# Improving Sustainable Urban Drainage Systems through Topography-Based Design

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***Abstract - This study examines the impact of cut and fill patterns on land development and their effects on the efficiency of drainage systems in medium-sized residential areas. Sustainable drainage systems are applied to offer an alternative to the conventional method of discharging surface water directly through channels into nearby rivers. Residential areas with excessively flat or steep original terrain require land grading. Therefore, it is necessary to simulate land grading patterns that meet the drainage channel flow requirements while maintaining cost-effectiveness. Design rainfall is analyzed using the Type-1 Gumbel Distribution. Design floods are calculated using the Rational Method with Kirpich and Mononobe methods to analyze the time of concentration. Manning's formula is used to design channel dimensions. Alternative land shapes with specific cut and fill patterns are assessed using AutoCAD Civil 3D. Infiltration chamber and bio-absorption hole are introduced to the system as sustainable design. The analysis results indicate that the original terrain topography does not meet the velocity and flow characteristics. The deviation of cut and fill volume from simulated land grading is 16,076 m$^3$, while the one from other alternative of topography is 40,213 m$^3$. The sustainable urban drainage facilities could reduce the designed flood from 1.103 m$^3$/s to 1.099 m$^3$/s.***

***Keywords :*** *urban drainage, topography, sustainable, infiltration chamber, bio-absorprtion hole*

## I. INTRODUCTION

Sustainable urban drainage systems refer to low-impact development techniques in stormwater discharging that mimic natural processes and reduces the environmental impact of urban development. The key principles of sustainable drainage include reducing runoff[1], promoting infiltration[2], improving water quality, as well as green construction with sustainable landscaping[3]. Sustainable drainage is needed because of land use change primarily, such as urbanization and increased development, that can significantly alter the natural water cycle and increase the potential for various environmental issues.

Sustainable landscaping approach seeks to minimize the environmental impact of construction and improve the long-term sustainability and functionality of the built environment by designing and constructing sewerage construction and the landscapes in an environmentally responsible and resource-efficient manner. The issue creating urban landscapes that allow for infiltration without causing floods requires careful planning and design to balance water management and flood prevention[4][5].

There have been numerous studies examining sustainable drainage systems that have consistently highlighted the value and benefits of implementing this approach. These studies have demonstrated the positive impact of the systems in various aspects of urban and environmental management. Some of the reported values and benefits include Saadeh et al. [6] and Vincent et al. [7]. Along with this growth in sustainable drainage multi-criteria analysis, however, researchers have not treated landscape management in much detail.

This paper attempts to simulate land grading patterns that meet the open channel flow requirements while maintaining cost-effectiveness of land cutting-and filling. At the same time, an analysis is conducted to assess the implementation of sustainable drainage facilities can effectively mitigate the occurrence of flooding. The research focuses on a new medium-sized residential community located in Malang City as the designated study area. Hydrological data for this study are collected from water authority office. A combination of topographical survey using unmanned aerial vehicle/UAV and available contour map are used in the landscaping analysis. This study assesses the effect of constructing infiltration chamber and bio-absorption hole to reduce the flood volume and the effect of topographical simulation in the earth work volume. Therefore, this study makes a major contribution to research on sustainable drainage for minimizing the environmental impact to urban growth.

## II. METHODOLOGY

### *A. Study Area*

The framework's effectiveness is assessed by applying it to a case study in The Sanata Village III residential area (7.988S, 112.681E), as illustrated in Figure 1. The designed area encompasses approximately 7.868 hectares of land, with two tributaries of the Bango River running along its left and right boundaries. The existing elevation varies from 493 meters above sea level (AMSL) in the western part to 514 meters AMSL in the eastern part. Figure 1 on the top displays the location map and topographical map,


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showcasing the layout of 520 unit of housing within this area. This new residential development holds particular significance as it forms part of the buffer zone surrounding the city of Malang in Indonesia. The Malang regency, encircling the metropolitan area of Malang, is strategically designated as an environmental conservation and development buffer zone for the city. The current land cover in this region is primarily used for agriculture, which raises concerns about the potential negative impacts of urban development. Figure 1 in the bottoms is the existing topographical map showing that the landscape is steep in the west area and relatively flat in the east area which is originally paddy field.

