2 wflow modelling approach

Figure 7-2 above describes the workflow to obtain flood design for SOBEK model. The workflow starts with gathering several data that can be used to run the WFLOW model with the main goal to get the desired flood design (flood hydrograph under different return period). Initially 6 scenarios that represent different source of rainfall data are collected. Among 6 scenarios only Scenario 4 which is derived from rain gauge data that is used to calibrate and validate WFLOW model. Scenario 4 is selected to be used because it is expected that local data could capture rainfall event better when compared to satellite data. By running WFLOW model with local data and compare it with discharge measurement, modelers can have a feeling about the quality of the local data and select which period that can be used to calibrate and validate the model. Here, selection of calibration and validation year is simply based on the suitability of rainfall pattern to the observed discharge. After the calibration and validation years are selected, model calibration followed with model validation can be carried out. In this project calibration will be carried out for Purwodadi station, whereas Validation at Selowongko station. Although Dhompo is the most downstream stream gauge, calibration at Dhompo is not feasible as WFLOW cannot take into account flow diversion.

With the calibrated and validated model, the only thing left to have to be able to get the desired flood design is the storm design itself. Storm design can be obtained by doing rainfall frequency analysis and create a synthetic rainfall based on the recorded rainfall distribution patterns. In this project, local rainfall measurement is not used to determine the storm design since the length of complete and continuous rainfall measurement are relatively short (13 years, from 2004-2016) compared to other satellite products and can cause a bias in determining the peak rainfall. Therefore, before performing frequency analysis, selection of satellite product which replaces the rain gauge data becomes important. In this project, the selection of satellite product to be used is done by looking at the correlation value of the observed and satellite datasets, visual appraisal between the cumulative rainfalls and visual appraisal on the event of heavy rainfall.

As hydraulic modelling using SOBEK will be done in hourly timestep yet in Welang Basin no hourly data is present, PSA 007 and West Java rainfall distributions are used. With the presence of rainfall distribution and rainfall under different return period, the storm design can be obtained. This storm design is then inserted into the calibrated wflow model to produce flood design at any desired location in Welang Basin. The generated discharge will then be used as an input for hydraulic modelling using SOBEK.

In this project, the SOBEK modelling framework is used to model the water levels in the Welang river during the passing of flood waves. SOBEK is a Deltares modelling suite that includes 1D and 2D hydrodynamics, Rainfall-runoff, real-time control and water quality. SOBEK is developed in the nineties and the first decade of the 21st century and has

proven its capabilities in many international projects. There are several applications of SOBEK models in Indonesia, e.g. for the Ciliwung basin and Jakarta area, for`the Upper Citarum area near Bandung, as well as for the water systems around the cities of Bima, Manado and Pontianak.

Because a sufficiently accurate Digital Terrain Model (DTM) was not available, it was not possible to use the SOBEK 1D2D module to model inundations in 2D. Instead, we used the 1D SOBEK module to analyse river water levels during the passing of flood waves along the lower section of the Welang river. Because of the 1D modelling approach, the model is especially suitable for identifying any weak spots along the embankments – by comparing maximum water levels to local embankment levels. Because the 1D model only represents the river itself, the model is only valid for situations until the river embankments start to overflow.

In a separate component of this project, this model shall be used to evaluate the effect of measures on the peak water levels.

1.1 WFLOW modelling methodology

1.1.1 Model setup

2 Static data

WFLOW uses a combination of static data (data that do not vary in time) to describe fixed catchment properties such as elevation, land use and soil type. The different datasets used for the Welang Basin are listed below.

1. Elevation data

   Model elevation was derived from the global 3 arc second (~90 meters) *MERIT Hydro Adjusted Elevations* dataset (Yamazaki et al., 2019). *MERIT Hydro* is a version of the *MERIT DEM* that was corrected for depressions to allow for hydrological simulations. *MERIT DEM* is a recently published global DEM that gathers and corrects several spaceborne DEMs in order to enhance their accuracy.

   MERIT Hydro is also used by WFLOW to derive several other information such as:

   - Catchment delineation
   - Flow direction (1D)
   - Slope
   - River network and characteristics (length, width, slope)

   These other static data are first computed on the original *MERIT Hydro* resolution (~90 meters) and then resampled to the wflow model resolution (~500 meters).

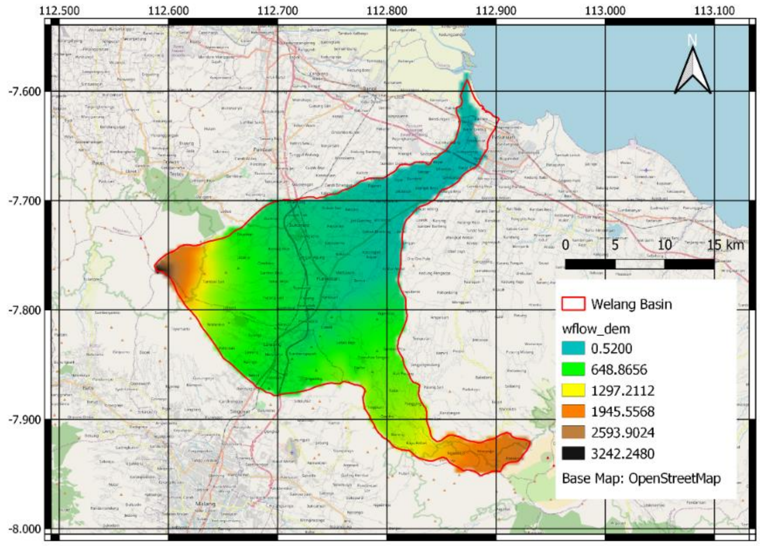


Figure 7-3 wflow elevation map (resampled from MERIT Hydro)

2. Land use

Land use data is derived from the global 300 meters GlobCover map for 2009 (Arino et al., 2012). The GlobCover map was created using satellite image from the 300 m MERIS sensor with observation period of January-December 2009. In this project, this data is updated to present situation (2014 and 2020) and future situation (2029) by looking at the Google Earth satellite imagery and RTRW 2029 respectively. These maps were resampled to the wflow resolution (~500 m) using the dominant landuse type in each wflow grid cells. Land use for Welang Basin according to GlobCover classification can be seen in Figure 7-4.

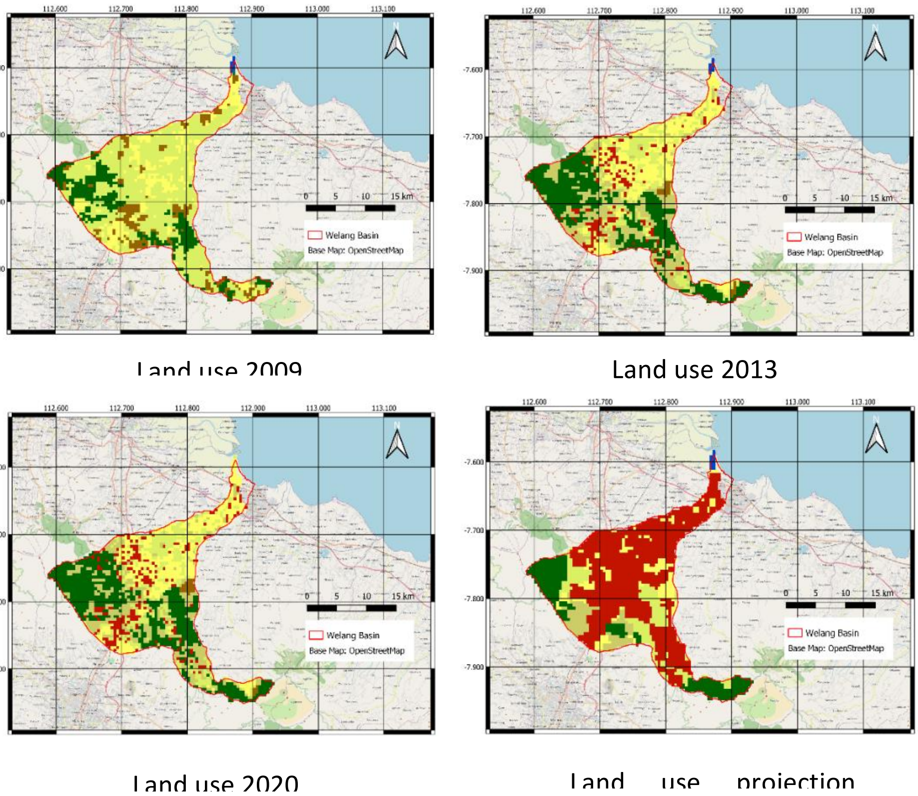


Figure 7-4 Welang basin land use comparison in 2009, 2013, 2020 and 2029

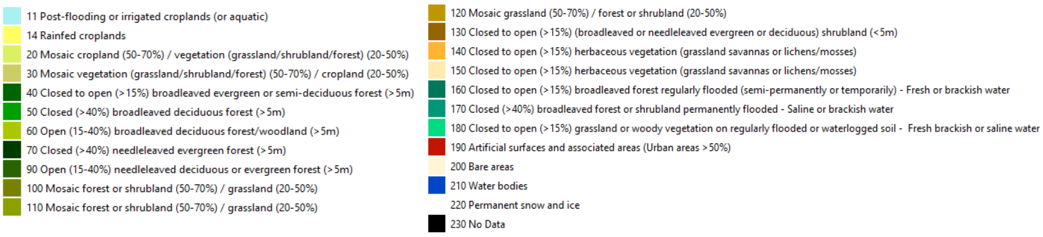


Figure 7-5 Land use classification according to GlobCover

3. Soil data

Soil data are derived from the global 250 meters SoilGrids Database (Hengl et al., 2017). SoilGrids is a collection of soil properties and classes that is based and extrapolated from local and national soil information. In this database, soil properties such as bulk density, clay/silt/sand content are available for up to seven soil layers (depth's intervals) up to 2 meters deep.

Soil properties in wflow are used to derive model parameters such as hydraulic conductivity and its exponential decrease, rooting depth etc. using pedo-transfer functions developed by Imhof et al. (2019). For this purpose, the maps used from SoilGrids are clay, silt, and organic carbon content as well as bulk density.

3 Dynamic data

Like any other hydrological model, wflow SBM needs rainfall, potential evapotranspiration and temperature data in order to determine how much precipitation that becomes river runoff.

This section describes the various datasets available for Welang Basin.

1. Rainfall, PET and Temp

   - In Welang Basin, there are around 36 rainfall stations that measure daily rainfall for different record durations from 1979 to 2021. These rain gauges are scattered around the basin and most of them doesn't cover the whole period as stated above. Further, as wflow requires a raster format (not point/vector format) as an input, these rain gauge data should then be checked first and converted into a raster format. Statistical check and method to convert point rainfall to raster format will be elaborated in detail in **Data Analysis** section.

   Other than ground station measurement, dynamic data can also be obtained from satellite products. The advantages of satellite product, among others, are that the available data is quite long, always continuous and has a global coverage area.

   Knowing that wflow also requires potential evapotranspiration (PET) and temperature data for the selected simulation time, yet PET is usually approached by using an empirical formula that requires for more meteorological input, it is much more practical that the PET and temperature is also obtained from satellite products.

In this project, there are 5 satellite products that are aimed to be used namely: 1) ERA5, 2) GPMF, 3) E2O, 4) Corrected TRMM and 5) CHIRPS. These data are already in raster format and has different spatial and temporal resolution as shown in. The length of rainfall data available for each product can be seen in **Data Availability**.

Table 5 Satellite products information

Satellite Products	Parameter	Original Spatial Resolution	Original Temporal Resolution
ERA5	P	0.25 x 0.25 (~27 x 27 km)	Daily
	PET	0.25 x 0.25 (~27 x 27 km)	Daily
	Temp	0.25 x 0.25 (~27 x 27 km)	Daily
GPMF	P	0.10 x 0.10 (~11 x 11 km)	3 hourly
E2O	P	0.25 x 0.25 (~27 x 27 km)	3 hourly
	PET	0.25 x 0.25 (~27 x 27 km)	Daily
	TEMP	0.25 x 0.25 (~27 x 27 km)	3 hourly
TRMM	P	0.25 x 0.25 (~27 x 27 km)	3 hourly
CHIRPS	P	0.05 x 0.05 (~5 x 5 km)	Daily

-

2. Water Level and River Discharge

   In Welang Basin, there are 3 locations where water level is measured. The three stream gauges from upstream to downstream of Welang River are AWLR Purwodadi, AWLL Selowongko and AWLR Dhompo. The timestep of which water level is recorded is in daily timestep. The earliest data available on these three water level recorders is from 1992. This water level data is used and converted into river discharge by UPT Pasuruan using stage-discharge relationship (rating curve). Although it covers a long period of time, prediction of river discharge highly depends on these rating curve. Based on the data obtained from UPT Pasuruan, it is known that the rating curve formula is updated sporadically. According to Dinas Pekerjaan Umum Pengairan Propinsi Jawa Timur data, it is also known that ground check (field measurement) has been carried out. However, the field measurement is only done during low flow throughout the year. Multiple coordinates for single station are also found in the spreadsheet and thus become a question whether the data comes from the same source or not. The length of discharge data available for these three locations can be seen in **Data Availability** section.

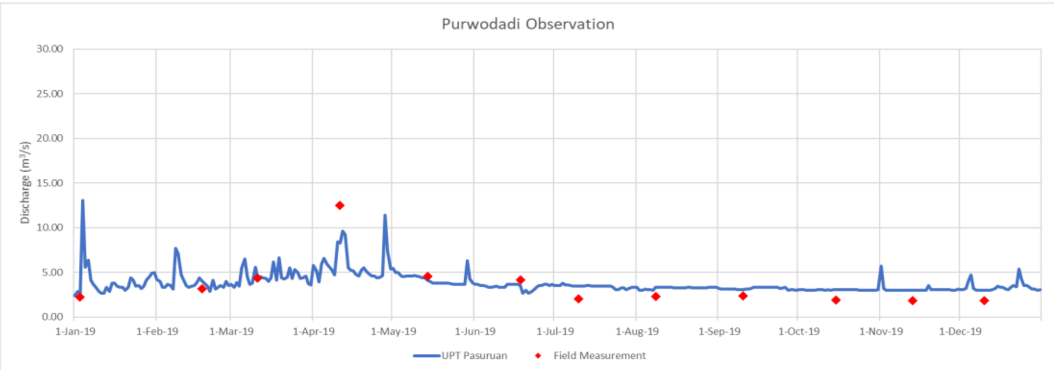


Figure 7-6 Rating-Curve Discharge and Discharge Measurement at AWLR Purwodadi

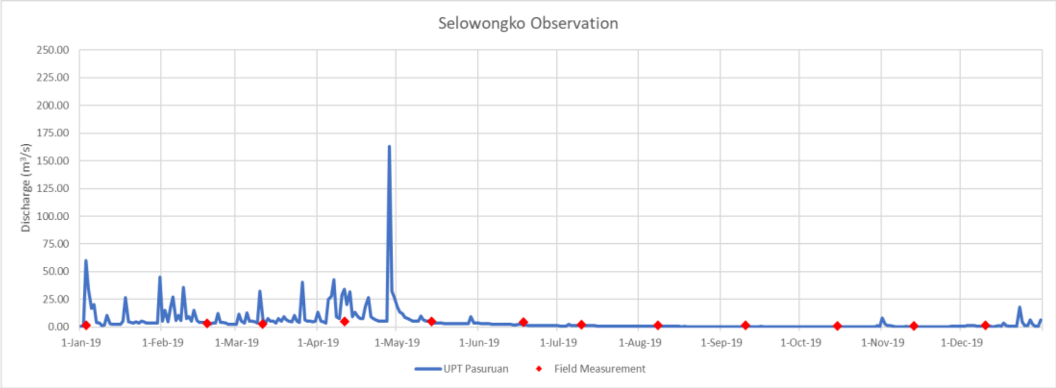


Figure 7-7 Rating-Curve Discharge and Discharge Measurement at AWLL Selowongko

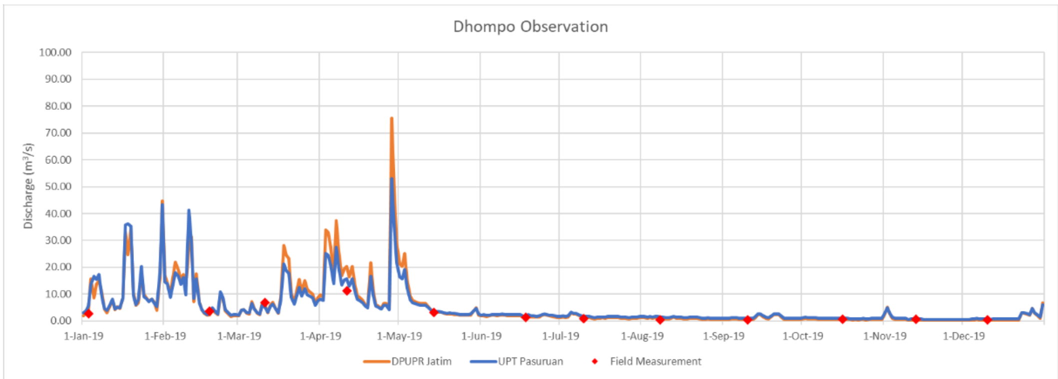


Figure 7-8 Rating-Curve Discharge and Discharge Measurement at AWLR Dhompo

The abundance of river water in Welang River is also used to irrigate paddy field in Welang Basin. The presence of intake structure above AWLR Dhompo in combination with the existence of irrigation outlet located at downstream part of Dhompo resulted in less amount of water passing through the Dhompo station. This also means that calibration of river discharges in Dhompo is no longer possible because water flows are already affected by man-made structures.

Figure 7-9 River diversion above AWLR Dhompo
(Intake Grinting, bottom left and Intake Licin, bottom right)
Source: Google Maps

Before being used for rainfall-runoff modelling the above data needs to be checked and analyzed. Section **Data Analysis** section provides information about the conducted analysis and decisions making process for modeling Welang Basin.

The important points from the analysis are:

1. Among 36 rain gauges, only 11 stations which pass preliminary inspection;
2. These 11 stations are consistent among each other;
3. Based on visual appraisal on catchment rainfall at Purwodadi and Dhompo and the correlation value between satellite products, E2O is chosen to be the best fit for representing catchment rainfall at Welang Basin;
4. Storm design will be created based on E2O data which covers the period of 1979-2014;
5. The three durations of rain events analysed are 6 hours, 12 hours and 24 hours;
6. Rainfall distribution that is used is coming from PSA 007 for 10-year, 25-year and 100-year rainfalls and from West Java rainfall distribution for 1-year rainfall;
7. From the observed data, runoff coefficient larger than 100% is found at Purwodadi station in 2018. This may be caused by several things among others are overestimation of discharge measurement/wrong water level measurement, underestimation of catchment rainfall as a result of sparse rain gauge coverage or it may be caused by additional water supply either from outside Purwodadi basin or from groundwater;
8. In the other hand, it is found that the runoff coefficient for Dhompo is below than 33% and less than the two other stream gauges. This indicates that most of the rainfall that falls into Dhompo catchment doesn't flow to AWLR Dhompo. Until now it is suspected that most river water is

diverted by the man-made structure (irrigation intake) that is existed along Welang River. And therefore, in this project Dhompo Station is not used for calibrating and validating the model.

3.1.1 Scenario analysis – simulation of discharges with WFLOW

To be able to determine the change of peak discharge due to land use change, in this project three scenarios that represent the past (2013), present (2020) and future (2029) land cover of Welang Basin were developed. As described in the land use section above, the land use data that is used to represent these three conditions are derived from the GlobCover map (2009) that is renewed with Google Earth satellite imagery in 2013 and 2014 and spatial plan (RTRW) for the year 2029. These maps were then resampled to the wflow resolution (~500 m) using the dominant landuse type in each wflow grid cells.

Apart from the land cover maps that need to be prepared, WFLOW model also requires an initial state and a storm design. In this project, the initial state chosen is the condition on 30 November 2013. This state is chosen because this state is before the rainy season starts and the period when the soil is no longer dry but filled with rainwater. The storm design in the other hand is obtained by performing frequency analysis on the E2O dataset over the period of 1997-2014 and followed with distributing the peak rainfall with the published rainfall distribution in the catchment (PSA 007 for 10-year, 25-year and 100-year rainfalls and from West Java rainfall distribution for 1-year rainfall). Although the rainfall data used for frequency analysis seems to have a noticeable deviation with the observed catchment rainfall (derived from Thiessen Polygon) and also doesn't cover the period from 2015 onwards, E2O data is still better on capturing high rainfall when compared to other remote sensing data and thus consequently gives a higher n-years rainfall (see **Precipitation, PET and TEMP**). Table 6 shows the peak rainfall at Welang Basin for period of analysis 1997-2014.

Table 6 Peak Rainfall for Various Return Period (Present Situation: 1979-2014)

Return Period (T)	t	Probability Distribution					
(Year)		Normal	Lognormal 2 Paramet.	Lognormal 3 Paramet.	Gumbel I	Pearson III	Log Pearson III
1.001	-3.09	4.4	24.1	32.5	21.4	39	32.5
2	0.00	62.6	59.9	58.6	59.7	57.9	58.6
5	0.84	78.4	76.7	75.1	78.5	75.1	74.8
10	1.28	86.7	87.3	86.6	91	87.3	86.4
20	1.64	93.5	97.2	98.1	102.9	99.2	98.2
25	1.75	95.5	100.3	101.8	106.7	103	102
50	2.05	101.2	109.6	113.6	118.4	114.7	114.5
100	2.33	106.3	118.8	125.7	130	126.4	127.7
500	2.88	116.7	139.7	155.3	156.9	153.7	161.7
1000	3.09	120.7	148.7	168.9	168.4	165.6	178
Maximum Deviation		16.36	10.87	7.83	10.23	8.87	7.76
Critical Delta (Sig. Level 5 %)		22.6	22.6	22.6	22.6	22.6	22.6

Note: Since Log Pearson III is the probability distribution that gives minimum deviation, the output of Log Pearson III probability distribution is then set as the peak rainfall to be used.

The peak rainfall shown in Table 6 needs to be converted to a hyetograph by using rainfall distribution. Since there is no hourly data rainfall measurement in the basin, the rainfall distribution that is used in this project comes from PSA 007 for 10-year, 25-year and 100-year rainfalls and from West Java rainfall distribution for 1-year rainfall. Figure 7-10 shows the rainfall distribution used to generate storm design for different rainfall duration and return period. Storm design for several important locations throughout the basin can be seen at **WFLOW Discharges** section.

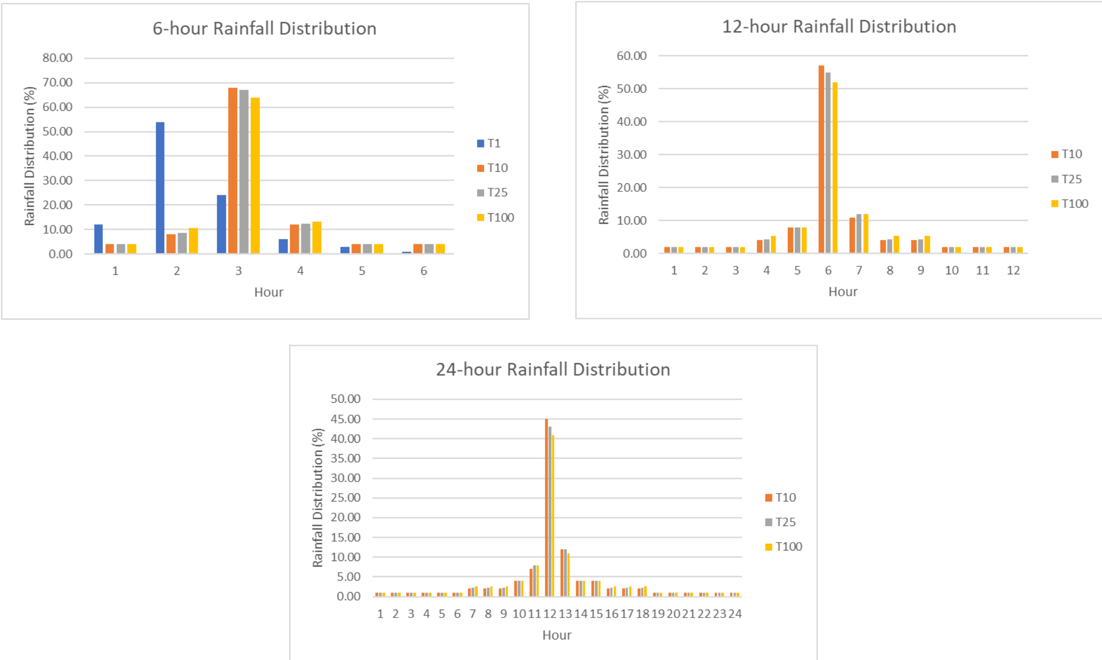


Figure 7-10 Rainfall distribution for different rainfall duration and return period

Some additional notes related with the process of generating flood design are:

1. The creation of flood design hydrograph is done by inserting synthetic storm design into the validated wflow model;
2. Since the length of complete and continuous rainfall measurement from the 11 rain gauges are relatively short (13 years, from 2004-2016), rainfall data used for determining the peak rainfall will be derived from E2O data which covers a longer period (36 years, from 1979-2014); and
3. PET and TEMP data used for the creation of flood design are E2O average catchment PET and TEMP.

3.2 SOBEK modelling methodology

3.2.1 Model setup

The model was built based on the best available data and knowledge available for the project. The Welang river is modelled over a stretch of some 41 km, from just upstream of Purwodadi to the river mouth close to Pasuruan (Figure 7-11). The 1D model contains 425 cross sections, 435 calculation points (mostly located at the locations of the cross sections for maximum accuracy), 12 lateral inflow points at the locations of the main tributaries, 2 boundaries and 5 weirs (Figure 7-11).

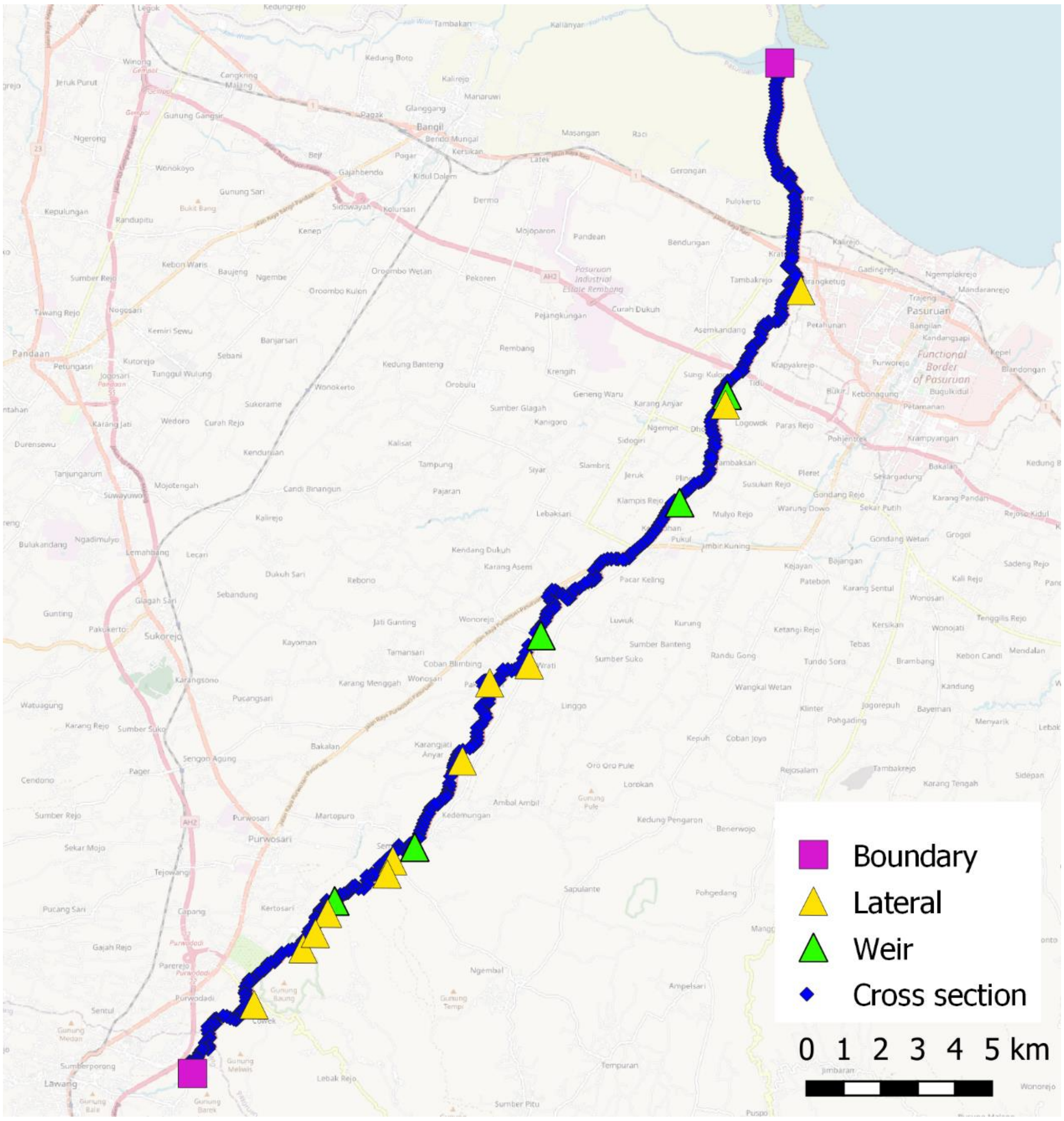


Figure 7-11 Welang river schematisation

The river centre line, cross-section (XY) locations and YZ cross section tables were derived from existing 2012 and 2017 HEC-RAS models as follows (Figure 7-12): Firstly, the HEC models could not be directly imported into SOBEK because they were not properly geo-referenced after import, leading to critical scaling issues. Instead, the river centre line as well as the XY locations of the cross sections were derived from the AutoCAD layers from the original 2012/2017 surveys that were originally used to construct the HEC models. Here, the 2017 data was used where available (i.e. the lower half of the Welang river, from Domas weir downstream), and the 2012 data for the rest (i.e. upstream of Domas). Secondly, the YZ tables were derived from the HEC'12 and HEC'17 models and imported into SOBEK.

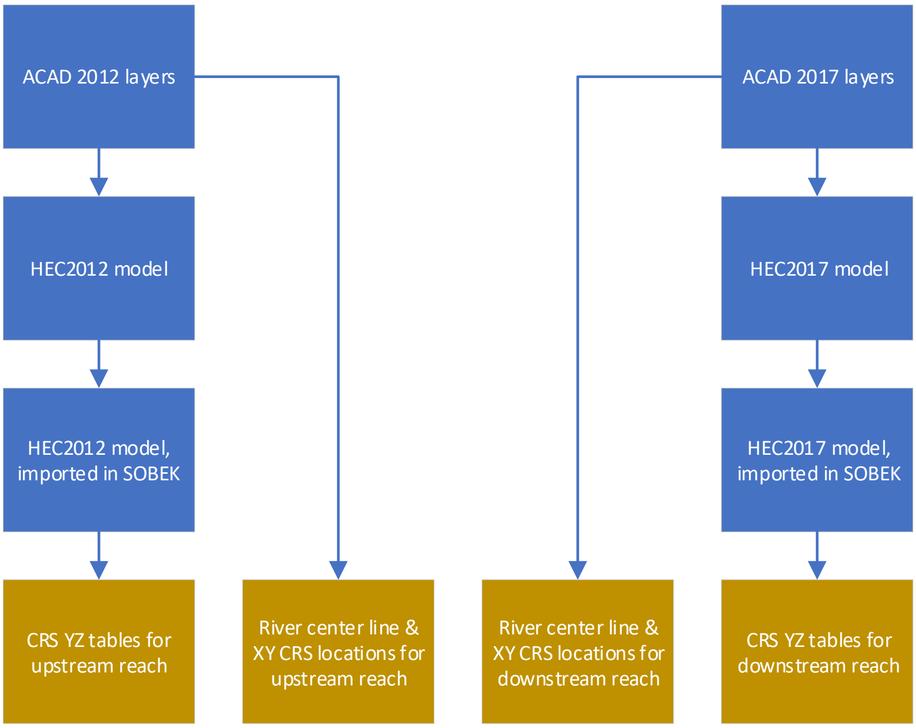


Figure 7-12 Procedure followed to derive SOBEK river centre line and cross section data from existing HEC-RAS models & AutoCAD data

Three corrections were then applied to the imported cross section datasets: 1) The 2017 cross sections were shifted upwards by 0.047 m to switch from the used local benchmark to MSL. 2) The HEC2012 CRS levels were originally surveyed according to an unknown local benchmark, and therefore had to be vertically shifted to align with the HEC2017 levels. We based the shift on the difference at location Domas Weir, which was included in both cross-section datasets, and which is Also, Domas weir is located right on the interface between the 2012 and 2017 datasets. The weir level according to the 2012 survey is 2.3 m lower than according to the 2017 survey. Hence, a shift of +2.3 m was applied to all cross sections of the HEC2017 model. 3) The original HEC cross sections extended beyond the highest point of the embankments, leading to an overestimation of the conveyance capacity of the river. Therefore, all cross-section tables were analysed and corrected where necessary (Figure 7-14).

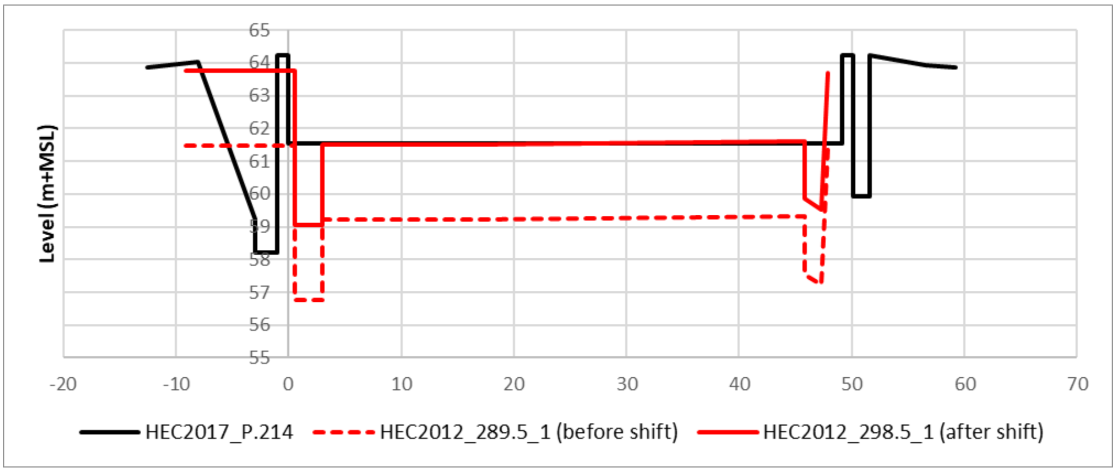


Figure 7-13 Vertical shift applied to HEC2012 cross sections (in red) based on HEC2017 cross section of Domas weir (in black).

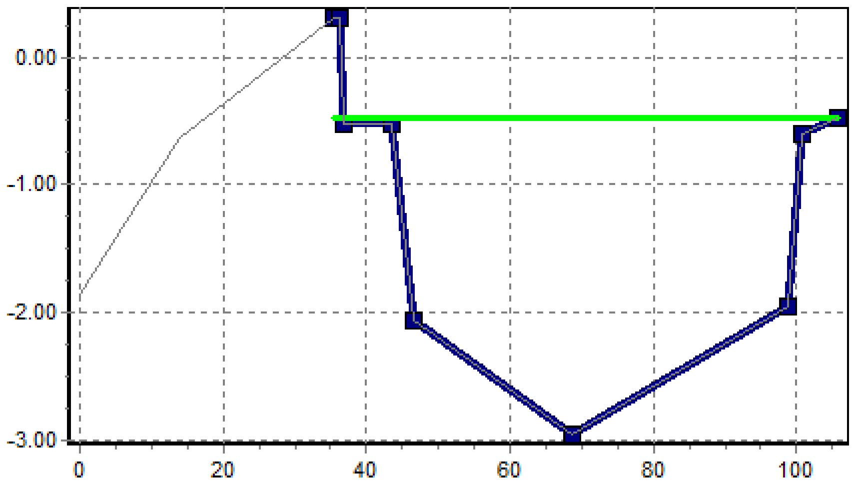


Figure 7-14 Example of corrected cross section (points to the left of the highest point of the left embankment were removed).

The Welang river contains 5 weirs that were included in the model because of their expected significant effect on the water levels during flood waves: Baong, Selowongko, Domas, Grinting and Licin (Figure 7-18). Due to lack of sufficiently accurate survey data, the properties of these weirs were partly based on expert judgement.

The upstream boundary condition of the model is located just upstream of Purwodadi (purple node in Figure 7-11). It consists of a discharge time series and is derived from WFLOW (**WFLOW Discharges**). The downstream boundary is located at the river mouth. Here a water level time series is applied. As there is no fixed tidal level gauging station close to the mouth of the Welang river, we make use of the data of a nearby tidal level measurement campaign that was carried out in 2017. A vertical shift of -1.3 m was applied to change the levels from a local benchmark to MSL. Figure 7-15 shows the boundary signal that was applied as downstream boundary condition with a periodicity of 1 month (30 days) for all simulations (so both the 2013-2014 calibration simulation and all scenario simulations. A horizonal shift (in time) was applied to ensure that the discharge wave of the scenario runs coincides with the highest registered high tide (1.7 m+MSL). Additional vertical shifts were applied to account for SLR based on the scenario year.

