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The Use of Infiltration Wells to Reduce the Impacts of Land Use Changes on Flood Peaks: An Indonesian Catchment Case Study

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ABSTRACT

The objective of this study is to investigate the effects of infiltration wells on flood peak reduction and flood frequency. The analysis was carried out with the use of a stochastic rainfall model incorporating a within-storm rainfall distribution of low, medium and high variability. This study was motivated by flooding in a catchment in Indonesia, which is potentially affected by land use changes. The parameterisation of the climate and landscapes was derived from a specific catchment in Indonesia. An analysis of land use changes underlines the importance of green land in reducing flood peaks. With city development, however, land is converted for settlements, industries and trade areas, which will increase flood peaks significantly. An analysis on the use of infiltration wells shows that flood peak reduction of up to 50% compared to without wells. The results also demonstrate that within-storm rainfall distribution affects flood peaks, where the effects of infiltration wells in reducing flood peaks are more observable when incorporating low within-storm variability.

Keywords: Infiltration well, within-storm rainfall distribution, land use, flood peak

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INTRODUCTION

During the wet season, flooding occurs frequently at several locations in Indonesia, including Bandar Lampung, the capital city and economic hub of Lampung Province and the entry point to Sumatera. The province is located in the southeast region of Sumatera Island. The city's area is approximately 169.21 km², with a population of 881,801 people (Bappeda, 2010). The population and economy of the city grew significantly over the past two decades. Recently, several flooding events in the city resulted in inundation for several

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hours and caused massive traffic jams and casualties. In addition, a landslide occurred in a canal within Bumi Kedaton Park and caused severe damage to its roads and a bridge (Kusumastuti & Jokowinarno, 2009).

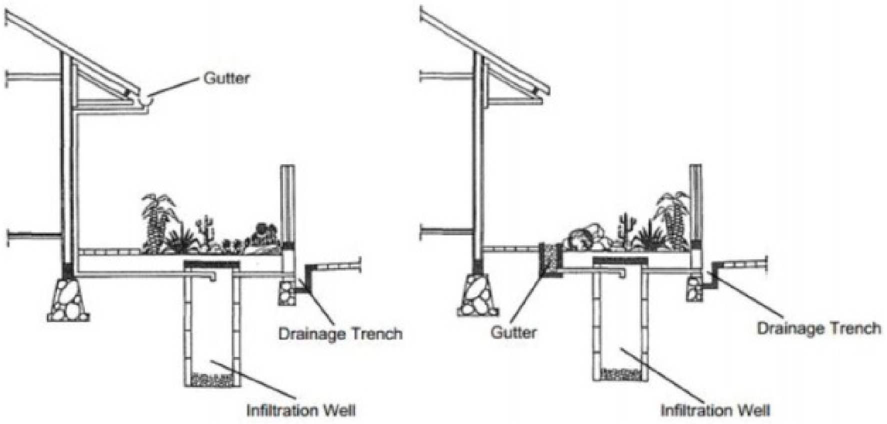
The most common causes of flooding are high rainfall intensity, land use changes, reduced infiltration areas, insufficient drainage systems and reduced river capacities. Combinations of these factors may lead to extreme flooding events. Although flooding is a natural process, the destructive effects of flooding and peak discharge increased due to anthropogenic impacts, such as land use changes (Ashagrie et al., 2006). Significant land use changes, due to rapid development in most portions of Indonesia's larger cities, are considered to be one of the major causes of flooding. Land use changes, including urbanisation, deforestation and industrialisation, are associated with urban development and contribute to flooding in terms of the peak discharge, volume and frequency of floods (Huong & Pathirana, 2013; Zheng et al., 2016).

Recently, the effects of land use changes on hydrologic responses resulted in interest among researchers due to intensified development in developing countries (Doe et al., 1996; Ashagrie et al., 2006). A number of researchers use GIS-based models to evaluate the impact of land use changes on hydrologic response (Gumindoga, 2010; Hacket, 2009; Juahir et al., 2010; He & Hogue, 2011; Koch et al., 2012; Camorani et al., 2005, Nobert & Jeremiah, 2012). Aside from surface hydrology responses, the effects of land use changes on groundwater hydrology attracted interest (DeSmedt & Batelan, 2001). This study investigated the impacts of land use changes on surface runoff, which contributes to the flood peak.

The flood peak is influenced by many factors, including storm intensity, which is governed by the within-storm rainfall distribution. The within-storm pattern of rainfall intensity is different between spatial locations on a worldwide scale. Several previous studies investigated the effects of within-storm rainfall distributions on floods (Robinson & Sivapalan, 1997; Kusumastuti et al., 2007) and found that the impacts of within-storm variability are most significant for fast-response mechanisms such as surface runoff. Within-storm rainfall patterns represent the variability of small timescales. For a catchment that has experienced significant land use changes such as the Way Kuala Garuntang Catchment, surface runoff can be considered a dominant runoff mechanism. Therefore, the within-storm variability will significantly affect the flood peaks.

