Irrigation & Drainage Systems Engineering

Mini Polders, as an Alternative of Flood Management in the Lower Bengawan Solo River

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Abstract

Sumbangtimun Village and Kandangan Village, in the lower part of Bengawan Solo River, are regularly flooded almost every year. These flood prone area are situated in the river meander with low natural levee. Losses due to flood damage were estimated to reach 2.5 billion rupiah in the year 2007/2008 with the greatest losses from agricultural sector. These losses were caused by flooding that comes early before the harvest time. Surround dike to prevent flood inundation is recommended by the river authority. Regarding different land uses, i.e. rice fields, tree crops plantation, settlement, with different inundation tolerant, a set of mini polder is proposed to overcome the problem of inundation and its water management. The polder system is attributed by surrounded dike, local drainage system and pond retention with or without pumping system. The mini polder system that is equipped with lateral gate as flood control structure is proposed to solve the problem of inundation in the agriculture and settlement areas. Hydraulic mathematical models (HEC-RAS and Pond Pack) for simulating flow characteristics in the flood prone area are employed to determine the design of an appropriate mini polder system and its operational procedures. In addition of technical aspects, the design is also reviewed for compliance of the non-technical aspects including agricultural, economic and environmental in the local communities. According to the result of frequency analysis, flood discharge in the Bengawan Solo River was 1,500 m^3/s for 2 year return period (Q2) and 2,525 m^3/s for 10 year return period (Q10). Flood water elevation based on 2 year flood return period was obtained at +17.50 m or inundation depth average was around 1 m. The area that inundated at this condition was around 250.48 ha and the inundation duration was in 2 days. Flood water elevation based on 10 year flood return period was at +19.05 m or inundation depth average was around 2.5 m. The area that inundated at this condition was 382.58 ha with the inundation duration was in 3 days. The use of storage area and lateral structures models can describe flood phenomena in the modeled flood prone area more accurate.

Keywords: Flood mitigation; Polder; Mini polder; Bengawan solo river; Skotbalk

Introduction

Bengawan Solo River is the longest river in Java Island (± 600 km length) that flows started from Wonogiri, in the south part of Central Java Province, passing through the north part of East Java Province, and its mouth is in Java Sea at Ujung Pangkah. Lower Bengawan Solo River, forming wide and meandering river channel, with the river channel length ± 300 km flowing through the alluvial plains of ± 6,273 km^2, an area which is regularly flooded. Close to the river mouth, the channel passing through a broad marshy area called Jabung Swamp and Bengawan Jero. Flood inundation in the lower part of Bengawan Solo river is almost always occurred yearly, covering an area of about 11,000 ha, in the month of December to May [1]. Sumbangtimun and Kandangan villages, that are located in the inner bank of a meander of lower part of Bengawan Solo River, upstream of Bojonegoro city, were frequently inundated during high flood. Its location is depicting in Figure 1. Sumbangtimun and Kandangan villages covering 289 ha of rice field and 120 ha settlement. The irrigation system in these area are supplied by pumps, elevating water from Bengawan Solo river (90 ha) and local well (199 ha). Agricultural water resources in this area is highly dependent on rainfall and Begawan Solo River. In the dry season water level in the river is so low that the cost of pumping water to the land is too expensive. Land some distance from the river can only utilize groundwater pumped from farmer well. Considering this source of water, the cropping pattern is different between land near to the river and the land away from the river. Land close to the river, use the river water in the rainy season for rice cultivation, from the first planting season in October and harvesting in late January, and start the second planting season in March and harvested in June. In the dry season the land is planted dry crop such as corn. The land is located away from the river, because of limited irrigation water, pumping available soil

water during the dry season for dry crop (corn and cassava). Cropping pattern in this area only plant rice once during rainy season and twice
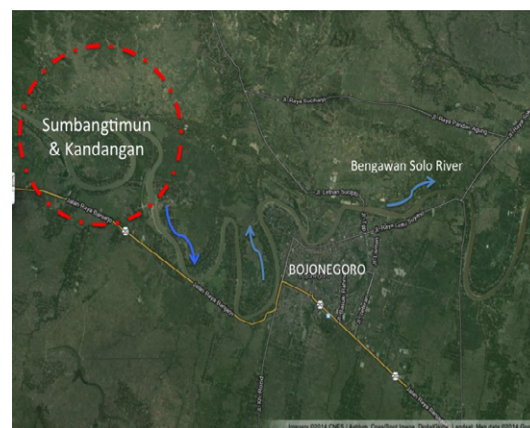

Figure 1: Location of Sumbangtimun and Kandangan villages.