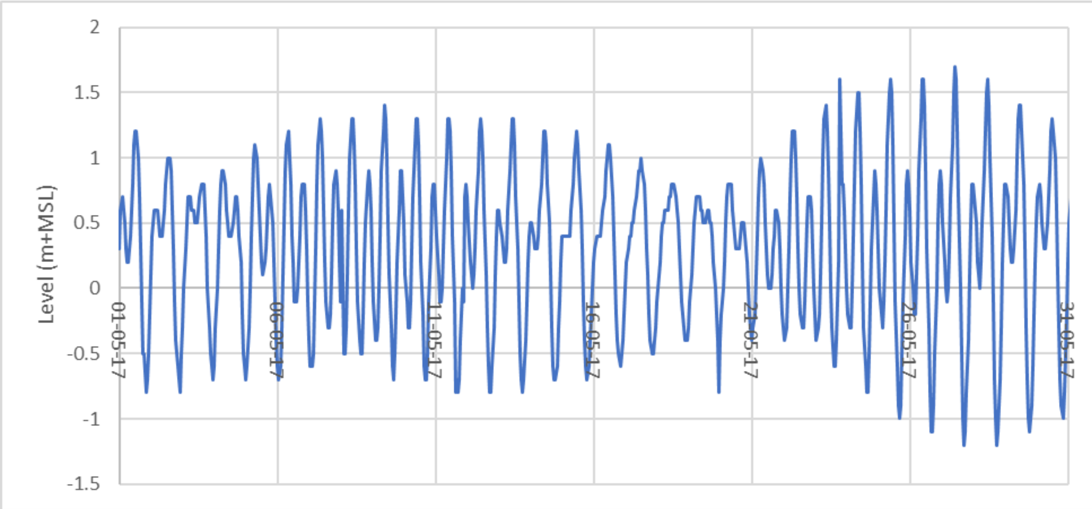


Figure 7-15 Measured tidal level signal as applied as downstream boundary condition (with a periodicity of 1 month) for all simulations

The Rainfall-Runoff process is modelled with WFLOW, both for the 2013-2014 calibration period and for all scenario runs. WFLOW simulates discharge waves at the tributary inflow locations along the Welang river, which are then applied to the Sobek model as lateral conditions (the yellow diamonds in Figure 7-11) and the upstream boundary condition ('18' in Figure 7-16, the purple square in Figure 7-11). Figure 7-17 shows an example of discharges applied to SOBEK (in this case for one of the flood hazard scenarios: T10, present conditions (2020), 6-hourly event).

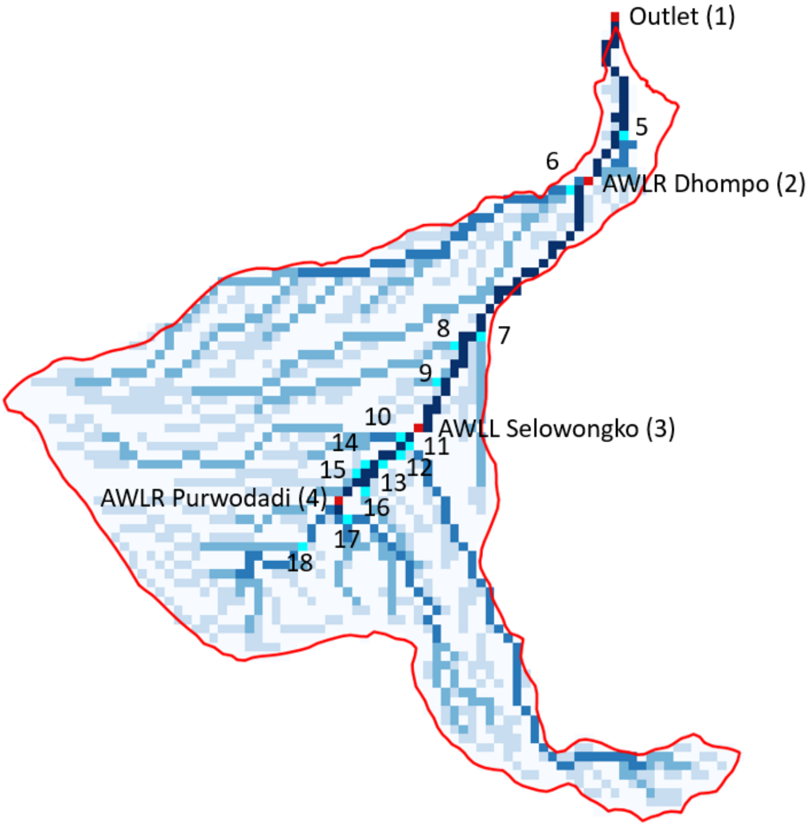


Figure 7-16 WFLOW model, with the tributary inflow points towards the SOBEK model indicated by numbers 5-11 and 14-18. Note that '18' is the location of the upstream boundary of the SOBEK model.

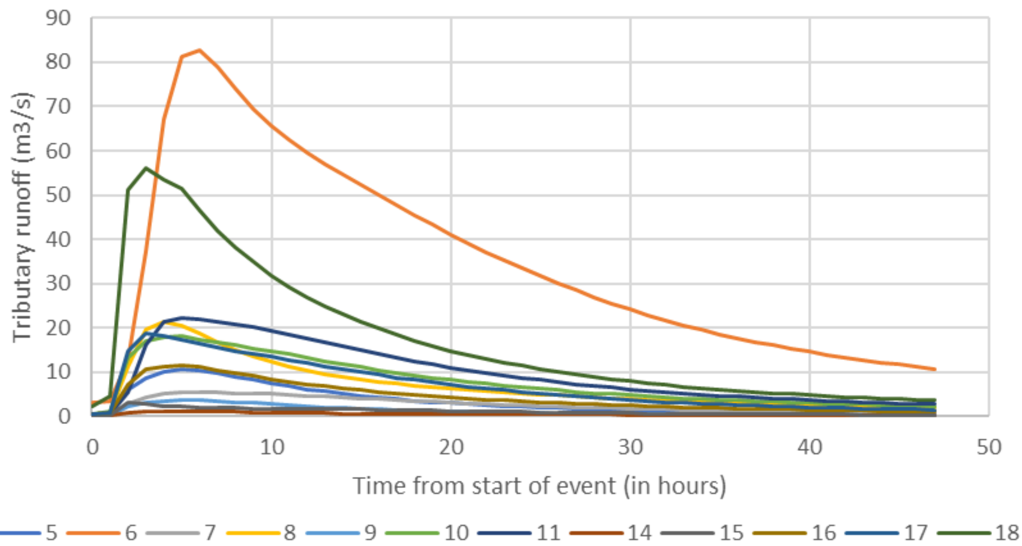


Figure 7-17 Example tributary discharges as calculated with WFLOW (for T10/2020/6 hours) and applied to the SOBEK model as lateral conditions. The legend numbers correspond to the numbers in Figure 7-16.

3.2.2 Model calibration

Model calibration of a 1D hydrodynamic model was carried out by tuning the friction coefficient, with the aim of reproducing the water levels at the gauging stations as accurately as possible, for one or more representative events. Accuracy is here expressed in both the BIAS and the RMSE (Root Mean Square Error).

There are two AWLR stations for which recorded water level measurements were available for the calibration period: Purwodadi station, located in the upstream of the 1D model domain close to the town of Purwodadi, and Dhompo station, located downstream, at the intersection of the Welang river with the Gempol-Pasuruan toll road. Unfortunately, no accurate information could be found on the levelling on the gauging stations. The following vertical shift was therefore applied **using expert judgment based on model results** on the recorded water levels of the AWLR stations: Purwodadi +269.7 m, Dhompo +3.6 m.

The calibration period was chosen identical to the WFLOW calibration period: 1/1/2013 to 31/12/2014. Discharge time series at the upstream boundary and at the tributaries along the Welang river were calculated with the WFLOW model and imposed as lateral conditions on the SOBEK model (see also paragraph 3.2.1 and Figure 7-17).

The measured 2017 tidal water level (see paragraph 3.2.1) was used as a downstream boundary condition. To correct for SLR, the levels of 2020 and 2029 were raised with 2.4 and 9.6 cm, respectively, assuming a yearly SLR in Indonesia of 8 mm/year compared to 2017.

The calibration was carried out manually by changing the roughness for the three chosen roughness sections. The following set of roughness parameters led to the lowest (= best) values of BIAS (0.18) and RMSE (0.46) and were therefore chosen for the scenario calculations:

- Section 1: Mn=0.03 $m^{1/3}/s$
- Section 2: Mn=0.04 $m^{1/3}/s$
- Section 3: Mn=0.06 $m^{1/3}/s$

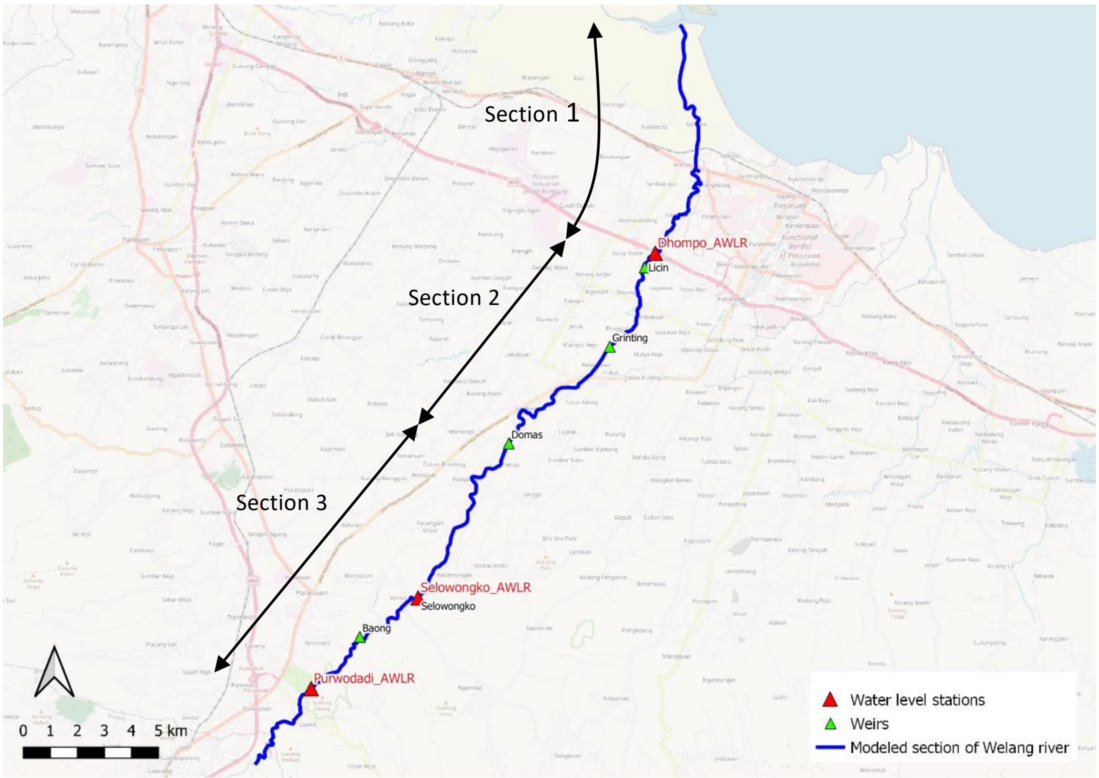


Figure 7-18 Overview of available gauging stations and calibration roughness sections. The weirs are added for reference.

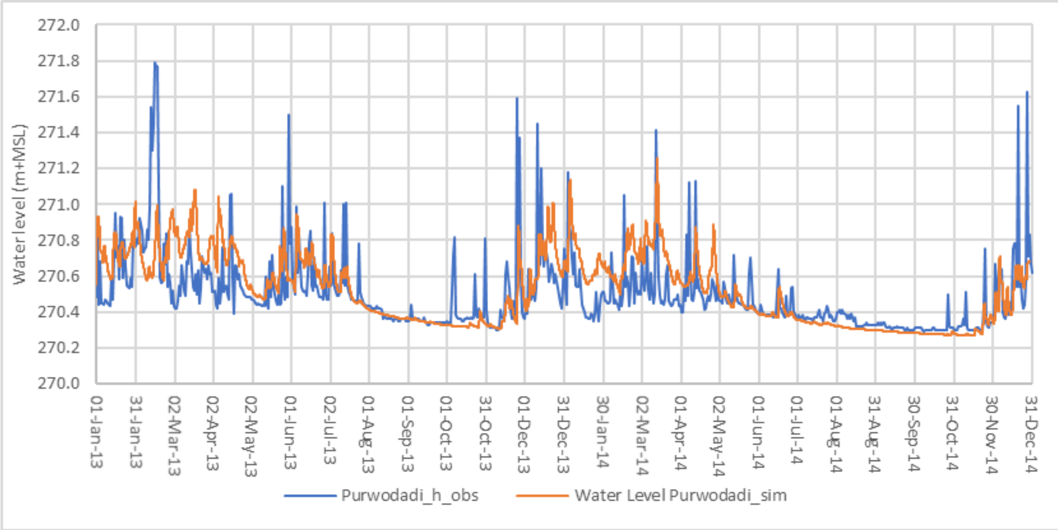


Figure 7-19 Comparison of registered and simulated 2013-2014 water levels (after calibration) for Purwodadi station.

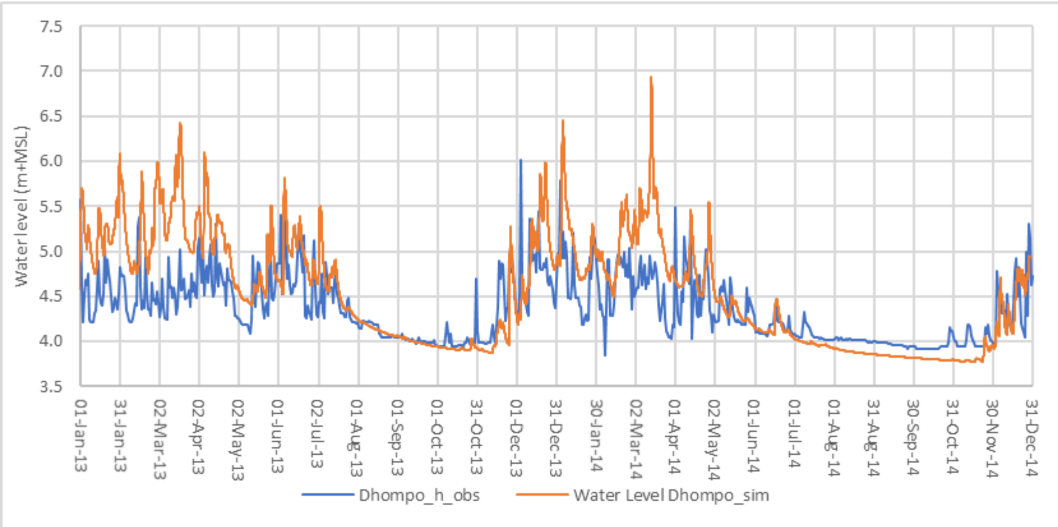


Figure 7-20 Comparison of registered and simulated 2013-2014 water levels (after calibration) for Dhompo station.

Note that the remaining values after calibration of BIAS and RMSE are quite high, meaning that there are still significant differences between the observed and simulated water level signals. There are two major reasons for this:

1. The WFLOW model still showed significant inaccuracies after calibration and any inaccuracies in the WFLOW model output are directly translated into inaccuracies in the SOBEK output. As an example, Figure 7-21 shows a comparison between recorded and simulated discharges and cumulative volumes at Purwodadi station, located very close to the upstream boundary of the Sobek model. The following differences can be observed: 1) the simulated baseflow is much lower than the observed baseflow, 2) the pattern in simulated runoff peaks is significantly different from the pattern in observed runoff peaks, especially in the first months of 2013. As a result of 1), the total simulated runoff volume is significantly lower than the observed runoff volume. These differences will likely affect the accuracy of the hydraulic model, as they are impossible to correct for during the calibration.

2. As stated previously, the 1D Sobek model is only accurate until the river water levels exceed the embankment levels, causing floods in the neighbouring areas. This means that simulated peak water levels may be overestimated. Note that although this limits the model application, the model is still useful to analyse where the river embankments need to be strengthened, by comparing maximum water levels to local embankment levels.

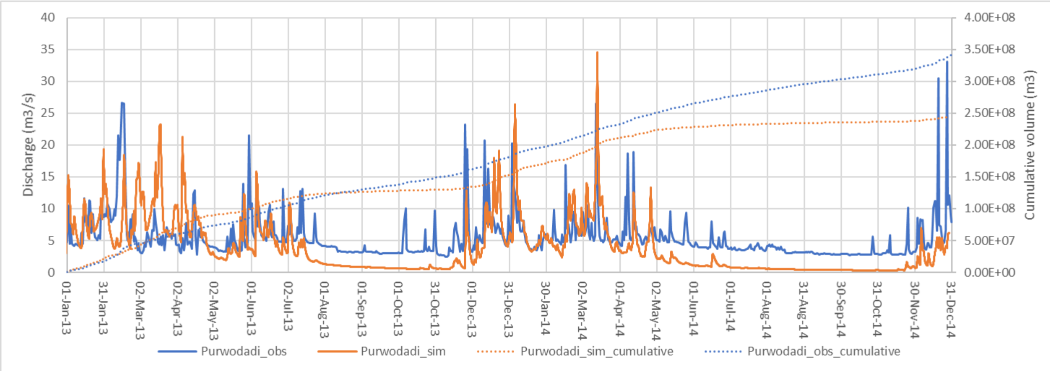


Figure 7-21 Comparison of registered and simulated 2013-2014 discharges and cumulative volumes for station Purwodadi, at the upstream boundary.

3.2.3 Scenario analysis – simulation of water levels with SOBEK

In order to analyse the effects of land use changes on peak water levels during flood events, the WFLOW model was used to estimate the peak discharge waves for the design rainfall events in the sub-catchments of the Welang river, for three scenario's (*past/2013*, *present/2020* and *future/2029*), for three return periods (T=1, 10 and 25 years), and for three rainfall event durations (6,12 and 24 hours). These discharge waves were then imposed on the SOBEK model as upstream boundary condition & lateral conditions. All calculations were carried out with downstream tidal boundaries based on the measured 2017 tidal signal, with a vertical shift to account for Sea Level Rise.

For the flood hazard analysis with the SOBEK model, we first evaluated which of the three rainfall events resulted in the highest water levels in the Welang river for every return period and could therefore be considered the most representative (normative) event. The results of this step are discussed in paragraph 6.2.1. Next, we simulated all combinations of return periods and scenarios for the normative event duration (Table 7) and evaluated how maximum water levels evolve over time (difference between past, present and future scenarios) for every return period (T=1, 10 and 25). By later comparing these results to local embankment levels (not represented properly in the present version of the model because this data was not available in time), it will be possible to evaluate weak spots in the flood defences along the river, as well as evaluate the effect of measures.

Table 7 Max discharge (in m3/s) imposed as upstream boundary of the SOBEK model as calculated with WFLOW for all analysed combinations of scenario's (past, present and future) and return periods (T = 1,10 and 25), for the 6-hourly events.

Scenario	T1	T10	T25
Past/2013	12.6	51.7	65.5
Present/2020	13.2	56.0	72.8
Future/2029	16.5	65.4	83.1

4 Results

4.1 WFLOW results

4.1.1 Model calibration & validation

In this section, the approach to do wflow modelling calibration and validation is described. Here it is important to note that WFLOW initially needs to be calibrated and validated by making use of the spatially interpolated rain gauge data. This is done because local data should be off better quality than the satellite products and should be able to capture local rainfall in the basin. Nevertheless, it is also important to note that due to only 11 stations that is used to account spatial variation in rainfall, this could easily lead to an overestimation and underestimation of rainfall.

5 Model Calibration

This section describes the procedures that need to be taken to calibrate wflow model. Looking at the available dataset, it was decided that the period of analysis should be done when all datasets overlapped with each other and when the rainfall and discharge data strongly correlates. The rain data used in the model calibration process is rain data measured at the ground that has been spatially interpolated with Thiessen Polygon method. The selected period for model calibration is year 2013 to 2014 with focus at Purwodadi station.

The model calibration is done by repetitively changing one model parameter at a single model run until a good fit between simulated discharge and observed discharge is achieved. Visual appraisal is used to determine whether the model has a good fit with the observed discharge. Although there are many skill scores that can be used to represent the accuracy of the calibrated model, in this project these skill scores are not used as it will give a poor result due big difference at the low flow. The result of model calibration at Purwodadi Station in 2013-2014 is shown in Figure 7-22.

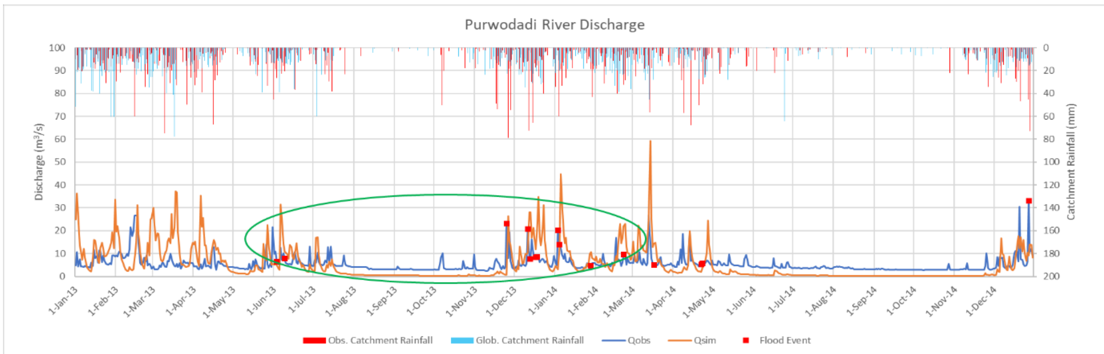


Figure 7-22 Result of Model Calibration at Purwodadi Station 2013-2014 (Qsim = Using Rain Gauge Data)

From calibration activity, the parameter that is sensitive to the simulated discharge are vertical saturated conductivity (KsatVer), horizontal saturated conductivity (KsatHorFrac) and the decay rate of vertical saturated conductivity against soil depth (M). Here the calibration process mainly focusses on getting the peak flow as much as possible when the rain is also captured by rain gauges. To get the simulated discharge as seen in Figure 7-22, KsatVer needs to be multiplied by 2 from its default value whereas M parameter needs to be multiplied by 3 from its default value.

6 Model Validation

In order to make sure that the calibrated model could already represent the condition of Welang Basin, model validation is carried out. Similar with model calibration, rain data infused to the model is rain data measured at the ground that has been spatially interpolated with Thiessen Polygon. Here, Selowongko station is selected to validate the model as there is no discharge measurement for Purwodadi on the year 2018-2019. Model validation is done by comparing the simulated discharge value of Selowongko station with the measured discharge.

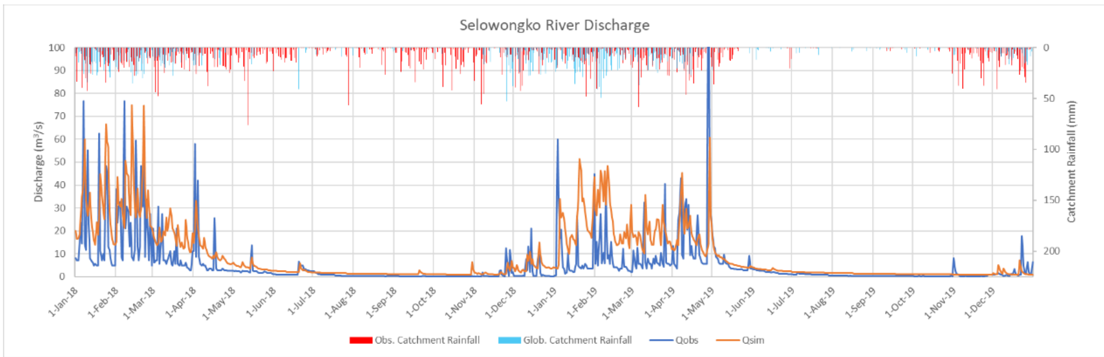


Figure 7-23 Result of Model Validation at Selowongko Station 2018-2019 (Qsim using Rain Gauge Data)

6.1.1 Scenario analysis

From the WFLOW model result the peak discharges under different return periods were estimated. It is estimated that the changes in land cover in the past decade have resulted in peak discharges that are now about 5-10% higher (Figure 7-24) compared to 2013 conditions. Observed discharges in 2006 and 2013 confirm that this trend has been going on for some time.

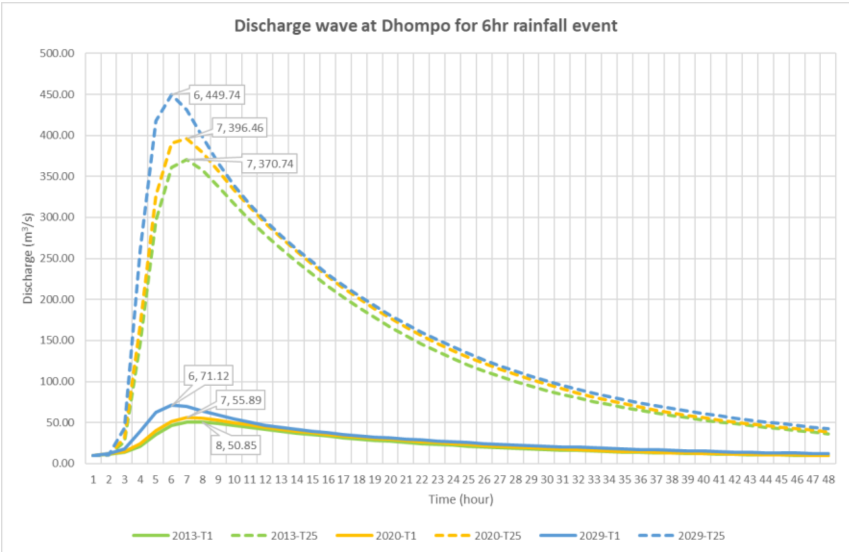


Figure 7-24 Discharge waves have significantly changed due to upstream land-conversion

From Figure 7-24 it is known that land-cover conversion also makes the peak discharge comes faster from time to time. Estimated peak discharge under different return period for the three stream gauges can be seen at Table 8 to Table 10. From the model, it is also known that the present peak may still increase up to 40% of current peak discharge if land use change will continue as planned in the RTRW 2029. Nevertheless, the future scenario result should not be used as is because the 2029 scenario is a reasonable estimate that the modeler uses to approach doubled paved area in <10yrs which is quite unrealistic. Therefore, this 2029 land cover, and the results, can only be used to give an insight in possible future run-off rates, but should not be used for any designs of protection measures. WFLOW results for other locations under different land cover scenario and return period scenario are provided in **WFLOW Discharges** section.

Table 8 Estimated Peak Discharge Under Different Return Period and Land Cover Scenario at Dhompo

Return Period	Past (2013)	Present (2020)	Future (2029)	Rel.Dif Past vs Present	Rel.Dif Present vs Future	Rel.Dif Past vs Future
T1	50.85	55.89	71.12	10%	27%	40%
T10	282.95	296.54	340.81	5%	15%	20%
T25	370.74	396.46	449.74	7%	13%	21%
T100	524.49	549.71	624.11	5%	14%	19%

Table 13 Estimated Peak Discharge Under Different Return Period and Land Cover Scenario at Selowongko

Return Period	Past (2013)	Present (2020)	Future (2029)	Rel.Dif Past vs Present	Rel.Dif Present vs Future	Rel.Dif Past vs Future
T1	25.62	28.07	39.25	10%	40%	53%
T10	154.39	162.82	195.78	5%	20%	27%
T25	205.09	221.37	261.01	8%	18%	27%
T100	293.45	310.45	365.55	6%	18%	25%

Table 10 Estimated Peak Discharge Under Different Return Period and Land Cover Scenario at Purwodadi

Return Period	Past (2013)	Present (2020)	Future (2029)	Rel.Dif Past vs Present	Rel.Dif Present vs Future	Rel.Dif Past vs Future
T1	18.02	19.43	24.35	8%	25%	35%
T10	94.76	100.02	112.78	6%	13%	19%
T25	123.29	133.37	147.53	8%	11%	20%
T100	173.28	184.60	202.95	7%	10%	17%

Considering the various existing government plans and the economic development trends, it is expected that in the next 10 years, land conversion in these areas will continue. This will lead to higher peak discharges. It is estimated that peak discharges of about 300m^3/s, which used to have a return period of about 12-15 years in 2013, will likely occur on average once every 7 years towards 2029 (Figure 7-25). Figure 7-25 shows that downstream floods will be more frequent if land conversion continues.

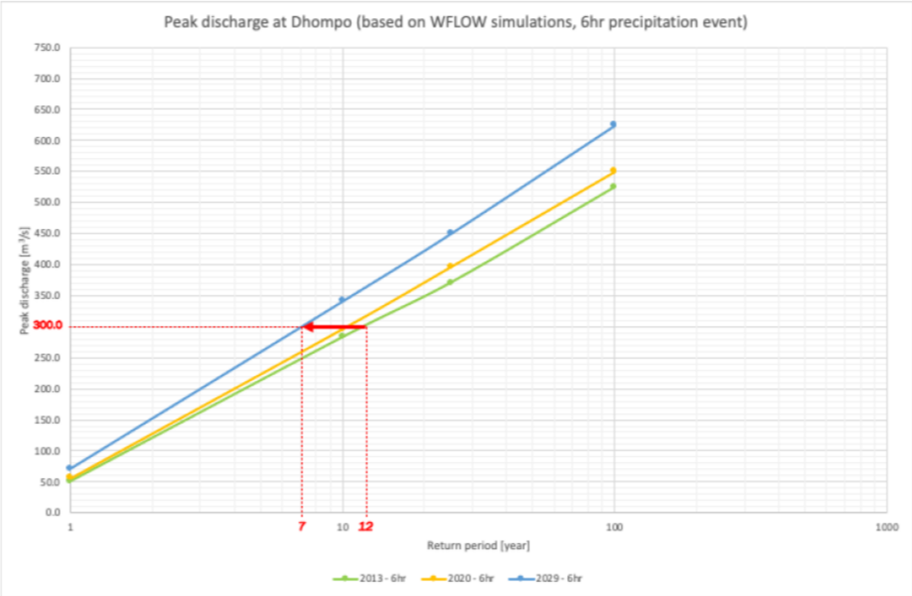


Figure 7-25 Return periods of peak discharges for past (2013), current (2020) and future (2029) land cover conditions

6.2 SOBEK results

6.2.1 Duration of normative rainfall event

Figure 7-26 shows the maximum water levels over the last 20 km of the Welang river for the present situation (2020) for a return period of 10 years (T10) for the 6-hourly event. When comparing these levels to the maximum levels of the T10 12-hourly and 24-hourly events (Figure 7-27), it can be concluded that the 6-hourly event leads to the highest water levels along the entire reach. This is to be expected, given the small Welang catchment size and corresponding travel times from upper catchment to river mouth. Similar results (not shown here) are found for the other return periods. We therefore conclude that the rainfall event of 6 hours is the representative event for this study, making it unnecessary to further analyse the events with a longer duration (12/24 hours).

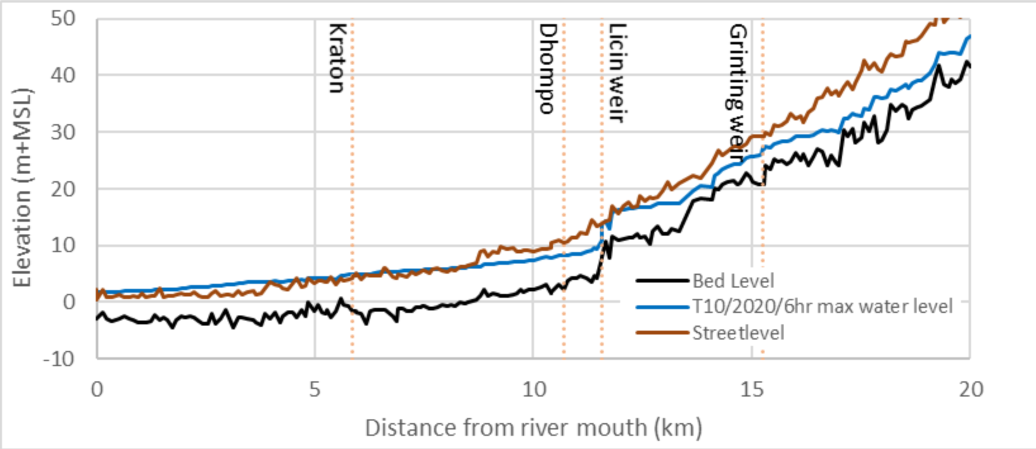


Figure 7-26 Welang river maximum water levels for T10 6-hourly rainfall event for the present situation (2020). Flood prone locations along this section (Kraton, Dhompo, Licin weir and Grinting Weir) are indicated with orange dashed lines.

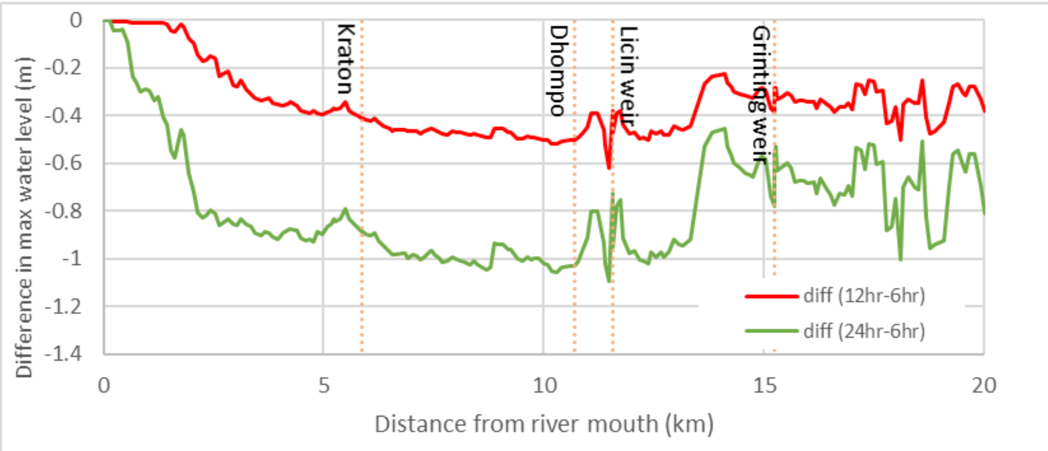


Figure 7-27 Maximum water levels for the T10 present situation 12-hourly and 24-hourly events, expressed as the difference with the 6-hourly event (12-hourly minus 6-hourly and 24-hourly minus 6-hourly, respectively).

6.2.2 Scenario analysis

T1 results

Figure 7-28 shows the maximum water levels for the present situation (2020) for a return period of 1 year (T1) for the normative (6-hourly) event. The longitudinal view shows the river bed in black, and in brown the street level (defined in SOBEK as the highest value of the left and right embankment levels in the YZ cross section tables).

Note that the actual left- and right embankment levels were not properly included in the HEC-RAS 2012 and 2017 models and are therefore also lacking in the SOBEK model. This makes it impossible to directly compare simulated maximum water levels to embankment levels in SOBEK. However, the maximum water levels can be extracted from the SOBEK model and compared to actual embankment levels as soon as these become available in an appropriate (GIS) format.

Figure 7-29 shows the evolution of maximum T1 water levels from 2013 to 2020 to 2029. Present/2020 T1 water levels are about 10 cm higher between Kraton and Dhompo than Past/2013 water levels. This difference is caused by a combination of land use changes (generally leading to faster runoff) and SLR in the downstream 5 kms. Future/2029 T1 water levels are about 45 cm higher than Present/2020 levels, which is significantly larger than the difference between 2013 and 2020. This indicates that the yearly increase in T1 max levels is accelerating, fuelled by a combination of expected land use changes and increase in rainfall the coming years.

Maximum water levels at the flood prone locations (Kraton, Dhompo, Licin weir and Grinting weir) for the different return periods and scenarios were analysed separately, see **Results at flood prone locations** section.

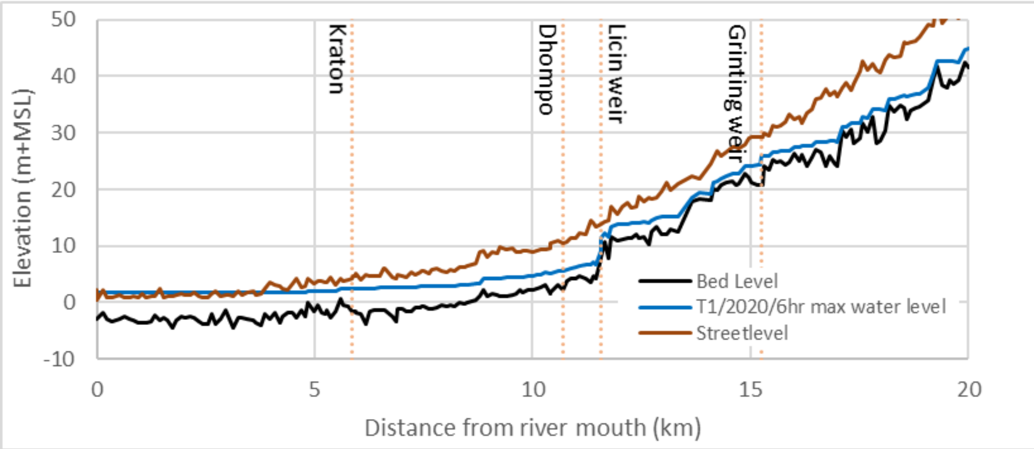


Figure 7-28 Maximum water levels for T1 flood event, present situation (2020)

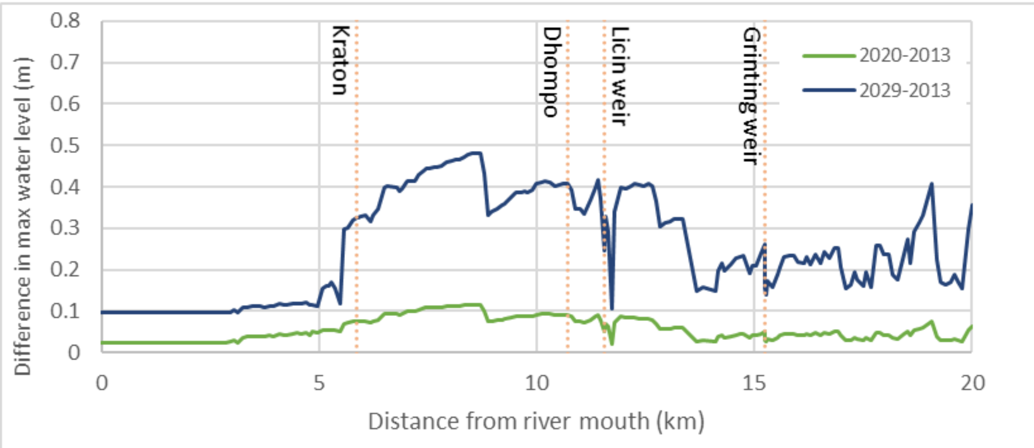


Figure 7-29 Maximum water levels for the T1 flood event, present situation (2020, in green) and future situation (2029, in blue), expressed as the difference with the past situation (2013). This graph therefore shows the evolution of the maximum T1 water levels evolve from the past => present => future scenario.

T10 results

The maximum water levels for the present situation (2020) for a return period of 10 years (T10) for the normative (6-hourly) event were already shown in Figure 7-26. Compared to the corresponding T1 event (Figure 7-28), the location where the graph of maximum water level intersects with the street level has shifted upwards from about 4 kms from the river mouth to about 8 kms, indicating that the flood prone zone is about twice as long for T10 compared to T1.