To reduce the impacts of flooding, this study investigated the use of an infiltration well, which is used for a water conservation technique that can be used to help reduce surface runoff and peak floods. Sunjoto (1993; 1994) conducted a study of infiltration wells in Indonesia based on the concept of natural water balance as part of the hydrological cycle. When ground surface is permeable, some precipitation will naturally infiltrate and the remaining precipitation will run off along the ground surfaces. However, recent and massive land use changes led to increased runoff because a large portion of the ground area was covered by impervious layers such as roofs and pavement, which prohibit water infiltration. Infiltration wells are ideal in this situation because the water collected from roofs and channels can be directed to wells for infiltration (Sunjoto, 1994) (Figure 1). Several studies on infiltration wells indicated that surface runoff could be significantly reduced when appropriate well dimensions and numbers are used. Furthermore, the use of infiltration wells supports the zero delta discharge policy that limits water discharge to drainage systems (Arafat, 2008; Indriatmoko, 2010; Iriani et al., 2013). Infiltration wells and infiltration techniques, such as basins, trenches, and deeper wells, should be used according to climate conditions to recharge water bodies and convey water from infrastructure and sealed surfaces (Bouwer, 2002).

This study is motivated by flooding problems in the Way Kuala Garuntang Catchment (Kusumastuti & Jokowinarno, 2009), which covers an area of 63.9 km^2 and lies across the centre of Bandar Lampung City (Figure 2). However, due to the lack of long-term data for this catchment, this study is mainly exploratory and uses a hypothetical catchment with climate and catchment parameters that are representative of the Way Kuala Garuntang Catchment. The main purpose of this study is to investigate the impacts of infiltration wells, combined with within-storm rainfall distribution, in reducing flood peaks. Therefore, the model used in this study is simple and sufficient for capturing the effects of catchment parameters, such as land use and rainfall intensity, governed by within-storm rainfall distribution. This analysis uses a synthetic realisation of rainfall time series, combined with simple rainfall-runoff models.



(a) (b)

Figure 1. Illustration of infiltration well applications; (a) house with gutter at the eaves, and (b) house with gutter at the ground (*Source*: Sunjoto, 1994)

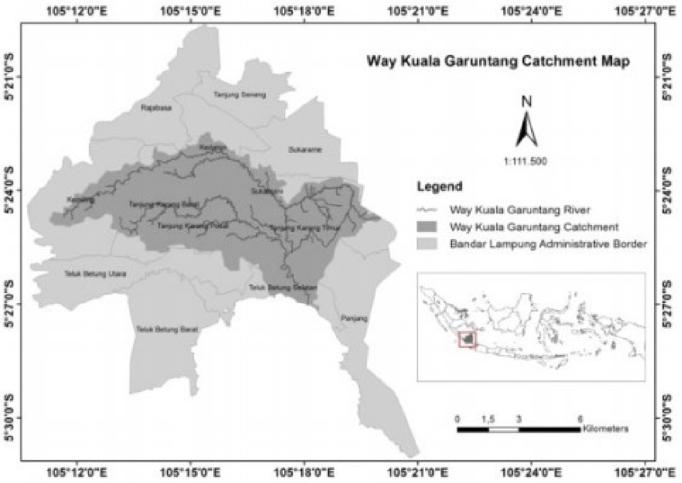


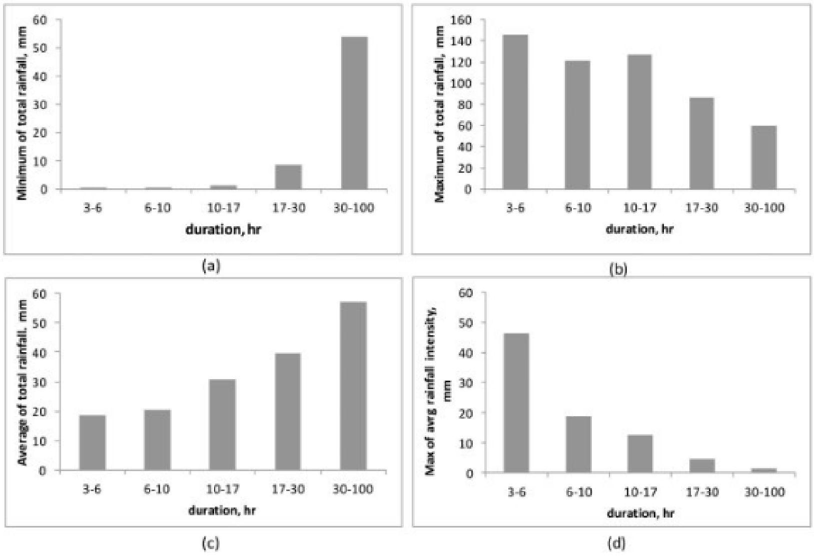
Figure 2. Way Kuala Garuntang Catchment within the city of Bandar Lampung

METHODOLOGY

Rainfall model that includes within-storm rainfall distribution

A long-term rainfall time series at hourly or sub-hourly time steps can be generated using the stochastic rainfall model developed by Sivandran (2002), which is an extension of the model developed by Robinson and Sivapalan (1997). The rainfall model accounts for the seasonal variability of dominant storm types and includes separate synoptic components that are assumed to operate year-round, as well as being a cyclonic component that only operates in the summer months. In this study, only synoptic components are considered; cyclonic components are set to zero. The synoptic component considers that each year consists of 12 months, with storm durations and inter-storm periods that are estimated from observed rainfall data obtained from the Meteorology and Climatology Berueu Panjang in Lampung from 2001 to 2015, which showed an annual average rainfall of between 1,500 and 2,500 mm (BMKG Panjang, 2016). Detailed descriptions of the rainfall model used in this study were included in previous works (Robinson & Sivapalan, 1997; Kusumastuti et al., 2007) and are not repeated in this study. Only the derivation of the parameters that are different from those described in the previous studies are explained below.

