Development of Sustainable Detention Ponds for Flood and Sediment Control in Urban Areas

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Abstract. Muddy floods often occur in Indonesia as a side effect of urban development. Flood and sediment control facilities have been so far developed separately. Flood is controlled by reservoirs, while sediment is trapped by check dam. The objective of this paper is to develop an integrated system between flood control and sediment trap analytically. The system consists of detention pond equipped with perforated spillway tower. Optimization is carried out on the dimensions of spillway tower, the diameter, number and layout of perforation orifices to obtain the highest trapped sediment and flood peak reduction for a certain pond capacity. The research was conducted in the Meteseh sub-watershed, located in Semarang. The results indicated that the position and arrangement of the orifices in the spillway tower affect sediment trap, while their size and number affect the reduction in peak discharge. The proper size, number, position and arrangement of orifices on the spillway tower be able to trap sediment and reduce flood discharge as high as 80%, and 24% consecutively.

Keywords: detention pond, flood control, perforated spillway tower, sediment trap

1. Introduction
Flooding is a common problem that occurs in some regions in Indonesia, especially in densely populated areas such as in urban areas. The loss that can be caused is quite large, both in terms of material and loss of life. Moreover, when flooding is accompanied by high sediment content, the damage caused is far greater. Every time a flood occurred, mud covered various facilities such as roads, parks, and private houses (Fig. 1). It was also deposited along the rivers downstream, consequently reduces their capacity. The solution to the problem of urban flooding has so far been focused on increasing the capacity of canals and / or rivers, whereas flood discharge continues to increase in line with land conversion due to the development being allowed. In some cases, flood is also reduced by developing reservoirs or ponds. While, sediment is captured by another structure called check dam, which is only able to trap bed load. Enlarging rivers and channels can no longer be applied due to the limited land in densely populated urban area. A new system that integrated between flood control and sediment trap have to be developed. The system is developed as close as possible to the sources of floods and sediments, in the suburbs.

The conventional paradigm of flood control, by removing storm water as quickly as possible from protected area to water bodies, is no longer suitable for application. Storm water should not be disposed directly but should be managed so as not to trigger disasters. Storm water must be stored as much as possible on land either on the surface or infiltrated into the soil. The possibility of water storage on surface in the urban area is done by constructing small reservoirs in the suburbs, here and after called ponds. They could also be associated with processes of the retention and deposition of suspended sediment in water [1, 2]. The main function of ponds is to capture and store water from...
rivers. The captured water is not pure water, but takes along sediment. When entering a pond, the current velocity decreases, the sediment transported in part will partially settle to the bottom of the pond. The natural discharge of the river will be reduced when it comes out of the ponds [3].

![Figure 1](image1.png)

**Figure 1.** Mud layer left behind after the flood of the Meteseh River.

Many factors affect the rate of sediment deposition in pond [4, 5]. The most important factors include the geotechnical parameters of the given pond, the type of outflow device used, and hydrodynamic conditions [6, 7]. The most informative attribute of pond sedimentation is trap efficiency (TE). This value is the proportion of the incoming sediment that is deposited, or trapped, in a pond. For most reservoirs, water retention capacity should be maintained at its highest level for as long a period as possible. This means that TE should be low. For sediment ponds, on the other hand, TE should be high. For a reservoir or pond to be economically successful, its TE should be designed very carefully [8].

Trap efficiency (TE) is primarily a function of sediment particle size and resident time (i.e., the average time the incoming runoff remains in the pond). The coarser particle of the sediment the faster it settles, conversely the finer particle size the longer it will take to settle. The resident time of a pond is related to the characteristics of the inflow hydrograph, and the geometric characteristics of the pond, including storage capacity, shape and outlet typology [8].

In cases where inflow entering a pond carries a very high sediment, density current may occur. Density current is driven by the density difference between inflow and ambient clear water in ponds, density current plunges clear water and moves towards a dam, while density current flows beneath [9, 10]. Increasing suspended sediment increases flow resistance as a result of decreased maximum flow velocity [11]. Sediment tends to settle more quickly. Based on Stokes’ results, the fall velocity of spherical particles in region of particle Reynolds number (Re) less than 1, can be calculated using [12]:

$$\omega = \frac{1}{18} \frac{g(s-1)d^2}{\eta}$$  

In which $\omega =$ particle fall velocity in (m/s), $g =$ acceleration due to gravity in (m/s²), $d =$ particle diameter (m), $\nu =$ kinematic viscosity in m²/s, and $s =$ relative density ($\rho_s/\rho$) where $\rho_s$ and $\rho =$ the density of sediment particle and fluid in t/m³, respectively.