The evolution in maximum T10 water levels from 2013-2020-2029 resembles the evolution for T1 levels: between 2013 and 2020, max levels between Kraton and Dhompo increase by around 10 cm. From 2020 to 2029, max levels are estimated to rise by an additional 40 cm beween Kraton and Licin, indicating that the increase in T10 levels is accelerating in the near future.

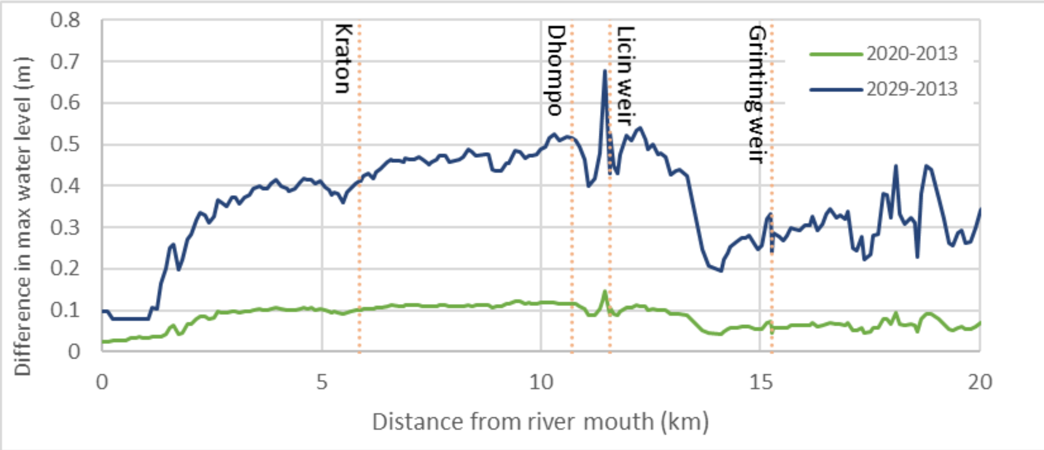


Figure 7-30 Maximum water levels for the T10 flood event, present situation (2020, in green) and future situation (2029, in blue), expressed as the difference with the past situation (2013). This graph therefore shows the evolution of the maximum T10 water levels evolve from the past => present => future scenario.

T25 results

Compared to the T10 event, the T25 flood event for the present situation leads to increased water levels especially between Kraton and Dhompo (Figure 7-31). Downstream of Dhompo, the effect of the increased discharge appears to be dampened by tidal backwaters.

Compared to the T1 and T10 events, the T25 flood shows a stronger increase in maximum levels from 2013 to 2020 (20 cm instead of 10) and from 2020 to 2029 (around 55 cm), suggesting that events with higher return periods are more heavily affected by changes in land use than smaller events.

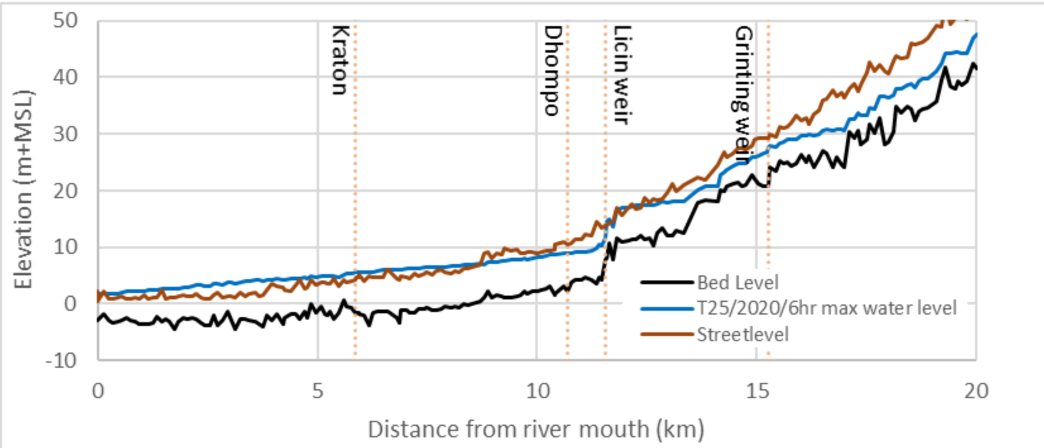


Figure 7-31 Maximum water levels for T25 flood event, present situation (2020)

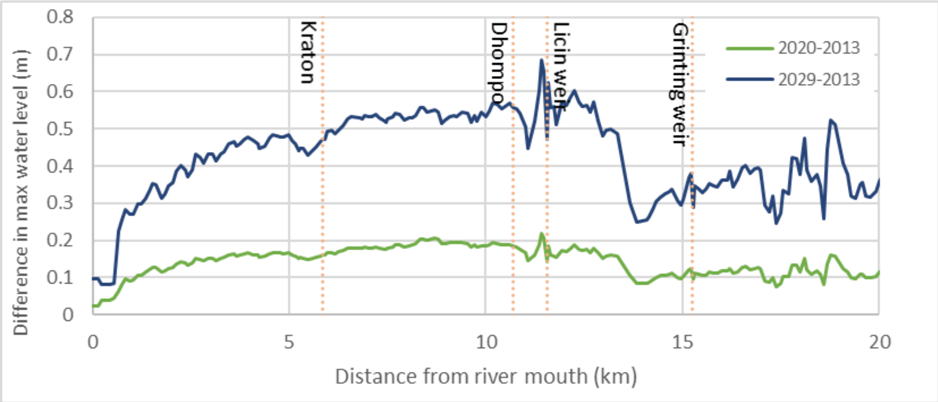


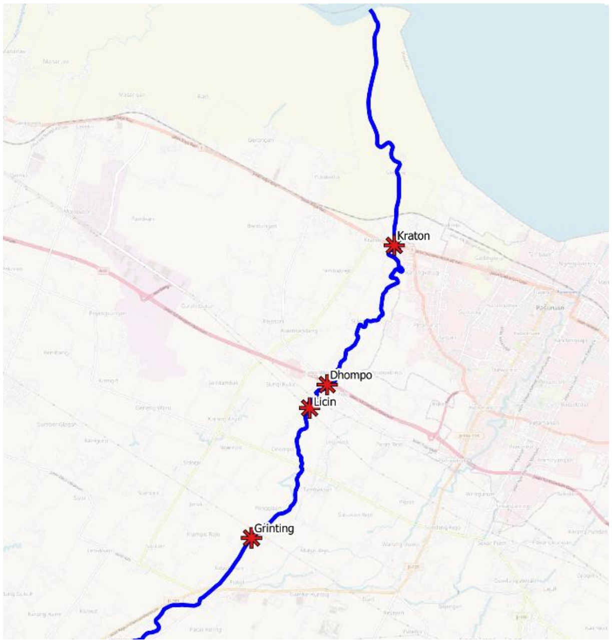
Figure 7-32 Maximum water levels for the T25 flood event, present situation (2020, in green) and future situation (2029, in blue), expressed as the difference with the past situation (2013). This graph therefore shows the evolution of the maximum T25 water levels evolve from the past => present => future scenario.

Results at flood prone locations

The maximum water levels at the four flood prone locations for all combinations of return period and scenario are summarized in **Error! Reference source not found.**. These values can be compared to local embankment levels (when available) to get an indication of flood hazards at these locations for the different scenarios. Note that the uncertainty in these results is significant due to the reasons in paragraph 3.2.2.

Table 15 Maximum water levels (m+MSL) at the four flood prone locations (Kraton, Dhompo, Licin and Grinting) for all combinations of scenarios (past, present and future) and return periods, for 6-hourly rainfall events.

Kraton	**T1**	**T10**	**T25**
2013	2.40	4.77	5.35
2020	2.47	4.87	5.51
2029	2.73	5.18	5.83
Dhompo	**T1**	**T10**	**T25**
2013	5.54	8.15	8.82
2020	5.63	8.27	9.00
2029	5.95	8.67	9.38
Licin	**T1**	**T10**	**T25**
2013	11.43	13.69	14.35
2020	11.50	13.80	14.53
2029	11.75	14.22	14.97
Grinting	**T1**	**T10**	**T25**
2013	25.92	27.16	27.53
2020	25.95	27.22	27.63



2029	26.08	27.42	27.85

Appendix B Groundwater modelling

iMOD-python

General description

The iMOD Python package is designed to help user in building MODFLOW groundwater model and its analysis. iMOD is an accelerated Deltares-version of MODFLOW with fast, flexible and consistent sub-domain modelling techniques. MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions. MODFLOW 6 is presently the core MODFLOW version distributed by the USGS (U.S. Geological Survey , 2021).

Aim

Pre-processing geohydrological raw data to a fully defined MODFLOW6 model, with the aim to make this process reproducible, and simulating and predicting groundwater conditions.

Wflow

General description

wflow is Deltares' solution for modelling hydrological processes, allowing users to account for precipitation, interception, snow accumulation and melt, evapotranspiration, soil water, surface water and groundwater recharge in a fully distributed environment (Deltares, 2021). WFLOW is a 1D model with fully distributed grid.

Aim

In this project, WFLOS is used to calculate groundwater recharge as input in groundwater model built in MODFLOW6.

iMOD-python

The iMOD approach allows gathering the available input data to be stored at its finest available resolution; these data don't have to be clipped to any pre-defined area of interest or pre-processed to any model grid resolution. Resolutions of parameters can differ and the distribution of the resolution of one parameter can also be heterogeneous. In addition, the spatial extents of the input parameters don't have to be the same. iMOD will perform up- and down scaling (Vermeulen, 2006) whenever the resolution of the simulation is lower or higher than that of the available data. iMOD-python can be found online in iMOD page (Deltares, 2021)

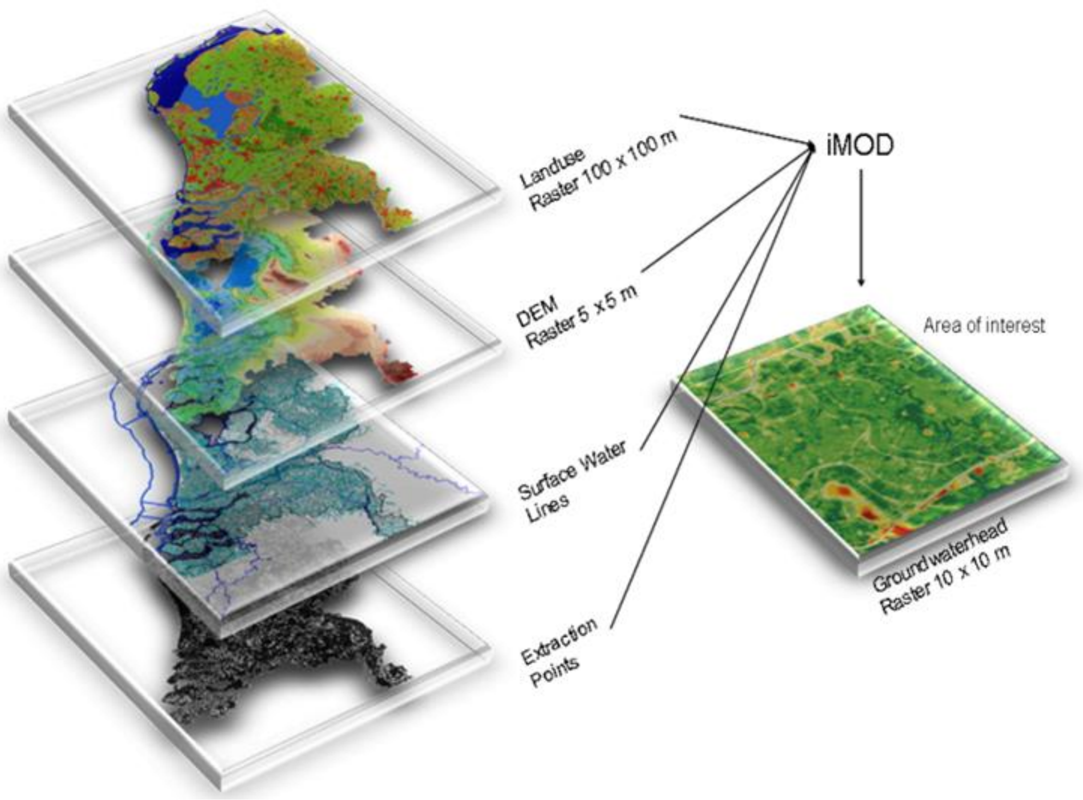


Figure 33: iMOD approach

Currently iMOD-python support the creation of the following MODFLOW-based models:

1. USGS MODFLOW 6 with the structured grids, and advanced stress packages has not yet been included (Lake Package, Multi-Aquifer Well Package Pane, Stream-Flow Routing, Unsaturated-Zone Flow Package).
2. iMOD-GUI that is an easy to use Graphical User Interface and an accelerated Deltares-version of MODFLOW with fast, flexible and consistent sub-domain modeling techniques. iMOD facilitates very large, high resolution MODFLOW groundwater modeling and also geo-editing of the subsurface.
3. iMOD-WQ which integrates SEAWAT (density-dependent groundwater flow) and MT3DMS (multi-species reactive transport calculations).

In this project we use iMOD python with USGS MODFLOW6 with the structured grids.

Modeling purpose

This modeling aim is to build Pasuruan groundwater model to analyze the effect of change in recharge related to

1. Change in land use
2. Change in abstraction rate
3. Climate change

We focus on the effect of land use change and abstraction rate change to the groundwater state instead of the prediction of the future scenario. For this research therefore, the assumptions used in land use change and abstraction rate does not have to be fully representing the future scenario, but the direction on which land use and abstraction rate may be developed in the future.

Study Area

The study area in this project is the Pasuruan Groundwater Basin as defined in Ministerial Decree Directorate General of Mineral and Coal Number 02 Year 2017 about Indonesian Groundwater Basin (Directorate General of Mineral and Coal, 2017).

Modelling Approach

In this project we use iMOD-python as a tool to build MODFLOW6 groundwater model and running its simulation. We choose iMOD python instead of iMOD-GUI to make it easy to process the raw data and organize it to a fully defined MODFLOW model, with the aim to make this process reproducible. Building a groundwater model, requires hydrogeological interpretation, recharge calculation, and interpretation of abstraction rate. That information is used to construct a groundwater conceptual model that was then translated into a discretized 3-D MODLOW6 model.

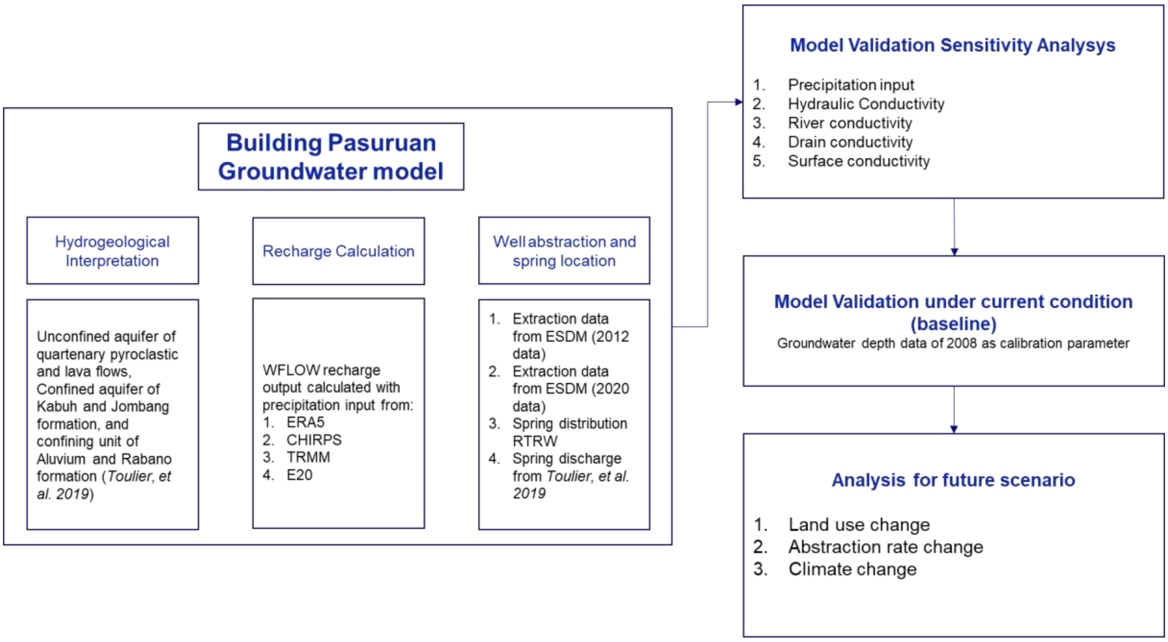


Figure 34: Modeling Approach

For model validation, we run our model with steady state run for the year 2013. We choose the year of 2013, because Welang WFLOW model, in which we calculate recharge was calibrated for this year and deep groundwater extraction data is available. Prior to the validation, we test sensitivity of the model to precipitation input, Hydraulic Conductivity, River conductivity, Drain conductivity, and Surface conductivity. We did the sensitivity analysis run with steady state run for the year 2013. For the analysis of future scenario under land use change, abstraction rate change, and climate change, we run the model for transient monthly simulation using the monthly average recharge as input. We use the average monthly recharge instead of daily recharge for the sake of computational efficiency as the groundwater head change is not a simultaneous process that may vary greatly in daily timestep. Therefore, the monthly average recharge is more suitable.

1. Model validation

As part of model validation, we test the sensitivity of the model with change in:

1. Precipitation input

- Precipitation input is used as input in WFLOW. Different precipitation input may lead to different calculated recharge value, hence, further lead to difference in calculated groundwater head. We use different input datasets in WFLOW to test the difference in recharge and further in groundwater head between:

    - ERA5 dataset
    - CHIRPS dataset
    - TRMM dataset
    - E2O dataset

  Based on ERA5 precipitation, average daily recharge is 0.74 mm and total daily recharge is 5500 mm

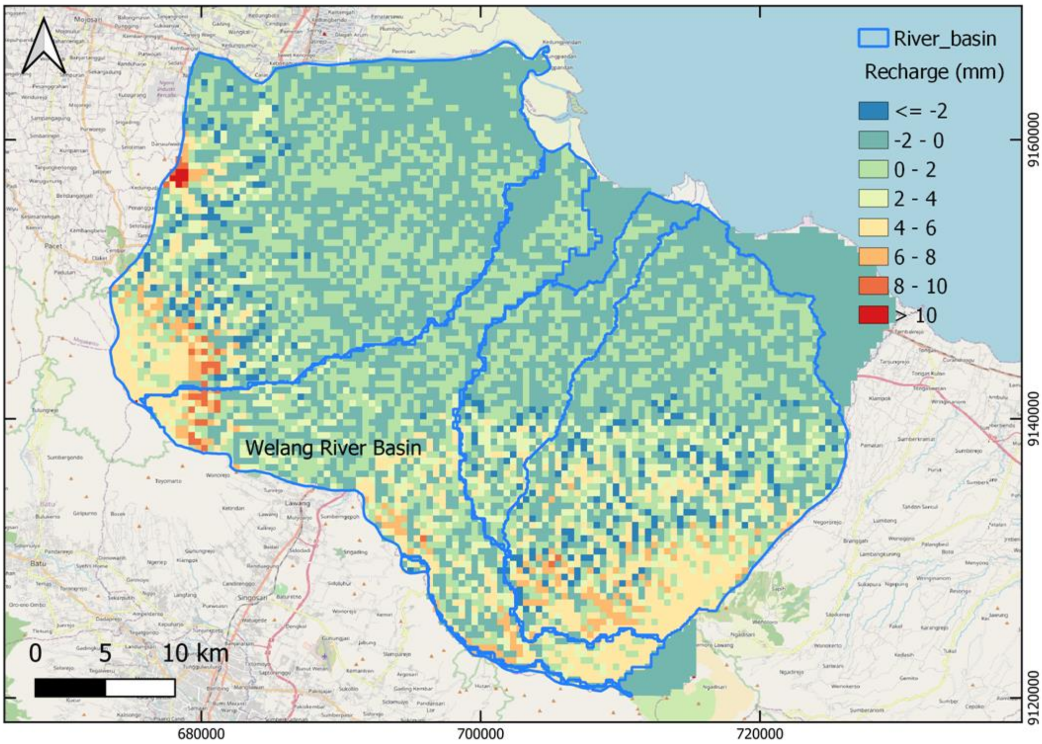


Figure 35: Recharge value for year 2013 calculated with precipitation input from ERA5 dataset

2. Hydraulic conductivity value

- Hydraulic conductivity value is needed to calculate the water flow between cells in MODFLOW6 grid. Hydraulic conductivity of the material can be defined as the ability of the fluid to pass through the pores and fractured rocks (Saravanan, Parthasarathy, & Sivaranjani, 2019). The higher the hydraulic conductivity the more easily water pass through the materials. There is limited available data of observed hydraulic conductivity value for each lithology found within the project area. Therefore, we use the hydraulic conductivity value range for each lithology that was found in literature. To choose the best value that is corresponds to the best simulated head, we did the hydraulic conductivity value sensitivity analysis.

3. River conductivity value

- River conductivity value is assigned to the river location to further calculate flux between river and aquifer using RIV package in MODLFOW (The United States Geological Survey). River conductivity value is the hydraulic conductance of the interface between the aquifer and river. The higher the conductivity value, the easier the water flows from the aquifer to the river. As there is no available data of the observed river conductivity value, hence we did river conductivity sensitivity analysis to choose the best river conductivity value that results in best simulated head.

4. Drainage conductivity Value

- Drainage conductivity value is assigned to the drainage network to further calculate drainage with drainage package in MODLFOW (The United States Geological Survey, 2020). Drainage conductivity value is the hydraulic conductance of the interface between the aquifer and the drainage network. The higher the conductivity value, the easier water flows from the aquifer to the drainage network. As there is no available data of the observed drainage conductivity value, hence we did drainage conductivity sensitivity analysis to choose the best drainage conductivity value that results in best simulated head.

5. Surface conductivity value

- Surface conductivity value is assigned to the surface elevation to further calculate drainage (overland flow) with drainage package in MODLFOW (The United States Geological Survey, 2020). Surface conductivity value is the hydraulic conductance of the interface between the aquifer and the land surface. The higher the conductivity value, the easier water flows from the aquifer to the surface. As there is no available data of the observed surface conductivity value, hence we did surface conductivity sensitivity analysis to choose the best surface conductivity value that results in best simulated head.
- Spring is also a form of drainage with the high discharge of water from aquifer through the low resistance surface. We assume that the surface where the spring is presents has the higher conductivity value. As there is no available data of the observed spring conductivity value, hence we did spring conductivity sensitivity analysis to choose the best spring conductivity value that results in best simulated head.

2. Analysis of the future scenario

As our goal is to analyze the effect of change in recharge to the change in groundwater state, we then analyze the effect of change in recharge to the groundwater head and spring discharge under:

1. Land use change

- We compare 3 different land use datasets:
    - Land use 2013
    - This land use dataset was based on the interpretation of satellite image of Pasuruan area in 2013. We use the same land use change scenario as land use scenario in WFLOW.
    - Land use 2020
    - This land use dataset was based on the interpretation of satellite image of Pasuruan area in 2020. We use the same land use change scenario as land use scenario in WFLOW.
    - Estimated land use 2029
    - This land use dataset was based on the planning document for Pasuruan Area for the year 2029 (Pasuruan Regency Government, 2010). We use the same land use change scenario as land use scenario in WFLOW.

- As the land use change scenario in 2020 and 2029 was only calculated for Welang river basin, we extrapolated the recharge change due to land use change, to the whole Pasuruan groundwater basin.

Table 16: Percentage of recharge with different land use input relative to recharge in 2013

Month	land use 2020 (%)	land use 2029 (%)
jan	100.0	99.5
feb	99.9	99.5
mrt	99.6	98.9
apr	100.5	100.2
mei	97.8	94.7
jun	100.7	101.2
jul	99.8	98.9
aug	98.5	93.3
sep	97.7	88.4
okt	97.8	89.6
nov	98.9	96.2
dec	99.5	97.0

-
- We assume that the precipitation input was the same for each land use change scenario, so the change in groundwater head can be exclusively attributed to land use change. This analysis does not aim to fully capture the groundwater condition in 2020, and 2029 as compared to the 2013 condition. However, this analysis aims to see exclusively the change in groundwater state if the land use is the only factor that changes from 2013 to 2020, and further to year 2029. This approach will not capture the full change in groundwater state as there must be more factor that changes from 2013 to 2029 like groundwater abstraction and climate change. However, this kind of approach can give information to the decision maker about the land use change planning effect on the future fate of groundwater state.

2. Abstraction rate change

- We compare 3 different abstraction datasets:
    - Abstraction rate 2013
    - The deep abstraction rate was based on the data of industrial abstraction rate for the year 2012 (Directorate General of Mineral and Coal of East Java Province, 2012), and the shallow abstraction rate was based on the total domestic water demand that was not fulfilled by the municipal water authority (PDAM; Perusahaan Daerah Air Minum).
    - Abstraction rate 2020
    - The deep abstraction rate was based on the data of industrial abstraction rate for the year 2020 (Directorate General of Mineral and Coal of East Java Province, 2020), and the shallow abstraction rate was based on the total domestic water demand that was not fulfilled by the municipal water authority.
    - Estimated abstraction rate 2029
    - The deep abstraction rate was based on the projection of the industrial abstraction growth for the year 2029, and the shallow abstraction rate was based on the projected total domestic water demand that was not fulfilled by the municipal water authority in year 2029.

The location of the shallow well cluster per district is assumed to be located in the urban area of each District. Total domestic groundwater demand was calculated based on domestic demand standard in Water Resources Management Plan in Welang Rejoso River Basin 2013 (Pola Pengelolaan Sumber Daya Air Wilayah Sungai Welang Rejoso 2013)

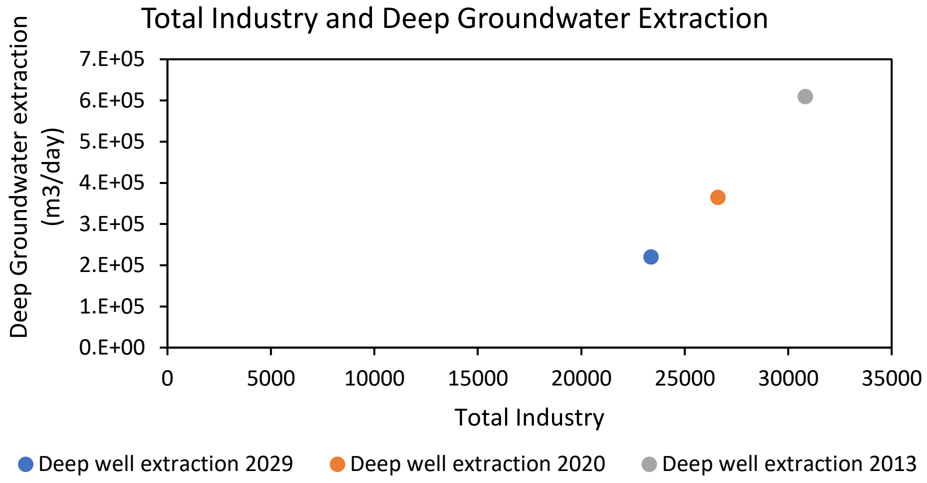


Figure 36: Total deep groundwater extraction

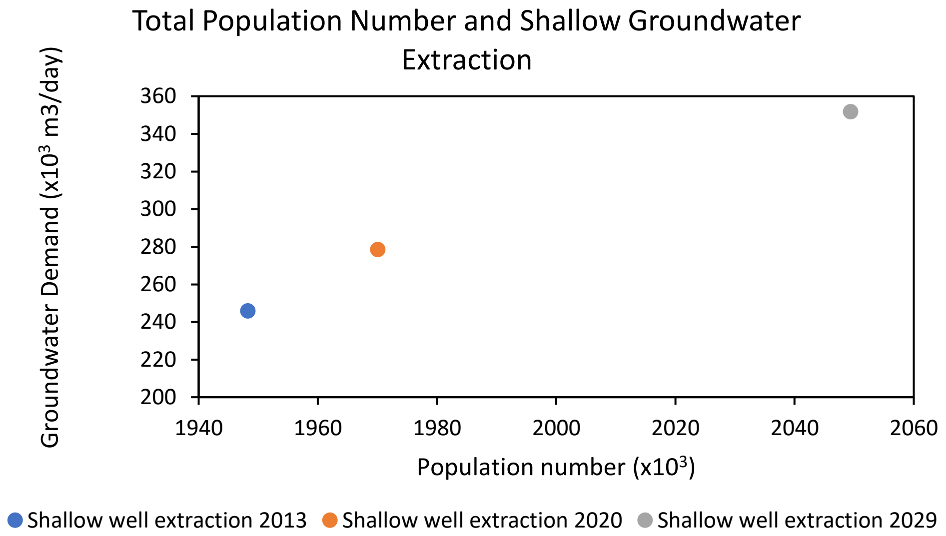


Figure 37: Total shallow groundwater extraction

- This approach is also not intended to fully capture the groundwater condition in 2020 and 2029 relative to the groundwater condition in 2013, however to estimate the scale of groundwater drop with the increase of groundwater extraction. The information from this analysis can be used by the decision maker to plan the future water supply sytem and extraction permission regulation.

3. Climate change

- As there is limited data and information about the projected climate change in the Pasuruan area, we test the effect of reduced precipitation with:
  - 90% precipitation
  - 80% precipitation

  This approach is also not intended to fully capture the groundwater condition in the future, however to estimate the scale of groundwater drop with the selected precipitation reduction. This analysis can serve as the base for the planning of sustainable water supply plan.

Model input

1. Groundwater Basin Boundary

Pasuruan groundwater basin boundary was obtained from official Indonesian Groundwater boundary (Directorate General of Mineral and Coal) and is used as the boundary of iMOD groundwater model.

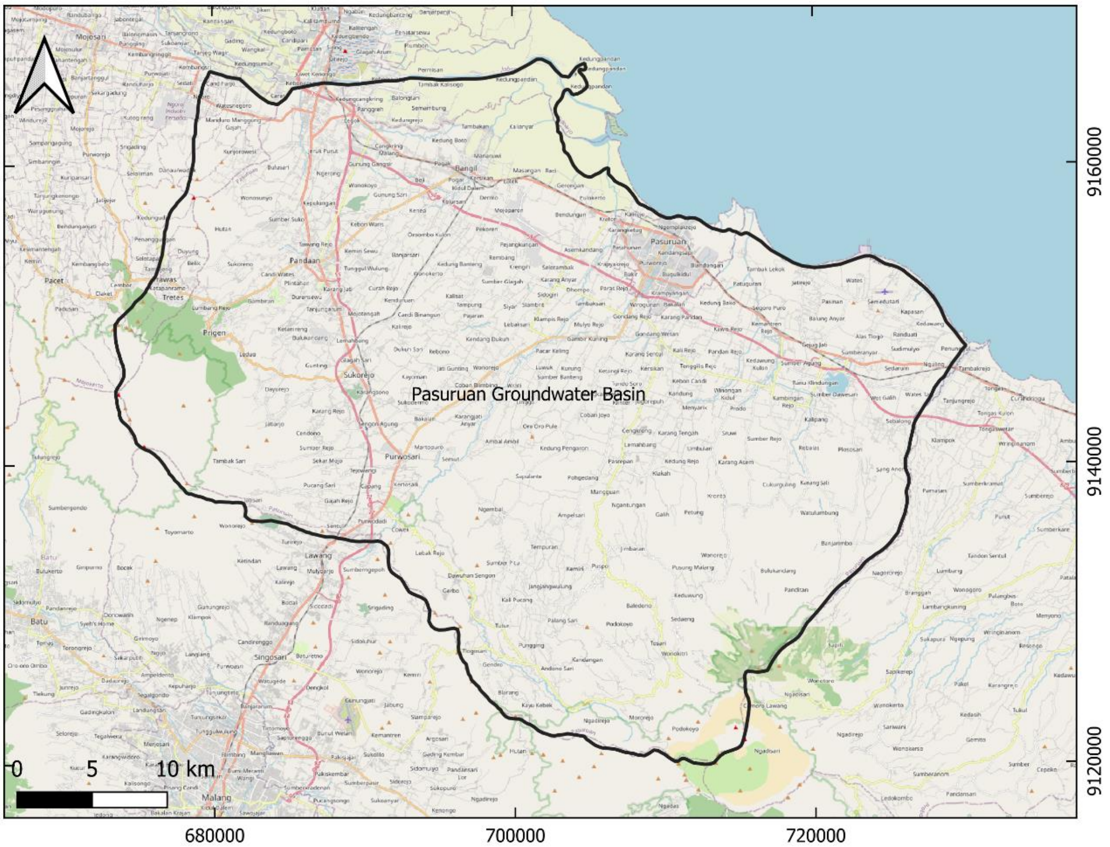


Figure 38: Groundwater basin boundary

2. Elevation model

Elevation model was obtained from National Digital Elevation Model (DEMNAS) (Indonesian Geospatial Information Agency). The National DEM is built from several data sources including IFSAR data (5m resolution), TERRASAR-X (5m resolution) and ALOS PALSAR (11.25m resolution), by adding the stereo-plotting Masspoint data. The spatial resolution of DEMNAS is 0.27-arcsecond, using the EGM2008 vertical datum (Geospatial Information Agency of Indonesia, 2021).

The area of interest covers two mountainous areas; Bromo and Arjuno Welirang area, in the south part of the model, and low-lying plain in the north part of the model.

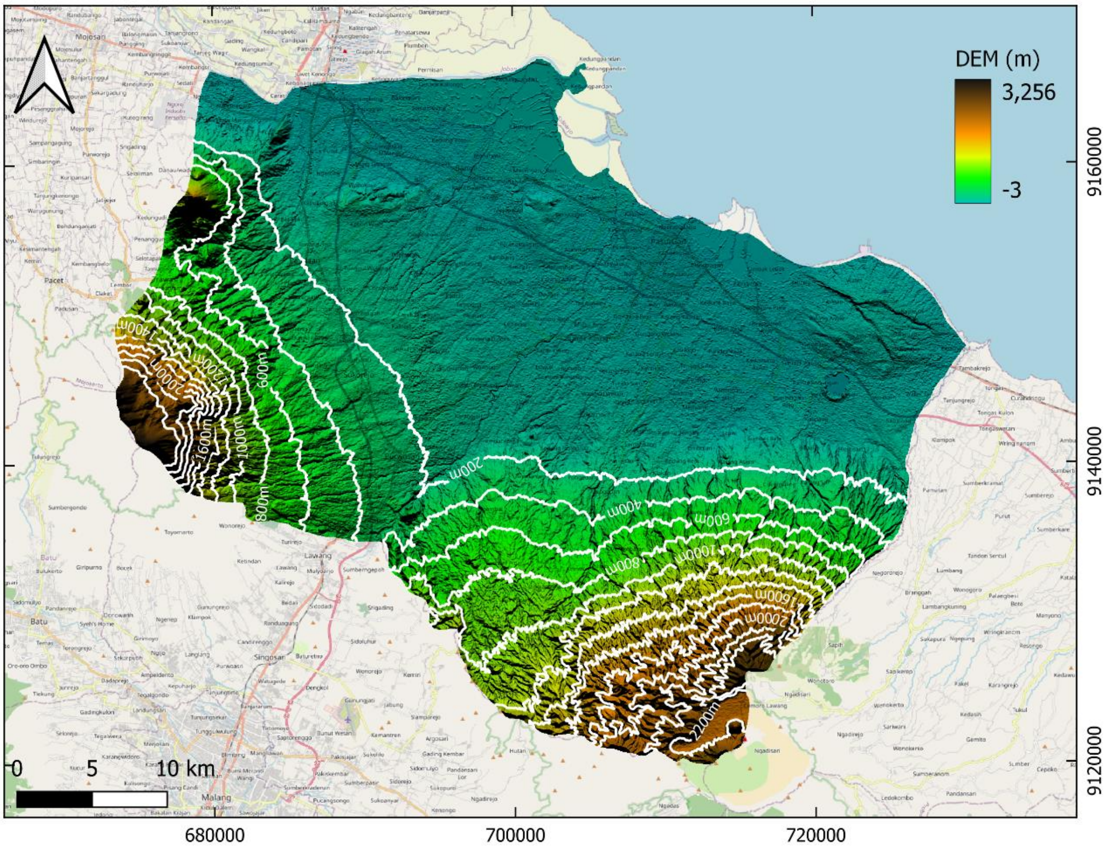


Figure 39: Digital Elevation Model of Project Area

3. *Geology map and hydrogeology information*

Geology map was obtained from official Indonesian geological map (Directorate General of Mineral and Coal). The geological information is then used to assign the hydraulic conductivity values to each unit.

Table 17: Geological lithology found in project area

Name of Unit	Description	Stratigraphic Relationship
Alluvium	pebble, gravel, sand, clay, mud	Conformably overlies the older unit such as the Kabuh and Jombang Formation.
Rabano Tuff	Sandy tuff, pumiceous tuff, tuffaceous breccia and ash tuff	Conformably overlies the older unit such as the Kabuh and Jombang Formation.
Upper Quarter	Volcanic breccia, lava, tuff, tuffaceous breccia, agglomerate and lahars	Overlies the older volcanics
Arjuna Welirang Volcanics	Volcanic breccia, lava, tuffaceous breccia and tuff.	Overlies the older volcanics and is overlain by the Rabano Tuff, Malang Tuff and Penanggungan Volcanics.

Lower Quarter	Volcanic breccia, tuff, lava, agglomerate, lahar	Overlies the older volcanic
Tengger Volcanics	Sandy tuff, pumiceous tuff, ash, tuff and agglomerate	This formation overlain by the volcanic rock of upper Quarternary age
Middle Quarter	Volcanic breccia, tuff, lava, agglomerate, lahar	Overlies the older volcanics
Bromo Volcanics	Volcanic breccia, lava, tuff, tuff breccia and lahars, andesitic-basaltic compositions	Covers the Tengger Volcanics and interfingers with Tengger Volcanic Sands.

