Indonesian Journal of Geography Vol. 51 No. 3, December 2019 (295 - 303)
DOI: http://dx.doi.org/ 10.22146/ijg.33721

INDONESIAN JOURNAL OF GEOGRAPHY
RESEARCH ARTICLE

Urban sediment in infiltration wells: A lesson from the northern area of greater Yogyakarta city

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Received: 2018-03-16
Accepted: 2019-10-16

Keywords:
grain-size,
runoff,
sediment,
urban hydrology.

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Abstract The development of housing in Yogyakarta eventually led to increased levels of runoff. To mitigate runoff increases, infiltration wells were constructed in a specific network. The northern part of Yogyakarta is now facing urbanization, and there are many housing blocks that are being constructed complete with the runoff drainage system. This study aims to reveal the role of the infiltration wells network about runoff and its effectiveness concerning the sediment load in the urban area. The drainage networks in the research area function as a watershed, but not with a single outlet. The runoff flow was spreading through the drainage system and did not accumulate on the single outlet. It can be seen that some infiltration wells supposed as a well, which is a place of accumulation of runoff and sediment. Most of the infiltration wells have been filled with sediment up to over a quarter, or even more than half, of their carrying volume. Granulometry measurement shows that the percentage of clay, loam, sand, and gravel in each well tend to differ for every sample. The differences between filled wells and their sediment grain depend on the location of those wells. Maintenance of the wells is required, such as sediment dredging, to rejuvenate them and improve their efficiency.

1.Introduction

Urbanization fundamentally changes natural processes in ways that lead to environmental degradation, such as changing recharge areas into residential areas with an impervious surface (Meyer et al., 2005). A rapid increase in impervious surfaces such as concrete and human-made infrastructure increases surface runoff and urban flooding. The most common problem involves areas that could previously infiltrate water easily being transformed into watertight areas (Sudarmadji, 1997a; Zhu et al., 2018). Many groundwater recharge areas have been changed into residential areas and other facilities, such as road networks, that are made from cement or paving blocks. The city of Yogyakarta has transformed along with the development of the Yogyakarta–Surakarta corridor (Giyarsih, 2010). This urbanization process has certainly affected the hydrological response of the area. The urban area in the northern part of Yogyakarta is now facing such changes that are affecting its hydrological characteristics and will cause higher runoff and flood risk. The runoff water coming from dense residential areas also contains high levels of sediment originating from the residential yard area as a result of splash and sheet erosion (Sudarmadji, 1997b). Sediments originating from upstream areas that enter urban areas also tend to increase in particle size due to increasing runoff (Russel et al., 2018). Further, in the long term, water quality will change due to water pollution.

To mitigate the impact of high runoff, as well as flooding, in the northern part of Yogyakarta, various efforts have been made, including the construction of infiltration wells (Suprayogi, 2015). In this area, this approach is well supported by the permeability of the soil, as it mostly consists of coarse sand and gravel (Indramaya & Purnama, 2013). Construction of infiltration wells has been proven to reduce surface runoff and increase recharge to groundwater effectively in densely populated areas (Arafat, 2008; Sunjoto, 1994). Most studies on urban sediment and hydrology have not focused on the role of infiltration wells in drainage runoff, specifically in residential yard areas. Some are mainly concerned with the effects of stormwater (Li et al., 2012; Locatelli et al., 2017). Furthermore, the studies technically make a calculation model related to the capacity of infiltration wells (Jang et al., 2018; Kusumastuti et al., 2014; Li et al., 2011). There is a need for a new evaluation of infiltration wells and preliminary findings regarding a new perspective on groundwater conservation in densely populated areas through direct measurements in the field.

This method for reducing runoff has been applied in most of the residential area of the northern part of Yogyakarta, including in the Banteng residential area.

This location has faced high runoff and flooding in the rainy season. To mitigate this, infiltration wells have been constructed on the sides and in the middle of the residential roads. This approach assumes that runoff will flow to the infiltration wells, thus draining the runoff and reducing flooding. However, some problems can disturb the drainage system, such as high sedimentation from anthropogenic activities and natural processes, or natural disasters. Solid material carried by runoff into infiltration wells may impact their effectiveness in infiltrating further runoff (Lassabatere et al., 2010). It also can be presumed that the effectiveness of infiltration wells in accommodating and infiltrating water will decrease over time. These problems need to be evaluated to propose effective mitigation strategies regarding the dynamic processes of infiltration wells.