The purpose of this study was to develop an artificial detention pond system in the suburb area that is able to capture sediment while reducing flood discharge. The approach used was storing muddy water in the pond and releasing ambient clear water from the pond. The muddy water flows beneath ambient clear water due to density current. The ambient clear water lifted up and flow out through perforated spillway tower.

2. Study site and methods

The designed detention pond equipped with perforated spillway tower was proposed to be implemented in Meteseh Village, Semarang City, Central Java Province-Indonesia (Fig 2). It is a suburb that functions as a horticulture farm. The topography is hilly with slopes varying from 5 to 45
percent. Land cover consists of shrubs interspersed with perennials and banana trees. The soil consists of sandy loam with high shrinkage and erosion rates. Several small river channels flow in this area which merge at the point of the pond location, which is called Meteseh River. The total catchment area is 84 ha. The proposed detention pond area is 1.5 ha, with length of 200 meter and average wide of 75 meter. Spillway tower was installed in downstream of the pond at the upstream foot of the embankment. Spillway tower is equipped with a number of orifices with a certain arrangement to allow water to flow out in accordance with the flow rate. The top end of the box is open and equipped with a trash rack to prevent the trash clog the spillway tower (Fig. 3). Spillway tower tower height is designed to be able to accommodate 2-year flood discharge without spill at the top of the spillway. While the spillway capacity is designed for 50-year flood discharge.

![Proposed Meteseh Detention Pond-Sediment Trap](image)

**Figure 2.** Location of study site, proposed Meteseh detention pond-sediment trap.

![Long section of the proposed Meteseh detention pond-sediment trap (unsealed)](image)

**Figure 3.** Long section of the proposed Meteseh detention pond-sediment trap (unsealed).

The study consists of various activities, both field activities and laboratory activities. The main fieldwork is taking water samples for sediment analysis. Water sampling is done when it rains, as the river is only flowing when it rains, by using US DH-48 with ¼” nozzle. Laboratory analysis is aimed to obtain sediment concentrations, as well as sediment characteristics, specifically grain size and sediment particle density. Grain size is done by using a combination of sieve analysis and hygrometer.

There were no flood or discharge data records at the study site, so flood discharge was predicted by using HEC-HMS software. Rainfall data used from the nearest station, i.e. Pucanggading rainfall station (station number 98, owned by BMG). Daily rainfall data is available for the period of 2001 to 2015. Design rainfall were analysed based on annual maximum daily rainfall. The distribution type was determined by the statistical fitting of probability distributions to these data [13, 14]. Two difference discharges were predicted: design flood discharges of various return period, and daily...
discharges during one hydrological year. The first was used to estimate spillway capacity and flood water level, while the second was used to estimate annual sediment inflow. Sediment inflow was estimated by discharge – sediment rating curve. It was also estimated based on soil erosion approach (Universal Soil Loss Equation = USLE) combined with Sediment Delivery Ratio (SDR) proposed by USDA, 1972 [15], Boyce, 1975 [16], and Vanoni, 2006 [17]. The dimension and capacity of pond were determined based on space availability. Dimensions of spillway tower; normal water level (NWL), high water level (HWL), flood water level (FWL); diameter, number, and lay out of orifices are determined through optimization by means of trial and error to get the highest sediment trapped, and highest flood reduction. In this case, NWL is defined as a level where the lowest orifice is installed. HWL is one level with the top of the spillway tower, and equivalent to water level for 2-year flood. While FWL is a level when 50-year flood is occurred. Annual deposited sediment was estimated based on falling velocity approach [12].

3. Results and Discussion
Introducing the main parameters of the SCS Unit Hydrograph for Meteseh River basin (Fig. 2), HEC-HMS was applied to estimate design flood hydrograph as well as daily hydrograph during a hydrologic year. The results of flood simulation for various return period, and daily hydrograph for the year 2015 are shown in Fig. 4. There were 84 flood events during the year of 2015.

Figure 4. Design flood hydrographs simulation for various return period (left), daily hydrographs simulation for the year 2015 in Meteseh River (right).

The results of sediment filtering of water samples obtained a very high concentration of suspended sediment, varying between 25,000 mg/litre to more than 70,000 mg/litre. Based on sediment concentration data, the suspended sediment rating curve was developed, i.e the relationship between water discharge (Qs, m³/s) and sediment concentration (Cs, mg/liter); water discharge (Qs, m³/s) and sediment discharge (Qs, kg/s) [18, 19].