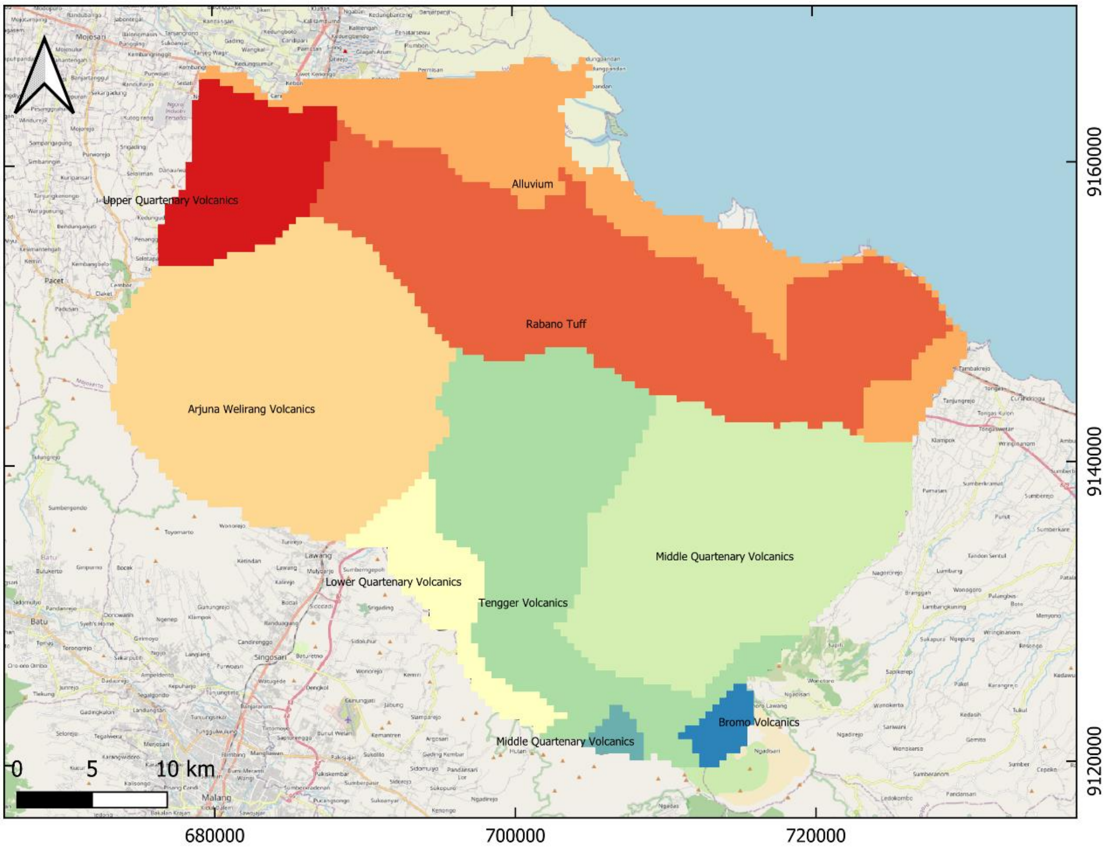


Figure 40: Geological map of project area (Directorate General of Mineral and Coal)

4. River network

River network was obtained from WFLOW model and was downscaled to the MODFLOW6 model resolution.

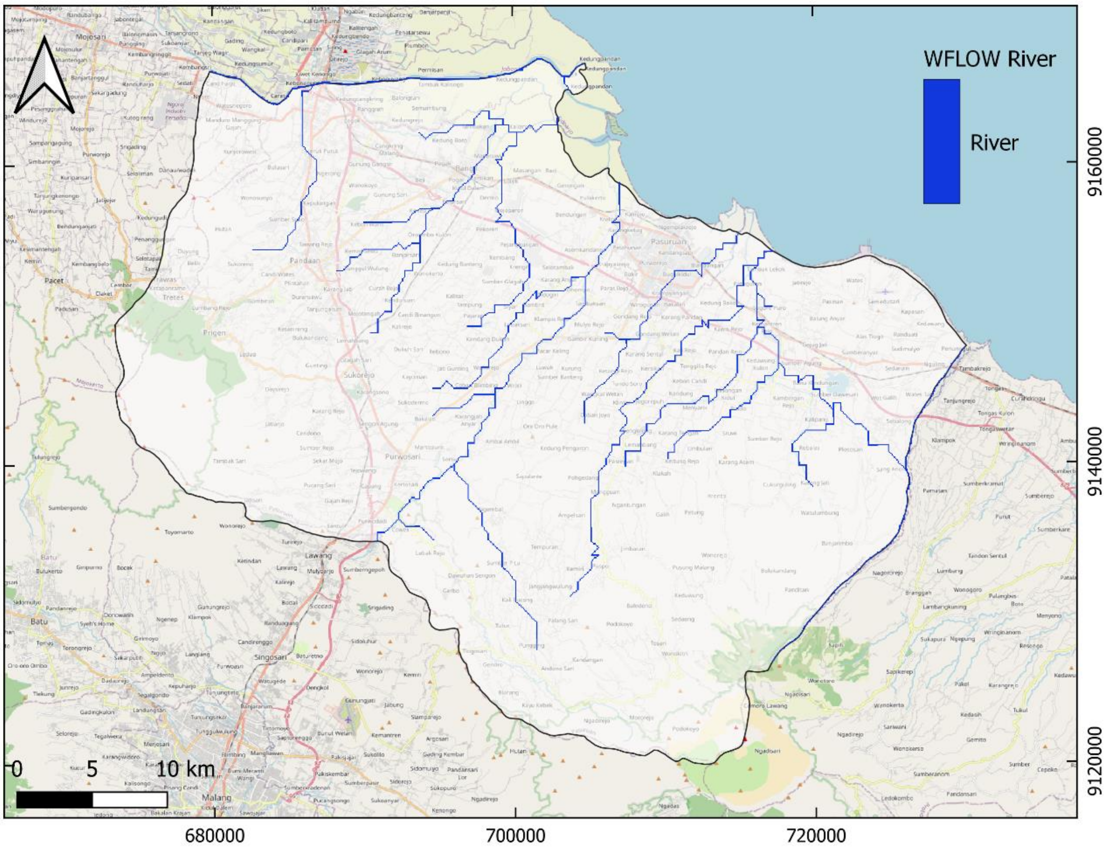


Figure 41: River network

5. Spring Location

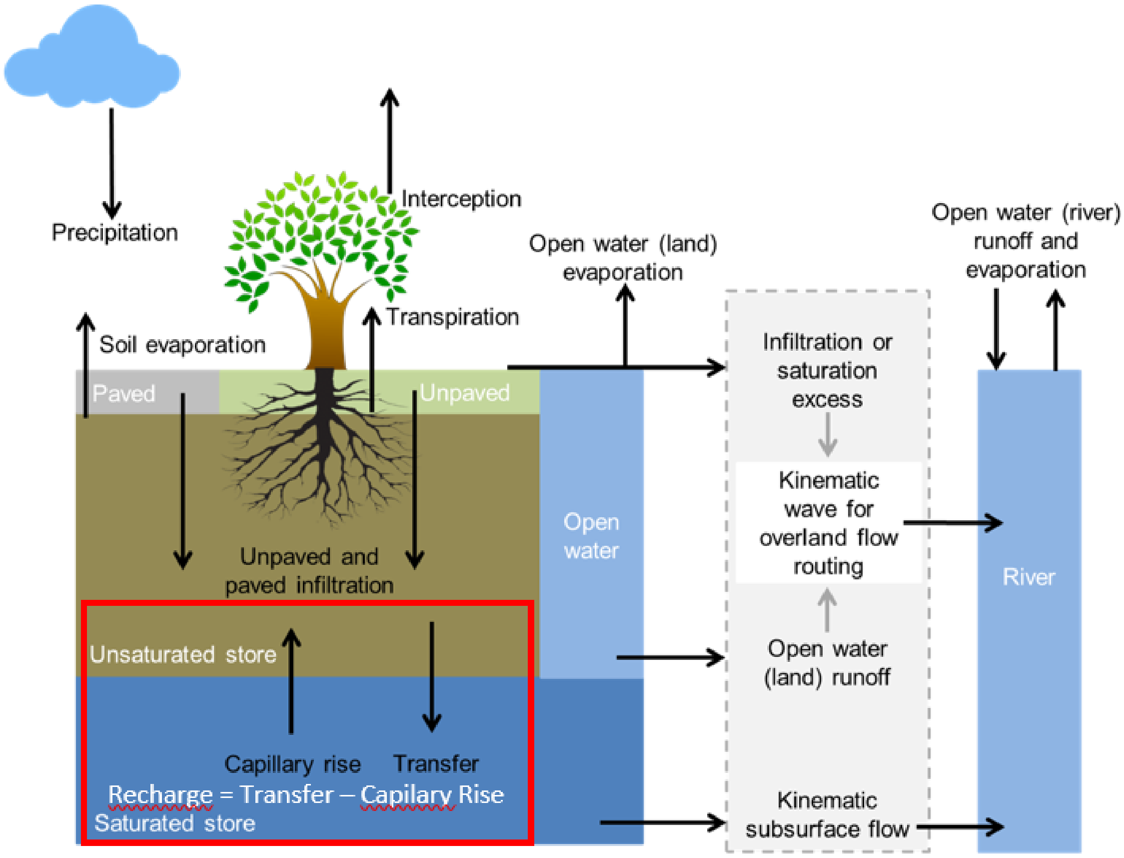
Spring location was obtained from official Spatial plans documents of Pasuruan Regency (Pasuruan Regency Government, 2010).

6. Drainage location

Drainage location was obtained from official Spatial plans documents of Pasuruan Regency (Pasuruan Regency Government, 2010).

7. WFLOW model

WFLOW is a distributed hydrologic model that make it possible to calculate the fluxes in a river basin; river discharge, evaporation loss, recharge, etc. In this project, we use WFLOW model to calculate recharge to be used as an input in MODFLOW6 model. WFLOW model built for this project has resolution of ~500 meters and was run in daily timestep.



Within Pasuruan groundwater model, there are 4 significant river basins. The WFLOW model has been calibrated for the year 2013 for Welang River Basin only.

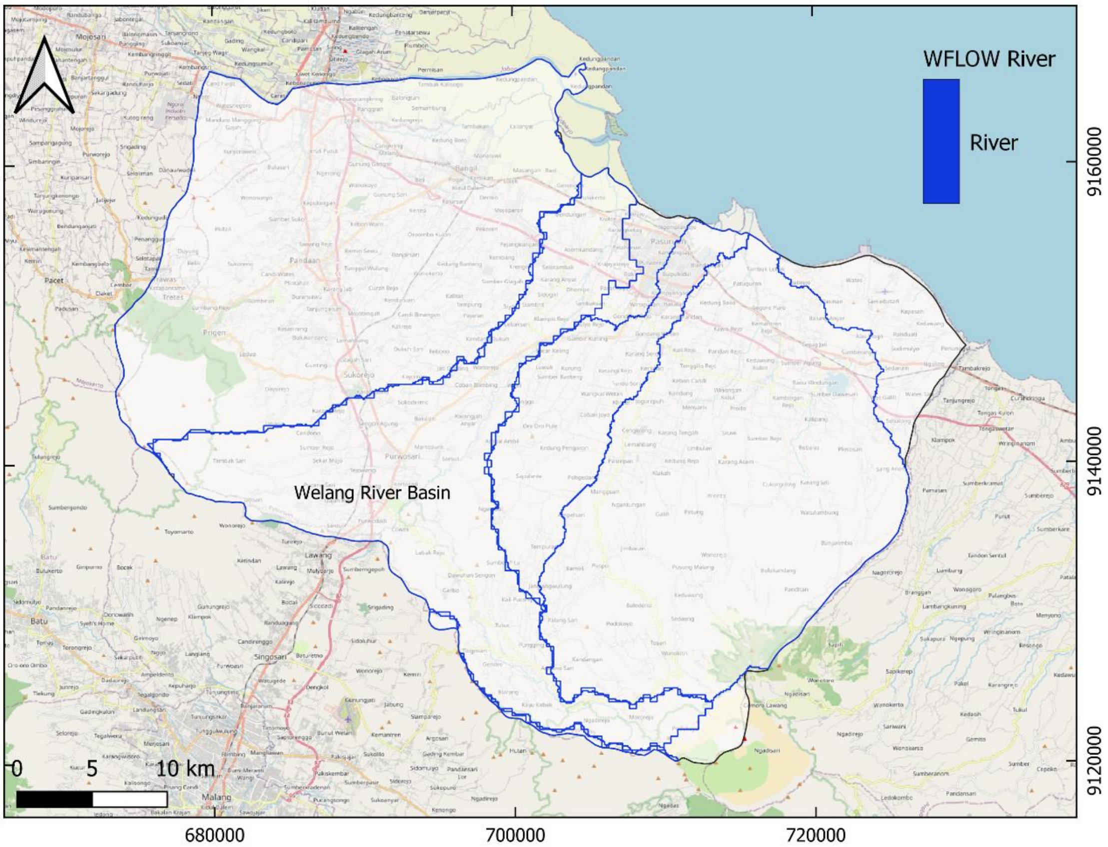


Figure 42: River basin in Pasuruan Groundwater Basin

8. Land use

We use similar land use data used in WFLOW model for the year 2013, 2020, and 2029.

9. Recharge

Recharge flux was obtained from WFLOW model output of each WFLOW river basin model. The simulated specified flux distributed over the top of the model is handled with Recharge package in Modflow6 (The United States Geological Survey, 2018).

10. Climate data

Climate data was used as input in WFLOW model, to further calculate recharge as input in iMOD. In this project, we use 4 different climate datasets. Dataset with higher temporal resolution than one day was downscaled with hydromt to temporal resolution of one day. hydroMT is a python package, developed by Deltares, to build and analysis hydro models (Deltares, 2021).

Table 18: Precipitation data used as input in WFLOW to calculate recharge

Satellite Products	Parameter	Original Spatial Resolution	Original Temporal Resolution	Spatial extent
ERA5	P	0.25 x 0.25 (~27 x 27 km)	Daily	Pasuruan Groundwater Basin

	PET	0.25 x 0.25 (~27 x 27 km)	Daily	Pasuruan Groundwater Basin
	Temp	0.25 x 0.25 (~27 x 27 km)	Daily	Pasuruan Groundwater Basin
E2O	P	0.25 x 0.25 (~27 x 27 km)	3 hourly	Welang River Basin
	PET	0.25 x 0.25 (~27 x 27 km)	Daily	Welang River Basin
	TEMP	0.25 x 0.25 (~27 x 27 km)	3 hourly	Welang River Basin
TRMM	P	0.25 x 0.25 (~27 x 27 km)	3 hourly	Welang River Basin
CHIRPS	P	0.05 x 0.05 (~5 x 5 km)	Daily	Welang River Basin

E2O, TRMM, CHIRPS and dataset only covers Welang river basin. Therefore, these datasets were upscaled to the whole Pasuruan groundwater basin, by analyzing the percentage of each climatic dataset relative to ERA5 dataset in Welang river basin.

Table 19: Percentage of precipitation relative to ERA5 precipitation

Month	E2O (% of ERA5)	TRMM (% of ERA5)	CHIRPS (% of ERA5)
jan	55.4	47.3	97.8
feb	72.8	86.6	97.0
mrt	73.8	68.9	83.5
apr	109.9	126.0	87.0
mei	99.3	127.1	98.5
jun	117.9	149.1	133.1
jul	116.4	181.4	160.5
aug	74.4	88.7	72.5
sep	161.8	151.3	138.9
okt	69.2	78.5	66.5
nov	73.5	100.2	71.0
dec	57.6	55.7	69.7

11. *Observed groundwater head*

As the WFLOW model has been calibrated for year 2013, the groundwater model was also calibrated for year 2013. Therefore, ideally, we 2013 groundwater head observation data is required. As the groundwater monitoring data is scarce, we use 2008 groundwater head observation for model calibration (Harnandi & Rengganis, 2010).

Table 20: Groundwater depth in Pasuruan Groundwater Basin for year 2008

Location	X	Y	2000	2008	Groundwater depth below surface (m)
Erindo Mandiri	682621	9151493	45.8	48	45.77
Tirta Bahagia	687814	9153966	5.5	9.8	5.49
Arto Toyo Utomo	687627	9155017	35	36.1	34.96
Kasrie Textile	686299	9155672	15.9	6.7	15.85
Sorini	686312	9159037	37.3	43.2	37.28
Aneka Tuna Indonesia	686570	9161003	10.3	11.6	10.26
Sun Chlorela	686471	9161213	43	49.7	43
Domosindo	688914	9161443	5.6	6	5.62
Sari R Indah	688869	9163794	6.1	19	6.05
Meiji	699004	9158890	6.6	9.8	6.63
Boma Bisma Indra	711511	9155113	4	2.4	3.95
PDAM 1	709248	9154281	4.7	3.6	4.69
PDAM 2	709243	9154267	7.2	4.8	7.15

Conceptual Model

1. Basic conceptual model interpretation

We built groundwater model based on our interpretation of the system that is simplified in our conceptual model. Our conceptual model criteria are as follows:

1. Four layers model based on hydrogeological interpretation
2. The top boundary of the model is surface level (DEMNAS) and is assumed as recharge boundary
3. The bottom boundary is at 350 m depth and is assumed as no flow boundary. Therefore, it is assumed that there is no vertical flux to the subsurface deeper than 350m.
4. The south boundary is a no flow boundary, as this boundary is a groundwater basin boundary with no groundwater flows from the adjacent groundwater basin.
5. The north boundary is a constant head boundary and is assumed as mean sea level.
6. The east and west boundary is no flow boundary, as this boundary is a groundwater basin boundary with no groundwater flows from the adjacent groundwater basin. For the first layer where river is present at the east and west side of the model however, river boundary is applied because there will be exchange flux between groundwater and river.
7. The cell size is ~80 m.

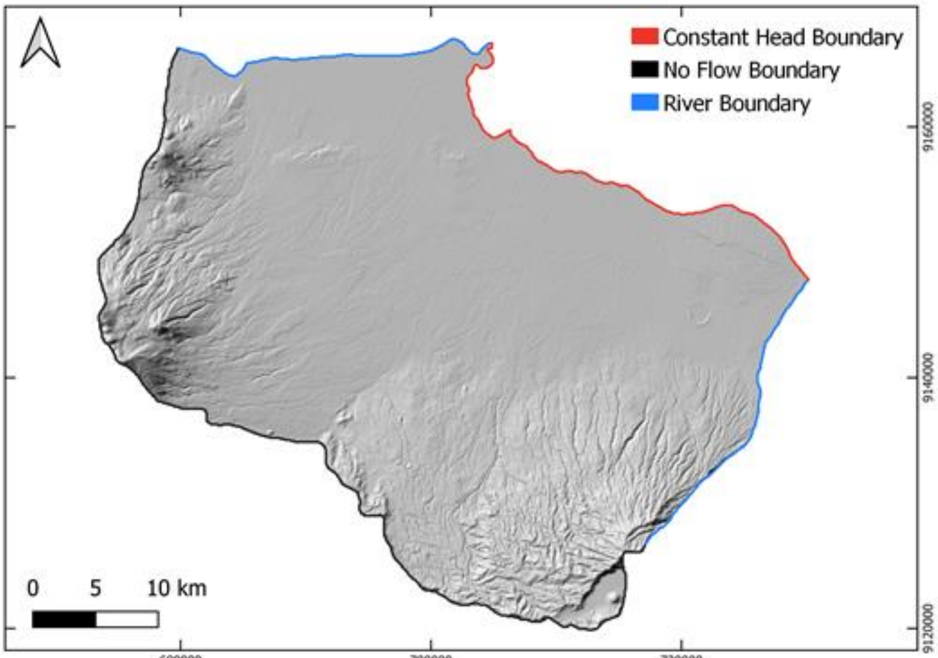


Figure 43: Boundary of the first layer in MODFLOW6 model

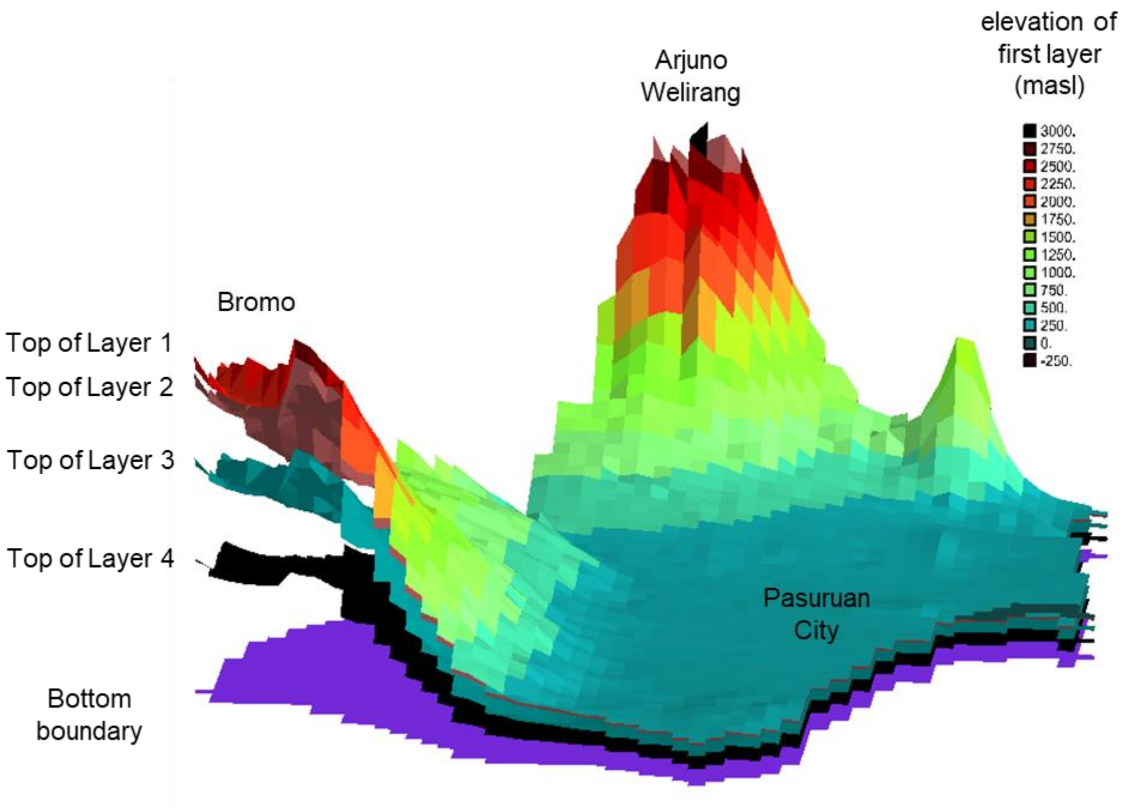


Figure 44: Elevation model and layer model

2. Geohydrological Interpretation

Interpretation to the geological information ang geohydrological information is necessary to assign the geohydrological parameter (hydraulic conductivity) to the model. The grological interpretation was based on the official geological map (Directorate General of Mineral and Coal).

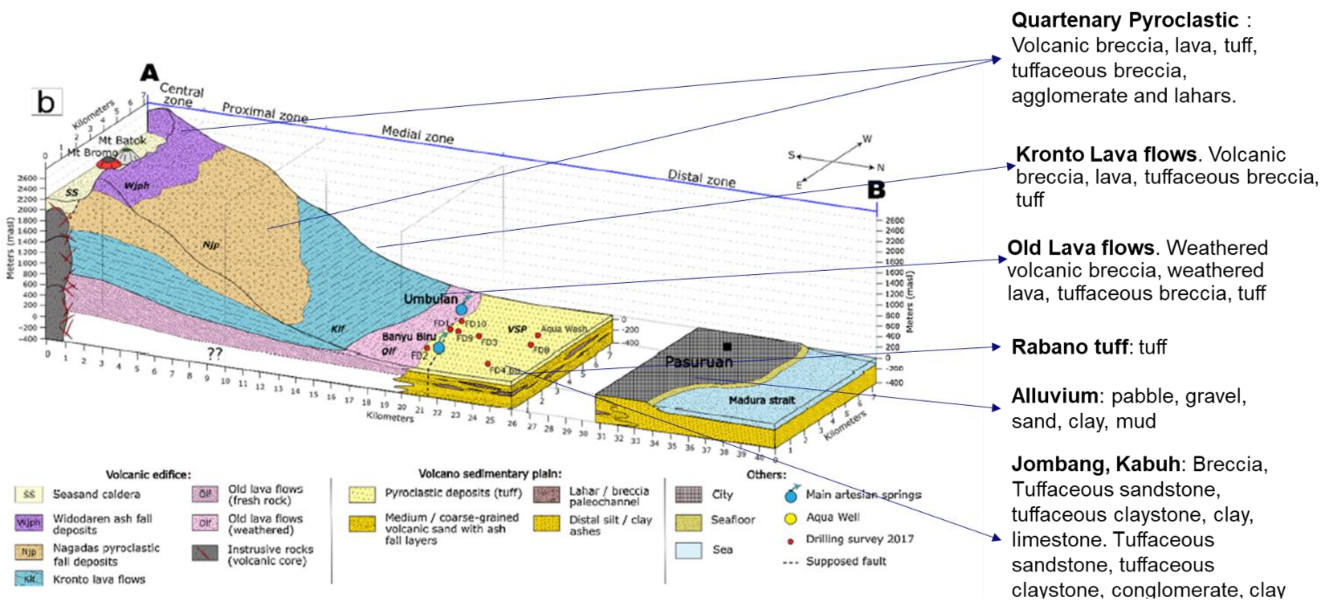


Figure 45: Schematic Geological Cross Section interpretation of the northern flank of Bromo Tengger (Toulier, et al., 2019)

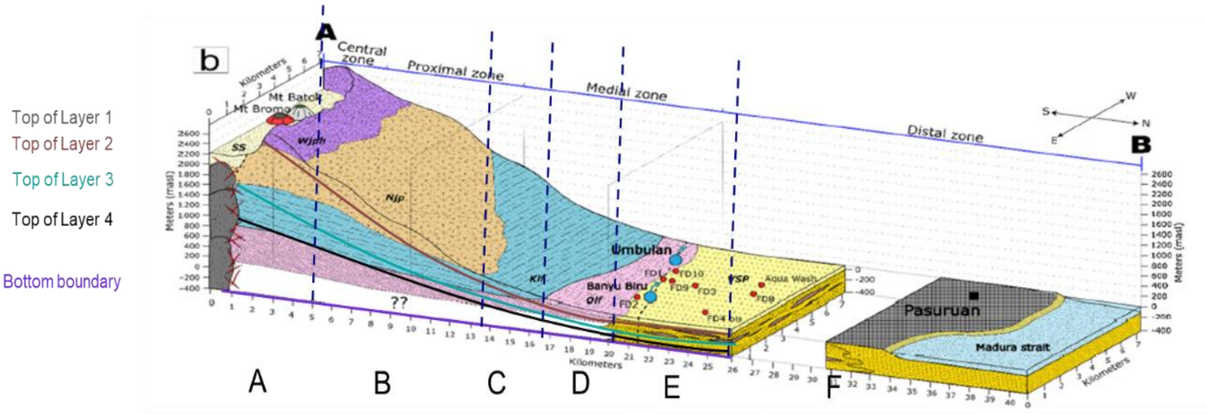


Figure 46: Layer model and lithology for each layer

Table 21: Lithology for each layer

Layer	A	B	C	D	E	F
1	Quartenary Pyroclastic	Quartenary Pyroclastic	Kronto Lava Flows	Old weathered lava	Rabbano Tuff	Alluvium
2	Quartenary Pyroclastic	Kronto Lava Flows	Kronto Lava Flows	Old weathered lava	Kabuh and Jombang formation	Kabuh and Jombang formation
3	Kronto Lava Flows	Kronto Lava Flows	Old weathered lava	Old weathered lava	Kabuh and Jombang formation	Kabuh and Jombang formation
4	Old weathered lava	Old weathered lava	Old weathered lava	Old weathered lava	Kabuh and Jombang formation	Kabuh and Jombang formation

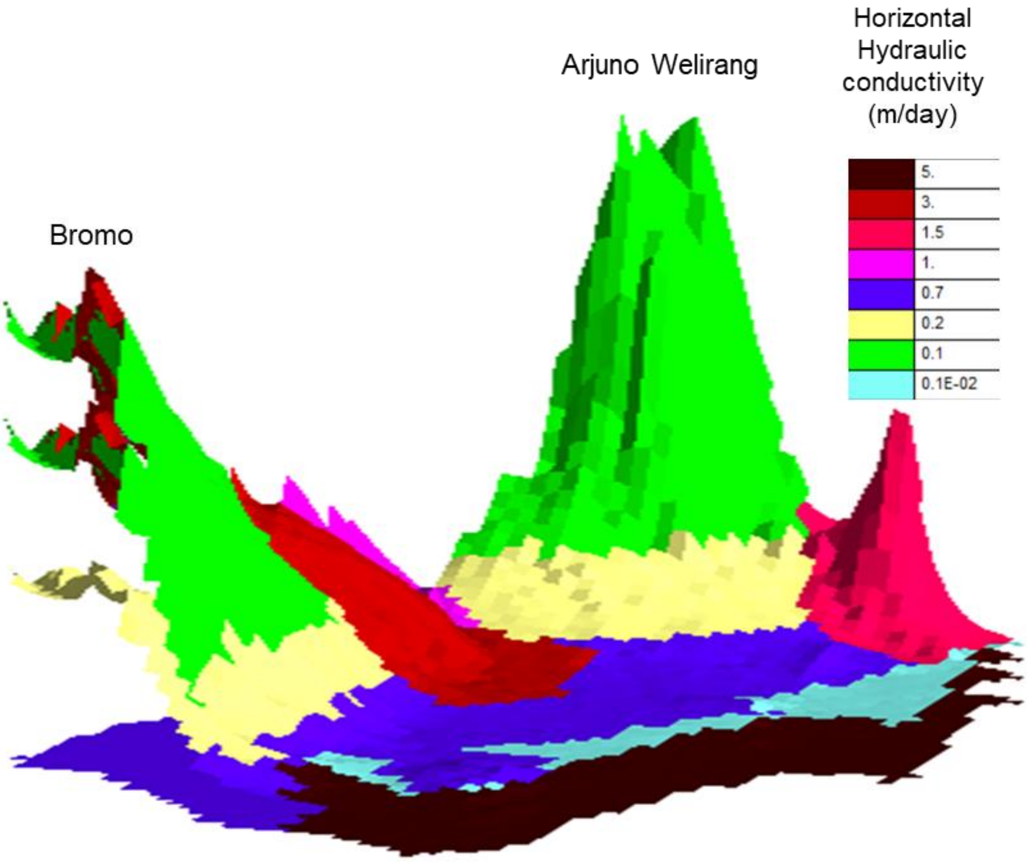
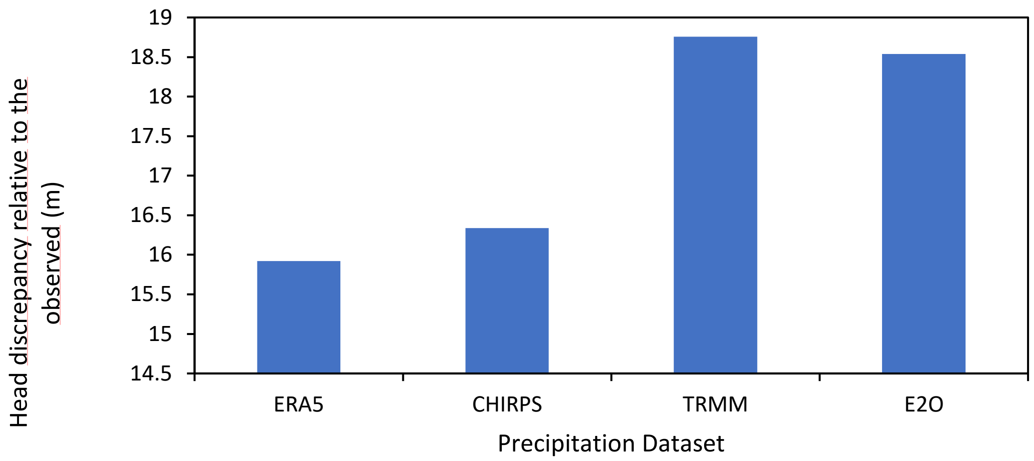


Figure 47; 3-D representation of hydraulic conductivity value in model area

Model Validation

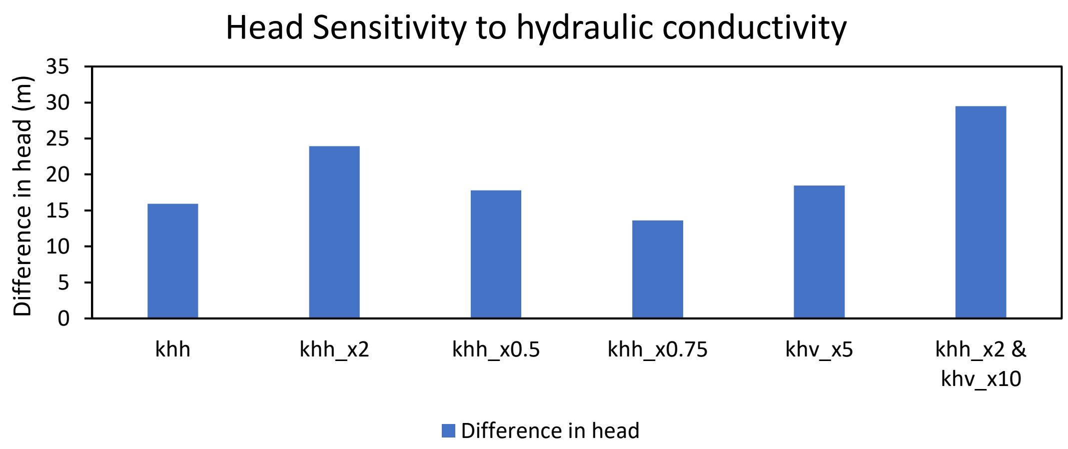
1. *Precipitation Input*

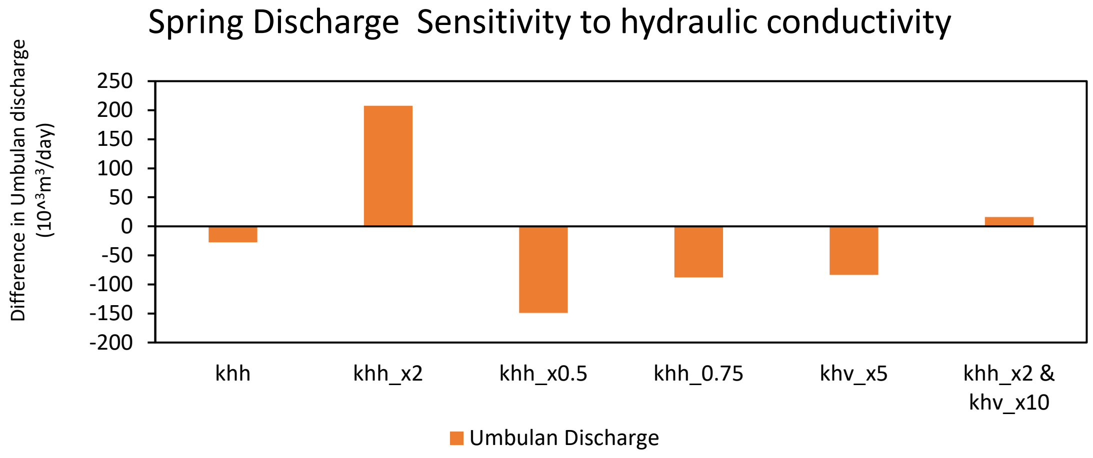
Running the model with steady state run for year 2013, shows that ERA5 dataset shows least head discrepancy between simulated and observed head. Therefore, we use ERA5 dataset for further simulation



2. *Hydraulic conductivity Value*

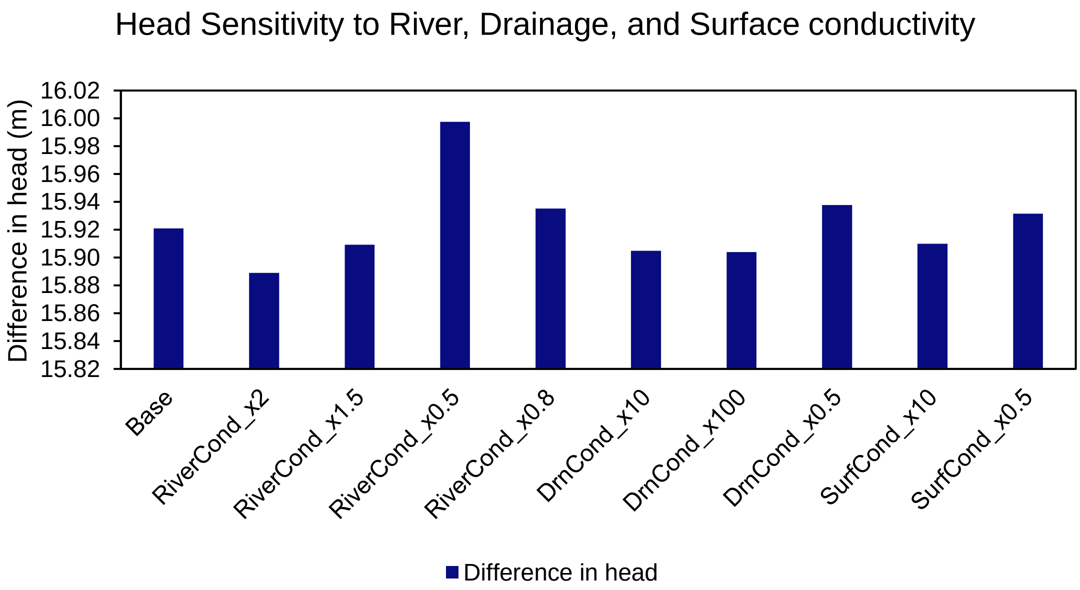
Khh representd the hydraulic conductivity value in Figure 47. Higher hydraulic conductivity leads to higher head discrepancy between observed and calculated head. It also leads to greater error in spring discharge. khh x 0.75 leads to better calculated head, however higher Umbulan discharge discrepancy. Therefore, we selected hydraulic conductivity in the Figure 47 to minimize the discrepancy between calculated and observed head and minimize the discrepancy between calculated and observed Umbulan discharge.