The Banteng residential area is located on the foot slope of an active volcano, where it faces potential hazards like ash and tephra fall. Natural disasters such as the eruptions of Merapi Volcano in 2006 and 2010, as well as of Kelud Volcano in 2014, have led to volcanic ash being deposited in many areas, including Banteng. A vertical ash column from the eruption of the Merapi volcano formed on 4–5 November 2010 and swept across the southern flank toward Yogyakarta (Jousset et al., 2013). Yogyakarta was also affected by volcanic ash from Keludʼs eruption: previous research has mentioned that ash spread to the southwestern area and has estimated a mass eruption rate of 3x107 to 4x107 kgs-1 (Suzuki & Iguchi, 2017). The tephra fallout from Kelud spread over 200 km southwest from its dome, with an estimated grain size of below 0.1 cm (Maeno et al., 2014). Ash and sand from all this volcanic activity were also transported by overland flow into the infiltration wells, thus leading to these natural disasters causing further problems.

Along with the development of urbanization, the increase in direct runoff caused by land-use change has become a major challenge for urban hydrological systems (Li et al., 2018). Other problems also derived from natural erosion and anthropogenic activities potentially reduce the effectiveness of the infiltration wells. Anthropogenic issues are a key problem for infiltration wells, particularly if no maintenance of the wells is carried out, as processes such as sediment dredging for rejuvenation are vital to keeping them functioning. This research aims to reveal the role of the network of infiltration wells with runoff and its effectiveness, considering the sediment load in densely populated areas.

2. The Methods

The research was conducted in the Banteng residential area, located in the northern part of Yogyakarta. The surroundings of Banteng have recently become developed into a densely populated and highly physically developed region. Located 20 km south of the summit of the Merapi volcano, the topography of the research area is gently sloping, characterized by a 0–8 slope degree (Fig. 1). Based on the geological map, the area is covered by alluvial material from the young Merapi volcano, which can still be detached by precipitation, thus generating erosion (Rahardjo et al., 1995). The thirty mean annual rainfall is 2,115 mm, as recorded by the Mlati rain gauge.

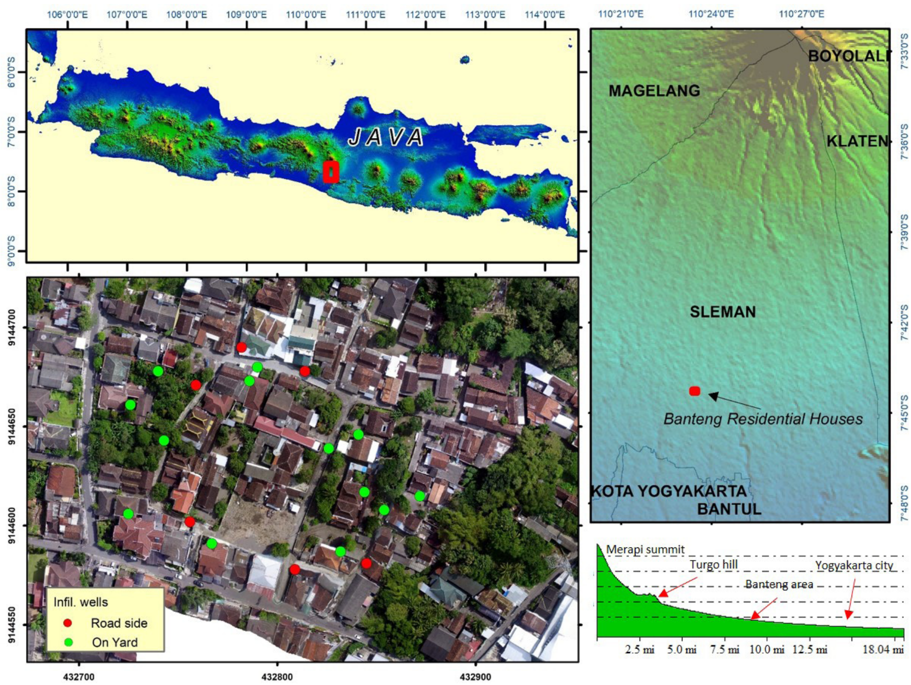

Figure 1. Location of Banteng residential area in the northern part of Yogyakarta city (20 km from Merapi summit)

Table 1. Samples of infiltration wells in the study area: 11 samples collected from the road; 8 samples from the yard; 1 sample of sediment from volcanic ash