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dry crop. Figure 2 shows the land use pattern and the existing irrigation system.

Losses due to flood damage were estimated to reach 2.5 billion rupiah in the year 2007/2008 with the greatest losses from agricultural sector. These greatest losses were caused by flooding that comes early before the harvest time. Table 1 shows the cropping pattern and the occurrence of flood. Land elevation of this area varies from +14.00 m ~ +22.00 m above mean sea level (msl), with average elevation of rice field is +16.50 m and average elevation of the settlement is about +21.00 m. The extreme flood level could reach +17.00 m ~ +20.00 m above msl, while the average river water level during dry season is +8.00 m ~ +10.00 m above msl. Natural levee elevation is relatively low, between +17.00 m msl ~ +18.00 m msl, so it cannot be said as a flood control system. Pumping system is only used by farmers for irrigation and cannot be operated during floods. Adaptation action of society to flooding is to elevate ground elevation at several locations for the purposes of access roads and settlements.

Mini Polder

A polder is a piece of land protected from water by a system of dams and dikes and within which the water level can be regulated. Originally the name "polder" was used in The Netherlands, nine to ten centuries ago, and was related to the land protected with dams from sea floods. Later, the same system of land protection was used on the flood plains of rivers, lakes, and shallow reservoirs, and they were all called polders. The polders on the banks of the major rivers were protected against high water from the river and discharged into it. In several parts, polders are a special type of drained agricultural land typically found in low-lying coastal areas, river plains, shallow lakes, lagoons and upland depressions. Before impoldering, polder areas were either waterlogged or temporarily or permanently under water. An area becomes a polder when it is separated from the surrounding hydrological regime in such a way that its water level can be controlled independently of its surrounding regime. This condition is accomplished by various combinations of drainage canals and dikes [2]. In other parts, polder are also dedicated to minimise the impact of flood water. The use of retention areas can be an efficient measure in flood risk management. By controlled flooding of sparsely or non-populated areas with relatively low damage potential, the risk of inundation for downstream areas with higher vulnerability can be reduced. The largest retention area along the Elbe River that is situated on the tributary Havel River, near its confluence with the Elbe is one of example. This retention area consists of six large polders and the floodplain of the Lower Havel River which together have a potential retention volume of up to 250 million m^3. The six polders comprise an area of 100 km^2 with a volume of 110 million m^3. The system was constructed in the 1950s, but was used operationally for the first time during the Elbe flood in 2002. By controlled flooding of the retention area the peak stages were attenuated by approximately 40 cm at the gauge of town of Wittenberge. Consequently, the risk of inundation for the town of Wittenberge and areas further downstream was significantly reduced. Before the extensive construction of dikes and water engineering works, the whole Lower Havel River floodplain was a natural retention area for the Elbe River and was characterised by frequent inundations. The dikes were constructed in order to protect settlements and agricultural areas from flooding [3]. Forster et al. [3] simulated the controlled flooding of the retention area by the use of a conceptual model and assessed economically for two flood scenarios. In a cost-benefit analysis, the damage to agriculture, the road network, buildings and fishery caused by the flooding of the polders was compared with the resulting reduction in potential damage in the town of Wittenberge, 30 km downstream. On the basis of a monetary assessment it was concluded that the use of the retention area for flood protection is highly cost-effective in economic terms.