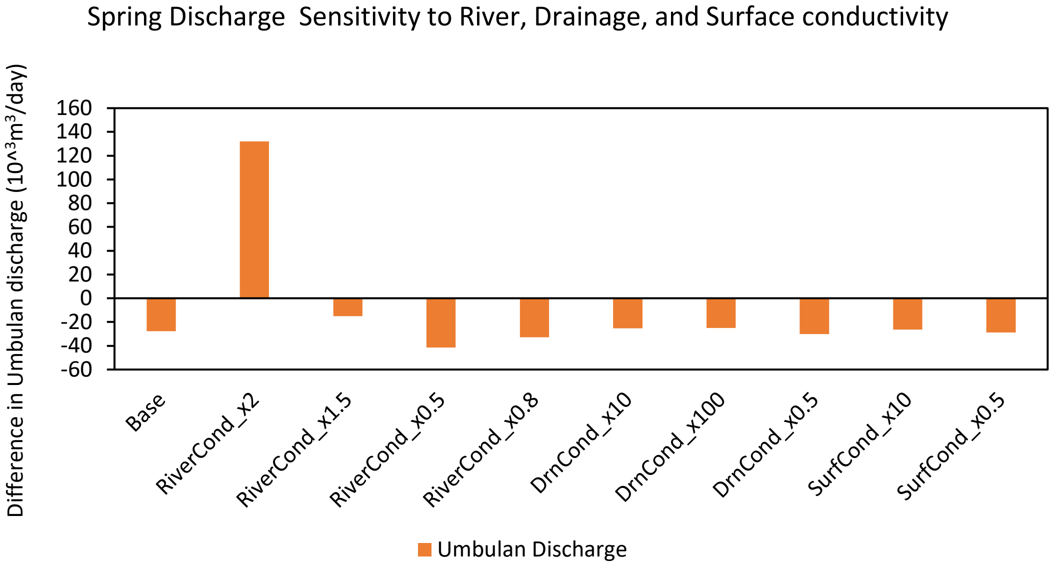




3. River, Drainage, and Surface conductivity value

Base value is the value that we choose after trying different set of river, drainage, and surface conductivity. We chose conductivity value of 5000 m/day, 5000 m/day, and 2000 m/day for river, drainage, and surface conductivity value respectively.





4. *Validation Result*

Calculated groundwater depth in some of the well shows good agreement with observed groundwater depth (red dot), while some does not (black dot). The calculated groundwater depth that are in a poor agreement with the observation are distributed at the North Eastern flank of Penanggungan mountain.

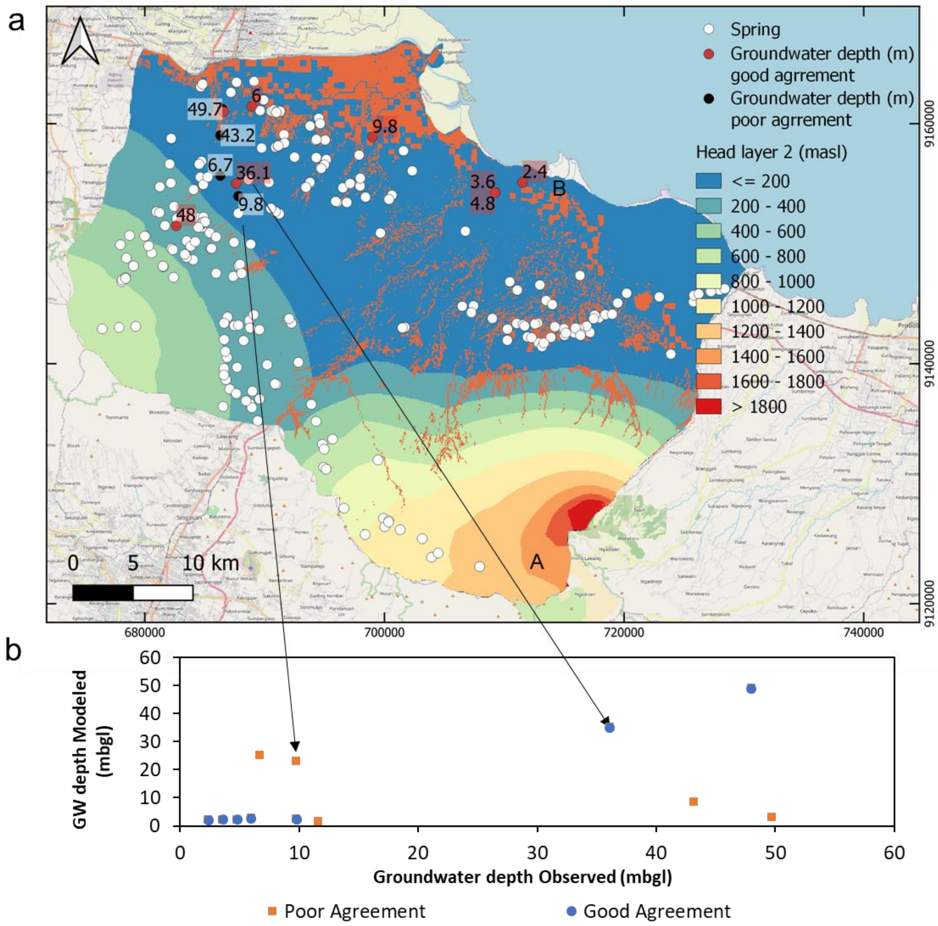


Figure 48: a) Validation Result, b) Simulated and Observed Groundwater depth (Harnandi & Rengganis, 2010)

This mismatch between the model and the observation is also observed in drainage calculation. The model shows too much drainage in north western area of the model. However, the model shows good correlation between drainage flux and the location of the Ranu Grati lake, that indicates sufficient drainage flux calculation in the north eastern area of the model. Because there's no information about groundwater depth in Eastern area, we use spring discharge information to calibrate our model. Calculated Umbulan discharge (calculated with drainalge package) that is 270 x 103 m3/day shows good correlation with the observed Umbulan discharge that is around 297 x 103 m3/day.

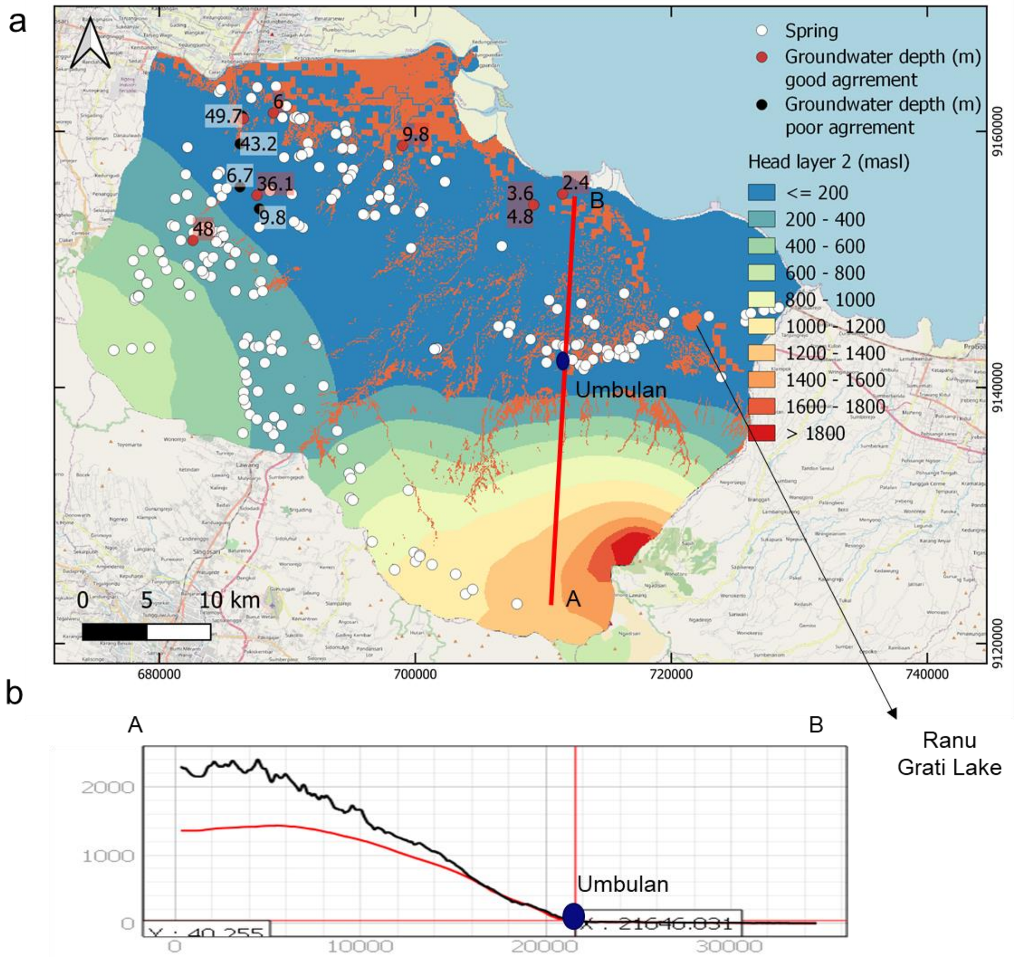


Figure 49: a) Validation result, b) Cross section of Groundwater head and Umbulan discharge location

Sensitivity to Land Use change

- We use 2013 recharge data in this analysis
- There's about 2 m head decrease from land use 2013 to land use 2020. However, land use 2029 shows little difference with the head from land use 2020. It may be because in 2029, land use change is located in the more downstream area, not in the upstream where majority of recharge is.

1. Head

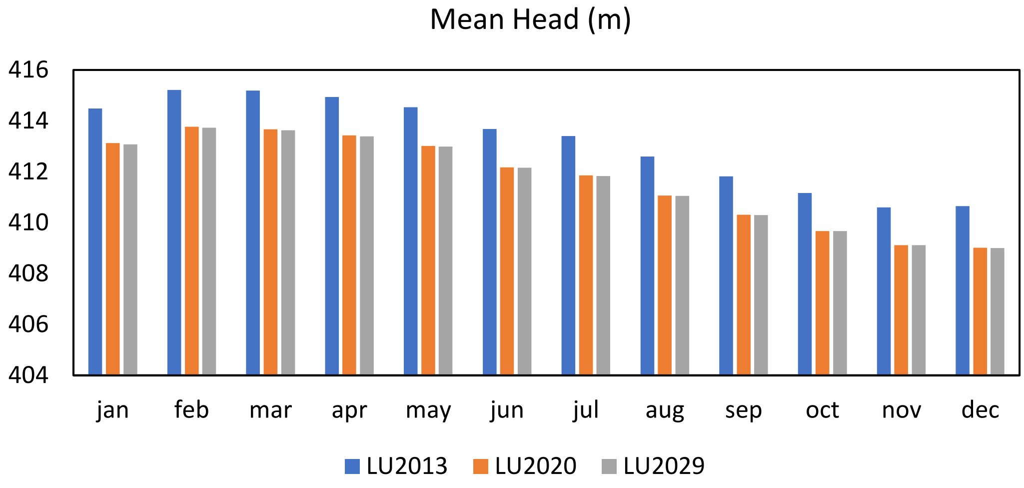


Figure 50: Head sensitivity towards land use change in Pasuruan groundwater basin

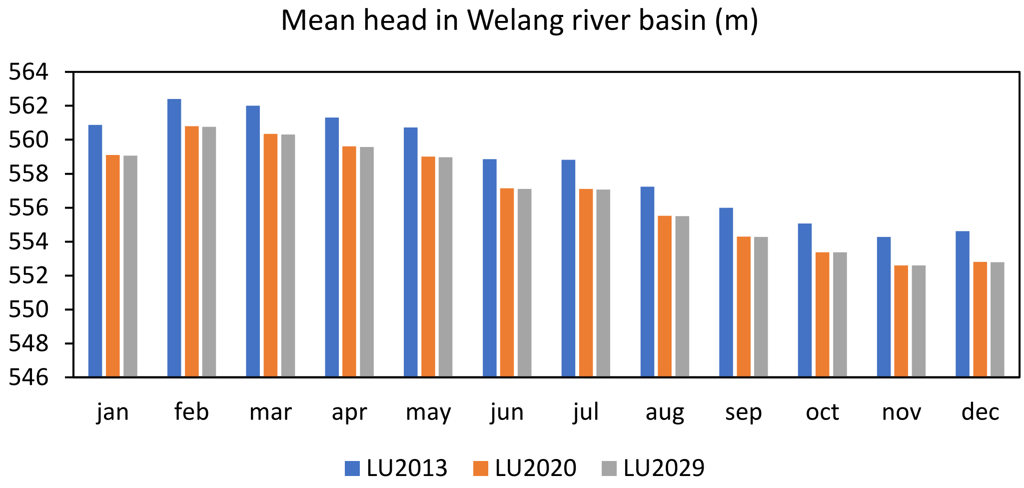


Figure 51: Head sensitivity towards land use change in Welang River Basin

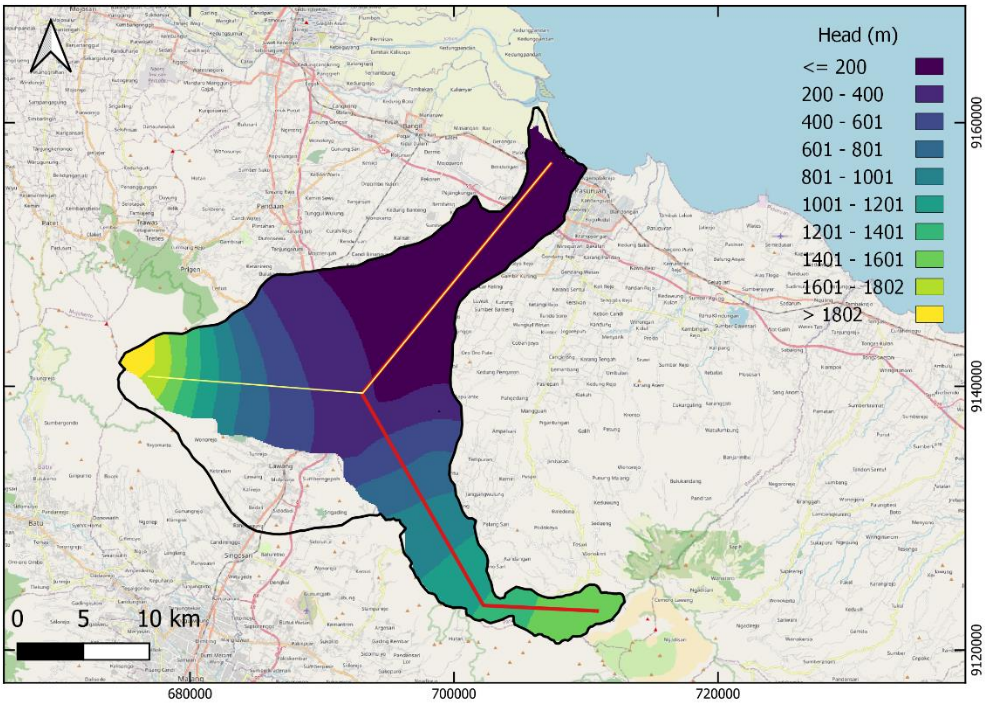


Figure 52: Head in Welang river basin under land use 2013 condition in month January

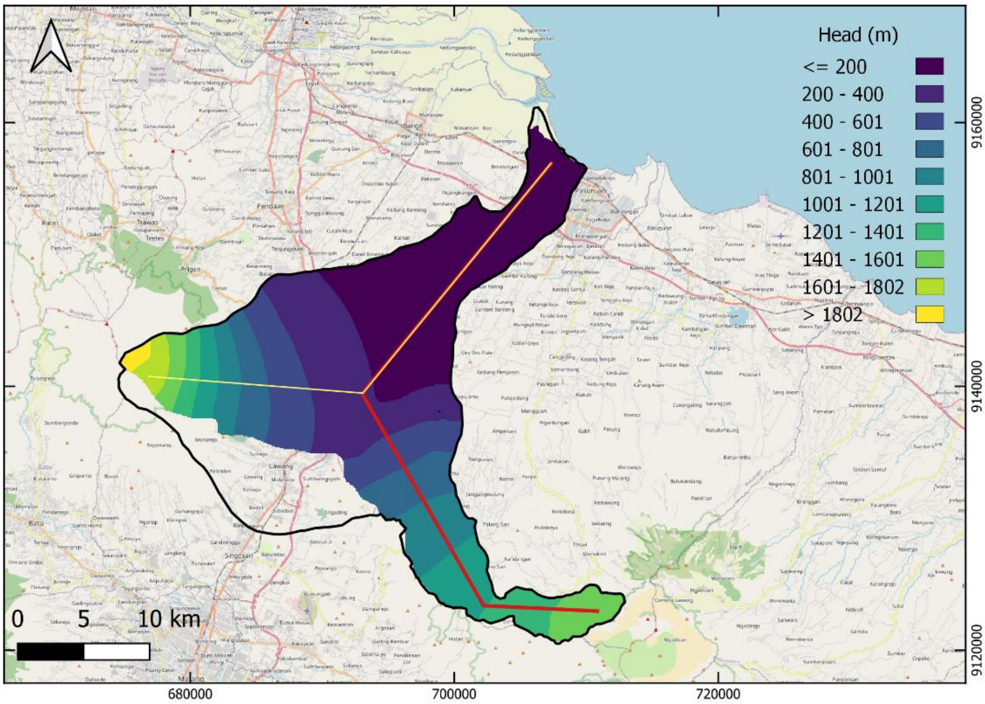


Figure 53: Head in Welang river basin under land use 2013 condition in month November

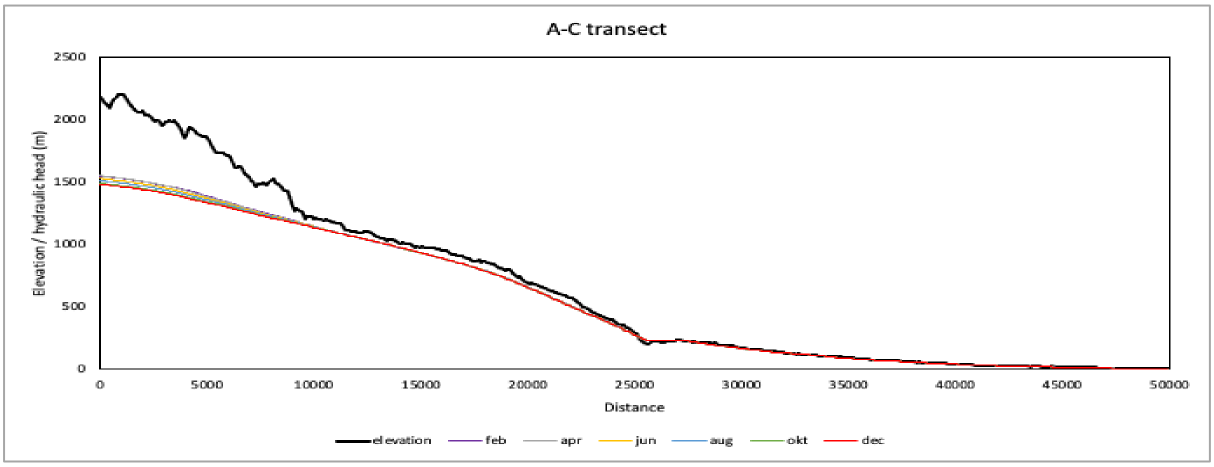


Figure 54: Cross sectional view of groundwater head in Welang river basin under 2013 land use in A-C transect

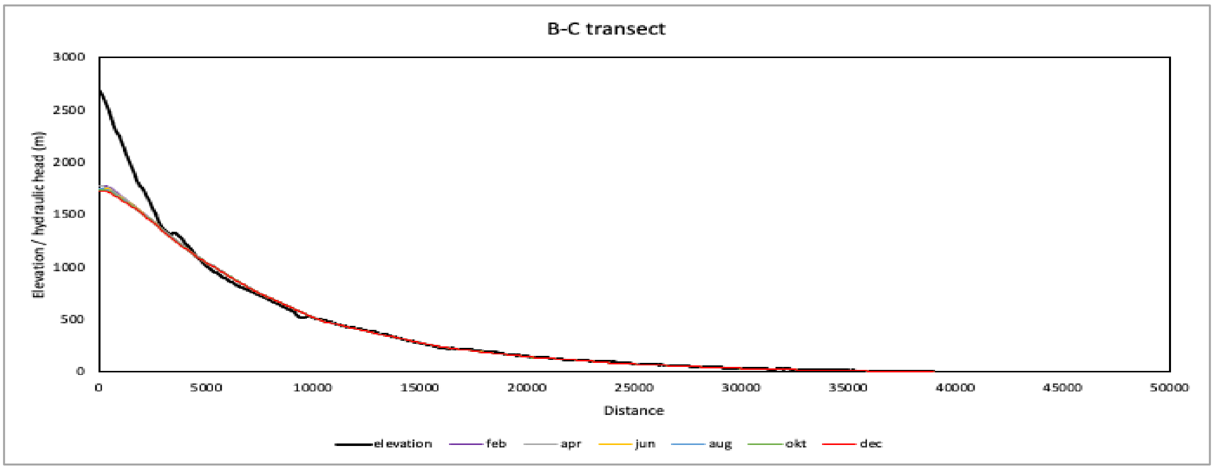


Figure 55: Cross sectional view of groundwater head in Welang river basin under 2013 land use in B-C transect

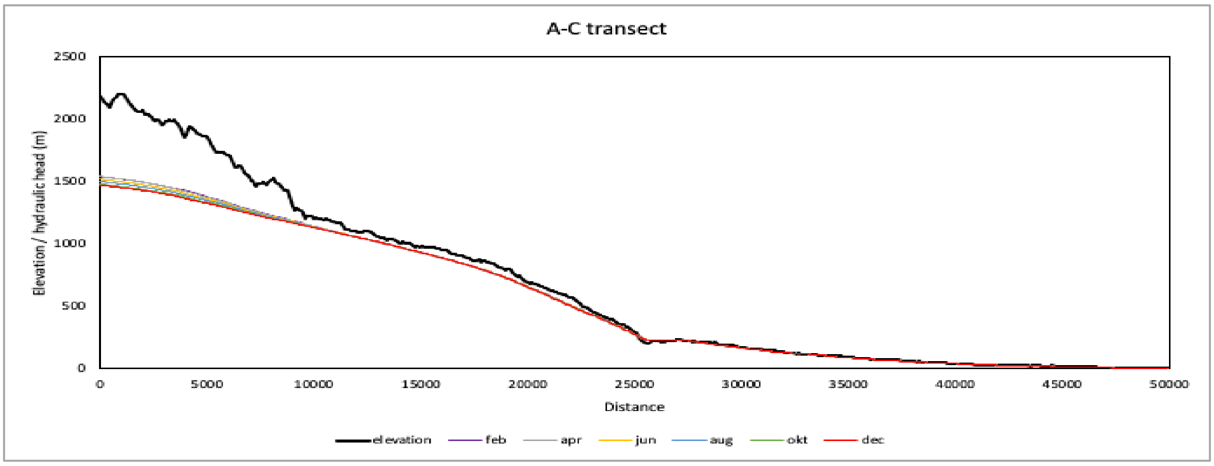


Figure 56: Cross sectional view of groundwater head in Welang river basin under 2020 land use in A-C transect

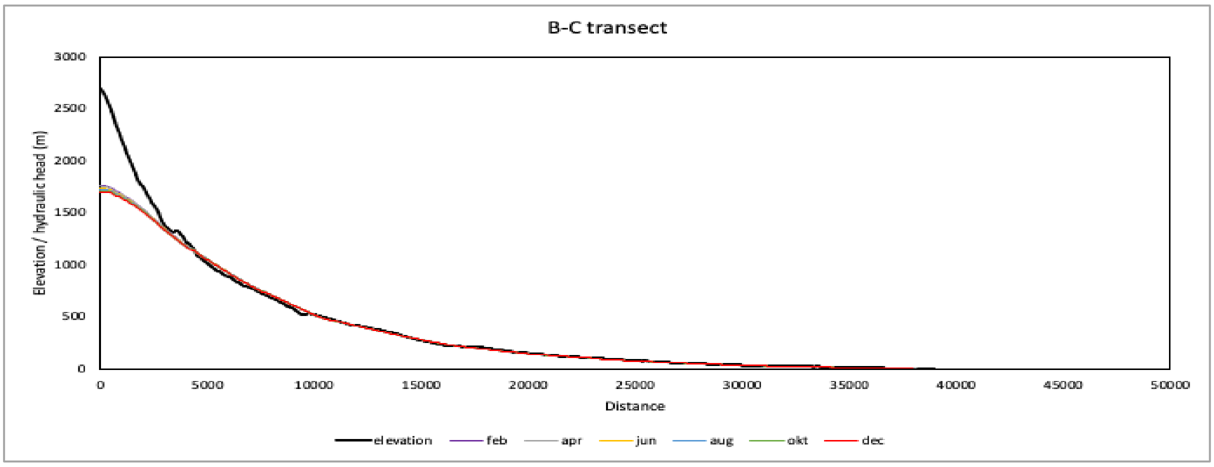


Figure 57: Cross sectional view of groundwater head in Welang river basin under 2020 land use in B-C transect

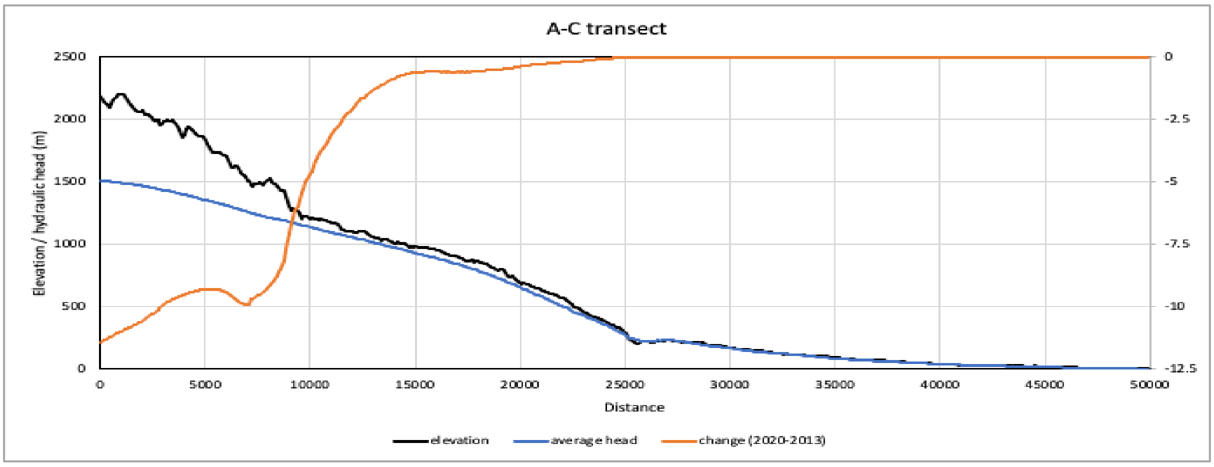


Figure 58: Groundwater head difference 2013-2020 (only land cover change) in A-C transect

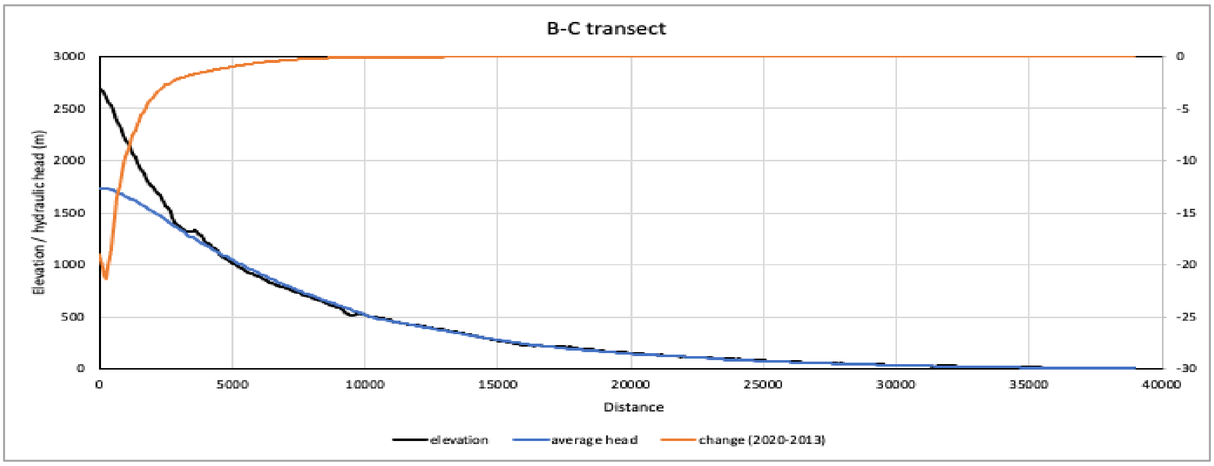


Figure 59: Groundwater head difference 2013-2020 (only land cover change) in B-C transect

2. *Spring discharge*

- The groundwater drop in dry season, was not reflected in Umbulan spring discharge. Under land use 2029, in September, October, and November, Umbulan discharge is even higher than under land use 2020 and land use 2013 scenario. Therefore, spring discharge fluctuation could not be used solely as an indicator of the groundwater drop.

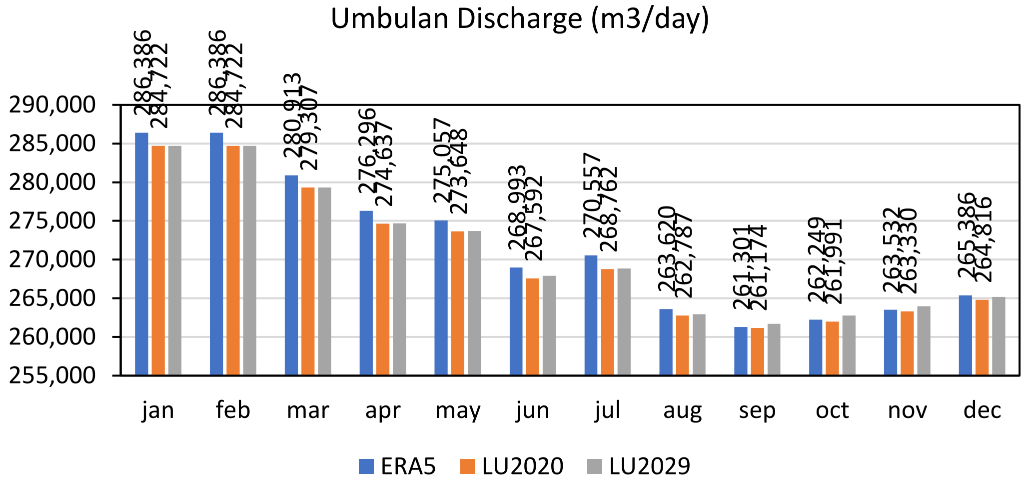


Figure 60: Sensitivity of Umbulan discharge change towards land use change

3. *River to groundwater flux*

- By assuming the river stage that is constant for the whole simulation, with change in land use, the river to groundwater flux will be higher. Even though in reality the river stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with land use change, will result in higher river to groundwater flux that can cause lower baseflow in river during dry period.

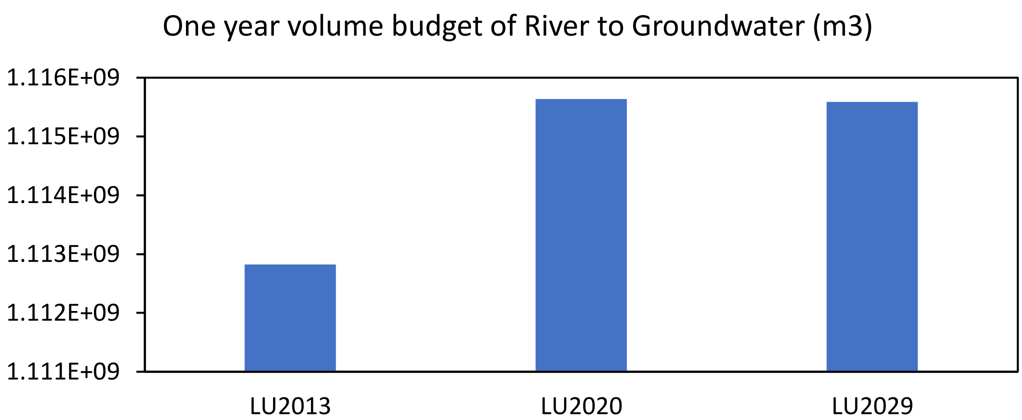


Figure 61: One year river to groundwater flux (m3) with different land use input

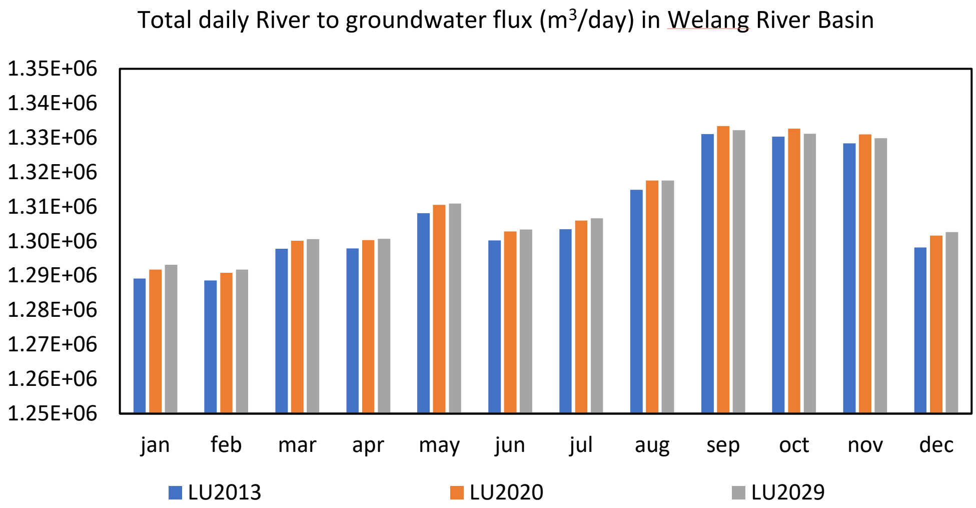


Figure 62: River to groundwater flux (m3/day) with different land use input

4. Groundwater to drainage

- By assuming the drainage stage that is constant for the whole simulation, with change in land use, the groundwater to drainage flux will be lower. Even though in reality the drainage stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with land use change, will result in lower groundwater to drainage flux that can cause agricultural drought.

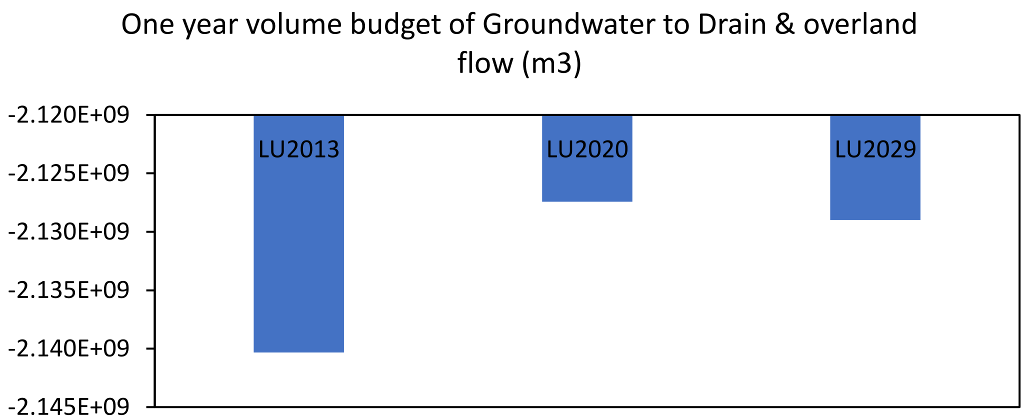


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Figure 63: One year groundwater to drainage flux (m3) with different land use input

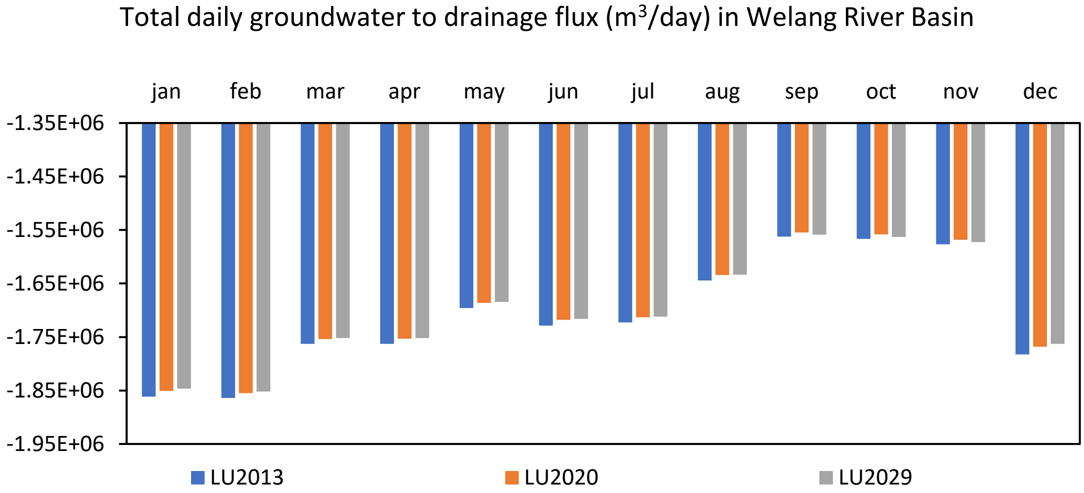

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Figure 64: Groundwater to drainage flux (m3/day) with different land use input

5. Conclusion

- Land use change, increase in groundwater abstraction, and decrease of precipitation will reduce groundwater head in Pasuruan basin and Welang river basin
- Land use change, increase in groundwater abstraction, and decrease of precipitation will increase river flux to groundwater that will lower river discharge
- Land use change, increase in groundwater abstraction, and decrease of precipitation will decrease groundwater flux to drainage network and overland flow that may affect the agricultural water source availability
- Land use change, and decrease in precipitation will lower Umbulan discharge, but the increase well abstraction does not have any substantial effect on Umbulan discharge. Therefore, the groundwater abstraction limitation policy could not be solely dependent on spring discharge monitoring

-

Sensitivity to Abstraction Rate

1. *Head*

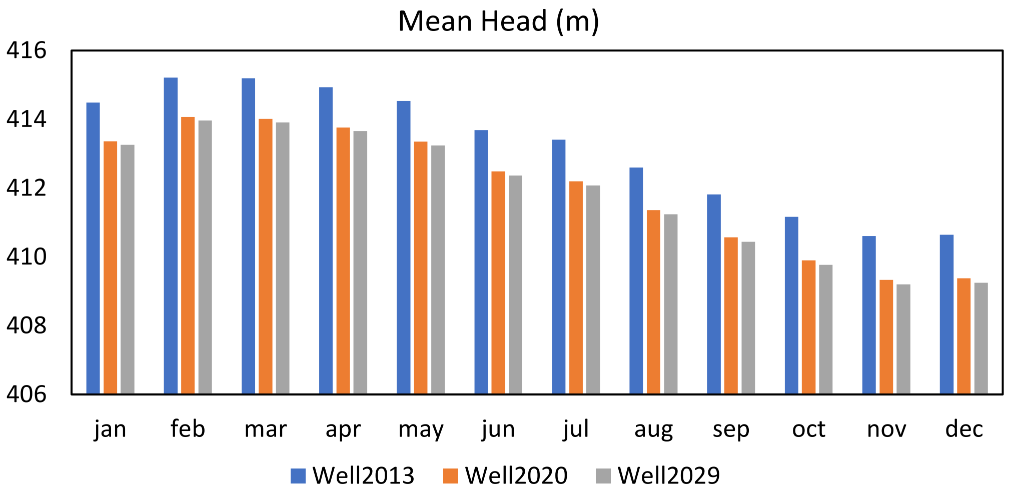


Figure 65: Head sensitivity towards increasing well abstraction in Pasuruan groundwater basin

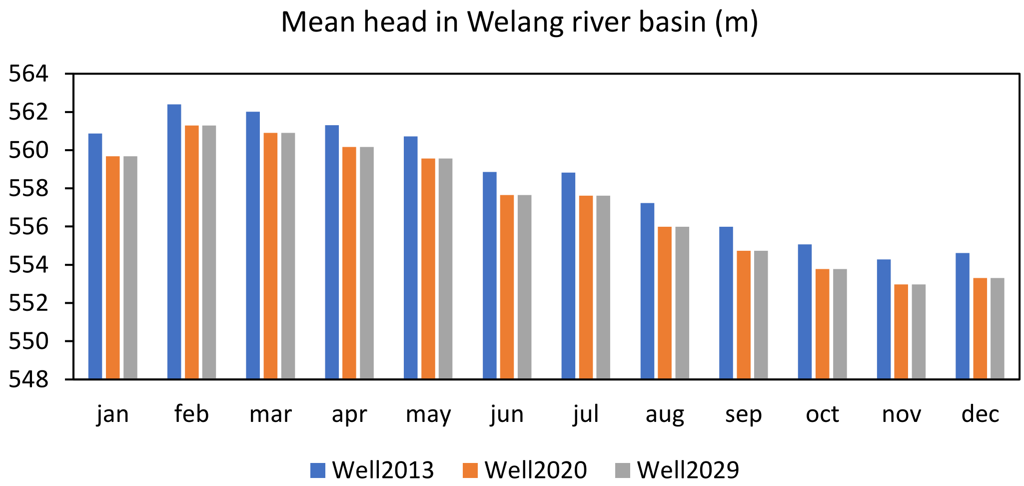


Figure 66: Head sensitivity towards increasing well abstraction in Welang River Basin

2. Spring discharge

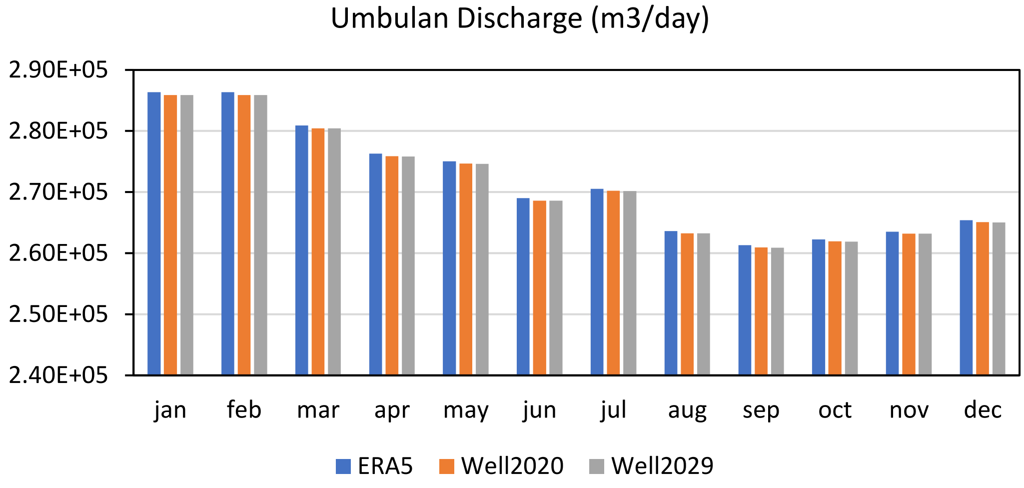


Figure 67: Sensitivity of Umbulan discharge change towards increasing well abstraction

3. River to groundwater flux

- By assuming the river stage that is constant for the whole simulation, with increase in abstraction rate, the river to groundwater flux will be higher. Even though in reality the river stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with increase in abstraction rate, will result in higher river to groundwater flux that can cause lower baseflow in river during dry period.