The characteristics of the storm data analysed in this study are presented in Figure 3. Storm durations are grouped into several ranges, including 3-6 h, 6-10 h, 10-17 h, 17-30 h, and 30-100 h. These durations represent very short, short, medium, long, and very long durations, respectively. The analysed storm data include the minimum total rainfall, maximum total rainfall, average total rainfall and average rainfall intensity. The minimum total rainfall generally increased as the storm duration increased (Figure 3(a)). In contrast with the minimum total rainfall trends, the maximum total rainfall generally decreased as the storm duration increased (Figure 3(b)). In addition, the average total rainfalls generally increased as the storm duration increased (Figure 3(c)) and the maximum average rainfall intensity generally decreased as the storm duration increased (Figure 3(d)).



(a) (b)

(c) (d)

Figure 3. Characteristics of the rainfall data

The rainfall duration classes were statistically analysed to determine the number of events for each duration range. Meanwhile, the mean and coefficient of the variance of the rainfall intensity for the given storm durations are presented in Table 1. Next, the exponent and coefficient values of $E[i|t_r]$ are assigned as variables a1 and b1, and the exponent and coefficient values of $CV^2[i|t_r]$ are assigned as variables a2 and b2, respectively (Table 2).

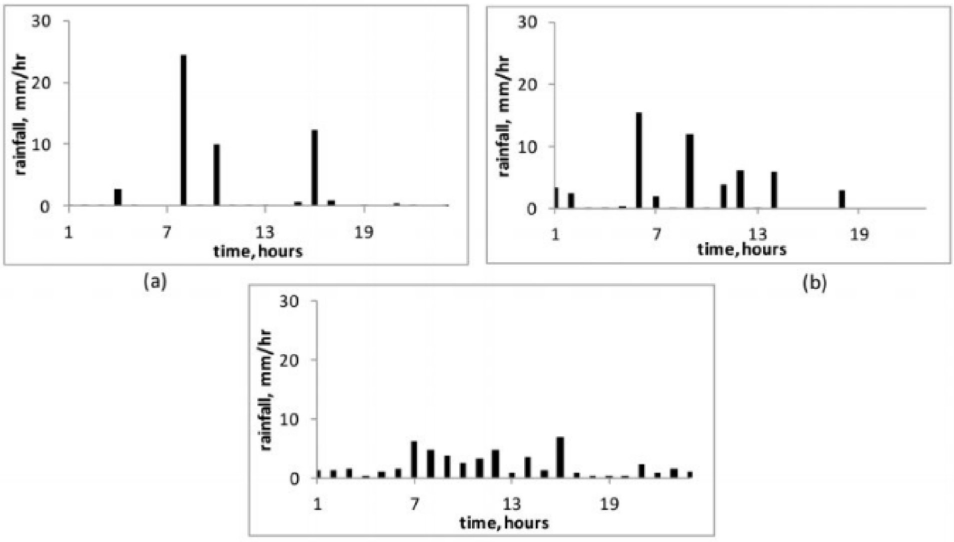
Table 1
Statistics from the rainfall duration classes

Class	Duration Range	Events	E[i/tr], mm/h	CV^2[i/tr]
1	3 <t<6	291	4.059	1.332
2	6<t<10	102	2.196	1.230
3	10<t<17	44	1.915	1.227
4	17<t<30	10	1.687	0.937
5	30<t<100	3	1.280	1.040

Table 2
Values of the exponents and coefficients for $E[i|t_r]$ *and* $CV^2[i|t_r]$

Parameter	$E[i|t_r]$, mm/h	$CV^2[i|t_r]$
Coefficient (a)	5.926	1.5392
Coefficient (b)	-0.3909	-0.1097

The within-storm distribution of rainfall intensity is stochastically governed by an indicator of variability, where the temporal patterns may include small, medium, or high variably. The within-storm pattern of rainfall intensity is represented by the variable, η. Greater η values correspond to the values that are more centred on the median. However, if small values are used, the resulting random variables are distributed at the extremes. The η values used in this study were 0.5, 1, and 3. This choice of η values is based on the analysis of within-storm patterns from several years of storm data in some regions (Robinson & Sivapalan, 1997; Hipsey et al., 2003; Kusumastuti et al., 2007). Figure 4 presents a typical rainfall hyetograph generated by the model for different values of η. The average intensity and total rainfall volume are the same in all the three cases. The simulated patterns demonstrate that lower η values produce highly variable and intermittent rainfall patterns, whereas higher η values generate less variable rainfall with nearly uniform rainfall intensities. The parameters used in the rainfall model in this study are presented in Table 3.



(a) (b) (c)

Figure 4. Variability of individual storms in the rainfall time series for (a) η=0.5; (b) η=1.5; and (c) η=3.0

Table 3

Rainfall model parameters

Parameter	Equation	Value	Units
δ_r	(3)	11	hours
α_r	(3)	4.4	hours
γ_b	(4)	100	hours
α_b	(4)	69	hours
$\tau_r = \tau_b$	(3),(4)	0	month
ω	(3),(4)	8760	hours
a_1	(6)	-	-
a_{1m}	(6)	5.9	-
a_{1a}	(6)	-5.9	-
b_1	(5)	-0.39	-
a_2	(5)	1.5	-
b_2	(5)	-0.1	-

Rainfall – runoff model

This study uses the rational method (ASCE, 1992), a simple rainfall-runoff model that is widely used to calculate the runoff-producing potential of a catchment. The rational method is based on a simple formula that relates the runoff producing potential of the watershed for rainfall intensity for a particular length of time (the time of concentration), in addition to the watershed drainage area (Viessman & Lewis, 2003; Young et al., 2009).

$$Q = Cu \cdot C \cdot I \cdot A \qquad [1]$$

Here, Q is the design discharge (m^3/sec), Cu is the unit conversion coefficient, C is the runoff coefficient (dimensionless), I is the design rainfall intensity (mm/hour), and A is the catchment area (km^2).