Several methods have been applied to mathematically represent water flow in rivers with floodplain by using numerical model. Huang et al. [4] analysed the effectiveness of polders system along the middle reaches of the Elbe River, in capping flood discharges and how much this capping effect recedes as the flood wave propagates downstream of the polder, by using mathematical model. Along the floodplain of Lower Bengawan Solo River that forming wide and meandering river channel, there are some settlement and agriculture area that are inundated during high flood but in times of drought, they need irrigation water that can be pumped from the river. The same idea of flood protection in Elbe River, for agriculture area and settlement with a minimum risk and irrigated when is needed, a series of polder are introduced along the Lower Bengawan Solo River. The polders on the banks of the rivers with small area, called mini polder, are protected against high water from the river and discharged into it. Inside the dike the water will be controlled either by being run off naturally through a sluice or by being pumped out. Within the mini polder, the capillaries of the whole water control system, the ditches and drains between the
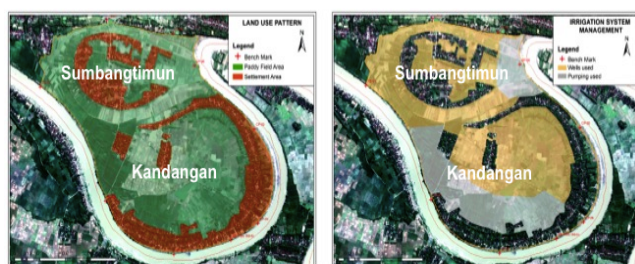

Figure 2: Land use pattern and its irrigation system.

Month	Sep		Oct		Nov		Dec		Jan		Feb		March		Apr		May		Jun		Jul		Aug		Losses
Half Monthly	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II	(Billion Rp)
Pumping Irr	Land Prep		Rice Cultivation								Land Prep		Rice Cultivation						Land Prep		Maize				
		Land Prep		Rice Cultivation								Land Prep		Rice Cultivation						Land Prep		Maize			
Flood 2007																									2.5
Flood 2008																									2.5
Flood 2009																									1.2
Flood 2010																									0.75
Flood 2011																									0.35
Flood 2012																									no flood
Local Well Irr	Maize/cassava				Land Prep		Rice Cultivation						Land Prep		Maize/cassava										
	Maize/cassava				Land Prep		Rice Cultivation						Land Prep		Maize/Cassava										

Table 1: The occurrence of flood, 2007-2012.

strips of land, carry the water to the bigger watercourses through which it flows to the pumping station. In this way excess water is removed through the sluice or by a pump into the river directly.

Flood Mitigation

Sumbangtimun and Kandangan areas are located on the inner bank of meanders, surrounded by a natural levee that is not quite high, so that at the time of the great flood, always inundated by flood water of Bengawan Solo River. Flood water also come through mouth of Toweng Creek that has not equipped with flood gate. Drainage system in this area, is natural drainage system that generally serves to dispose of rain water into the Bengawan Solo River.

In the rainy season, the area has potential agricultural crop failure due to flooding. The main causes of crop failure is due to depth as well as duration of inundation, compare to the age of crop were flooded. The duration of inundation less than 24 hours is relatively safe, it will be less safe if the duration of inundation is more than 2×24 hours. Compare to the age of crop, inundation will give a high risk for crop with age of 0 ~ 30 days and 60 days (harvest time), and will give less risk for age of the crop of 30 ~ 60 days. In the dry season, as the river water drop too low, the farmers have a difficulty to lift up the irrigation water to the rice field. The farmers also face the problem of water scarcity during dry season, especially for domestic use and sanitation. Therefore flushing during rainy season using flood water is sometime needed (Figure 3). Regarding the water level measurements in Karangnongko and Bojonegoro during several years from 2009 up to 2012 [5], the land elevation of the area of Kandangan and Sumbangtimun generally always above the river water level, except during high flood that come during several days in the rainy season. Polder is an alternative of flood control measures to protect the area from being flooded. A polder is an area that is protected from outer water by a dike and that has a controlled water level on the inside of the diked area. Any water entering the polder (rain, seepage water) that is not used or stored, has to be pumped out [6]. Actually, this flood prone area is already surrounded by dikes along the river meander, but another dike in the north part along the Toweng Creek is still needed to form an artificial hydrological entity, and it should also be equipped with internal drainage system and pumping station. Considering hydro-topographical condition of the area, by comparing the land level to the river water fluctuation, the system of dikes is not really serve as polder system, because most of the time, more than 8 months/year, the land level is higher than the river water level, except 1 ~ 3 months/year during rainy season, the area is sometimes flooded. Due to the need of supply of water for irrigation purposes, several skotbalks (lateral gate) are proposed to be installed along the dikes that face to the Bengawan Solo River, as an intake of irrigation or flushing water (Figure 4).