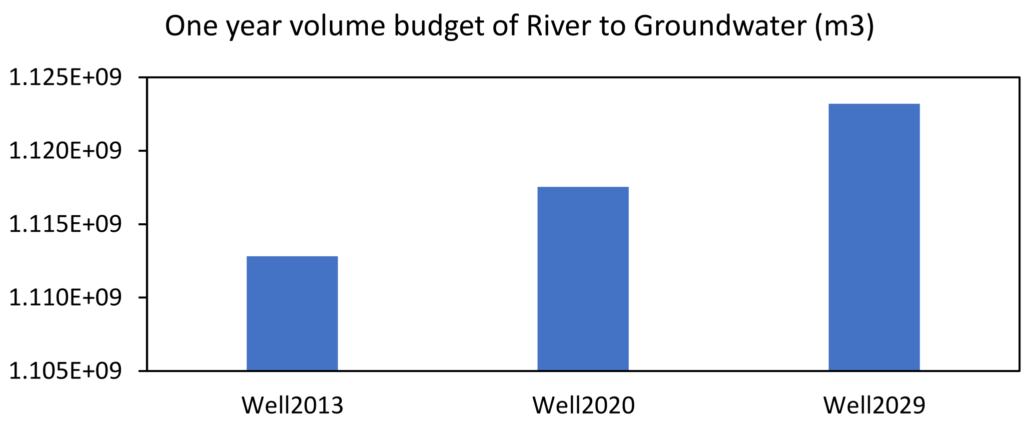


Figure 68: One year river to groundwater flux (m3) with different well abstraction input

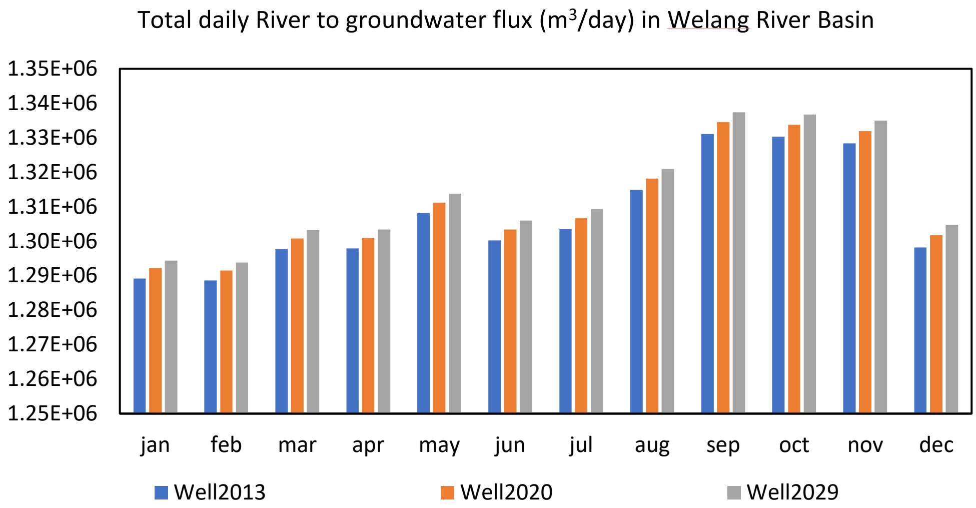
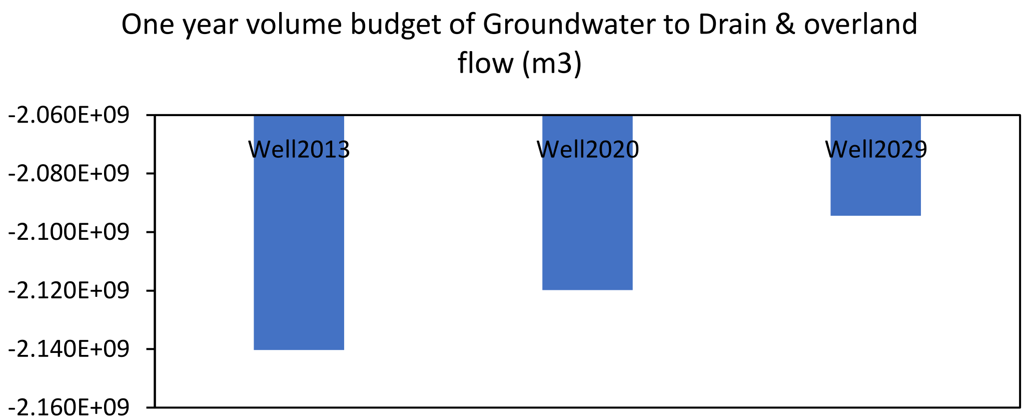


Figure 69: River to groundwater flux (m3/day) with different well abstraction input

4. Groundwater to drainage

- By assuming the drainage stage that is constant for the whole simulation, with increase in groundwater abstraction, the groundwater to drainage flux will be lower. Even though in reality the drainage stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with increase in groundwater abstraction, will result in lower groundwater to drainage flux that can cause agricultural drought.



-

Figure 70: One year groundwater to drainage flux (m3) with different well abstraction input

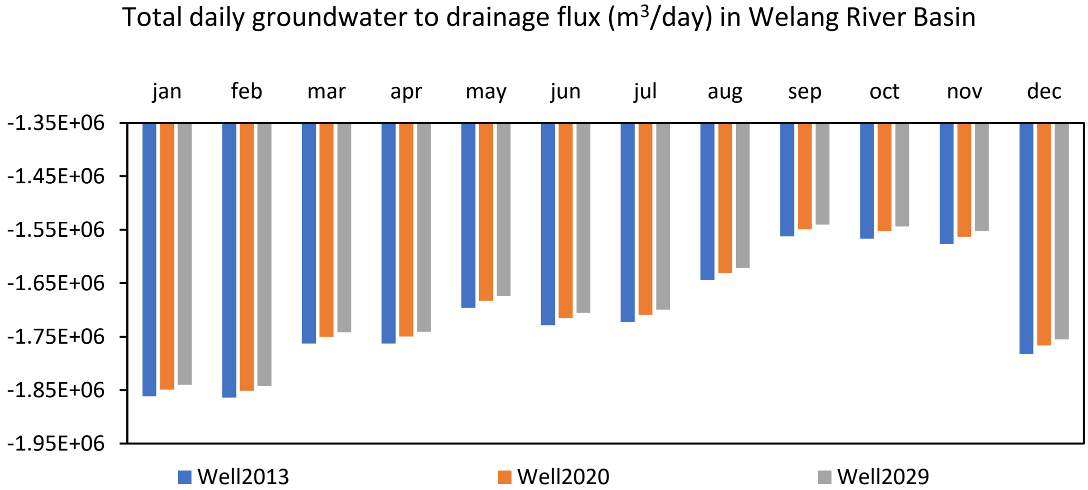


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Figure 71: Groundwater to drainage flux (m3/day) with different well abstraction input

Sensitivity to climate change

- To assess the climate change effect, we try to reduce precipitation input to reduce recharge.

1. Head

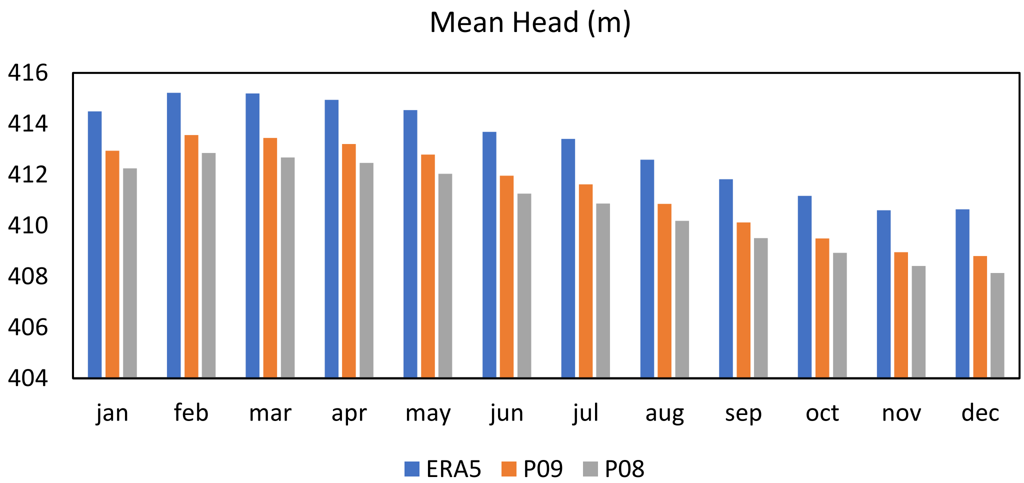

Figure 72: Head sensitivity towards decrease in precipitation in Pasuruan groundwater basin

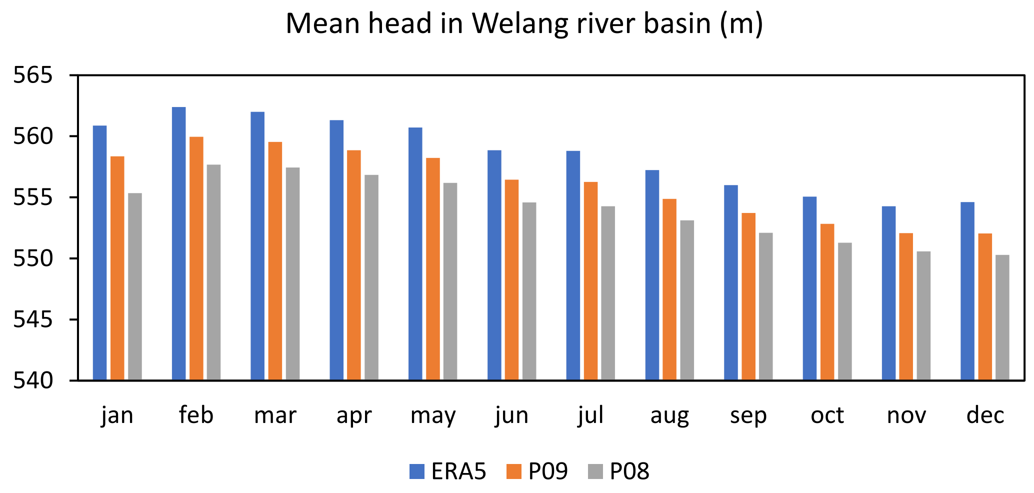

Figure 73: Head sensitivity towards decrease in precipitation in Welang River Basin

2. *Spring discharge*

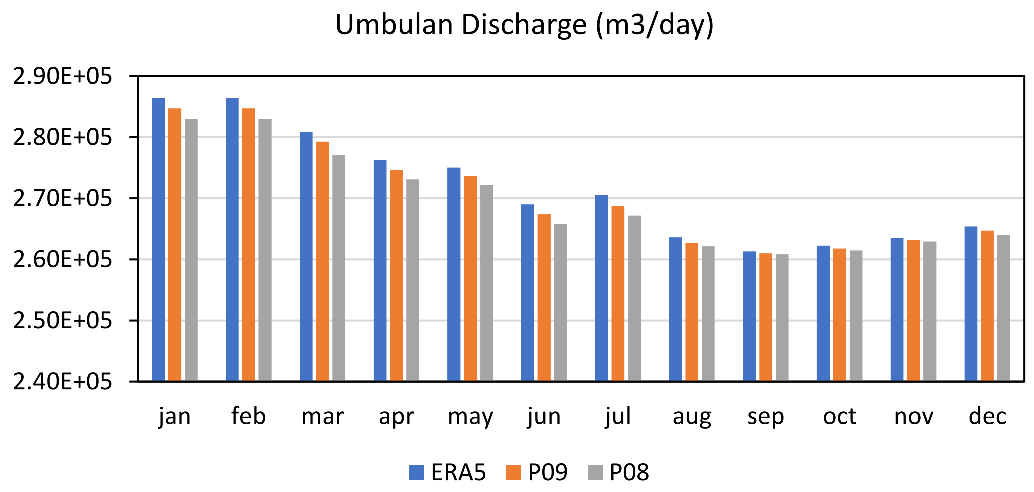

Figure 74: Sensitivity of Umbulan discharge change towards decrease in precipitation

3. *River to groundwater flux*

- By assuming the river stage that is constant for the whole simulation, with decrease in precipitation, the river to groundwater flux will be higher. Even though in reality the river stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with decrease in precipitation, will result in higher river to groundwater flux that can cause lower baseflow in river during dry period.

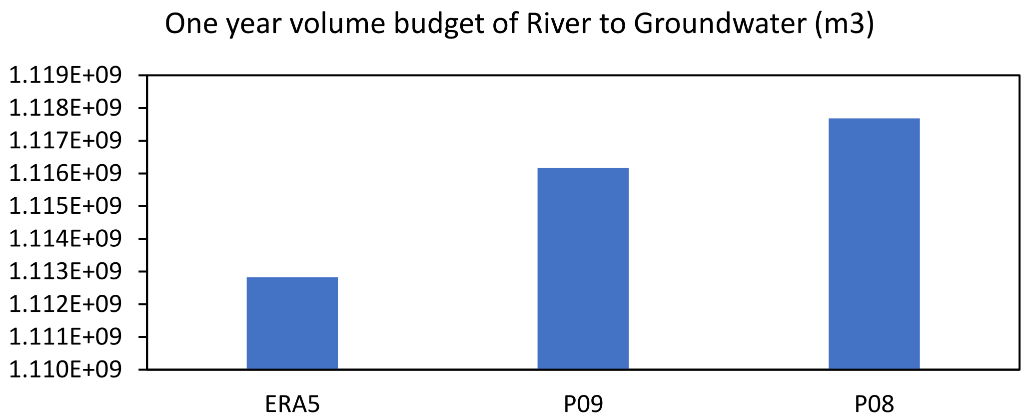

Figure 75: One year river to groundwater flux (m3) with different precipitation input

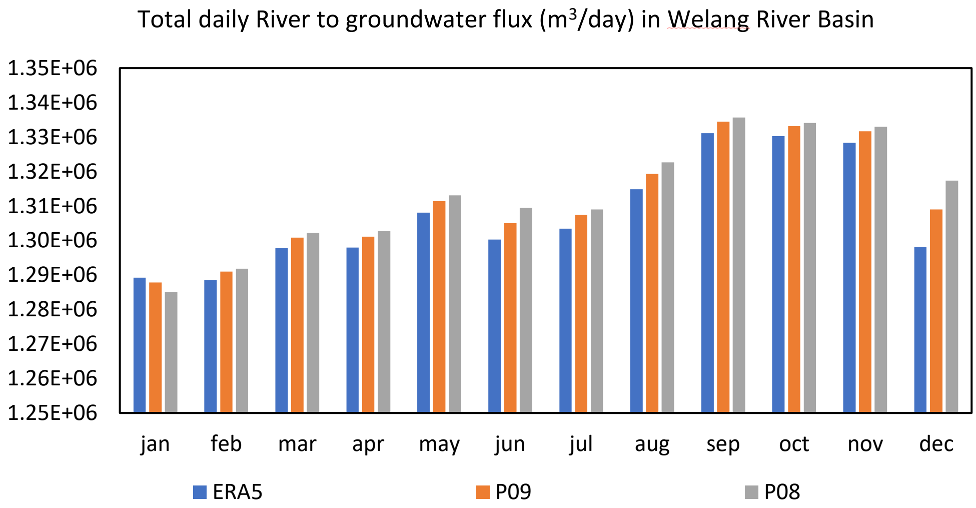

Figure 76: River to groundwater flux (m3/day) with different precipitation input

4. Groundwater to drainage

- By assuming the drainage stage that is constant for the whole simulation, with decrease in precipitation, the groundwater to drainage flux will be lower. Even though in reality the drainage stage is not constant for the whole year, this can be used as an indication that the lower groundwater head that is associated with decrease in precipitation, will result in lower groundwater to drainage flux that can cause agricultural drought

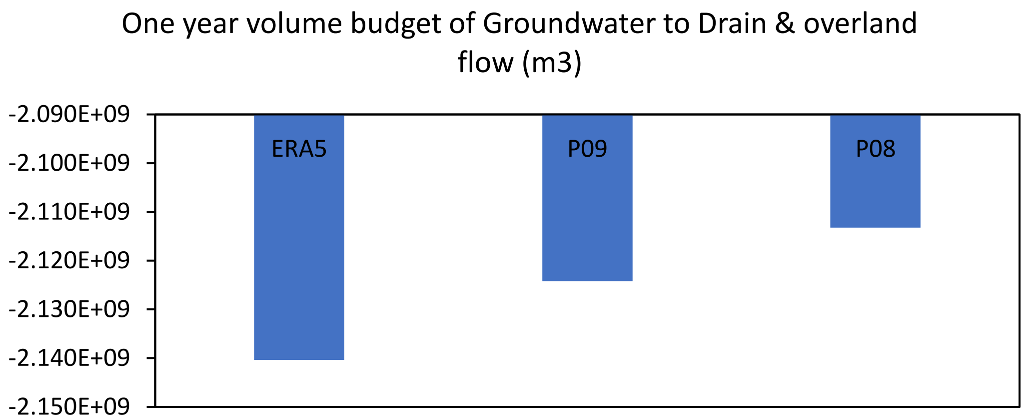

Figure 77: One year groundwater to drainage flux (m3) with different precipitation input

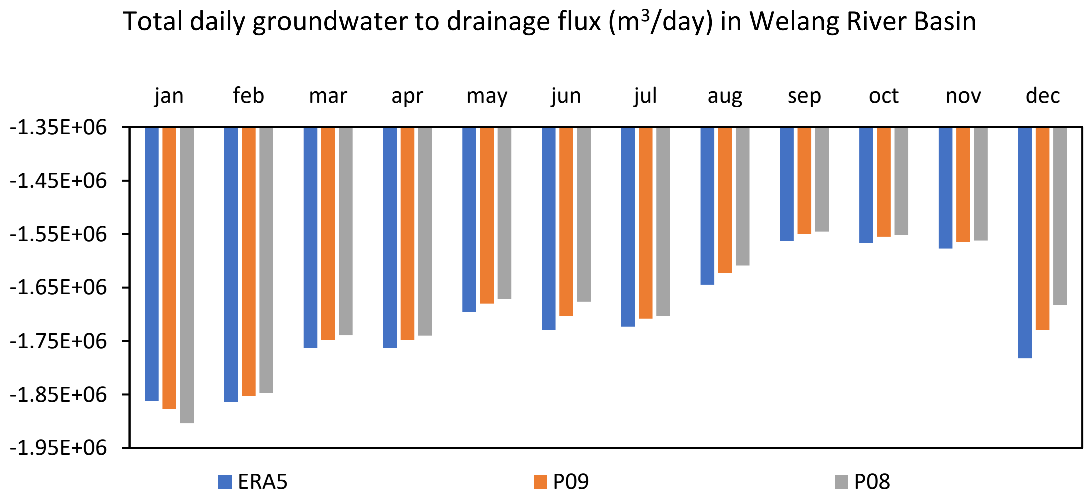

Figure 78: Groundwater to drainage flux (m3/day) with different precipitation input

How to improve what we already know

1. Collect more groundwater observation data especially in the mountain area
2. Groundwater quality modeling to look at solid transport within groundwater (contaminant transport)
3. Aquifer test to improve the geohydrological parameterization (khv, kvv, Sy, S)
4. Geophysical logs to improve the geohydrological parameterization (khv, kvv, Sy, S)
5. Extraction data to improve the rate of groundwater extraction reliability
6. Use climate projection model to estimate climate change effect
7. Data sharing

Appendix C Data Availability

Rain Gauge Data

Year	Rainfall Data										
	Lawang	**P3GI**	**Pager**	**Purwosari**	**Selowongko**	**Wonorejo**	**Tutur**	**Puspo**	**Oro-Oro Pule**	**Telubuk**	**Badong**
	38	**37**	**38**	**17**	**39**	**35**	**40**	**29**	**15**	**40**	**39**
1980											
1981											
1982											
1983											
1984											
1985											
1986											
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1989											
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2009											
2010											
2011											
2012											
2013											
2014											
2015											
2016											
2017											
2018											
2019											

- Length of data in years
- From UPT Pasuruan
- From PU SDA Jatim
- No data (full year/number of days in a year with missing data)

Deltares

All Data

Meteorological Dataset																																											
Source	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Rain gauge (Precip)																																											
Downscaled ERA5 (Precip)																																											
TRMM (Precip)																																											
GPMF (Precip)																																											
E2O (Precip)																																											
CHIRPS (Precip)																																											
Downscaled ERA5 (Temp)																																											
E2O (Temp)																																											
E2O (PET)																																											
Downscaled ERA5 (PET)																																											
River Discharge																																											
Purwodadi (wflow id = 4)																																											
Purwodadi A (Upstream)																																											
Purwodadi B (Midstream)																																											
Purwodadi C (Downstream)																																											
Selowongko (wflow id = 3)																																											
Dhompo (wflow id = 2)																																											
Dhompo A (Upstream)																																											
Dhompo B (Downstream)																																											
Tidal Dataset																																											
Probolinggo																																											
Prediction 2017 (May & June)																																											
Prediction 2019-2021																																											
Pasut.xlsx (unknown location)																																											

Appendix D Data Analysis

Precipitation, PET and TEMP

- Before satellite rainfall data can be compared with the ground measurement, initially, rain gauge data must be checked before being translated to raster format. Looking at the available rain gauge data, only in the range of 2004-2016, a long enough continuous rain data series is found. In this period there are 11 stations that have a continuous measurement. These stations are 1) Lawang, 2) P3GI, 3) Pager, 4) Purwosari, 5) Selowongko, 6) Wonorejo, 7) Tutur, 8) Puspo, 9) Oro-oro pule, 10) Tebuluk and 11) Badong.

-

- Among 36 rain gauges, only these 11 stations which pass preliminary inspection (no duplicates value for two consecutive years, no daily data larger than average monthly data, has same measurement value UPT and PU SDA Jatim dataset and doesn't have missing data especially in a leap year). Important to note that although there are more stations that also cover the period of 2004-2016 with some missing data in between; and these missing data can be filled with other adjacent station during the creation of catchment rainfall using Thiessen Polygon method, these stations are not used for further analysis as it will give a fluctuate area of influence for the 2004-2016 period. Although the area of influence of each rain gauge over time will be the same, this approach would make the area of influence of these 11 stations become larger compared to using more rain gauges to derive catchment rainfall and would easily overestimate the catchment rainfall due to high value of local rainfall.

-

- Apart from the preliminary inspection these 11 stations were also checked for its consistency. The checking for inconsistency of a record is done by the double-mass curve technique. From this analysis, it is known that these 11 stations are consistent among each other as indicated by no break in the slope on the graph between the accumulated annual rainfall at each station and the accumulated annual rainfall mean (**B.3. Double Mass Curve**). With consistent dataset, these point data are then translated into catchment rainfall by making use of the area of influence obtained from Thiessen Polygon method. The area of influence obtained from Thiessen Polygon Method with its percentage of influence to catchment rainfall is given in Figure 1.

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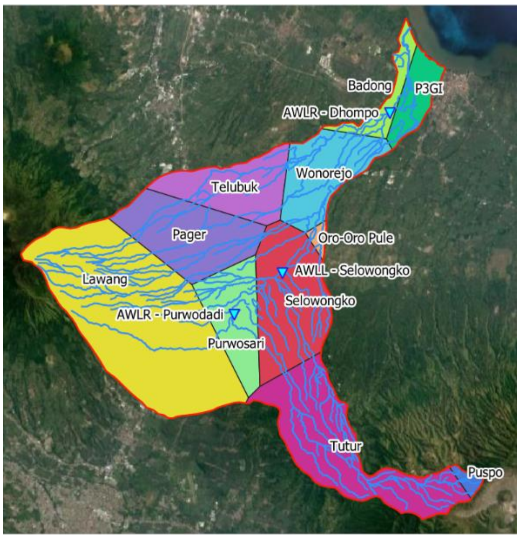


Rainfall Station	Lat	Lon	Area (km²)	Area of Influence (%)
Lawang	-7.8044	112.6983	153.39	30.84
Tutur	-7.8808	112.8372	78.18	15.72
Selowongko	-7.7806	112.7825	60.76	12.22
Pager	-7.7605	112.7322	53.40	10.74
Wonorejo	-7.7093	112.8173	40.60	8.16
Telubuk	-7.7006	112.7503	39.43	7.93
Purwosari	-7.7820	112.742	34.20	6.87
P3GI	-7.6592	112.9092	17.44	3.51
Badong	-7.6325	112.8289	14.01	2.82

Figure 1 Used rain gauge station with its area of influence

Puspo	-7.8381	112.8981	3.29	0.66
Oro-Oro Pule	-7.7441	112.8383	2.73	0.55

As rainfall plays a very important role on determining the storm design, yet in this study the length of continuous ground rainfall data is relatively short when compared to the satellite products, in this project the storm design will then be created based on precipitation data from satellite product. The selection of which satellite product to be used for getting storm design is done by looking at the correlation value of the observed and satellite datasets, visual appraisal between the cumulative rainfalls and visual appraisal on the event of heavy rainfall.

Judging from the data availability, the overlapping period between the observed rainfall and the observed river discharge is in the years 2010-2014. Although the period from 2004-2010 discharge data is also available for Purwodadi and Dhompo stations, this period is not chosen as there is a possibility that the data comes from several locations as indicated by different coordinate values among each other. The selected period of 2010-2014 is further narrowed down to 2013-2014 as the correlation between observed catchment rainfall with observed river discharge for the period of 2010-2012 seems not realistic especially during the event of heavy rainfall (Figure 2). In this project, only Purwodadi station is used to find the best satellite products to represent catchment rainfall in Welang Basin. The underlaying arguments for only using Purwodadi station is because the river discharge measured at Dhompo station is already influenced by man-made structure (Grinting and Licin Irrigation Intake) and there is no river discharge measurement at Selowongko for the period of 2013-2014.

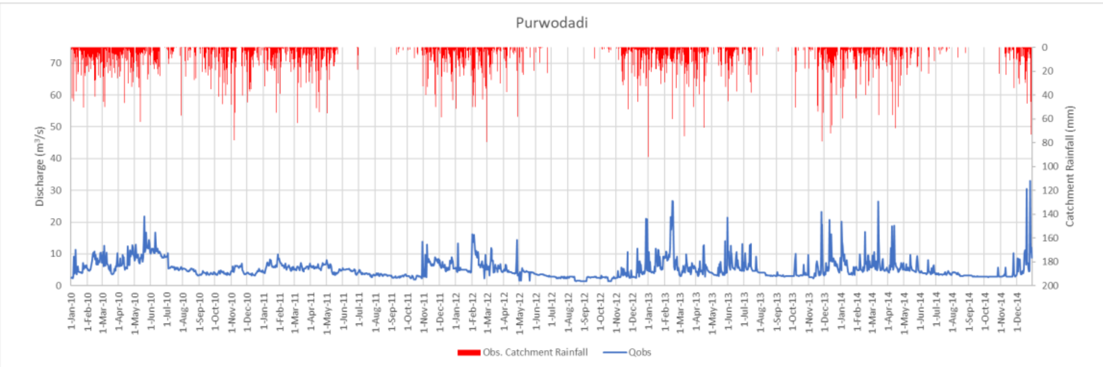


Figure 2 Observed catchment rainfall for catchment area above Purwodadi station and stream discharge at AWLR Purwodadi

In order to give a better insight on the quality of the data, correlation value between datasets are seek after. The correlation value between the observed catchment rainfall above Purwodadi station and the observed discharge at Purwodadi station in 2013-2014 is 0.38. This small correlation value may be caused by constant discharge value that is measured during no rain/less rain into the catchment. Until now these constant discharge values are still physically unexplained as there is no pond/reservoir upstream of Purwodadi station. Correlation values between satellite datasets to the observed catchment rainfall are also checked and given on Table 22.

Table 22 Correlation between observed catchment rainfall with catchment rainfall from various satellite products

Catchment Rainfall 2013-2014	ERA5	GPMF	E2O	TRMM	CHIRPS
Observed Catchment Rainfall (Processed Rain Gauge)	0.38	0.53	0.52	0.52	0.26

The correlation value in Table 22 is not the determining factor to choose the satellite products to be used in frequency analysis. Table 22 is only used to have a better understanding on the correlation between rain gauge data and satellite products. As rainfall frequency analysis highly depends on the annual maximum rainfall, the capability of satellite rainfall on capturing heavy rainfall is of importance. Comparison between observed catchment rainfall and cumulative catchment rainfall above Purwodadi station for different satellite products are shown in Figure 3 to Figure 7. Cumulative catchment rainfall upstream Dhompo for different satellite products are also provided in **B.4 Cumulative Rainfall Upstream Dhompo**.

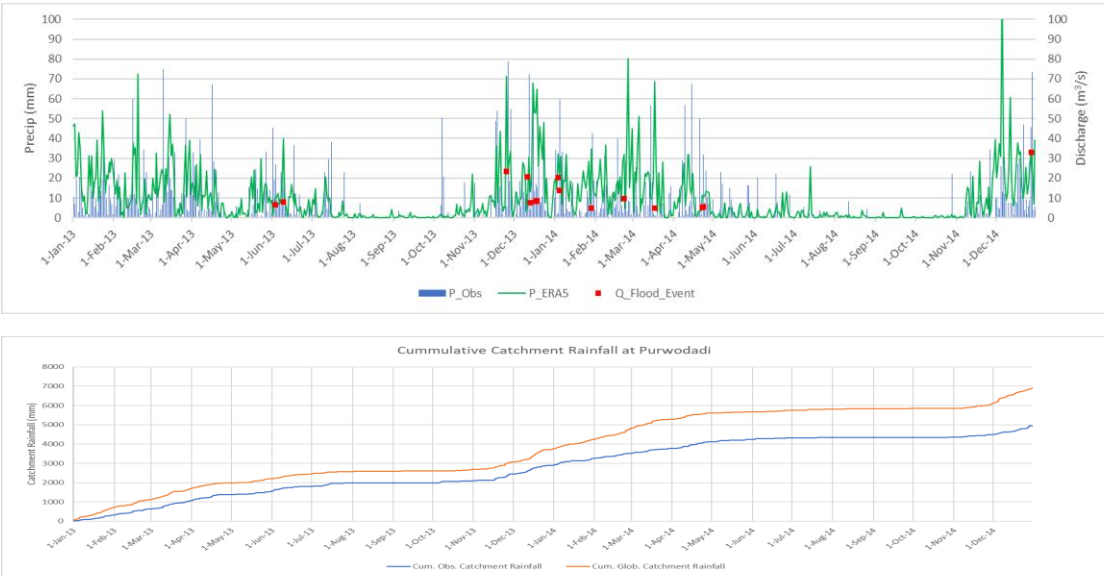
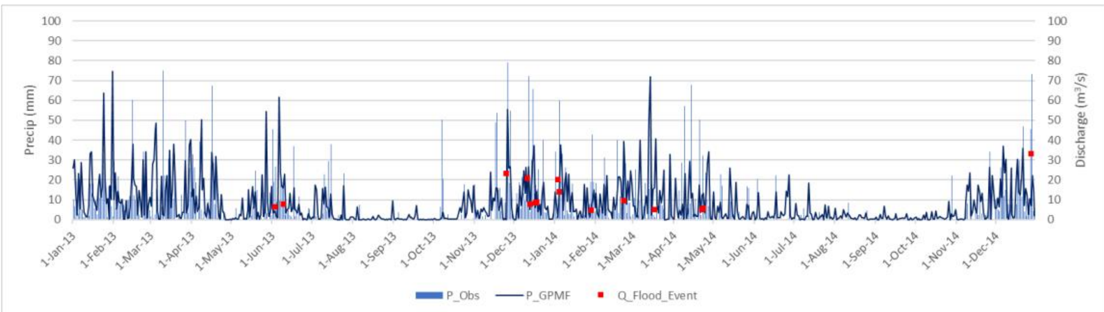


Figure 3 Comparison between observed catchment rainfall and ERA5 catchment rainfall at Purwodadi



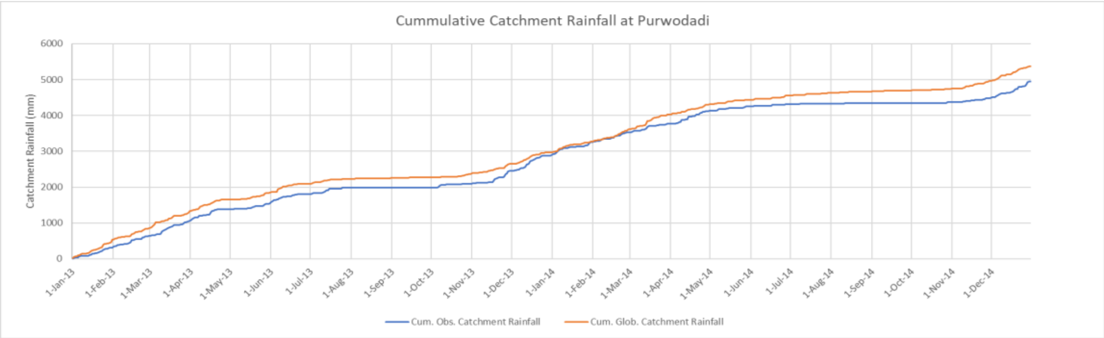
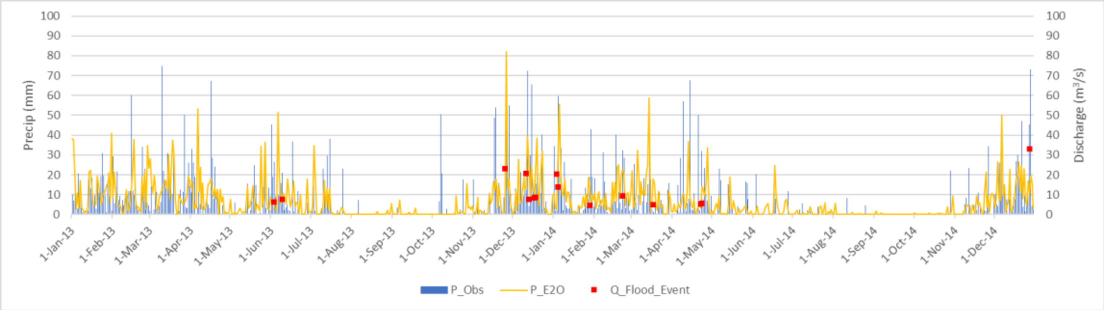


Figure 4 Comparison between observed catchment rainfall and GPMF catchment rainfall at Purwodadi