The runoff coefficient (C) plays an important role in catchment management because it can be used as a surface runoff indicator in a catchment and for flood estimation. In order to estimate the runoff coefficient for the Way Kuala Garuntang Catchment, a runoff coefficient must be estimated for each land use in the Way Kuala Garuntang Catchment. Land uses in the Way Kuala Garuntang Catchment (Bappeda, 2010) and their corresponding runoff coefficients (Triatmodjo, 2008) are presented in Table 4.

Scenarios for the land use sensitivity analysis

The existing distribution of land uses in the Way Kuala Garuntang Catchment is presented in Figure 5. In order to understand the impacts of land use on the flood peak, this study considers four scenarios in the land use sensitivity analysis performed using Quantum GIS (Ramadana & Kusnanto, 2010). In Scenario 1, all vacant lands are converted into green lands. Based on the Regional Spatial Plan of Bandar Lampung 2010-2030, approximately 30% of the area is reserved for green land. In Scenario 2, all vacant lands are converted into green lands (as in Scenario 1), and half of the agriculture area is used for settlement or industrial purposes.

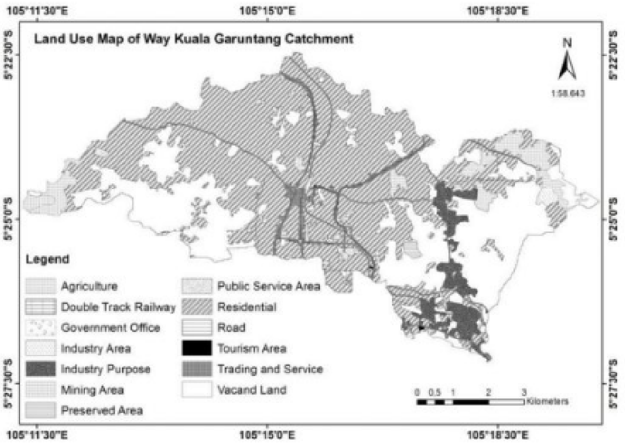


Figure 5. Land use map of the Way Kuala Garuntang Catchment showing its existing conditions (*Source*: Bappeda, 2010)

Scenarios 3 and 4 consider land use changes that are different from those of Scenarios 1 and 2. In Scenario 3, all vacant lands are converted into industry, and half of the settlement is converted into trading and service. There is a trend in Bandar Lampung of building *ruko*, a term in Indonesia that means homes and stores used for living, trading and services. A *ruko* typically consists of three or more storeys, where the first storey is used as a store and the second and third storeys are used as home. Scenario 4 considers the conversion of all vacant lands into industry areas and a quarter of the settlement areas into trading and service areas. Scenarios 3 and 4 assume that more lands will not be required with the projected increase in population by 2030 because more people will live in apartments and *ruko*. As significant industrial growth requires more space, the policy to preserve 30% of the areas for green land cannot be maintained. The land use descriptions and corresponding percentage of the catchment area for each scenario above are presented in Table 4.

Table 4

Runoff coefficient (C) and percentage of land use in the catchment area

Land Use	Runoff Coefficient (C)	Percentage of Land Use in the Catchment Area				
		Existing	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Mining Area	0.95	0.40	0.40	0.40	0.40	0.40
Residential	0.65	54.14	54.14	56.50	27.07	40.60
Industrial Purposes	0.55	4.11	4.11	-	4.11	4.11
Vacant Land	0.40	31.23	-	-	-	-
Trading and Service	0.80	1.79	1.79	1.79	28.86	15.33
Government Office	0.75	0.23	0.23	0.23	0.23	0.23
Tourism Area	0.80	0.05	0.05	0.05	0.05	0.05
Industry Area	0.85	0.38	0.38	4.49	31.60	31.60
Preserved Area	0.30	0.46	0.46	0.46	0.46	0.46
Agriculture	0.35	4.72	4.72	2.35	4.72	4.72
Public Service Area	0.75	1.27	1.27	1.27	1.27	1.27
Road	0.90	1.16	1.16	1.16	1.16	1.16
Double Track Railway	0.35	0.07	0.07	0.07	0.07	0.07
Green Land	0.05	-	31.23	31.23	-	-

Source. analysis results

Requirements and number of infiltration wells

During application, the natural condition of the area should be checked to determine whether an area meets the following criteria: (1) land permeability should be more than 2 cm/hr, (2) shallow ground water is greater than 3 m below the ground level during the wet season, and (3) the land slope is less than 30° (Public Work Department, 1991). In this study, conditions of the Way Kuala Garuntang Catchment were established by using maps of land permeability, shallow groundwater levels and land slopes with existing land use maps to determine suitable areas for the application. The number of infiltration wells can be calculated as follows (Suripin, 2004):

$$\begin{aligned}\text{The number of wells} &= \frac{Q_{\text{runoff}}}{Q_{\text{well}}}\\ &= \frac{Q_{\text{runoff}}}{((A_{\text{well base}}\ \text{x}\ k) + (A_{\text{well wall}}\ \text{x}\ k)}\\ &= \frac{Q_{\text{runoff}}}{((\pi\ .\ r^2\ \text{x}\ k) + (2.\ \pi\ .\ r\ .\ h\ \text{x}\ k)}\end{aligned} \qquad [2]$$