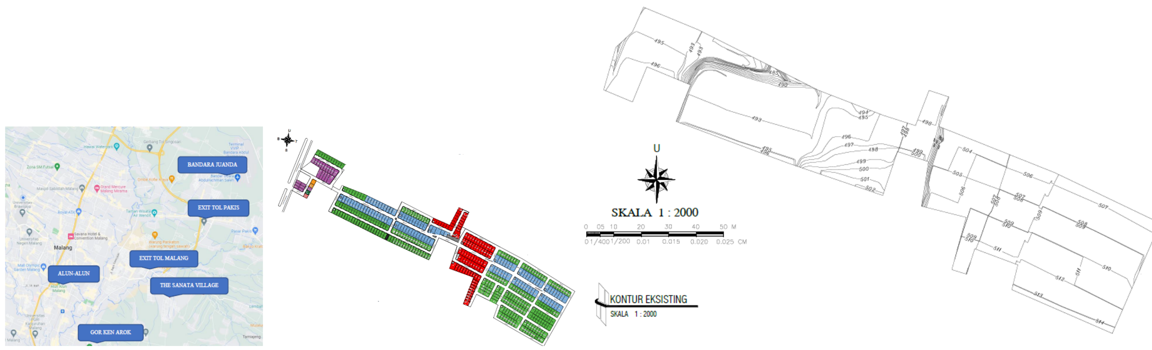


Fig. 1. Study Area (Source: PT Yudistira Alfian Sanjaya, UAV Survei, Malang Topograhical Line Map 2003)

### *B. Data*

Data were gathered from multiple sources including hydrological data and spatial data. Table 1 shows the data and the source.

TABLE 1 Data

| Data | Specification | Source |
|---|---|---|
| Rainfall | Daily maximum rainfall (mm/day), Sta. Ciliwung, Tajinan, Jabung, 2013-2022 | Dinas Pekerjaan Umum Kota Malang |
| Soil | Soil classification parameter | Soil Mechanic Laboratory, Brawijaya University |
| Topography | 1 m contour line | Malang Topograhical Line Map 2003<br>UAV survey |
| Land use | | Google Earth<br>UAV survey |

### *C. Hydrology and Hydraulic Analysis*

The rational method serves as a tool for analyzing storm drain design, particularly for relatively small drainage areas covering less than 100 hectares[8]. The formula below is employed to calculate the peak runoff discharge:

$$Q_T = kCi_TA$$

Where $Q_T$ is the peak flow rate for a given return interval of T years ($m^3/s$), K is conversion factor (0.00278), C is the runoff coefficient specific to the land use, $i_T$ is designed precipitation intensity (cm/hr) for a return period of T years with a duration equivalent to the time of concentration for the drainage basin, and A is catchment area (ha).

Rainfall frequency analysis is employed in the design of stormwater control structures. One commonly utilized method is the Log Pearson Type III distribution, as noted by Millington et al.[9]. The estimator X for a specific time return period or exceedance probability is:

$$Log[X_q]=X+K_qS$$

Where X is sample mean, S is sample standard deviation, Kq is frequency factor dependent on the selected return period and data skewness. The distribution is verified by goodness-of-fit tested called Chi-Square and Smirnov-Kolmogorof.

In this research, a 10-year recurrence interval is selected for analysis, as it is deemed appropriate for minor drainage within the residential area[10]. According to Kirpich[11], the formula for determining the crucial concentration time in an urban setting, referred to as the travel time (in minutes) from the furthest upstream point to the watershed outlet, is as follows:

$$Tc=0.0078(L^2/S)^{0.295}$$

Where L is length of channel from headwater to outlet (ft) and S is average gully slope (ft/ft).

The designed flood is therefore reduced by the infiltrated water from sustainable drainage facilities. The residual discharge is for each channel are analyzed using open channel hydraulic formula to determine the channel dimensions. This analysis is conducted using Manning Formula as described below[12].

$$V=n^{-1}R^{2/3}S^{1/2}$$

Where V is channel velocity (m/s), n is channel roughness coefficient, R is hydraulic radius (m), S is channel slope.

The channel flow velocity must be kept within the range of 0.2 – 3 m/s to ensure that sediment transport is maintained, preventing issues of sedimentation, erosion, as well as allowing time for water to infiltrate. In drainage engineering, maintaining a Froude number less than 1 is desired because it generally represents a more stable and controllable flow regime that is better suited for various sustainability purposes.