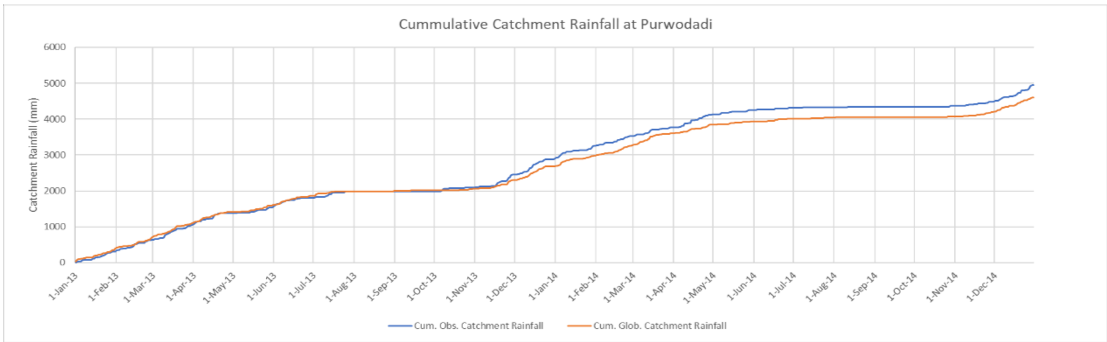
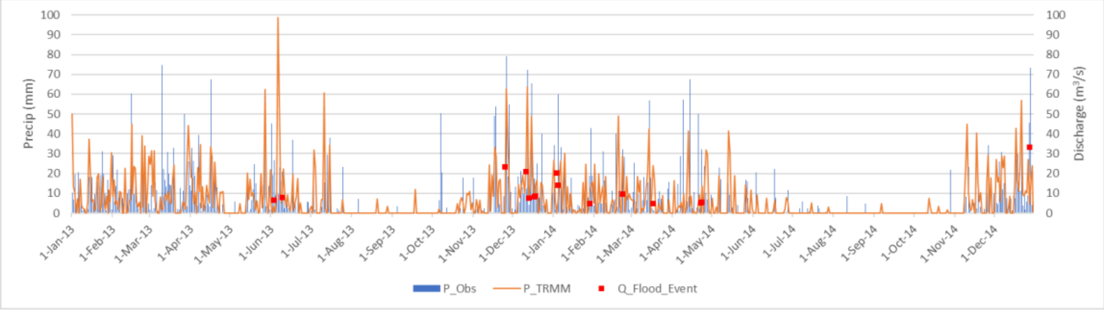


Figure 5 Comparison between observed catchment rainfall and E2O catchment rainfall at Purwodadi



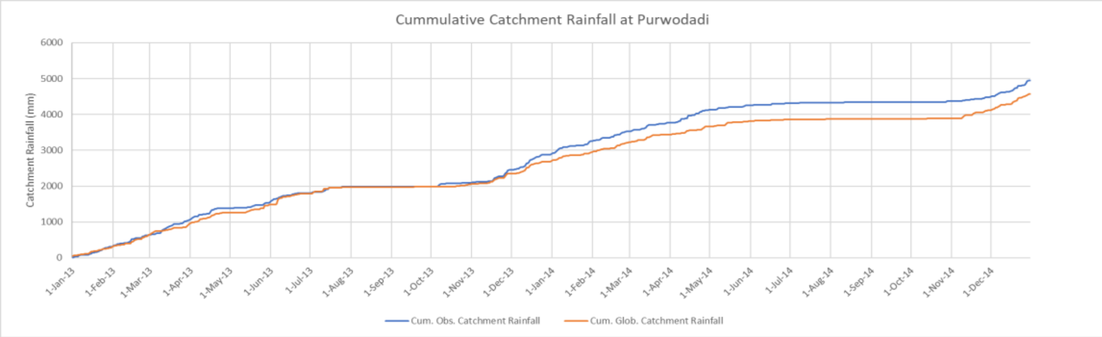
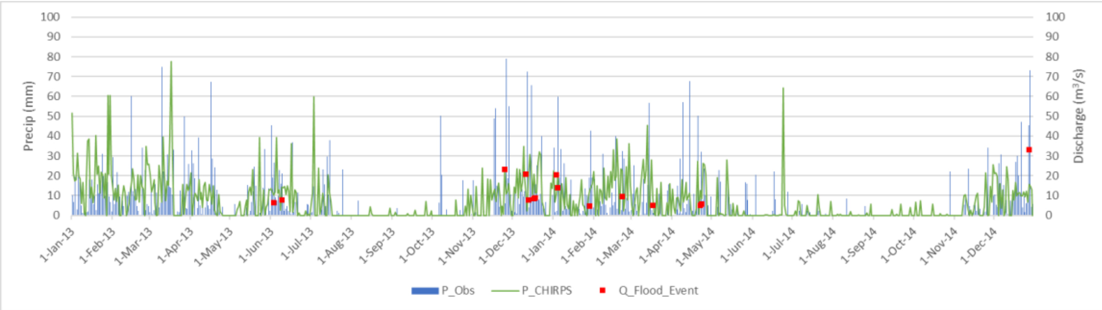


Figure 6 Comparison between observed catchment rainfall and TRMM catchment rainfall at Purwodadi



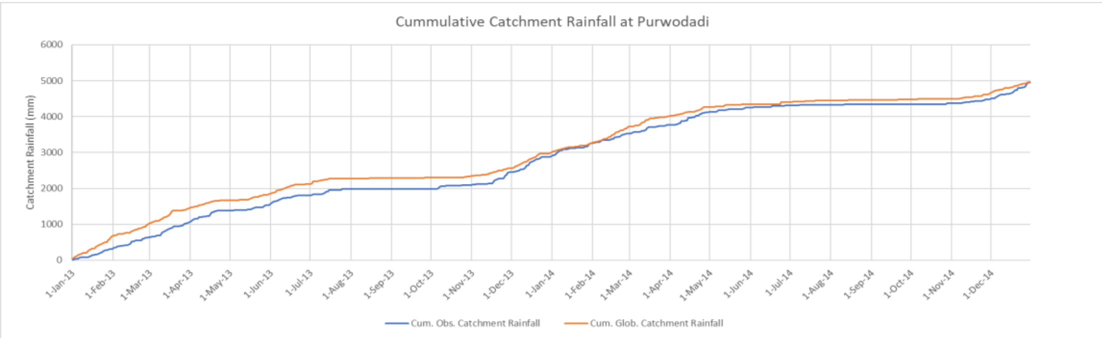


Figure 7 Comparison between observed catchment rainfall and CHIRPS catchment rainfall at Purwodadi

Based on visual appraisal on catchment rainfall at Purwodadi and Dhompo and the correlation value between satellite products, E2O is chosen to be the best fit for representing catchment rainfall at Welang Basin. It is therefore in this project storm design will be created based on E2O data (1979-2014).

In order to get the desired storm design for various return periods, initially maximum rainfall for each year should be seek after. This annual maximum rainfall is then used to find the most fit probability distribution function. In order to make sure that the probability distribution used for determining the peak rainfall for various return period is correct, series of annual maximum rainfall has to pass several statistical checks namely: 1) outlier test, 2) trend test (Spearman's Rank-Correlation Method, F-Test and t-Test) and 3) independency test. Result of rainfall frequency analysis for past and present situation are elaborated in the next section.

In Indonesia, most rainfall occurs for around 6 hours. In order to get a storm design (graph of rainfall depth against time), a rainfall distribution needs to be known. In this project the rainfall distribution that is used is coming from PSA 007 for 10-year, 25-year and 100-year rainfalls and from West Java rainfall distribution for 1-year rainfall. With the rainfall distribution, a synthetic storm design for various peak rain fall can be simply obtained by multiplying the value of peak rainfall with the percentage of rainfall depth over time.

The average catchment PET and TEMP according to E2O for the period of 1979-2014 are 3.74 mm/day and 22.7°C. These values are in-line with the catchment PET and TEMP according to ERA5 for the same period of time with PET of 3.46 mm/day and temperature of 23.47°C. As scenario 3 (E2O) is selected to be used for generating storm design, the creation of flood design will also make use of E2O average catchment PET and TEMP in order to ensure data uniformity.

Water Level and River Discharge

- Similar to meteorological datasets, water level and river discharge also need to be checked before being used to calibrate the model. The check that has been carried out includes visual check and statistical check.

1. Visual check
   - This check is done by plotting the discharge and water level data to see if there is any jump or a trend at a glance. A jump or a trend might be caused change of discharge prediction formula, change of water level measuring device or even due the change of location where water level is recorded. Visually it is known that there is an indication that the recorded water level and discharge at Purwodadi station for the years 2002-2006 are not correct. Moreover, a noticeable jump is also found in the year 2019 at Purwodadi station. At Selowongko, there is no irregularities found between measured water level and predicted discharge. At Dhompo station, inconsistent water level measurement with the predicted discharge data is also found for the years with high discharge (2003, 2009-2011, 2016 and 2018).

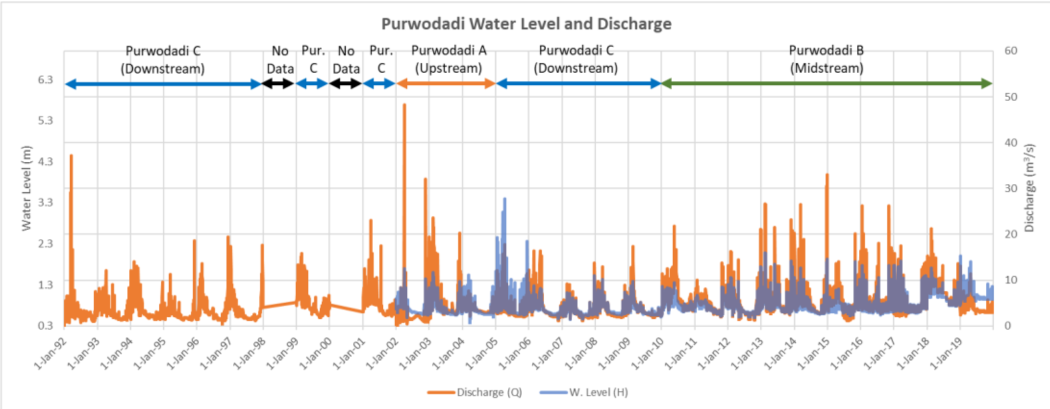


Figure 8 Purwodadi Water Level and Discharge

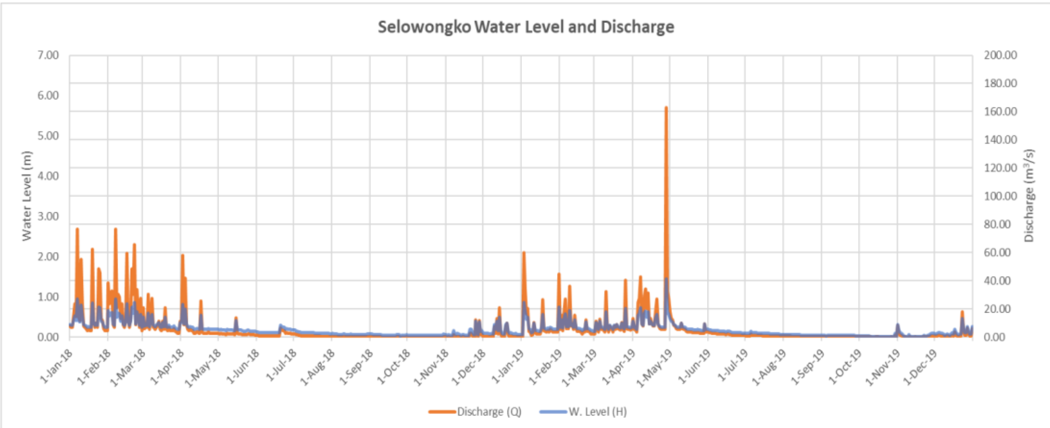


Figure 9 Selowongko Water Level and Discharge

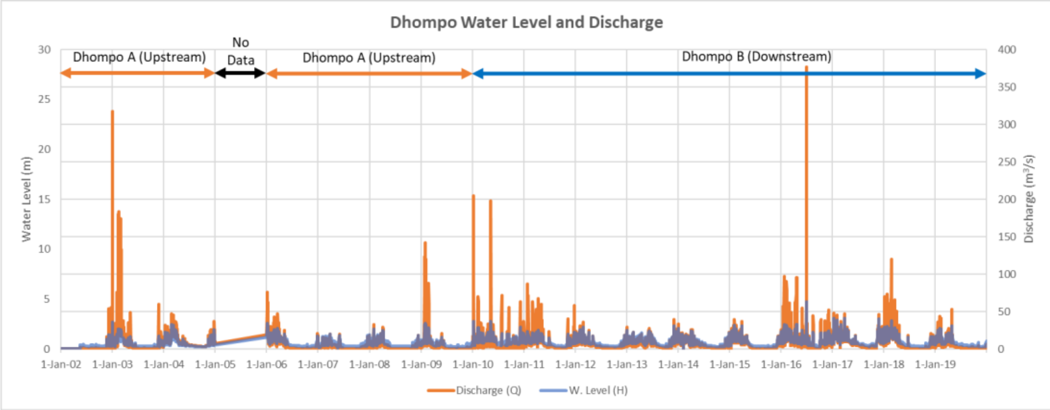


Figure 10 Dhompo Water Level and Discharge

2. Statistical check

   Some statistical checks that have carried out to have a better insight on the water level and the predicted discharge data are: 1) check of discharge value in a short timestep with a longer timestep (daily vs monthly data) and 2) check of the statistical properties of discharge data (mean, max and average). From the first check, it was found that no daily discharge data that has higher value than the average monthly data. The statistical properties of each stream gauge are presented in Table 23.

   From Table 23 it was found that the average discharge value over the three stream gauges are not proportionally adding up as it goes downstream in the period of 2018-2019. A higher average value at Purwodadi, might be attributed to the constant flow that is still available in the river during no/minimum rain. In the other hand, a relatively small average discharge at Dhompo may be attributed to the amount of water diverted from the main river to the irrigation channel.

Table 23 Min, max and average discharge at AWLR Purwodadi, AWLL Selowongko and AWLR Dhompo

Data	- **2013-2014**		- **2018-2019**		
	- **Purwodadi (C.A. = 123.45 km^2)**	- **Dhompo (C.A. = 474.59 km^2)**	- **Purwodadi (C.A. = 123.45 km^2)**	- **Selowongko (C.A. = 267.89 km^2)**	- **Dhompo (C.A. = 474.59 km^2)**
- Q_{Min} (m^3/s)	0.93	2.39	2.40	0.01	0.20
- $Q_{Average}$ (m^3/s)	6.54	5.41	5.59	5.23	7.05
- Q_{Max} (m^3/s)	39.38	33.07	21.26	163.03	119.52

3. Runoff Coefficient

- Apart from checking rainfall and discharge data, there is additional check that often used to represent the correlation between rainfall and discharge data. This check is a simple water balance check that calculates the proportion of water that becomes discharge over the amount of water that fall into the basin. The proportion itself is often called runoff coefficient and often calculated in yearly timestep. A small runoff coefficient value indicates the small proportion of water converted into discharge, while a large coefficient value (> 90%) often indicates that the watershed is critical (unable to infiltrate or store rainwater).
-
- Based on the observation datasets, the annual runoff coefficient for Purwodadi, Selowongko and Dhompo can be obtained. These values are summarized in Table 24.
-

$$Runoff\ Coefficient\ (R.C.) = \frac{Volume\ of\ water\ measured\ at\ stream\ gauge}{Volume\ of\ water\ entering\ basin}$$

Table 24 Runoff Coefficients for AWLR Purwodadi, AWLL Selowongko and AWLR Dhompo

Period	AWLR Purwodadi	AWLL Selowongko	AWLR Dhompo
	Q_Obs/P_Obs (%)	Q_Obs/P_Obs (%)	Q_Obs/P_Obs (%)
2013	50.68	-	17.79
2014	63.21	-	22.16
2010-2014	55.99	-	19.63
2018	100.98	34.05	33.08
2019	57.29	34.25	21.95
2018-2019	80.71	34.14	28.08

Based on the runoff coefficients formula, it is known that the runoff coefficient should always range from 0% to 100%. A value larger than 100% as found in AWLR Purwodadi in 2018, may be caused by several things, among others are overestimation of discharge measurement/wrong water level measurement, underestimation of catchment rainfall as a result of sparse rain gauge coverage or it may be caused by additional water supply either from outside Purwodadi basin or from groundwater. In the other hand, small runoff coefficient at Dhompo indicates that most of the rainfall that falls into Dhompo catchment doesn't flow to AWLR Dhompo. This finding is inline with the presence of Licin Intake and Grinting Intake upstream of AWLR Dhompo that might divert a lot of water from the main river. Low runoff coefficient values at Dhompo is also confirmed by a small difference of discharge between Dhompo and Purwodadi stations during the flood event which recorded by BNPB (DIBI Database), **B.7 Discharge Recorded During Flood Events**.

4. Remarks

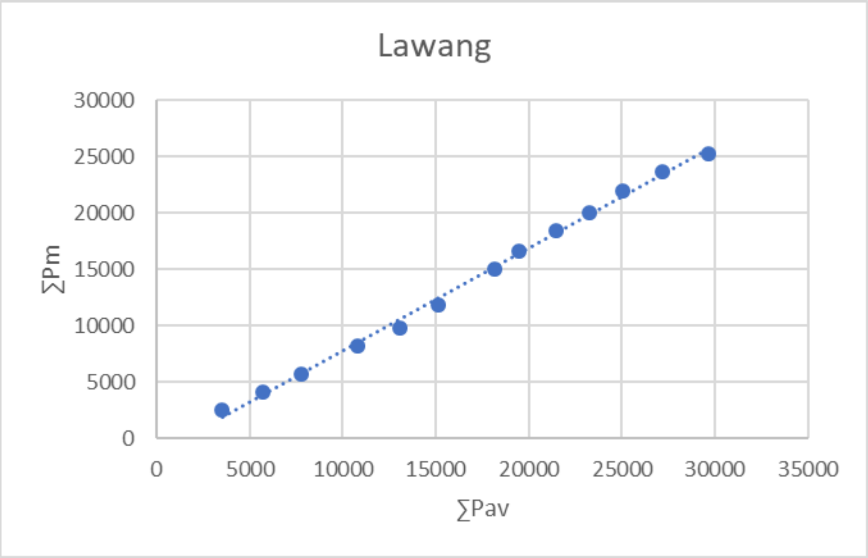
The following is some important remarks which are obtained during data analysis.

1. Among 5 satellite products, E2O precipitation product is considered to be the most sensitive on capturing heavy rainfall and has correlation value of 0.52 when compared to the observed catchment rainfall.
2. There are some heavy rainfall events that E2O cannot catch (December 2014).
3. Calibration cannot be done at Dhompo station as most of water that flows into the main Welang River is used for irrigating paddy field. This water only flows back to the main river after AWLR Dhompo (Downstream of AWLR Dhompo, Figure 7-9).
4. Until now constant discharge values found at Purwodadi station are still physically unexplained as there is no pond/reservoir upstream of Purwodadi station.
5. Local rainfall at Lawang, Tutur, Selowongko and Pager highly determines the observed catchment rainfall.

Double Mass Curve

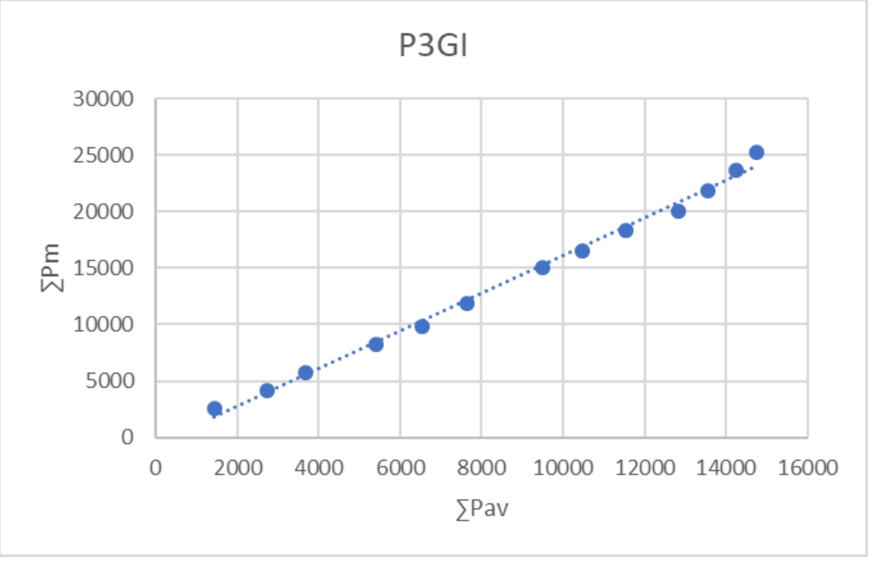
Year	Yearly Rainfall (mm)											Average (mm)
	Lawang	P3GI	Pager	Purwosari	Selowongko	Wonorejo	Tutur	Puspo	Oro-Oro Pule	Telebuk	Badong	
2016	3534	1442	2918	3413	1262	1865	3489	3021	1591	2466	2624.7	2511.4
2015	2164	1277	2208	1987	842	1167	1871	1937	1057	1641	1590	1612.8
2014	2092	948	1935	1876	1147	1128	2185	2164	946	1641	1713	1615.9
2013	3032	1755	2871	2938	1635	1619	2752	3183	1740	2484	3017	2456.9
2012	2220	1131	1849	1780	1193	1041	2110	2118	1079	1684	1934	1649.0
2011	2082	1097	2549	2657	1650	1322	2941	2299	1445	2522	1892	2041.5
2010	3012	1842	3431	3383	2290	2157	5298	4183	2500	3085	3133	3119.5
2009	1362	979	1954	1688	1489	1286	2045	1885	1249	1678	1381	1545.1
2008	1972	1059	2058	1932	1456	1502	2651	2460	1395	2215	1521	1838.3
2007	1757	1292	1575	1343	1188	1351	2374	2620	1209	2187	1501	1672.5
2006	1783	736.6	2295	2006	1410	1499	2293	2232	2206	2263	1390	1828.5
2005	2148	688.7	1854	1673	1334	1628	2347	1915	1521	2273	1844	1747.8
2004	2469	509.5	1897	2101	1326	1020	1951	1345	1380	1840	1752	1599.1

Year	Lawang	Average (mm)	∑P_{av} (mm)	∑P_m (mm)
2016	3534	2511	3534	2511
2015	2164	1613	5698	4124
2014	2092	1616	7790	5740
2013	3032	2457	10822	8197
2012	2220	1649	13042	9846
2011	2082	2041	15124	11888
2010	3012	3119	18136	15007
2009	1362	1545	19498	16552
2008	1972	1838	21470	18390
2007	1757	1672	23227	20063
2006	1783	1829	25010	21891
2005	2148	1748	27158	23639
2004	2469	1599	29627	25238



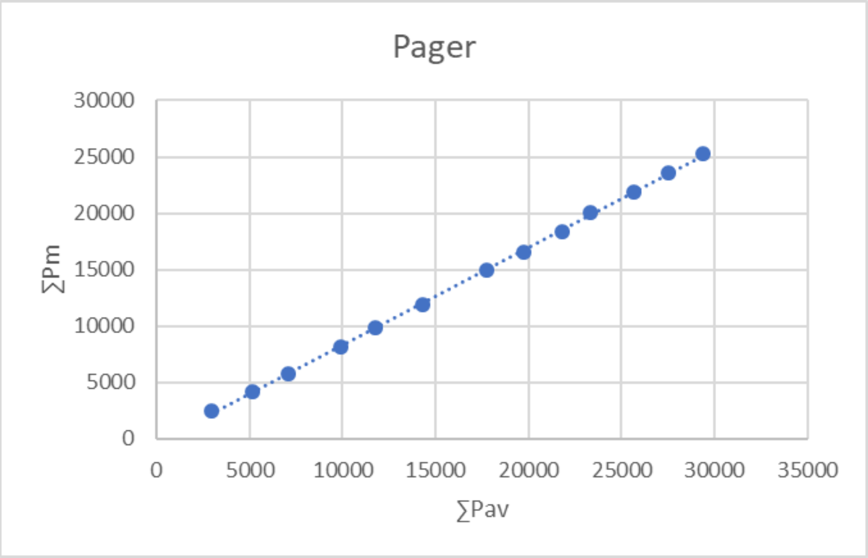
Year	P3GI	Average (mm)	∑P_{av} (mm)	∑P_m (mm)
2016	1442	2511	1442	2511
2015	1277	1613	2719	4124
2014	948	1616	3667	5740
2013	1755	2457	5422	8197
2012	1131	1649	6553	9846
2011	1097	2041	7650	11888
2010	1842	3119	9492	15007
2009	979	1545	10471	16552

2008	1059	1838	11530	18390
2007	1292	1672	12822	20063
2006	737	1829	13559	21891
2005	689	1748	14247	23639
2004	510	1599	14757	25238



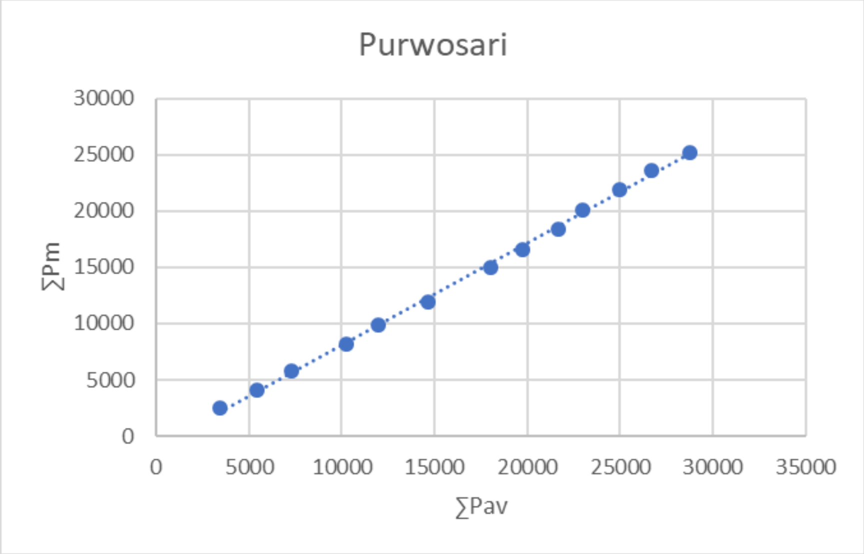
Year	Pager	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_{m}$ (mm)
2016	2918	2511	2918	2511
2015	2208	1613	5126	4124
2014	1935	1616	7061	5740

2013	2871	2457	9932	8197
2012	1849	1649	11781	9846
2011	2549	2041	14330	11888
2010	3431	3119	17761	15007
2009	1954	1545	19715	16552
2008	2058	1838	21773	18390
2007	1575	1672	23348	20063
2006	2295	1829	25643	21891
2005	1854	1748	27497	23639
2004	1897	1599	29394	25238



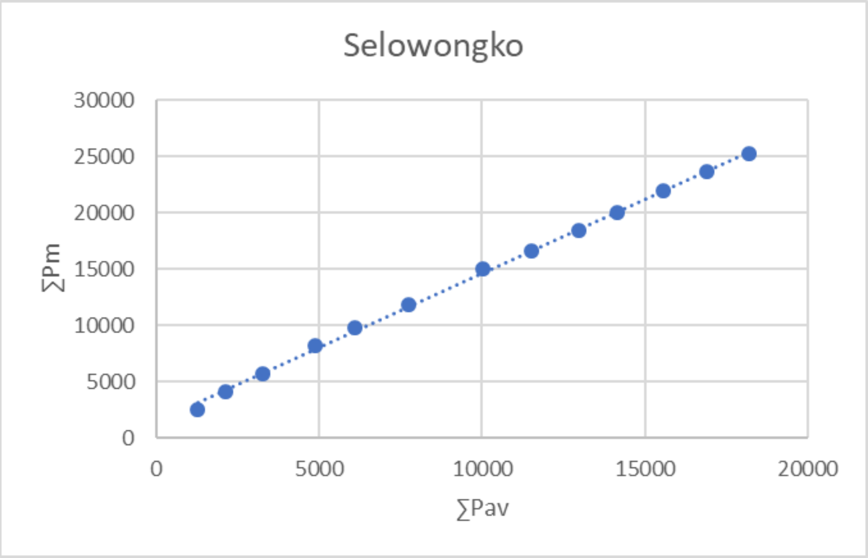
Year	Purwosari	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	3413	2511	3413	2511
2015	1987	1613	5400	4124
2014	1876	1616	7276	5740
2013	2938	2457	10214	8197
2012	1780	1649	11994	9846
2011	2657	2041	14651	11888
2010	3383	3119	18034	15007
2009	1688	1545	19722	16552
2008	1932	1838	21654	18390
2007	1343	1672	22997	20063

2006	2006	1829	25003	21891
2005	1673	1748	26676	23639
2004	2101	1599	28777	25238



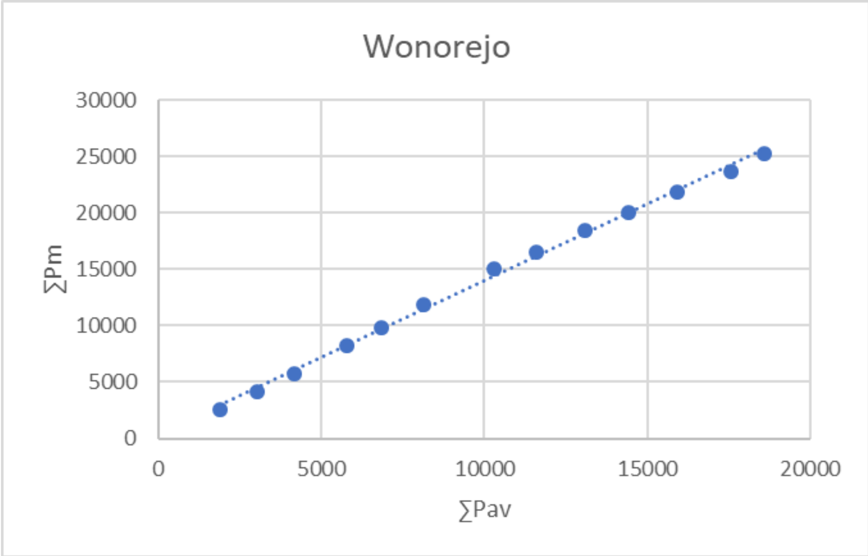
Year	Selowongko	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_{m}$ (mm)
2016	1262	2511	1262	2511
2015	842	1613	2104	4124
2014	1147	1616	3251	5740
2013	1635	2457	4886	8197
2012	1193	1649	6079	9846
2011	1650	2041	7729	11888
2010	2290	3119	10019	15007
2009	1489	1545	11508	16552

2008	1456	1838	12964	18390
2007	1188	1672	14152	20063
2006	1410	1829	15562	21891
2005	1334	1748	16896	23639
2004	1326	1599	18222	25238

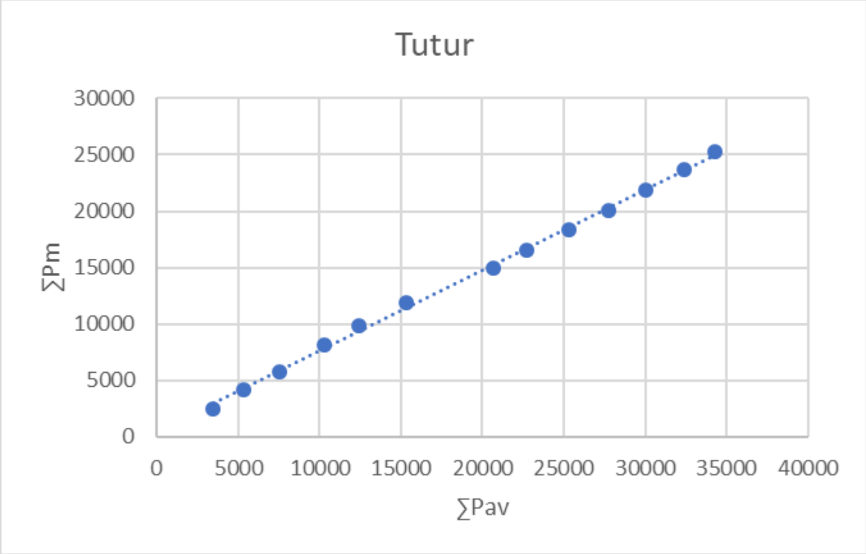


Year	Wonorejo	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	1865	2511	1865	2511
2015	1167	1613	3032	4124
2014	1128	1616	4160	5740
2013	1619	2457	5779	8197
2012	1041	1649	6820	9846
2011	1322	2041	8142	11888
2010	2157	3119	10299	15007
2009	1286	1545	11585	16552
2008	1502	1838	13087	18390
2007	1351	1672	14438	20063

2006	1499	1829	15937	21891
2005	1628	1748	17565	23639
2004	1020	1599	18585	25238

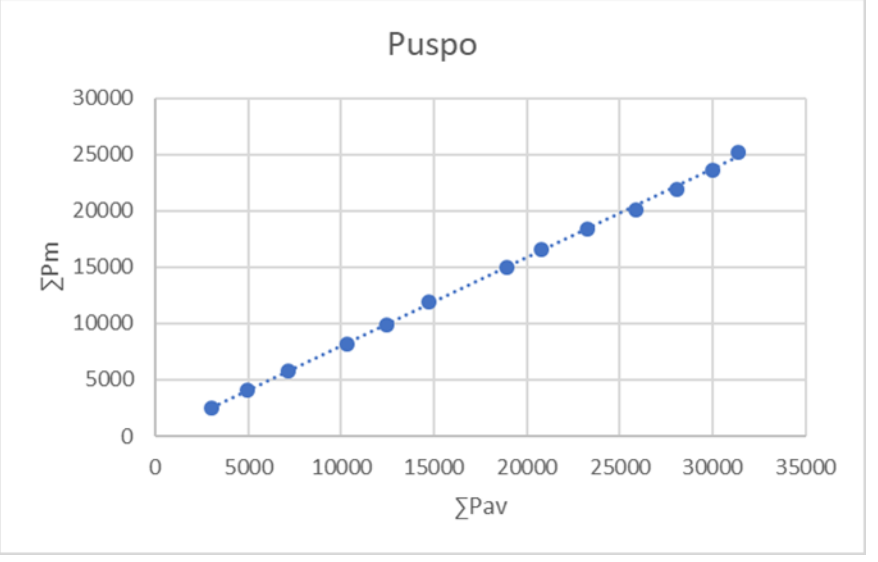


Year	Tutur	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	3489	2511	3489	2511
2015	1871	1613	5360	4124
2014	2185	1616	7545	5740
2013	2752	2457	10297	8197
2012	2110	1649	12407	9846
2011	2941	2041	15348	11888
2010	5298	3119	20646	15007
2009	2045	1545	22691	16552
2008	2651	1838	25342	18390
2007	2374	1672	27716	20063
2006	2293	1829	30009	21891
2005	2347	1748	32356	23639
2004	1951	1599	34307	25238



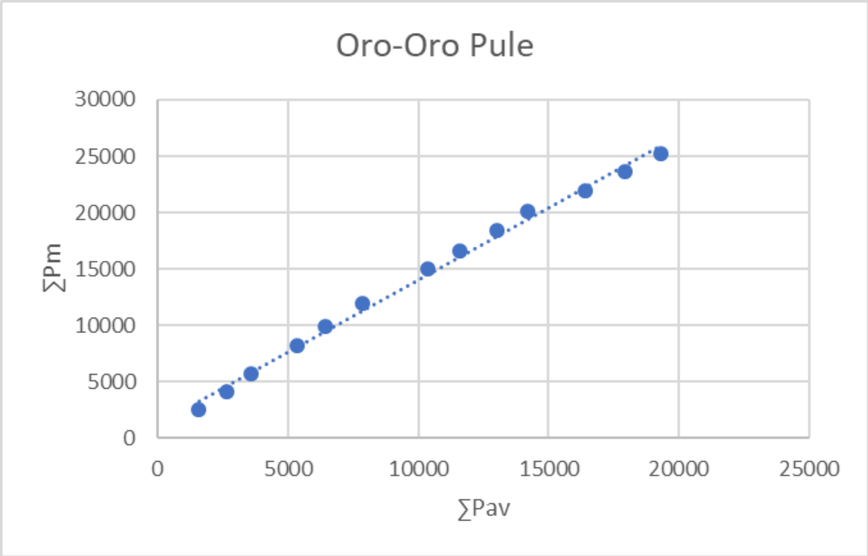
Year	Puspo	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	3021	2511	3021	2511
2015	1937	1613	4958	4124
2014	2164	1616	7122	5740
2013	3183	2457	10305	8197
2012	2118	1649	12423	9846
2011	2299	2041	14722	11888
2010	4183	3119	18905	15007
2009	1885	1545	20790	16552
2008	2460	1838	23250	18390
2007	2620	1672	25870	20063

2006	2232	1829	28102	21891
2005	1915	1748	30017	23639
2004	1345	1599	31362	25238



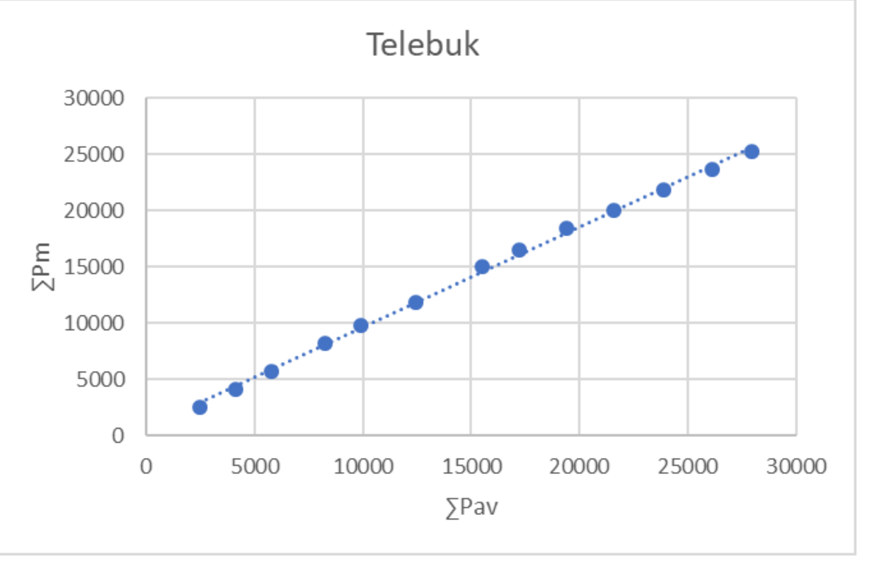
Year	Oro-Oro Pule	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_{m}$ (mm)
2016	1591	2511	1591	2511
2015	1057	1613	2648	4124
2014	946	1616	3594	5740
2013	1740	2457	5334	8197