Sampling Code	Location	Sampling code	Location
1/Sed/Sub/16	Road	11/Sed/Smj/16	Road
2/Sed/Swl/16	Road	12/Abu-KLD/16	volcanic material
3/Sed/Yot/16	Road	13/Sed/R-Swl/16	Yard
4/Sed/Gyt/16	Road	14/Sed/R-Ags/16	Yard
5/Sed/Anr/16	Road	15/Sed/R-Bud/16	Yard
6/Sed/Mjr/16	Road	16/Sed/R-Kart/16	Yard
7/Sed/Kar/16	Road	17/Sed/R-Dar/16	Yard
8/Sed/Sdn/16	Road	18/Sed/Dar/16	Yard
9/Sed/Bej/16	Road	19/Sed/Parw/16	Yard
10/Sed/Har/16	Road	20/Sed/Parw/16	Yard

Figure 2. Sediment collected from infiltration wells with the help of local residents

This research required the collection of primary data through fieldwork. Primary data were collected based on direct observations and measurements in the field, of factors such as sediment thickness and depth of infiltration wells. The samples were taken during the rainy season. The help of residents was requested for collecting sediment during the field surveys (Fig. 2). Laboratory analysis was conducted to define the granulometry of the sediment samples, using a sieving method. Twenty infiltration wells were selected for examination. For each of these, we measured the well's depth from the surface and the thickness of the sediment within the well. The Global Positioning System (GPS) was used to plot their locations and to track the entire network of drainage and infiltration wells. Each well was given name through a unique coding system, consisting of number/type/resident name/date. The two major locations were classified and had wells located on the roads (both at the sides or in the middle) and in residential yards. The classification was applied for assuming the differences between the infiltration wells on two sites. As the field measurements were conducted after the Kelud event, the volcanic ash from Kelud was also subjected to granulometry sampling. The kind of sampling procedure used is essential because the volcanic event in the study area could potentially happen again in the future. To obtain landcover information, aerial mapping was conducted using a drone. The orthophoto was then interpreted to produce a land cover map to predict the runoff coefficient.

3. Results and Discussion

Flow direction and runoff coefficient

The Banteng residential area is located on a gently sloping area, covering 25,209 m^2 in total. The slope direction is mainly toward the south, following the foot slope direction of the Merapi volcano. On a detailed scale, the slope direction is not significantly influential to the runoff direction. The runoff is mainly controlled by micro-slopes and drainage construction. Fig. 3 shows the flow direction in the research area interpreted from the field survey (GPS tracking), and micro-slope direction from, derived from an aerial photograph. However, the network of infiltration wells was not constructed in a neatly arranged manner: it is a scattered network. Areas of the network function can be classified as small watershed but do not have a single outlet. The runoff flow spreads throughout the drainage system rather than accumulating at a single outlet. The runoff direction is highly influenced by the sediment load trapped in the infiltration wells. The level of runoff supplied by an individual infiltration well is estimated based on how heavily loaded each well is with accumulated sediment. Runoff trapped in the infiltration wells comes not only from the research area but probably also from the outside of the study area (north). If this were the case, the infiltration wells in the northern part of the research area would contain sediments from other areas. However, the infiltration wells in the northern area (5/Sed/Anr/16 and 10/Sed/Har/16) do not have as much sediment accumulated as some other wells. This suggests that the outskirts of the research area have their drainage system that functions in the same way as that within the research area. The location of the wells with the highest accumulation is also by the runoff coefficient, as they are located in areas surrounded by houses, which are the areas that have the highest runoff coefficient.