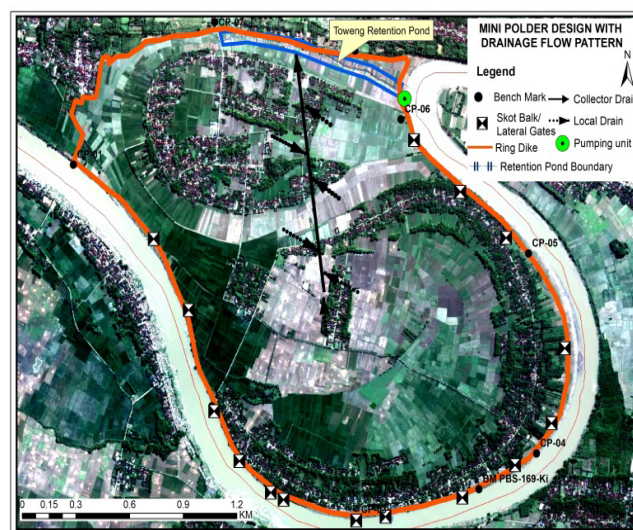**Figure 3: (a)** Existing drainage pattern**(b)** Existing Toweng Creek.

Figure 4: Design of Mini Polder and its flow pattern.

Flood simulation

Several methodologies have been applied to mathematically represent water flow inrivers with floodplain. The simplest method of river modeling consists of using a one-dimensional (1D) model and considering the floodplain as storage areas or adopting compound cross sections [7]. Horritt and Bates tested 1D and 2D models of flood hydraulics (HEC-RAS, LISFLOOD-FP and TELEMAC-2D) on a 60 km reach of the river Severn, UK. The three models are calibrated, using floodplain and channel friction as free parameters, against both the observed inundated area and records of downstream discharge. The predictive power of the models calibrated against inundation extent or discharge for one event can thus be measured using independent validation data for the second. The results show that for this reach both the HEC-RAS and TELEMAC-2D models can be calibrated against discharge or inundated area data and give good predictions of inundated area. Huang et al. [4] simulated the effectiveness of polder system on peak discharge capping of flood along the middle reaches of the Elbe River in Germany, by using DYNHYD (1-D hydrodynamics) from WASP5 modelling package and extended to incorporate the quasi-2-D approach. It is sought in which a 1-D hydrodynamic model is used to allows the discretisation to be extended into polder system to give 2-D representation of the inundation area. In that simulation the inlet and outlet discharges of a polder are controlled by a virtual weir. To simulate the control of polders, the weir is opened gradually, by lowering the weir crest to the hinterland ground level, over a time period of up to 12 hours. The result show the quasi-2-D modeling is a powerful tool for provision and operational management of floods due to its robustness, ease of use and computational efficiency. The polder system can cap the flood peak effectively and the capping is relatively stable along the river down-stream.

In this research, a model for simulating flood propagation along the main river channel was combined with a reservoir model applied to the floodplain. The main flow along river channel was simulated with a 1-D hydrodynamic model (HEC-RAS), while the floodplain is considered a reservoir that is filled up gradually with a horizontal water surface, a catchment pond both function as flood control reservoirs pool (retention pond) as well as reservoirs and ponds reservoir (Pond Pack).

The hydrodynamic model HEC-RAS contains four one-dimensional river analysis components for: (1) steady flow water surface profile computations; (2) unsteady flow simulation; (3) movable boundary sediment transport computations; and (4) water quality analysis [8]. The equations that govern the unsteady flow of water in a stream are : (1) conservation of mass, and (2) conservation of momentum.

These laws are expressed mathematically in the form of partial differential equation as follows.