Where, Q_{runoff} is the daily peak flow (m^3/day), Q_{well} is the total runoff collected in a well during 1 day (m^3/day), Q_{well} is calculated based on infiltration and well discharge (m^3/day) and wall infiltration well discharge (m^3/day), k is the land permeability coefficient (m/day), r is the well radius (m), $A_{well\ base}$ is the well base area (m^2), $A_{well\ wall}$ is the well wall area (m^2) and h is the well depth (m). For analysis, the land permeability coefficient was set to 2 cm/hr, and the well depth was 3 m.

RESULTS AND DISCUSSION

Impacts of land use on flood peaks

Land use simulations in the Way Garuntang Catchment are presented in Figure 6. Based on the runoff coefficients for various land uses in the Way Garuntang Catchment and the proportion of catchment area associated with the particular land uses presented in Table 1, the composite runoff coefficients for the existing condition, Scenarios 1 (Figure 6(a)), 2 (Figure 6(b)), 3 (Figure 6(c)) and 4 (Figure 6(d)) were 0.56, 0.45, 0.47, 0.74 and 0.72, respectively.

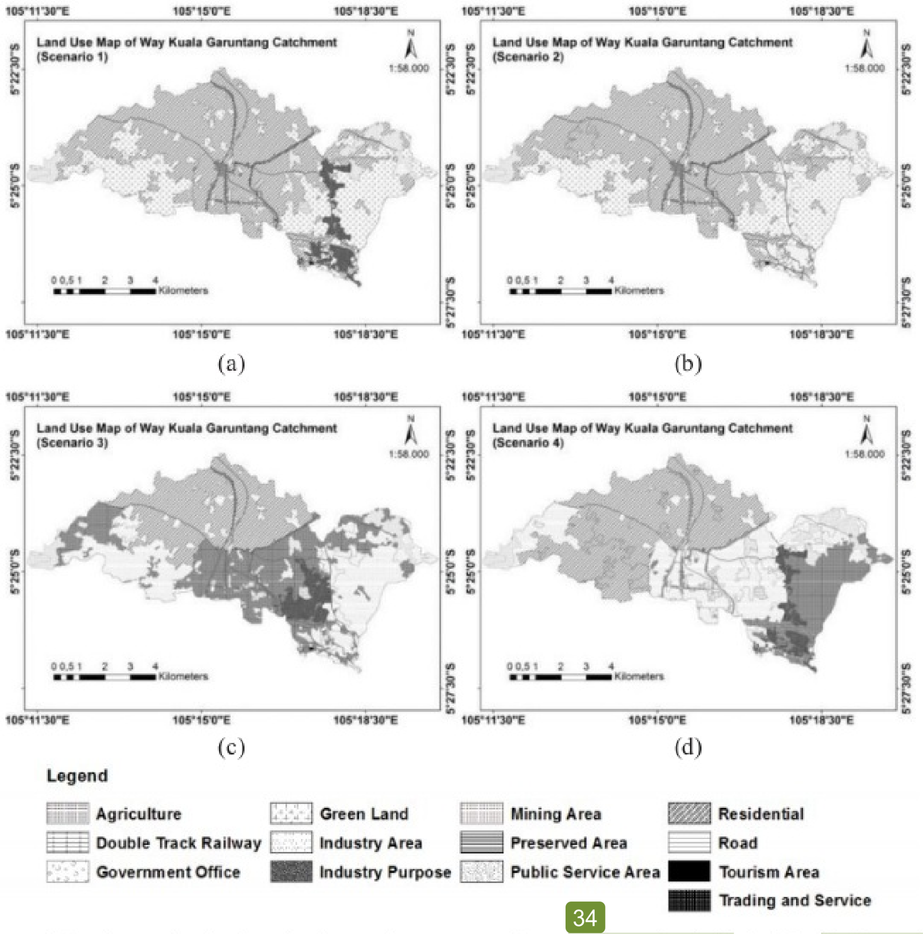
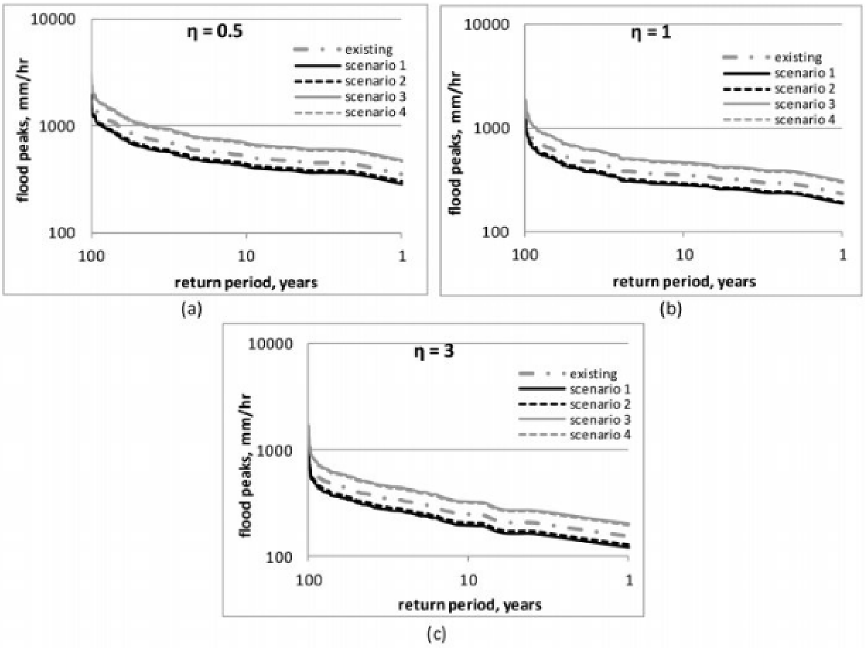