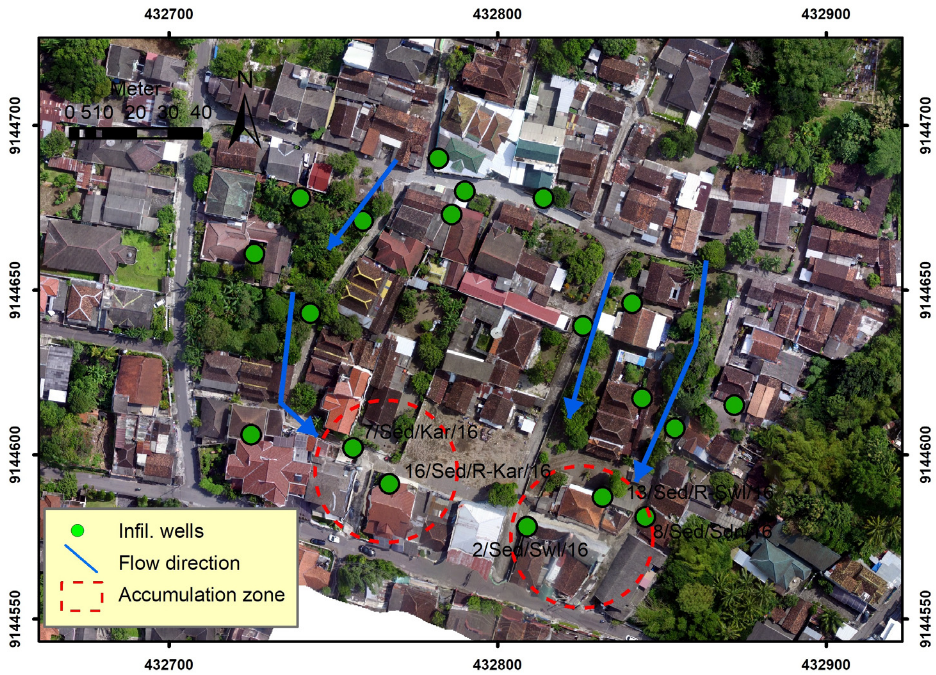

Figure 3. Flow accumulation in the research area. From this map, it can be inferred that four of the selected infiltration wells can be assumed to be accumulation wells.

Figure 4. Land cover of the research area, generated from aerial photo mapping.

The research area is mostly covered by houses, but some of these houses have small yards with active gardens (Fig. 4). Splash and sheet erosion still possibly take place in those small yards, that potentially produce sediment that flows to the infiltration wells. Also, some areas have impermeable surfacing materials, such as cement or paving blocks, giving them the high potential to generate runoff. In the research area, the highest runoff rate is seen from houses, which have a runoff coefficient of 0.9. The housing blocks cover 14,505 m^2 (57%) of the research area. Another type of land covering that contributes to a high level of runoff is roads. Road coverage of the research area is 3,914 m^2 (15%), with a runoff coefficient of 0.8. Both houses and roads produce higher levels of runoff than other land coverings, such as open space and vegetation. Covering an area of 1,380 m^2 (5%), soil in open spaces that have been mostly left in a natural condition, covered by grass or bare land, allows for natural water infiltration, with a runoff coefficient 0.25; however, such areas are also very susceptible to becoming sediment source areas. The runoff rate of vegetation cover is lower than in other areas. Covering 5,410 m^2 (23%), vegetation allows high water infiltration, with a runoff coefficient of 0.15. The runoff coefficients are adopted from the ODOT (2014). The open space and vegetation coverage areas may potentially change since further building development is still possible in the research area. The bared land on open space is particularly vulnerable to erosion processes, while vegetation can lead to rill erosion through stem flow or splash erosion by drip. These processes also have a strong influence on the levels of sediment carried by overland flow into the infiltration wells.

Sediment Load

Sediment transport by a runoff on the study area starts with splash erosion occurring on soil, mostly in open space and vegetation coverage areas. However, in housing areas, the erosion process is still possible due to some part of residential yards being covered by bared land. Our field investigations show that open space remains naturally bared, which leads to high levels of erosion, marked by a pedestal (Fig. 5). In open spaces, splash erosion can take place as a direct result of rainfall. Splash erosion can also occur on land areas with vegetation cover, caused by water droplets from the crown drip. Furthermore, erosion may occur after the formation of overland flow, made more significant by rill erosion. In this research, we mainly focus on sediment carried by runoff that then collects in infiltration wells. Since it is not possible to take bedload samples on overland flow or runoff, the samples collected are from sediment that has gathered in infiltration wells, which accumulates across a considerable period. As mentioned above, 20 sediment samples were collected to analyze the characteristics of infiltration wells (Table 1), one of which consisted of material from the Kelud Volcano eruption in 2014. This was used as a comparison since another volcanic event could impact the study area in the future. Volcanic ash from a huge eruption could quickly gather in infiltration wells and affect sustainability by decreasing the usage life of infiltration wells.