The continuity equation (conservation of mass)

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} - q_l = 0$$

The momentum equation (conservation of momentum)

$$\frac{\partial Q}{\partial t} + \frac{\partial QV}{\partial x} + gA\left(\frac{\partial z}{\partial x} + S_f\right) = 0$$

in which q_l is the lateral flow per unit length, A is wetted area, Q is flow discharge, V is flow velocity, z is channel bottom elevation, S_f is slope of energy.

Pond Pack allows users to model rainfall runoff urban and rural watershed to design detention and retention facilities, outlet structures and channels. The Pond Pack engine computes outlet rating curves with tail-water effects, account for pond infiltration, calculates pond detention times, analyses channels and performs interconnected pond routing with multiple outfalls. A pond may discharge to location influenced by downstream tidal effect or flooding [9]. Flood propagation of Lower Bengawan Solo River and its influence to the flood plain were simulated with HEC-RAS mathematical model combined with PondPack, for the reach of Karangnongko ~ Bojonegoro Barrage (Figure 5). Two schemes of simulation were done, started with simulation of existing condition and continued with simulation of system with mini polder scheme. The upstream boundary condition were 2- and 10-years return period flood hydrographs at Karangnongko, while downstream boundary condition was stage hydrograph at Bojonegoro Barrage [10]. According to results of the frequency analysis, the design flood discharge in the Bengawan Solo River at Karangnongko section for 2- and 10-year return period were 1,500 m³/s and 2,525 m³/s, respectively. By using stage gauge data in Karangnongko on December 31st 2007 and February 28th 2009, flood hydrograph of the two return periods could be determined.
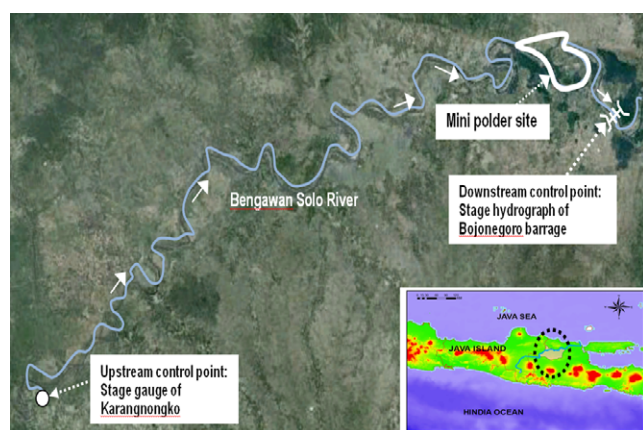

Figure 5: Reach Karangnongko~Bojonegoro Barrage.

Simulation of existing condition

Result of simulation of 2-year return period of flood, for existing condition, showed that the maximum water elevation in the project area was +17.50 m and average inundation depth was around 1 m. The inundated area was about 250.48 ha (Figures 6a and 6b). Stage hydrograph of 2-year return period flood with 2 days inundation time. In case of 10-year return period of flood, the simulation result show that the maximum water level in the project area was +19.05 m. This flood inundated the flood prone area up to 382.58 ha. Figure 7a shows the inundation area that covers almost the whole area of Sumbangtimun and Kandangan Villages. Results of hydraulic simulation explained that inundation due to 10-year return period of flood, occur for almost 3 days and the water level in Bengawan Solo River raised about 2.5 m above the ground elevation of storage area (Figure 7b).