Figure 6. Land uses in the four land use change scenarios; (a) Scenario 1 (C=0.45); (b) Scenario 2 (C=0.47); (c) Scenario 3 (C=0.74), and (d) Scenario 4 (C=0.72)

The flood frequency curves, generated by all the scenarios incorporated with the selected within-storm patterns, are presented in Figure 7. The results can be categorised into two groups. The simulation results obtained using Scenarios 1 and 2 had lower flood peaks, whereas Scenarios 3 and 4 resulted in greater flood peaks (Figures 7(a), (b) and (c)). The decrease in flood peaks from Scenarios 1 and 2 resulted from considering approximately 30 percent of the catchment area as green land. A preliminary study by Yuniarti et al. (2013) on the impacts of land use changes in this catchment highlighted the importance of green land. Green land is necessary for providing sufficient space for infiltration, which is good for groundwater recharge and flood control. Scenario 2 includes green land and the conversion of some agriculture areas into settlement. Therefore, the flood peaks from Scenario 2 are greater than those from Scenario 1 because the land use conversion tends to change the recharge potential area into semi-impervious areas. In contrast with the simulation results from the first two scenarios, Scenarios 3 and 4 resulted in significant increases in flood peaks because the land use was converted from recharge potential areas into semi-impervious areas and semi-impervious areas were converted to impervious areas.



(a) (b)

(c)

Figure 7. Flood frequency related to land use and the within-storm rainfall pattern

Within-storm patterns were found to significantly affect flood peaks for the same land use scenario because higher degrees of within-storm variability resulted in higher flood peaks (Figures 7(a), (b) and (c)). For example, the flood peaks resulted for Scenario 1 for return period of 10 years are 244.8 mm/hr, 346.5 mm/hr and 518.6 mm/hr for η equals 3, 1 and 0.5 respectively, or as the degree of within-storm variability increases. In addition, similar behaviours were observed for the return periods, and the flood peaks resulting from all scenarios also increased as the return period increased.

Impacts of infiltration wells on flood peaks

When aiming to understand the possible impacts of land use changes presented above, efforts should be made to reduce the impacts of land use changes on flooding. Infiltration is an alternative solution for conserving water and reducing floods. Before analysing the impacts of infiltration wells on flood peaks, the area that is suitable for applying infiltration must be defined. Figure 8 presents a ground water level map (Figure 8(a)), a soil permeability map (Figure 8(b)), a land slope map (Figure 8(c)) and a map of the suitable areas for infiltration wells (Figure 8(d)), which were obtained by overlying the three other maps. Overall, 52.06 km^2, or 81.47% of the catchment area, was identified to be suitable or effective for applying infiltration wells.