### D. Sustainable Drainage Facilities

Considering the natural characteristics of the locality, including its topography and zoning regulations, the chosen elements for sustainable drainage include the use of infiltration wells and bio-absorption holes in conjunction with conventional drainage channels. Theoretical calculations of the volume and efficiency of infiltration chamber can be determined using the water balance equation, based on Darcy's Law, as outlined by Sunjoto[13].

$$H=\frac{Q}{FK}\left[1-e^{\frac{-FKT}{\pi R^2}}\right]$$

Where H is well water depth (m), Q is inflow discharge (m3/s), F is geometric factor (m), K is hydraulic conductivity (m/dt), T is dominant duration of precipitation, and R is chamber radius (m). The positioning, configuration, and particulars of the well are devised following the standards established by the U.S. Environmental Protection Agency (US-EPA) as outlined in their 2003 guidelines. These standards are further customized to align with the local environmental conditions. Based on the results of processing the soil data, it is found that the soil type was sandy sand or clayey loam – silt. The permeability coefficient K is 0.000583 m/sec.

A biopore absorption hole is a cylindrical, vertical cavity dug into the ground and filled with organic compost to stimulate the natural growth of biopores. These biopores facilitate increased infiltration by expanding the surface area available for water entry. This method was introduced by [14], and the quantity of necessary holes is specified by Rianawati et al.[15].

$$N=RA/I$$

Where n is number of holes, R is hourly rainfall intensity (mm/hr), A is area of infiltration surface (m2), and I is infiltration rate (litre/hr).

Infiltration chambers and bio-absorption holes reduces flood discharge by collecting and absorbing rainwater runoff into the soil. The channel dimension is designed according to the reduced runoff after applying sustainable drainage facilites.

### E. Topographical Simulation

Topographical simulation is done by carrying out the hydraulic analysis first. Once the elevation for all drainage channel locations required in the hydraulic calculation are known, simulated contour lines are generated using AutoCAD Civil 3D. A contour grading lines are established utilizing the highest and lowest elevations observed in the current state as reference points to determine the most suitable elevation. Elevation is simulated through two different alternatives aimed at optimizing costs of earth work. The second alternative is derived from the first by reducing the elevation by increments ranging from 0.1 to 1.0 meters while implementing a distinct grading pattern. This step is essential not only for designing drainage channels in the catchment area but also for defining the housing layout boundaries.

### F. Hydraulic Simulation

HEC-RAS (Hydrologic Engineering Center's River Analysis System) is used after channel design. After channel design, it is needed to analyze how water will flow through the designed channels. From HEC-RAS analysis the detailed flow can be obtained, including flow velocities, depths, and stages, under different hydraulic conditions. This analysis helps ensure that the designed channel system functions as intended and does not result in overtopping. HEC-RAS helps to optimize channel designs by evaluating two different alternatives of elevation.

## III. RESULTS AND DISCUSSIONS

### *A. Conventional Drainage Channel Design*

The design of a drainage layout particularly using a side channel from in the both sides of road with culvert outlet into a natural waterway. The number of channels is 35 units. Figure 2 shows the designed drainage channel layout according to the existing landscape.

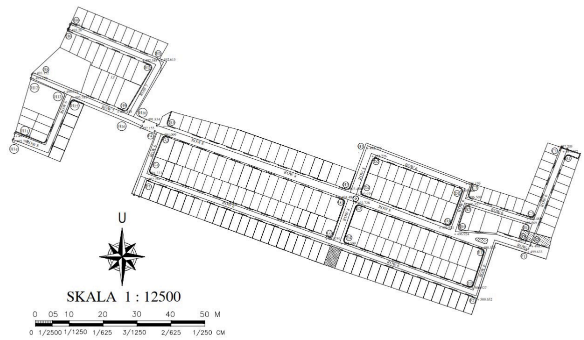


Fig. 2. Designed Drainage Layout

The designed rainfall with 10-year return period from the corrected raw rainfall data is 80.917 mm/day. From the topographical profile, the catchment area, where rainwater drains into each channel, is determined. Afterward, concentration time is calculated using channel length and slope. The runoff amount ranges from 0.007 to 0.0842 m3/s. The existing condition provide results in out of 13 units channels requires big amount of excavation to reverse the channel flow from the natural direction.

### *B. Sustainable Drainage Channel Design*

Figure 3 and Figure 4 show the alternative of land grading. The hydrology and hydraulic analysis are therefore conducted using these two scenarios. Meanwhile, infiltration chamber and bio absorption hole are also applied in the simulation. Table 2 shows the infiltrated Q for the designated chamber for each type of house. In this study, bio-absorption holes are designed along the channels side parallelly. It is known that the soil type in the study area is clayey-silty, so the infiltration rate is 10 mm/hour per 1 m², or the rate of water infiltration is 10 liters/hour or 2.78 x $10^{-6}$ m³/s. The infiltrated water of one unit of the hole is 0.0000068 m3/s.