Simulation with mini polder system

The proposed mini polder system should meet several objectives, i.e. this system should work as flood protection during high flood; it could give possibility to allow river water flows to the area for irrigation purposes during normal flow; the cost of construction and operation should not expensive, and it should be equipped with reasonable drainage system and pumping station.
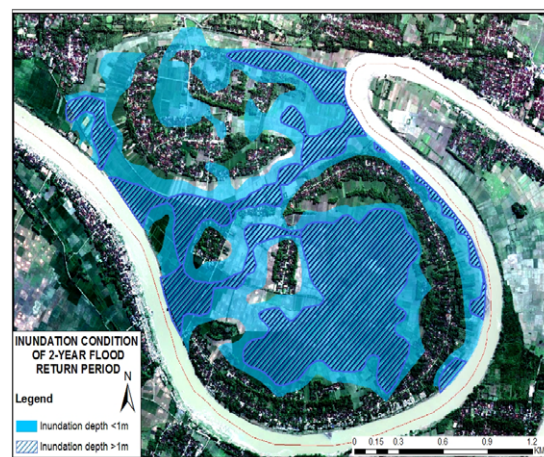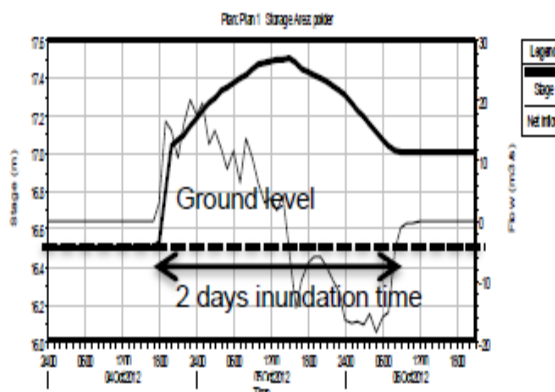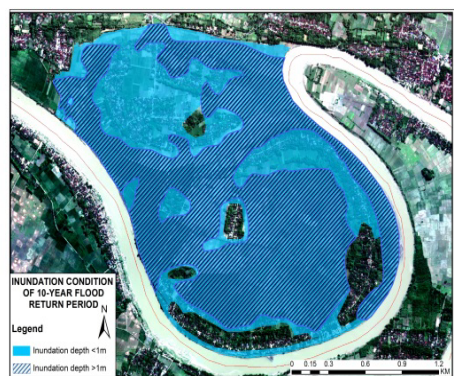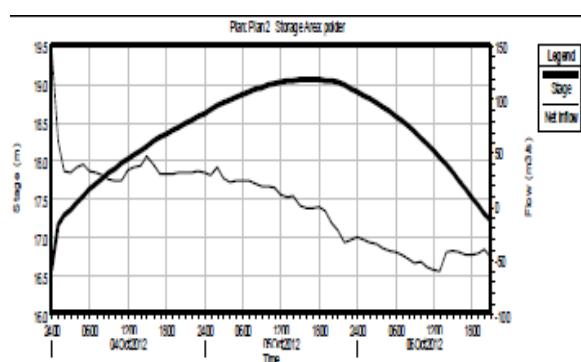

Figure 6: (a) Inundated area for 2-years return period of flood. **(b)** Stage hydrograph for 2-years return period of flood.

Figure 7: (a) Inundated area for 10-years return period of flood. **(b)** Stage hydrograph for 10-years return period of flood.
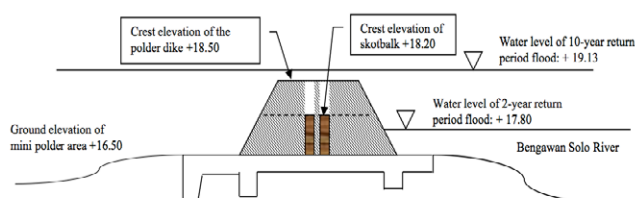

Figure 8: Cross section of skotbalk and dike.

Flow of water from the river to the area is regulated with skotbalks. In order to prevent the structural damages of dike due to overtopping risk of mean annual flood, skotbalks have to be fully opened when the water level in the river reach the crest of skotbalk, i.e. +18.20 m. Under this operation rule of skotbalk, the dike will be overflowed by 10-year return period flood in which the maximum water level is higher than 0.60 above the crest. Therefore when the river water level is rising close to the crest of skotbalk, the flood warning should be informed to people for evacuation preparation. The design of mini polder system was equipped with 15 skotbalks which has function as flood control gates. Situation of mini polder system can be seen in Figure 4. Figure 8 illustrates cross section of skotbalk and dike. According to result of simulation, for 2-year return period flood, the peak river water level was +17.80 m. Since the crest level of dike is +18.50 m, there is no water flows through the lateral weir (dike) and the lateral gates (skotbalk). Output of the simulation also the stage hydrograph in mini polder

area with constant value that equal to the ground elevation (+16.5 m) and zero discharges of the hydrograph. Result of simulation with 10-year return period of flood concluded that the dike of mini polder was overflowed. River Water level in the project area could raised up to + 19.13 m. Figure 9 describes fluctuation of water level and discharge of flood flow through dike and skotbalk.