The scatter plot of discharge versus sediment data was presented in Fig. 5. The regression results are as follows:

Suspended sediment concentration  \[ C_s = 31.492 Q^{0.3138} \]  
Suspended sediment discharge  \[ Q_s = 31.492 Q^{1.3138} \]
The grain size distribution of a sediment sample is determined by combination of sieve analysis and hygrometer. The sediment is composed of clay 20%, silt 67%, sand 12%, and gravel 1%. Based on triangle chart of sediment it is categorized into silty loam. The sediment density is 2.4 tons/m$^3$.

Applying discharge-sediment rating curve, annual sediment for the year 2015 could be estimated. Total annual sediment inflow is 52,057 tons equivalent to 21,690 m$^3$. The erosion approach resulted total sediment yield that is not much different, namely 117,229 tons / year, obtained from erosion rate 50,590 tons / year and SDR 43%.

Based on the topographic map and the available land potential, the proposed Meteseh flood detention-sediment trap has basic morphometric and hydrological parameters as in Table 1. It is an artificial pond formed by damming downstream of the Meteseh River confluence and dredging it to get the proposed capacity.

Table 1. Basic morphometric and hydrological parameters of Meteseh flood detention-sediment trap.

| Parameter                  | Unit | Value  |
|---------------------------|------|--------|
| Catchment area            | ha   | 84.00  |
| Water surface area        | ha   | 1.50   |
| Total capacity            | m$^3$| 57,000 |
| Average depth             | m    | 4.00   |
| Lowest base elevation     | m    | +53.50 |

Based on the basic morphometric and hydrological parameters as Table 1 combined with the previous results of discharge and sediment inflow, optimization is performed to find out dimension of perforated spillway tower system. The results found that the spillway tower height required is 1.6 m, with the same length and width, i.e. 3 meters. Low water level (LWL) at +54.00 m, equivalent to the capacity of the pool 17,500 m$^3$, HWL at +55.10 m, equivalent to the capacity of the pool 28,250 m$^3$, and FWL at +57.50 m. Total orifice required are 36 pieces with a diameter of 0.25 m each. The orifices are installed on all four sides of the spillway tower, each side with 9 pieces arranged in a row from bottom to top, 2, 3, and 4 pieces respectively (Fig. 6). The trapped and deposited sediment in the pond is 17,352 m$^3$, equivalent to 80% of sediment inflow during the year 2015. Flood routing analysis on 50-year flood, the peak discharge of 34.28 m$^3$/s is reduced to 26.20 m$^3$/s, or equivalent to 23.62%.
Figure 6. The size, number, position and arrangement of perforated orifices on spillway tower of Meteseh Detention pond-sediment trap.

Applying the approach of Barfield and Clar, 1986 [20], where trap efficiency is function of ratio of surface area to peak inflow rate (Fig. 7), for the system found similar result of the trap efficiency. During 2015 there were 84 flood events, with an average peak discharge of 1.79 m$^3$/s, varying from 0.01 m$^3$/s to 19 m$^3$/s. Sediment in the study area, based on the triangle charts, could be classified into silt loam. With a surface area of 1.5 ha of pond, the TE values varied between 74% to 98%, with an average of 84.6%.

Figure 7. Trap Efficiency as function of surface area/peak discharge for ponds (Barfield and Clar, 1986).

4. Conclusion and Recommendation
The promising system to be developed in urban areas with limited land that is capable to reduce flood discharge as well as trap sediment consists of detention pond equipped with perforated spillway tower, called detention pond-sediment trap system. In the case of Meteseh, with a catchment area of 84 ha, the system consisted of 1.5 ha area of pond (1.78% of basin area) with total capacity 57,000 m$^3$, perforated spillway tower of 1.6 m height, 3 m length and 3 m width. The tower is equipped with 36
orifices of 0.25 m in diameter. The system be able to trap sediment as high as 80% of sediment inflow. This result is similar to studies in Maryland USA reported by Barfield and Clar (1986) [20], by using a different approach. The system capable to reduce 23.62% of 50-year flood.

The results of this study opens opportunity for further study to develop design criteria of detention pond-sediment trap, particularly for Indonesian situation. Implementation of the results of this study in the field as a pilot is highly recommended. It is also used for validation of the proposed detention pond-sediment trap.

5. References

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