TABLE 2 Infiltration Chamber Design

| Roof catchment area (m) | Diameter x depth (m) | Infiltrated discharge (m3/s) | Time to full (min) |
|---|---|---|---|
| 6x10 | 1x1.8 | 0.0029 | 51.458 |
| 6x12 | 1x2.1 | 0.0035 | 60.034 |
| 6.5x16 | 1x1.8 | 0.0028 | 51.458 |
| 6x20 | 1x1.9 | 0.0030 | 54.317 |

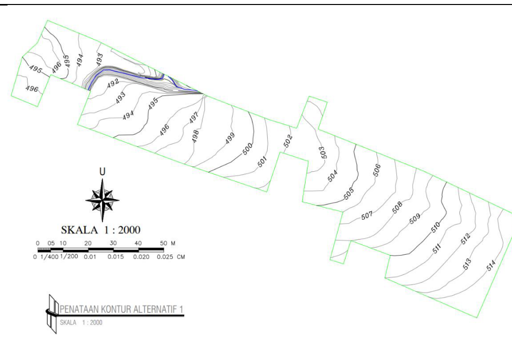


Fig. 3. Land Grading Alternative 1

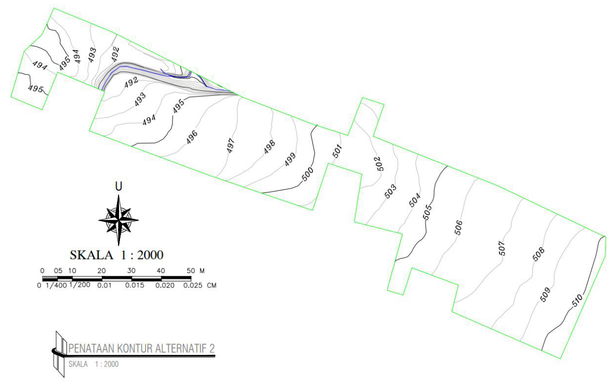


Fig. 4. Land Grading Alternative 2

The analysis is the comparing the reduced runoff from conventional design as well as sustainable design taking some channels as examples. The results are given in Table 3. The results indicate a decrease in runoff up to 49.78%, suggesting that the eco-drainage facilities are assumed to have the capacity to infiltrate more than half of the rainfall. It is worth noting that the infiltrated water from the infiltration chamber and bio-absorption hole contributes to a minor reduction in runoff. According to the Indonesian Standard of Infiltration Well Design (SNI 06-2405-1991, 1991), this method is effective in reducing runoff and increasing groundwater recharge, especially in areas with a hydraulic conductivity of 0.00001 m/s or higher. However, this housing development is situated in soil with lower permeability, although it still has a slightly higher hydraulic conductivity rate than the value suggested by Suripin[16].

TABLE 3 Comparison of Runoff Amount/Capacity (m3/s)

| Channels | Conventional | With ecodrainage Alt. 1 | Reduction | With ecodrainage Alt.2 | Reduction |
|---|---|---|---|---|---|
| B23-B24 | 0.656 | 0.656 | 99.97% | 0.647 | 98.67% |
| B21-B22 | 0.102 | 0.101 | 99.69% | 0.094 | 92.35% |
| B25-B26 | 1.103 | 1.103 | 100.00% | 1.099 | 99.58% |
| C8-C7 | 0.002 | 0.002 | 96.51% | 0.001 | 49.78% |
| C10-C11 | 0.029 | 0.029 | 99.63% | 0.028 | 96.09% |

To compare the channel dimension before and after the application of sustainable design, Table 4 is given to show the hydraulic parameters. It is apparent from this table that channel size for sustainable drainage system is smaller than the conventional one. As an example, in channel B25-B26 the channel depth can be reduced from 1 to 0.8 m with the depth reduction from 0.723 to 0.642 m. Further analysis shows that the land grading simulation provide more normal flow shown by flow velocity and Froude number which meets the criteria.