Retention pond and pumping system

The computation of retention pond and pumping capacity was done by using Pond Pack software. The input design scenario of simulation are the overflow hydrograph for 2- and 5-years return period of rainfall. The existing capacity of Toweng Creek retention pond with the area of 7,000 m^2 and bottom elevation at +12.00 m, could not accommodate the runoff volume due to local rainfall of 2- and 5-year return periods. The capacity of retention pond without pumping system was 32,092 m^2 with the bottom elevation at +7.5 m. By using pumping system with the capacity of 6 m^3/s, the storage area become 32,322 m^2 with the bottom elevation at +10 m. If the storage capacity is maintained in the existing condition (without dredging and widening) the required pump capacity becomes larger than 12 m^3/s. The result of retention pond simulation, the inflow hydrograph, outflow hydrograph and surface water elevation are depicted in Figure 10.
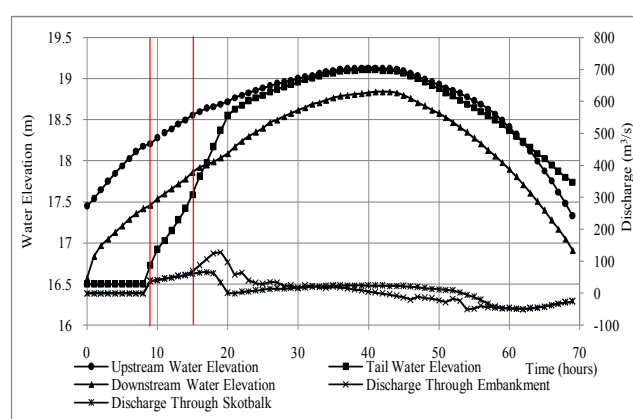

Figure 9: Fluctuation of water level and discharge of flood flow through dike and skotbalk.
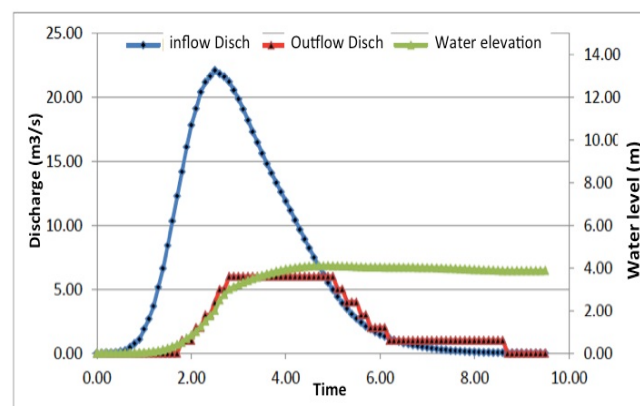

Figure 10: The inflow hydrograph, outflow hydrograph and surface water elevation in retention pond.

Conclusion

The use of 1-D hydrodynamic model (HEC-RAS) combined with Pond Pack for simulating the flood propagation along the main river channel and the floodplain storage area with lateral structures models can describe flood phenomena in the flood prone area more accurate. The mini polder system that is equipped with lateral gate as flood control structure could solve the problem of inundation in the agriculture and settlement areas. The crest of embankment is designed at elevation + 18.5 m. Mini polder area is still inundated by the flood that is greater than 2 year return period. When the greater flood occurred, people must follow the evacuation procedures. To anticipate a greater flood occurrence, the flood control gates are opened if the water level reaches elevation higher than +18.2 m (crest elevation of flood control gates) or opened for leaching the farming land. The analysis of retention pond concludes that by using pumping system with the capacity of 6 m^3/s, it showed reduction of storage capacity up to 30% becoming 205,309 m^3. If the storage capacity in the Toweng River is maintained in existing condition then the required capacity of pumping system become higher than 12 m^3/s.

Acknowledgement

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