2012	1079	1649	6413	9846
2011	1445	2041	7858	11888
2010	2500	3119	10358	15007
2009	1249	1545	11607	16552
2008	1395	1838	13002	18390
2007	1209	1672	14211	20063
2006	2206	1829	16417	21891
2005	1521	1748	17938	23639
2004	1380	1599	19318	25238



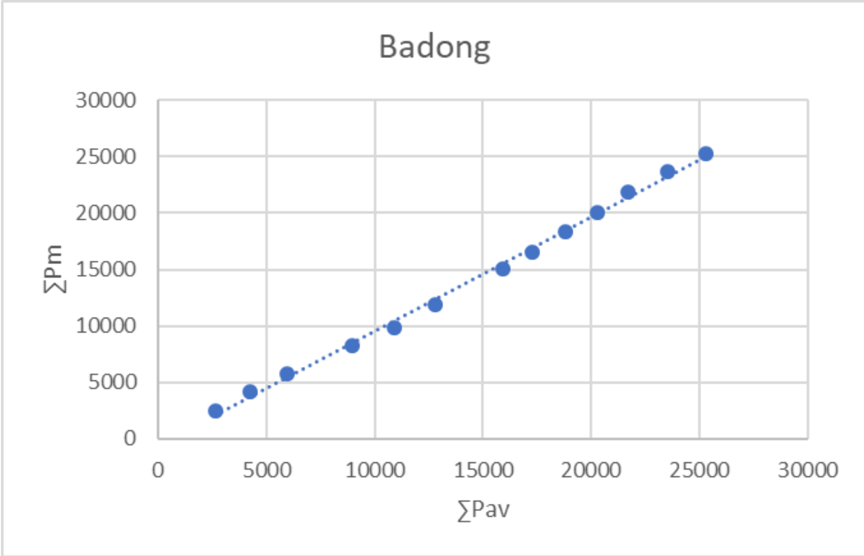
Year	Telebuk	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	2466	2511	2466	2511
2015	1641	1613	4107	4124
2014	1641	1616	5748	5740
2013	2484	2457	8232	8197
2012	1684	1649	9916	9846
2011	2522	2041	12438	11888
2010	3085	3119	15523	15007
2009	1678	1545	17201	16552
2008	2215	1838	19416	18390
2007	2187	1672	21603	20063

2006	2263	1829	23866	21891
2005	2273	1748	26139	23639
2004	1840	1599	27979	25238



Year	Badong	Average (mm)	$\sum P_{av}$ (mm)	$\sum P_m$ (mm)
2016	2625	2511	2625	2511
2015	1590	1613	4215	4124
2014	1713	1616	5928	5740
2013	3017	2457	8945	8197
2012	1934	1649	10879	9846
2011	1892	2041	12771	11888

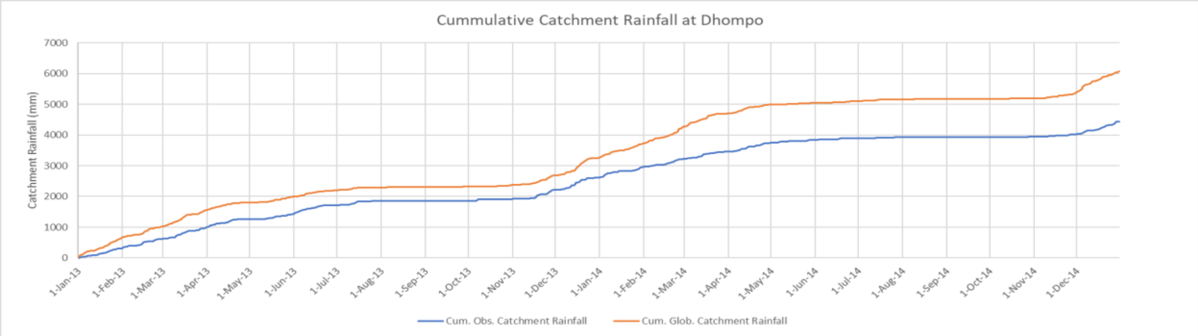
2010	3133	3119	15904	15007
2009	1381	1545	17285	16552
2008	1521	1838	18806	18390
2007	1501	1672	20307	20063
2006	1390	1829	21697	21891
2005	1844	1748	23541	23639
2004	1752	1599	25293	25238



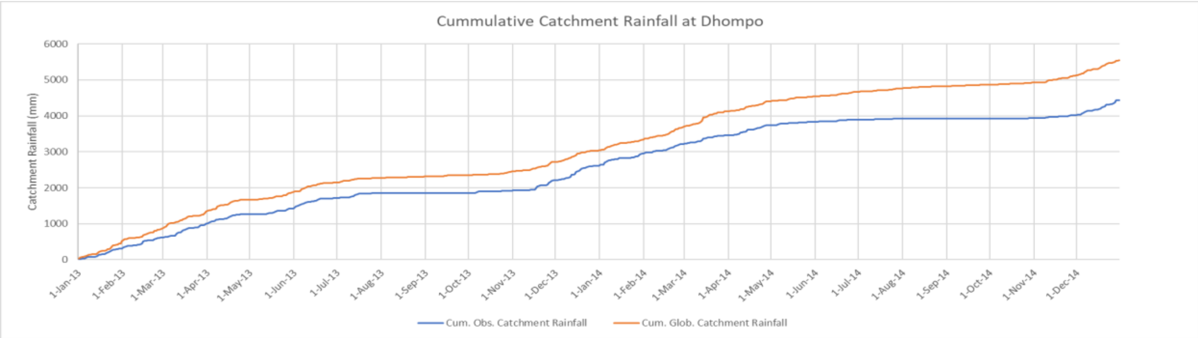
Note: $\sum P_{av}$ = accumulated annual rainfall of 11 stations mean where as $\sum P_m$ = accumulated annual rainfall at specific station.

Cumulative Rainfall Upstream Dhompo

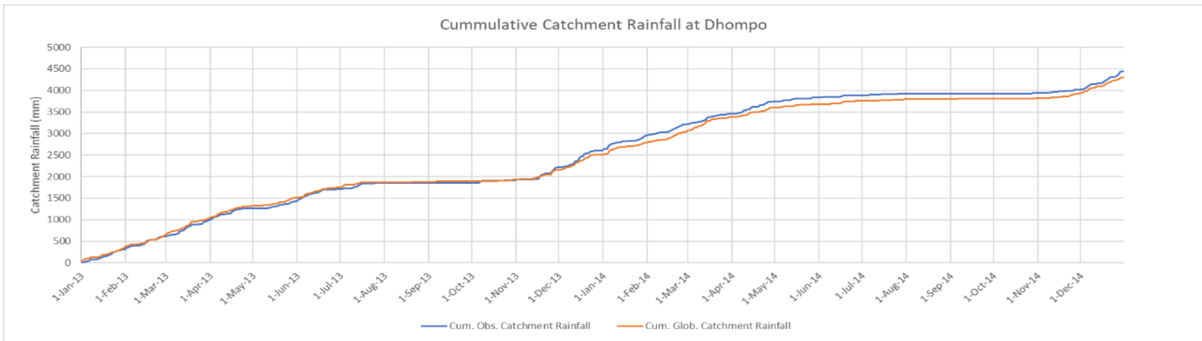
ERA5



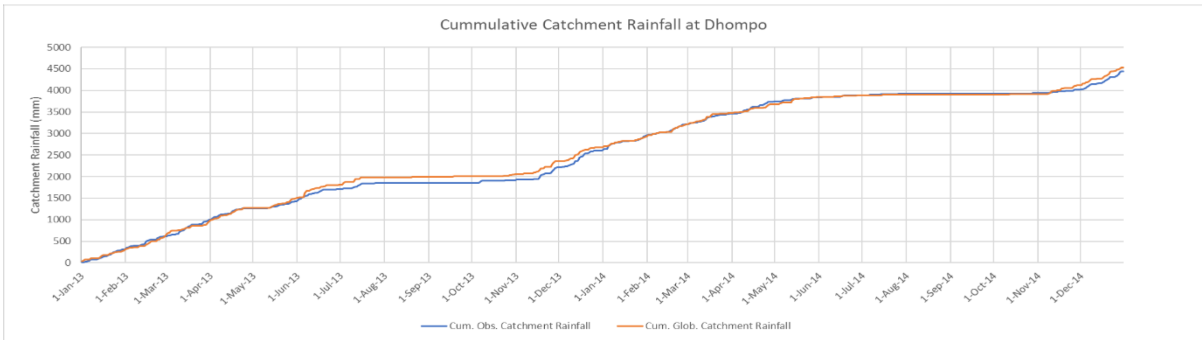
GPMF



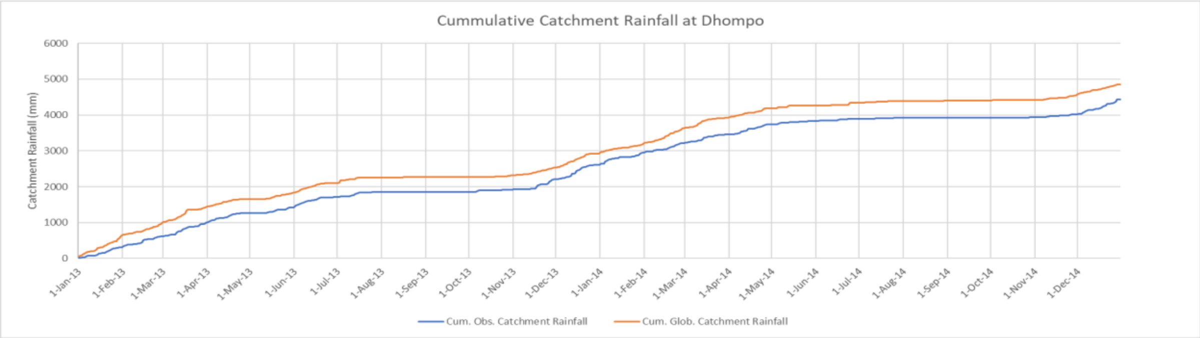
E2O



TRMM

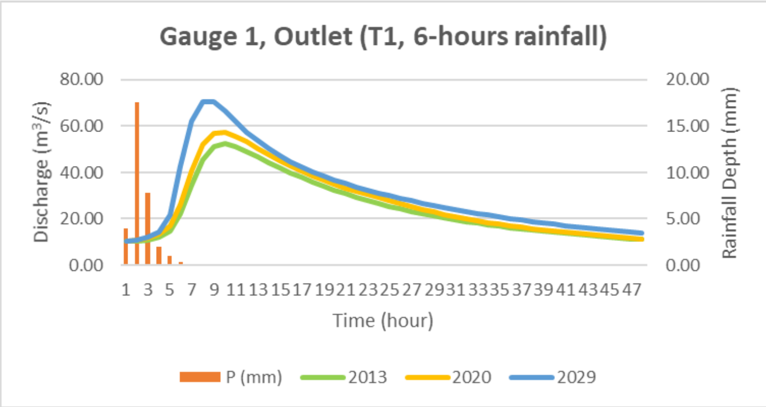


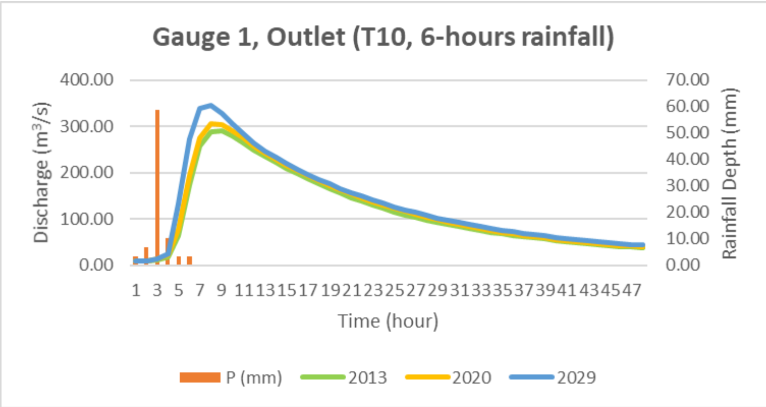
CHIRPS

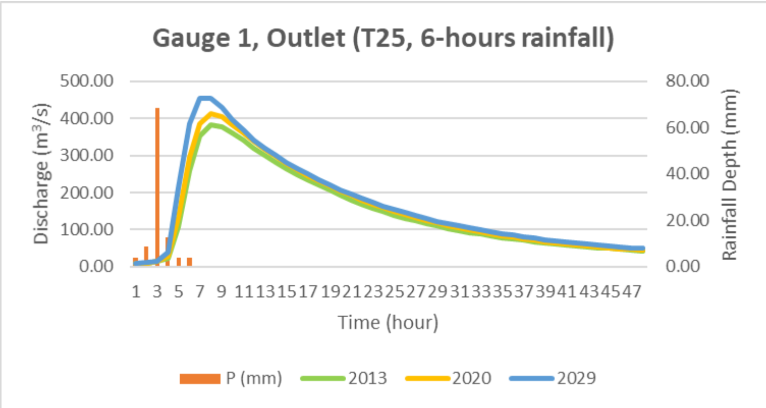

Cummulative Catchment Rainfall at Dhompo
Catchment Rainfall (mm)
6000
5000
4000
3000
2000
1000
0
1-Jan-13
1-Feb-13
1-Mar-13
1-Apr-13
1-May-13
1-Jun-13
1-Jul-13
1-Aug-13
1-Sep-13
1-Oct-13
1-Nov-13
1-Dec-13
1-Jan-14
1-Feb-14
1-Mar-14
1-Apr-14
1-May-14
1-Jun-14
1-Jul-14
1-Aug-14
1-Sep-14
1-Oct-14
1-Nov-14
1-Dec-14
Cum. Obs. Catchment Rainfall
Cum. Glob. Catchment Rainfall

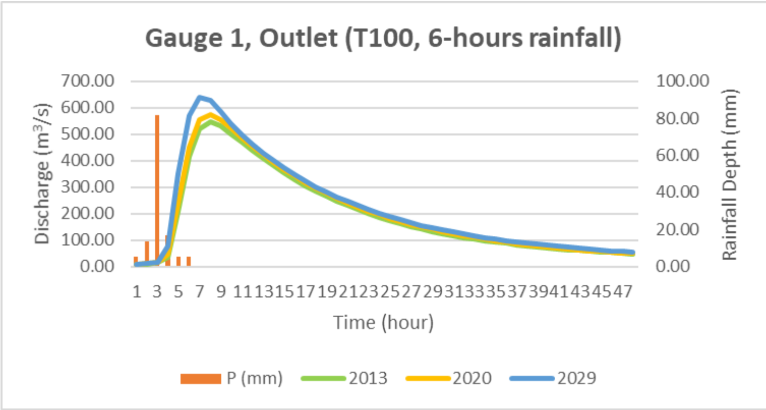
WFLOW Discharges

Gauge 1 (Outlet)

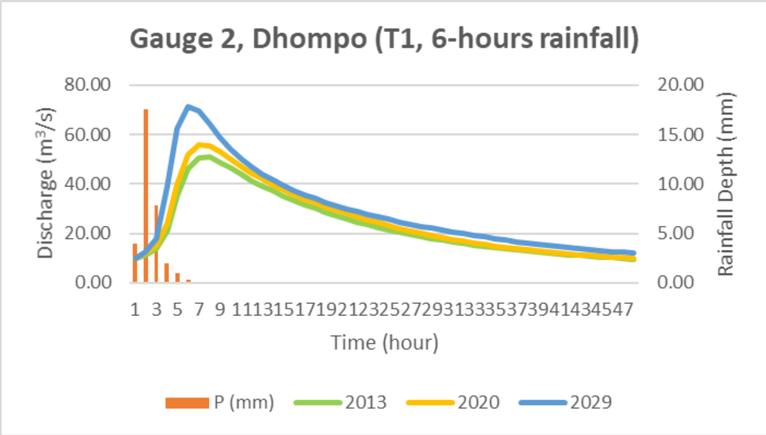


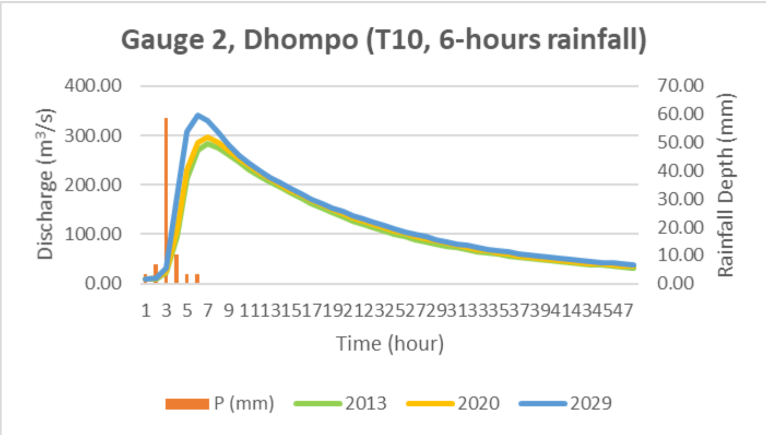


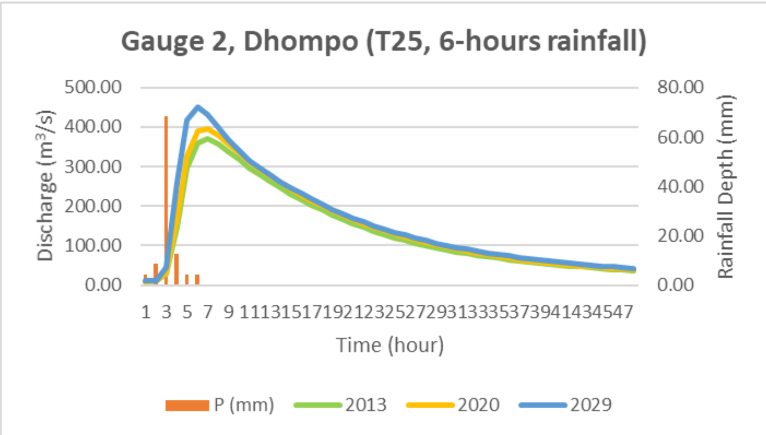


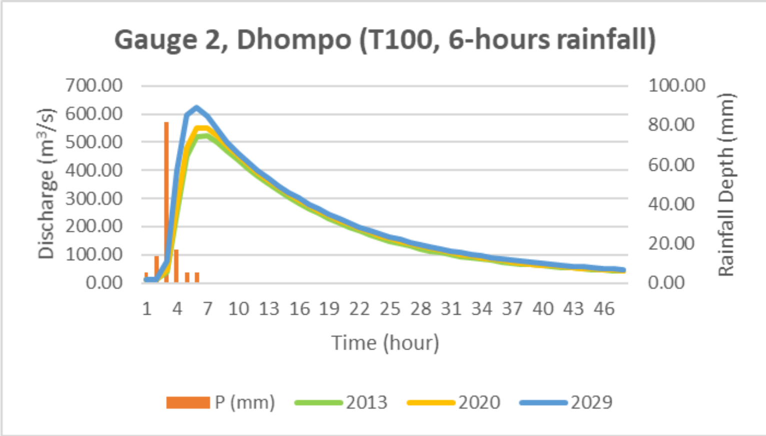

Gauge 1, Outlet (T100, 6-hours rainfall)
Discharge (m³/s)
Rainfall Depth (mm)
Time (hour)
P (mm)
2013
2020
2029

Gauge 2 (Dhompo)

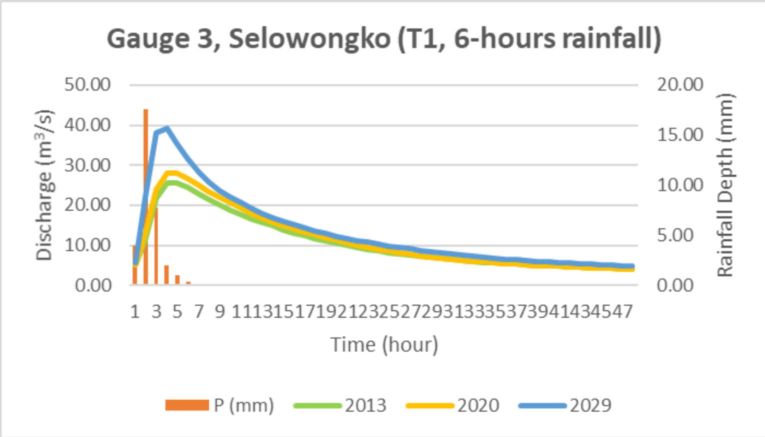


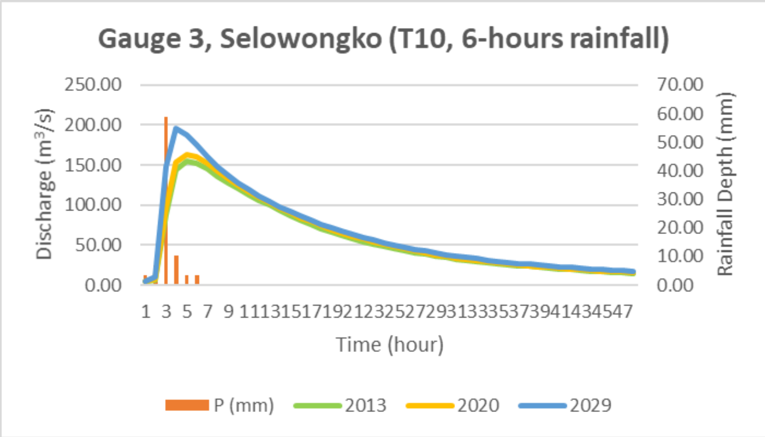


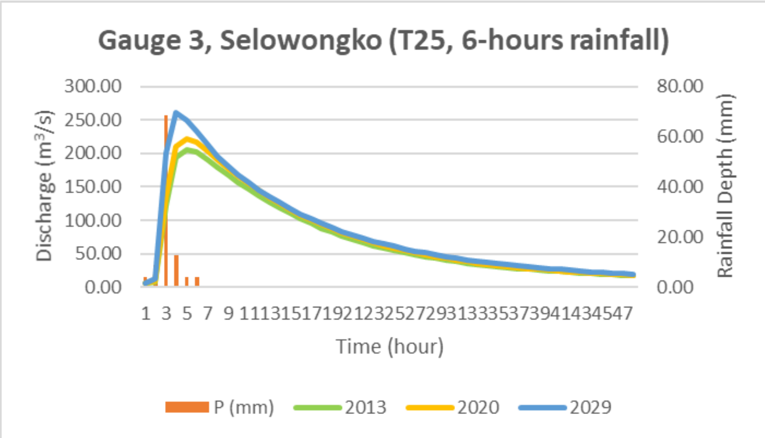


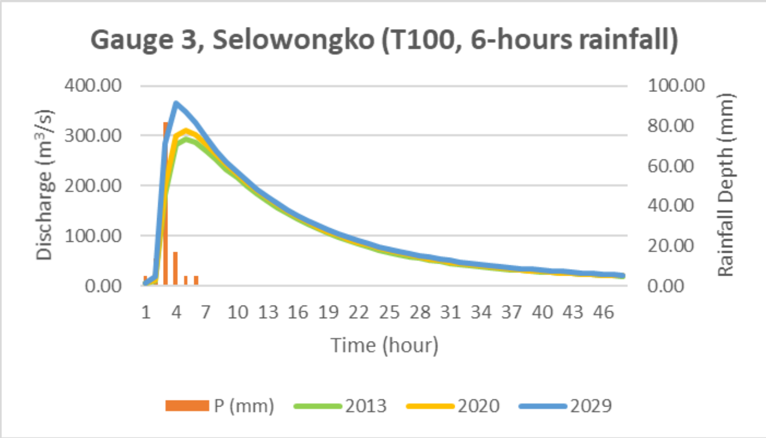

Gauge 2, Dhompo (T100, 6-hours rainfall)
700.00
600.00
500.00
400.00
300.00
200.00
100.00
0.00
Discharge (m3/s)
100.00
80.00
60.00
40.00
20.00
0.00
Rainfall Depth (mm)
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46
Time (hour)
P (mm)
2013
2020
2029

Gauge 3 (Selowongko)

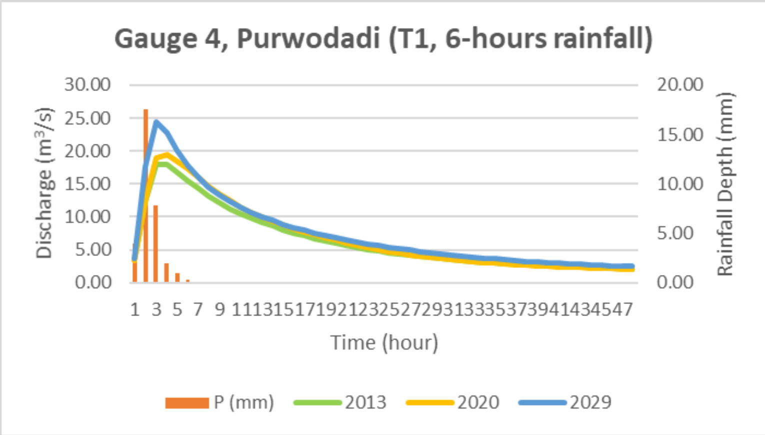


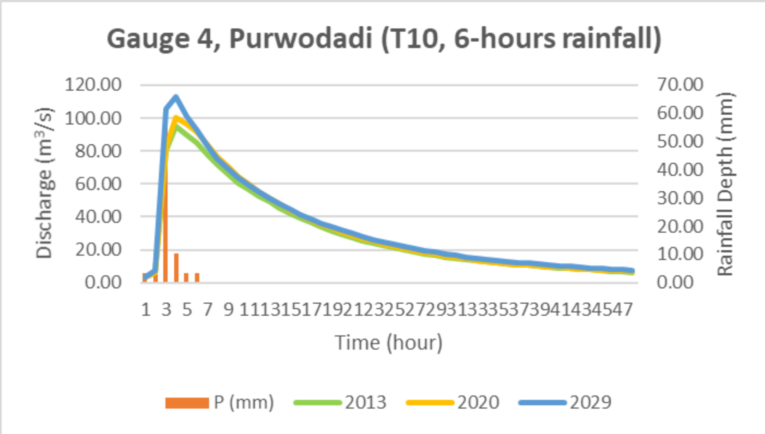


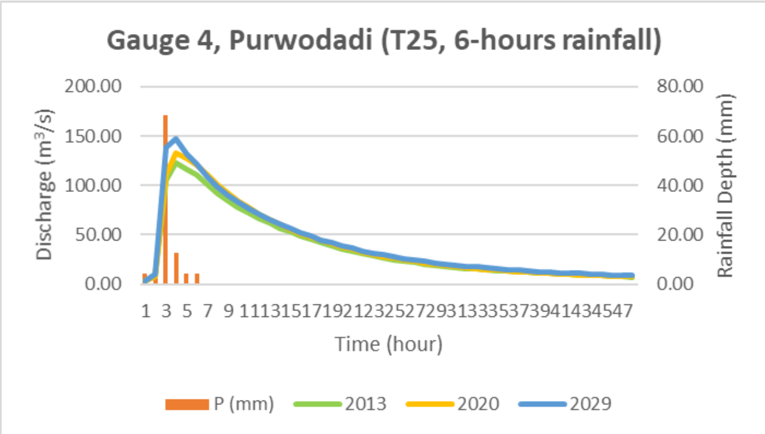


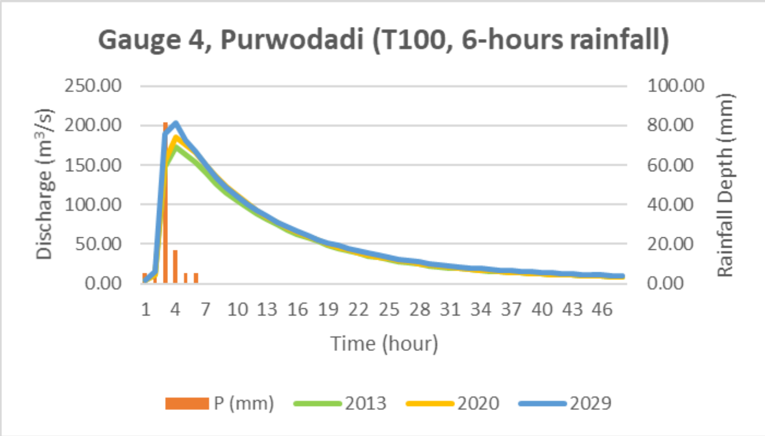

Gauge 3, Selowongko (T100, 6-hours rainfall)
Discharge (m³/s)
Rainfall Depth (mm)
Time (hour)
P (mm)
2013
2020
2029

Gauge 4 (Purwodadi)









Runoff Coefficients

Period	Yearly Observed Rainfall (mm)			Volume of Yearly Observed Rainfall (m³)		
	Dhompo	Selowongko	Purwodadi	Dhompo	Selowongko	Purwodadi
2013	2,615	-	2,892	1,239,848,230	-	356,764,620
2014	1,825	-	2,055	865,597,164	-	253,526,419
2013-2014	4,440	-	4,947	2,105,445,394	-	610,291,039
2018	1,841	1,944	1,945	872,771,003	520,637,478	239,934,130
2019	1,501	1,664	1,683	711,851,089	445,805,850	207,666,845
2018-2019	3,342	3,608	3,628	1,584,622,092	966,443,328	447,600,975

Period	Yearly Observed Discharge (m³/s)			Volume of Yearly Observed Discharge (m³)		
	Dhompo	Selowongko	Dhompo	Dhompo	Selowongko	Purwodadi
2013	2,552	-	2,093	220,516,992	-	180,796,320
2014	2,230	-	1,863	192,685,824	-	160,926,048
2013-2014	4,782	-	3,955	413,202,816	-	341,722,368
2018	3,341	2,052	2,804	288,699,144	177,255,671	242,292,512
2019	1,808	1,767	1,377	156,246,120	152,706,934	118,968,873
2018-2019	5,150	3,819	4,181	444,945,265	329,962,604	361,261,385

Period	Runoff Coefficients (%) = Q_{obs}/P_{obs}		
	Dhompo	Selowongko	Purwodadi

2013	17.79	-	50.68
2014	22.26	-	63.48
2013-2014	19.63	-	55.99
2018	33.08	34.05	100.98
2019	21.95	34.25	57.29
2018-2019	28.08	34.14	80.71

Discharge Recorded During Flood Events

Date	Qobs Purwodadi (m^3/s)	Qobs Dhompo (m^3/s)	People Affected	City/District	Regency	Type of Disaster
6/30/2016	13.05	376.48	58706	Pasuruan City	Bangil, Beji, Kraton, Pohjentrek, Grati, Rejoso, Winongan, Gempol	Flood
12/16/2016	3.53	26.92	32020	Pasuruan	Gempol, Beji, Bangil	Flood
2/3/2004	4.47	14.90	27501	Pasuruan		Flood
1/11/2017	15.82	47.82	27500	Pasuruan	Kraton, Pohjentrek, Grati, Winongan, Pandaan, Nguling, Bangil	Flood
1/25/2017	4.06	37.73	25210	Pasuruan	Grati, Nguling, Winongan, Rejoso	Flood
10/10/2016	4.70	39.55	24660	Pasuruan	Kraton, Pohjentrek, Grati, Gondangwetan, Winongan	Flood
1/28/2014	4.69	16.56	21535	Pasuruan		Flood
2/21/2016	7.86	61.68	14021	Pasuruan	Pohjentrek	Flood
2/28/2016	4.83	27.36	13578	Pasuruan	Gadingrejo	Flood
12/26/2011	7.47	32.35	12931	Pasuruan		Flood
2/22/2014	9.53	14.07	12235	Pasuruan		Flood
6/15/2013	6.77	10.92	11455	Pasuruan		Flood
12/11/2013	20.76	23.93	10901	Pasuruan City		Flood
11/28/2017	4.27	28.31	10500	Pasuruan	Gempol	Flood
1/30/2017	3.13	32.33	10000	Pasuruan	Kraton, Pohjentrek, Gondang Wetan, Beji, Bangil, Wonorejo	Flood
3/30/2013	5.73	6.28	9500	Pasuruan		Flood
2/28/2017	14.53	37.10	8244	Pasuruan City	Gadingrejo	Flood
2/9/2016	5.35	90.32	6530	Pasuruan City	Gadingrejo	Flood
2/2/2015	6.42	17.75	6500	Pasuruan	Kraton. Pohjentrek	Flood
2/5/2015	6.25	39.02	5536	Pasuruan City	Gadingrejo	Flood
12/11/2017	5.09	11.15	5000	Pasuruan	Bangil	Flood
12/5/2016	4.21	52.12	4776	Pasuruan City	Gadingrejo	Flood
3/25/2017	2.36	17.77	4500	Pasuruan City	Gadingrejo	Flood
6/9/2013	7.79	14.15	4000	Pasuruan		Flood
12/13/2013	7.67	15.22	3591	Pasuruan		Flood

Date	Qobs Purwodadi (m^3/s)	Qobs Dhompo (m^3/s)	People Affected	City/District	Regency	Type of Disaster
1/19/2015	5.93	16.74	3580	Pasuruan	Bangil	Flood
1/19/2009	3.48	3.81	3500	Pasuruan		Flood
4/7/2013	3.48	9.78	3425	Pasuruan		Flood
12/17/2013	8.36	19.92	3325	Pasuruan		Flood
12/18/2013	8.68	26.51	3278	Pasuruan City		Flood
1/30/2015	5.85	31.61	3176	Pasuruan City	Gadingrejo	Flood
5/19/2016	5.48	5.95	3160	Pasuruan City	Panggungrejo, Gadingrejo	Flood
1/10/2017	8.80	22.42	3098	Pasuruan City	Gadingrejo	Flood
1/11/2017	15.82	47.82	3098	Pasuruan City	Gadingrejo, Panggungrejo	Flood
1/3/2014	20.26	33.22	3000	Pasuruan		Flood
2/10/2015	6.69	22.42	2565	Pasuruan City	Gadingrejo	Flood
3/2/2017	2.49	27.32	2506	Pasuruan City	Gadingrejo	Flood
1/30/2008	9.74	32.28	2247	Pasuruan		Flood
11/25/2013	23.22	16.12	2205	Pasuruan City		Flood
1/9/2010	11.39	204.75	2056	Pasuruan		Flood
3/17/2014	4.91	16.54	1450	Pasuruan City		Flood
4/30/2015	10.05	18.13	700	Pasuruan	Gadingrejo	Flood
2/3/2012	13.60	29.83	500	Pasuruan		Flood
3/14/2016	4.21	22.71	425	Pasuruan	Winongan	Flood
4/23/2014	5.60	8.10	270	Pasuruan City		Flood
1/5/2017	9.46	21.76	250	Pasuruan	Purwodadi	Flood
6/10/2010	16.69	15.54	72	Pasuruan City		Flood
1/24/2017	8.47	40.29	31	Pasuruan	Kraton, Pohjentrek, Bangil, Beji	Flood
2/8/2008	4.32	6.35	24	Pasuruan		Flood
1/7/2010	3.72	3.85	7	Pasuruan		Flood
2/2/2009	7.41	33.50	2	Pasuruan		Flood
3/28/2004	6.50	25.97	1	Pasuruan		Flood
1/13/2005	2.88	7.13	1	Pasuruan		Flood
2/10/2005	2.95	7.13	1	Pasuruan		Flood
12/6/2010	3.63	62.76	1	Pasuruan		Flood
2/3/2003	17.79	3.57	0	Pasuruan		Flood
1/1/2004	3.04	8.04	0	Pasuruan		Flood
3/14/2005	6.57	7.13	0	Pasuruan		Flood
1/1/2006	5.67	18.97	0	Pasuruan		Flood
2/1/2006	6.87	18.31	0	Pasuruan		Flood
3/1/2006	6.23	9.13	0	Pasuruan		Flood
1/6/2007	2.93	0.86	0	Pasuruan		Flood
3/27/2007	8.98	20.09	0	Pasuruan		Flood
2/16/2009	7.40	5.49	0	Pasuruan		Flood
3/4/2009	5.87	5.17	0	Pasuruan		Flood
5/11/2009	4.21	3.09	0	Pasuruan		Flood
6/17/2009	3.00	2.32	0	Pasuruan		Flood
4/1/2010	6.53	5.70	0	Pasuruan		Flood
6/1/2010	10.08	4.87	0	Pasuruan		Flood
7/1/2010	9.13	0.50	0	Pasuruan		Flood

Date	Qobs Purwodadi (m^3/s)	Qobs Dhompo (m^3/s)	People Affected	City/District	Regency	Type of Disaster
12/1/2010	4.11	7.97	0	Pasuruan		Flood
1/1/2011	4.18	36.84	0	Pasuruan		Flood
3/5/2011	5.70	63.23	0	Pasuruan		Flood
4/1/2011	6.16	23.10	0	Pasuruan		Flood
4/15/2011	6.80	67.18	0	Pasuruan City		Flood
2/1/2012	15.54	24.33	0	Pasuruan City		Flood
6/1/2012	3.55	3.72	0	Pasuruan		Flood
2/24/2013	9.14	3.31	0	Pasuruan		Flood
3/15/2013	7.73	3.47	0	Pasuruan		Flood
12/31/2005	3.59	7.13	0	Pasuruan		Flood
2/25/2007	9.16	15.19	0	Pasuruan		Flood
5/11/2010	7.06	4.70	0	Pasuruan		Flood
6/3/2013	6.47	24.87	0	Pasuruan		Flood
7/24/2013	9.22	7.39	0	Pasuruan		High tide/abrasion
4/3/2015	8.04	7.31	0	Pasuruan	Pasrepan	Flood
11/25/2013	23.22	16.12	0	Pasuruan		Flood
2/15/2016	5.22	10.79	0	Pasuruan	Gempol	Flood
1/4/2014	13.90	16.84	0	Pasuruan		Flood
4/22/2014	5.13	9.06	0	Pasuruan		Flood
12/27/2014	33.07	5.68	0	Pasuruan		Flood
3/1/2015	8.08	14.50	0	Pasuruan	Kraton	Flood
4/3/2015	8.04	7.31	0	Pasuruan	Tosari, [Uspo	Flood
2/28/2017	14.53	37.10	0	Pasuruan	Pohjentrek	Flood
11/21/2017	4.83	31.96	0	Pasuruan City	Gafingrejo	Flood
11/21/2017	4.83	31.96	0	Pasuruan	Pohjentrek. Kraton	Flood

Note: Text highlighted with red are the date when discharge value at AWLR Dhompo is lower than discharge value at AWLR Purwodadi.

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