TABLE 4 Comparison of Geometric and Hydraulic Parameters

| Channels | | Max elevation | Min Elevation | Water depth (m) | Channel width (m) | Slope (%) | Flow velocity (m/s) | Froude number |
|---|---|---|---|---|---|---|---|---|
| B23-B24 | **Existing/ Conventional** | 496.945 | 490.504 | 0.430 | 0.800 | 0.50 | 1.905 | 0.927 |
| | **With ecodrainage Alt. 1** | 496.945 | 490.504 | 0.430* | 0.800 | 0.50 | 1.905 | 0.927 |
| | **With ecodrainage Alt.2** | 496.945 | 490.504 | 0.426* | 0.800 | 0.50 | 2.138 | 0.852 |
| B21-B22 | **Existing/ Conventional** | 501.007 | 493.057 | 0.365 | 0.250 | 0.50 | 1.118 | 0.590 |
| | **With ecodrainage Alt. 1** | 501.007 | 493.057 | 0.362* | 0.250 | 0.50 | 1.116 | 0.592 |
| | **With ecodrainage Alt.2** | 501.007 | 493.057 | 0.340* | 0.250 | 0.50 | 1.104 | 0.604 |
| B25-B26 | **Existing/ Conventional** | 496.915 | 492.972 | 0.723 | 1.000 | 0.20 | 1.526 | 0.573 |
| | **With ecodrainage Alt. 1** | 496.915 | 492.972 | 0.644* | 0.800* | 0.50 | 2.140 | 0.851 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **With ecodrainage Alt.2** | 496.915 | 492.972 | 0.642* | 0.800* | 0.50 | 2.138 | 0.852 |
| C8-C7 | **Existing/ Conventional** | 495.621 | 493.426 | 0.040 | 0.250 | 0.05 | 0.167 | 0.267 |
| | **With ecodrainage Alt. 1** | 495.621 | 493.426 | 0.040 | 0.250 | 0.05 | 0.167 | 0.267 |
| | **With ecodrainage Alt.2** | 495.621 | 493.426 | 0.024* | 0.250 | 0.20 | 0.256 | 0.525 |
| C10-C11 | **Existing/ Conventional** | 496.460 | 495.094 | 0.334 | 0.250 | 0.05 | 0.348 | 0.192 |
| | **With ecodrainage Alt. 1** | 496.460 | 495.094 | 0.334 | 0.250 | 0.05 | 0.348 | 0.192 |
| | **With ecodrainage Alt.2** | 496.460 | 495.094 | 0.320* | 0.250 | 0.05 | 0.345 | 0.195 |

* Indicates the channel size reduction

### *C. Land Grading Analysis*

To illustrate the significance of two possibilities of landscape adjustment, the next step involves calculating the excavation and embankment volumes. The procedure starts by processing the existing contour file and the planned contour file with the same format, resolution, and coordinates. Subsequently, a contour crop is performed on the designed contour to ensure that the excavation and embankment volumes produced are align with the designed area. The elevation difference analysis between the existing and planned contours, as shown in the Figure 5 where green areas represent excavation, pink-red areas represent embankment. For both alternative 1 and alternative 2, excavation and embankment volume calculations are performed. The calculations demonstrate that alternative 1 is more efficient with a residual excavation volume of 16,076 m3, while alternative 2 residual is 40,213 m3 (Table 5).

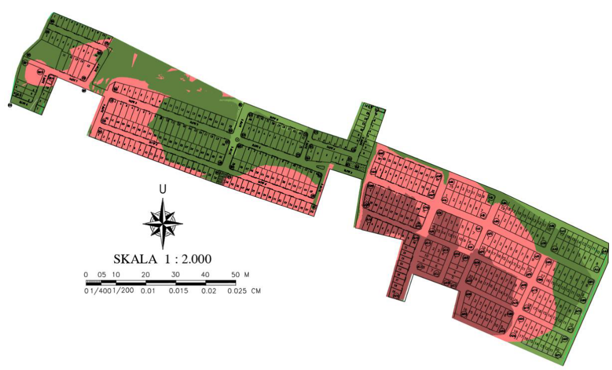


Fig. 5. Cut and Fill Map of Alternative 1

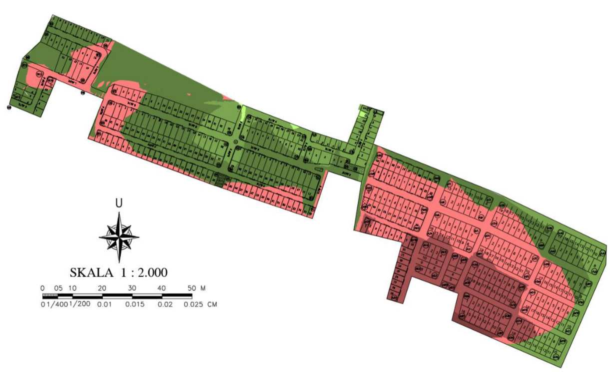


Fig. 6. Cut and Fill Map of Alternative 2

TABLE 5 Comparison of Cut and Fill Volume (m3)

| Alternative | Excavation volume | Embankment volume | Residual earthwork |
|---|---|---|---|
| 1 | 76,891 | 36,678 | 40,213 |
| 2 | 68,467 | 52,361 | 16,076 |