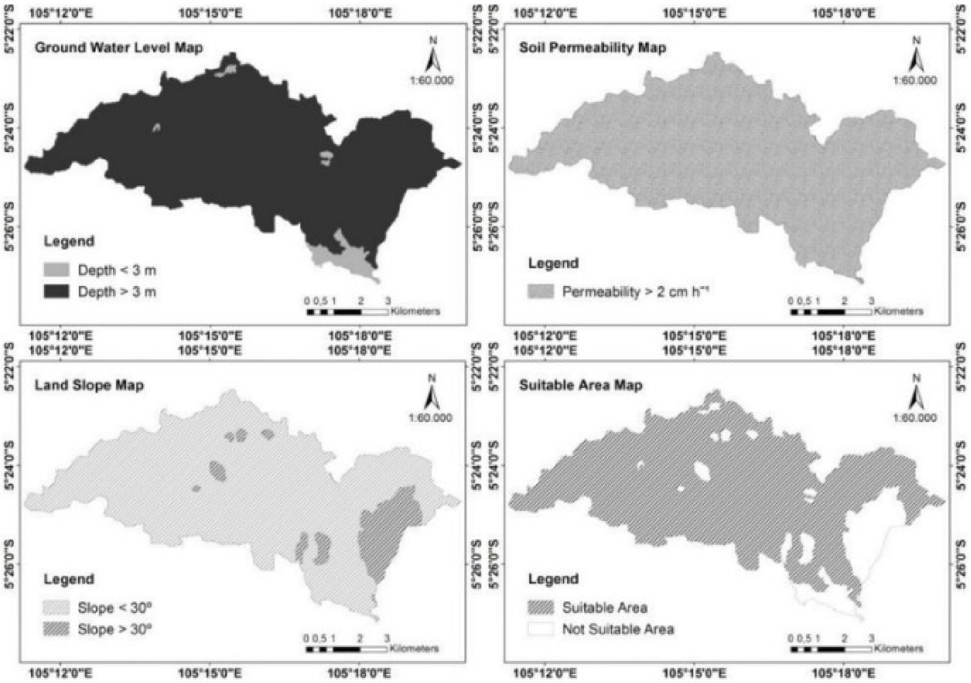


Figure 8. Suitable area for applying infiltration wells

The density of infiltration wells was applied over an average land area and the effects of one infiltration well on the flood peak while incorporating the within-storm pattern were investigated, and these results are presented in Figure 9. The density of infiltration was represented by No Well, Well 1, Well 2, Well 3, and Well 4 symbols, which correspond to no well applied and one well applied within 1,000, 2,000, 5,000, and 10,000 m^2, respectively. The results showed that denser applications of the infiltration wells resulted in lower flood peaks (Figures 9(a) to (f)). In addition to the application density of the infiltration wells, the magnitude of the flood peaks was determined based on the well diameter. Two well diameters, 1 and 1.4 m, were analysed. The results illustrate that larger-diameter wells result in lower flood peaks. This finding can be observed when comparing the flood peaks that were generated using the same within-storm pattern for the same infiltration well densities. For example, flood peaks that were simulated using a well diameter of 1.4 m (Figure 9(b)) were lower than those using a well diameter of 1.0 m (Figure 9(a)). Similarly, the flood peaks in Figure 9(d) are lower than those in Figure 9(c), and flood peaks in Figure 9(f) are lower than those in Figure 9(e).

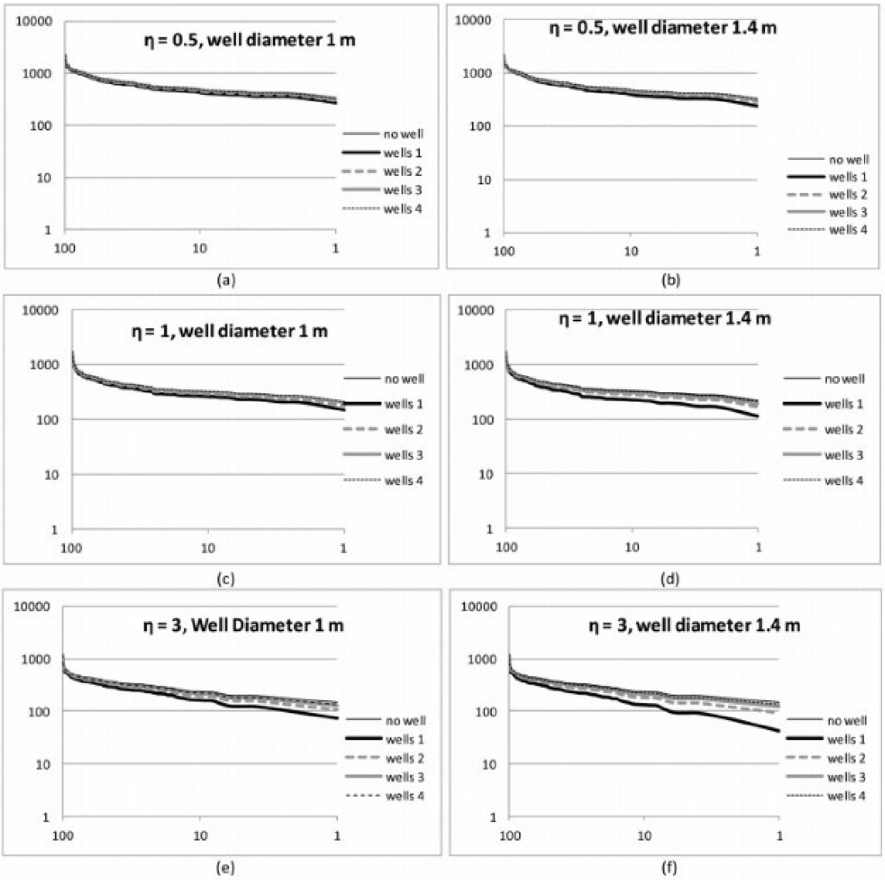
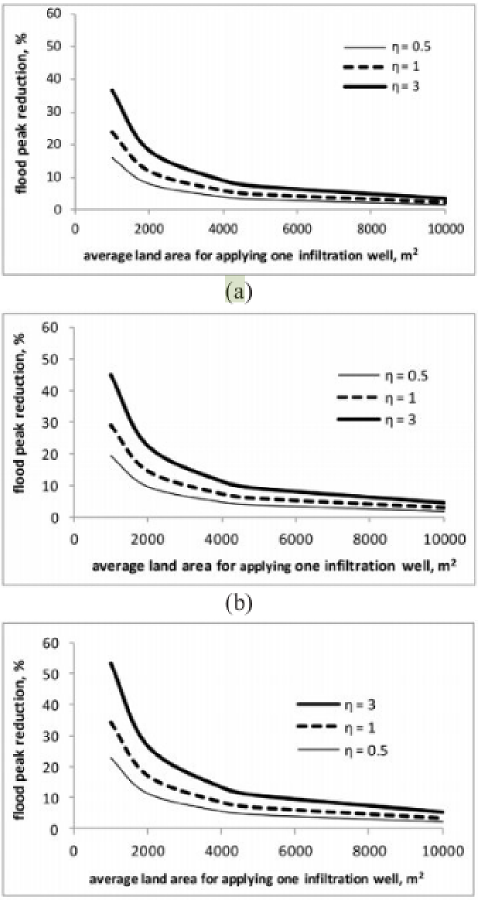