Sediment is carried by runoff then deposited in the infiltration wells. Fig. 6 shows the depth of the selected infiltration wells and the thickness of the sediment layers in each well. From the comparison shown in Fig. 6, it is clear that most of the infiltration wells are filled with sediment up to over a quarter, or even more than half, of their carrying volume. The maximum proportion is 58%, and the minimum proportion is 17%. It is assumed that the sediments gathered in the infiltration wells would reduce the effectiveness of the wells' functioning. The infiltration well with the highest sediment load is 13/Sed/R-Swl/16.

The depth of the wells ranges between three values: 300, 500, and 600 cm. From field observations and interviews, it could not be clearly determined why the wells were constructed to different depths, and those assumed the construction depending on the concrete ring dimension. Each concrete ring is 50 cm in depth.

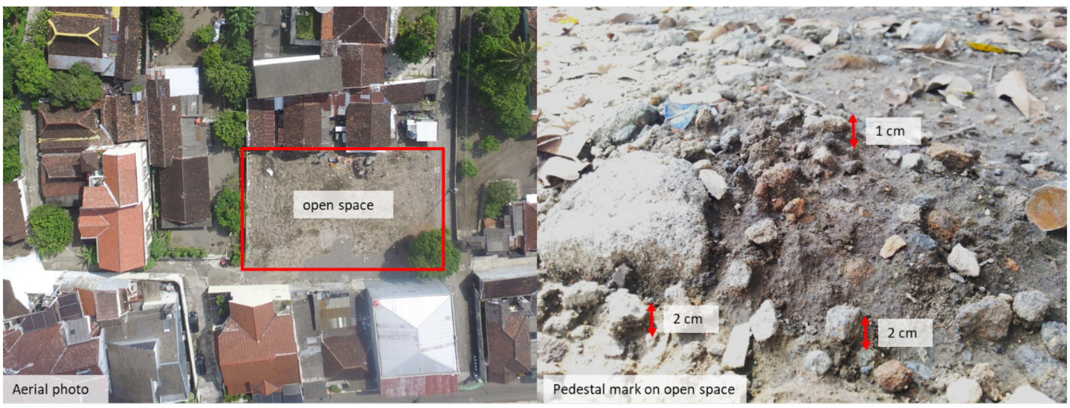

Figure 5. Erosion processes are active, especially in open spaces. Erosion processes are marked by a pedestal with various dimensions, depths ranging from 1–2 cm.

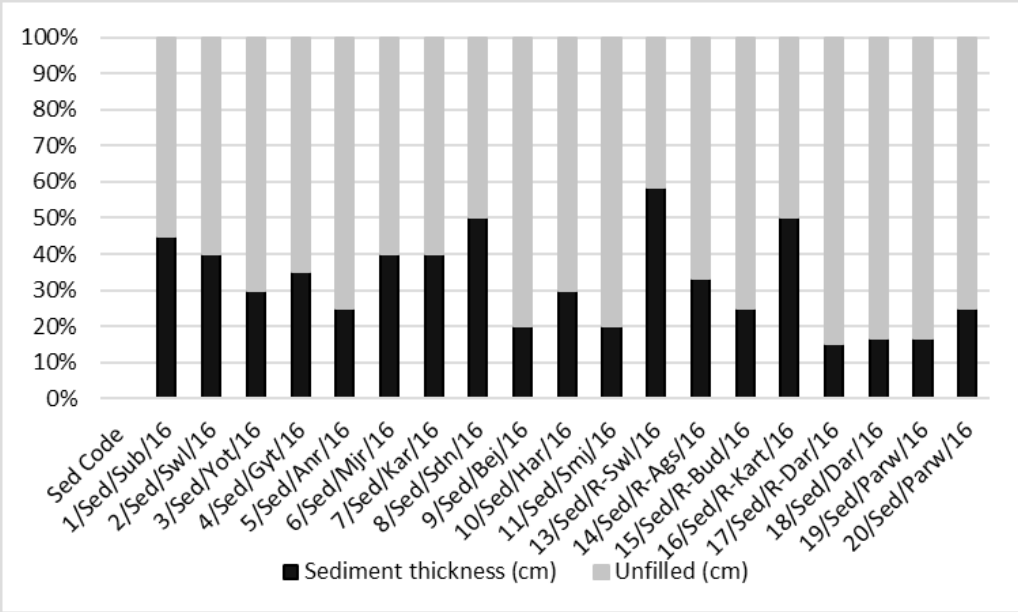

Figure 6. Comparison between the depth of infiltration wells and their sediment thickness: most sediment measurements are below 50% of the full depth of the wells.