### D. *Hydraulic Modeling*

The next section of the hydraulic analysis is concerned with the open channel flow simulation. The channel to be analyzed using the HEC-RAS application in steady-flow scheme is a single segment of the longest channel, conveying water from the highest contour to the lowest contour near the river of the Alternative 2, namely channel AA22-B29. The result of the water level simulation in longitudinal view is shown in Figure 7. From this data, we can see that the channel design could accommodate the runoff effectively. This means that during heavy rainfall or storm events, the channel can effectively carry the excess water, reducing the risk of flooding in the residential area.

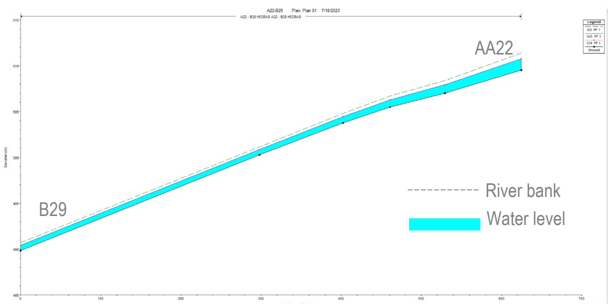


Fig. 7. Long Section of HEC-RAS Simulation

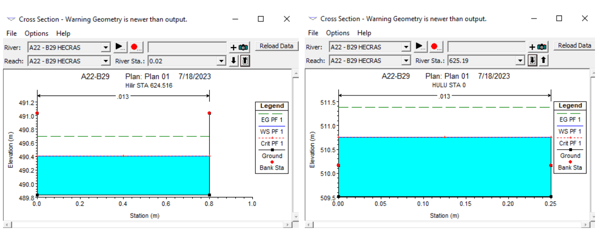


Fig. 8. Example of Cross Section of HEC-RAS Simulation

Together these results provide important insights into the drainage system planning method that differs from conventional planning. This planning approach is suitable for implementation in new areas to be developed as new residential zones. This approach proposes integrated earthwork planning and drainage channel design, with the expectation of achieving more cost-effective construction. Until now, urban drainage master plans in Indonesia have typically focused on swiftly collecting and channeling stormwater from urban areas to water bodies through pipelines and channels. The findings from this initial case study provide support for the importance of integrating sustainable drainage systems into urban development to enhance water management practices within residential areas and reducing the cost of construction. Beyond their primary role in infiltration, sustainable urban drainage systems can be designed to serve various purposes, including water harvesting, pollutant reduction, flood mitigation, and controlled conveyance of water. To assess sustainability more comprehensively, it is necessary to expand the range of recognized benefits. The evaluation framework employed in this case study has demonstrated that as more objectives are considered, the trade-offs between them can become intricate and non-linear. This framework facilitates the implementation of best practices in sustainable drainage in a more quantitative manner, maximizing the potential for multiple benefits.

## IV. CONCLUSIONS

This research investigates the influence of excavation and embankment patterns in land development and their consequences on the effectiveness of drainage systems within medium-sized residential communities. Sustainable drainage facilities namely infiltration chamber and bio-absorption hole are introduced as an alternative approach to the traditional method of directly channeling surface water into nearby rivers. This study has shown that it is not possible to apply the existing topography as the 13 units channels requires big amount of excavation to reverse the channel flow from the natural direction. Alternative 1 and 2 of landscape adjustment provides more reasonable results, in which the residual earthwork is 40,213 and 16,076 m3 respectively. The drainage channel dimension could be decreased from 1 m depth to 0.8 m depth. The second major finding is that the two sustainable drainage facilities could reduce flood up to 49,78% compared to the conventional design. This method suggests a combined approach to planning earthwork and designing drainage channels. The results obtained from this case study demonstrates the significance of incorporating sustainable drainage systems into urban planning. This integration serves to improve water management practices within residential areas and can lead to cost savings in construction projects. More research is needed to include other criteria, such as total life-cycle-cost, amenity, and local public acceptance. Further work needs to be done to establish the multi-criteria decision making of the implication of sustainable urban drainage system.

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