Figure 9. Flood frequency for applying infiltration wells

The impacts of within-storm patterns on flood peaks with and without infiltration wells can be observed in Figure 9. The high variability of the within-storm patterns demonstrates small differences in flood peaks between those that resulted from simulations, with and without infiltration wells. For the smaller well diameter, the difference of flood peaks between those generated from simulation, with and without infiltration wells, is insignificant when the high variability of the within-storm pattern is considered (Figure 9(a)). The difference in flood peaks becomes more significant as the within-storm variability decreases. This result can be observed when comparing the flood peak differences in Figures 9(a), 9(c) and 9(e). When using the larger well diameter, the difference in flood peaks becomes more significant as the variability of the within-storm pattern decreases, as shown in Figures 9(b), 9(d) and 9(f).

The results presented in Figure 9 suggest that the effects of within-storm patterns on reducing flood peaks are more significant at lower return periods. Therefore, when [illegible]ng flood peaks with a low return period such as at 5 years, further investigations can be used to examine the effects of within-storm patterns and infiltration wells on flood peak reduction. Figure 10 presents flood peak reductions and corresponding infiltration well densities for various within-storm patterns. It is shown that the use of infiltration well results in flood peak reduction up to 50%. Well diameters of 1, 1.2, and 1.4 m are used in these simulations—and the results are presented in Figures 10(a), (b) and (c), respectively. Overall, the results confirmed that larger well diameters resulted in more significant reductions in a flood peak. Furthermore, these results strengthen the idea that lower within-storm in regards to storm variability results in more significant flood peak reduction impacts, as shown in Figures 10(a), (b) and (c).



(a)

(b)

(c)

Figure 10. Flood peak reduction vs. infiltration well density for well diameters of (a) 1 m; (b) 1.2 m; and (c) 1.4 m

The use of infiltration wells as one water conservation technique was selected because it was relatively cost-effective and can be applied by individuals or communities. In addition, this approach is similar to the introduction of the so-called green infrastructures in cities that conducted trials around the world. The concept of green infrastructure is related to storm water runoff management at the local level through the use of natural systems or engineered systems that mimic natural systems. Green infrastructure corresponds to integrated catchment management and is used to address climate change, water quality, flooding and other urban issues. In addition, green infrastructure can be implemented with sequential infrastructures that contribute to storm water before it leaves the site. Through sequential infrastructures, storm water is collected by distributing green infrastructure technologies, such as rain barrels, infiltration wells, infiltration trenches and bio-retention. Subsequently, the excess water from those infrastructures is directed to a centralised outlet before the excess water is added to the urban drainage.

This study demonstrates that infiltration wells are capable of reducing the impacts of land use changes on flood peaks. However, there are some limitations in this study in that the use of the method and corresponding results only cope with a hypothetical catchment. Furthermore, the model parameterisation is limited to the catchments that have similar climatic and catchment characteristics. Climatic and hydraulic data from the studied catchment is also limited, therefore, a validation of the model cannot be carried out. In addition, there were some straightforward assumptions used in the analysis. For example, the well walls are of the same type, which are screened continuously along the bore. In practice, the type of well walls may be different from one location to another depending on geology, soil type and soil slope. The well walls may be screened continuously, screened at specific depth intervals or a cement wall. Similarly, the depth of the walls is considered to be the same in the analysis, while in implementation—ground water level and rainfall intensity are the factors in determining the depth of the wall. In order to simplify the analysis, this study considered soil permeability to be the same in vertical and horizontal directions, which may not be the case in the field. Therefore, to implement an infiltration well in such a location, each of the factors mentioned above need to be considered when designing an infiltration well. Despite its limitations, the results are valuable for understanding the impact of within-storm rainfall patterns—with the presence and absence of infiltration wells on flood peaks.

Several issues regarding the implementation of infiltration wells include the willingness of people to provide land and costs for constructing wells. With little participation from people for implementation, the number of infiltration wells will be low. Consequently, the application of infiltration wells may have less significant effects for flood peak reduction. Required commitment and relevant policies from the government could be used to encourage the use of these applications as well as community participation to address flood reduction. In addition, the implementation of infiltration wells with other green infrastructure techniques, such as rain barrels, porous trenches, retention ponds, and bio-retention, would have a greater impact on flood reduction.

CONCLUSIONS

Urbanisation, population growth and economic increases require more settlements, trading areas and industries, which may result in land use changes. Several scenarios were applied to demonstrate the effects of land use changes on flood peaks. The results indicate that the conversion of lands to obtain space for more settlements, industries and trading areas will increase flood peaks significantly. This study analysed the use of infiltration wells to reduce flood peaks. The volume and densities of the wells determine the degree to which runoff will be reduced. Greater application densities of infiltration wells in a catchment result in greater reductions in runoff and lower flood peaks. Similarly, larger well diameters allow a greater proportion of runoff to be retained in infiltration wells. Flood peak reduction using infiltration wells is up to 50% compared to without wells. When incorporating the within-storm pattern in the presence and absence of infiltration wells, high variability in the within-storm pattern indicates only a small proportion of the excessive runoff generated by the corresponding individual storm that can be stored within the infiltration wells. This study demonstrates that the effects of infiltration wells in reducing flood peaks are more observable in regions with rainfall patterns exhibiting low within-storm variability.

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