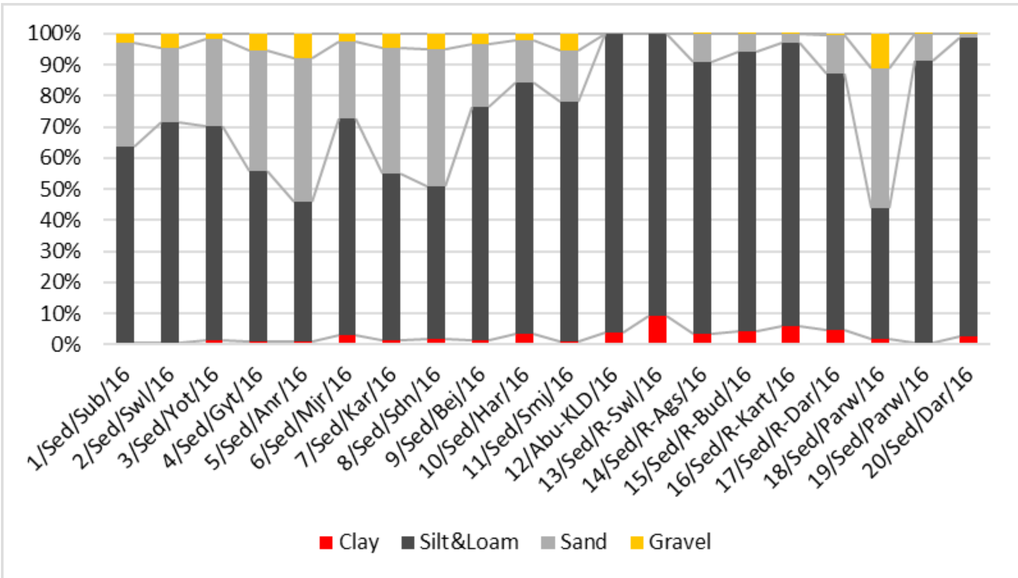

Figure 7. Textural grain characteristics of sediment from infiltration wells (mostly dominated by silt and loam textures)

Sediment Size Characteristics

The infiltration wells in the study area collect water runoff containing sediment load directly from houses, yards, and roads. Water coming from different source areas—the rooves of houses, yards (vegetation), and roads—has different characteristics. It is influenced by the strength of the water for soil erosion, and the source of runoff can be deduced from sediment texture. Infiltration wells that contain a high volume of sandy materials can be assumed to have come from very eroded soil. On the contrary, for sediment containing high volumes of silt or loamy material, it can be assumed that soil erosion is minimal in the area. Fig. 7 shows the sediment size characteristics of the sampling wells, demonstrating that the percentages of clay, loam, sand, and gravel content differ between each well. Most of the samples are dominated by silty and loamy material, while larger sandy and gravelly materials are found in the well-designated 18/Sed/Parw/16. The volcanic ash found in the research area contains silt and loamy material, showing almost the same composition as the sediment in two other wells—13/Sed/R-Sw/16 and 20/Sed/Dar/16.

Discussion

The infiltration wells and drainage network in the study area are considered dense, with around 20 infiltration wells for every 80 houses; thus, it is estimated that each infiltration well covers four houses. This number of infiltration wells would be considered sufficient to actualize a zero-runoff program in the study area. The construction is also suitable for the national standard, which advises that the minimum distance between infiltration wells should be three meters (SNI, 2017). However, the natural and anthropogenic sediments that can potentially impair the infiltration processes must be considered. In addition, a substitutional drainage system has been built to flush runoff directly to the river. The leading drainage system network in the Banteng area is connected to sewers or channels for disposal toward the river near the study area, around the infiltration well 2/Sed/Swl/16. In some cases, sewers are required to increase drainage efficiency in urban areas (Jang et al., 2018). However, from a zero-runoff perspective, sewers for flushing runoff to the river should not be necessary. Fig. 8 shows the disposal channel (sewer) for runoff excess that flows to the river. In the previous section, it was mentioned that most of the infiltration wells are filled with sediment up to a quarter, or even a half, of their total dimensions. On average, the infiltration wells on roads are filled to a higher proportion than those in yards; however, at only 4%, the difference level is not significant (Fig. 9). Although the infiltration wells on the road are filled to a greater degree on average, the most filled well is 13/Sed/R-Swl/16, which is located in a yard in the accumulation area. In general, most of the infiltration wells in yards are only filled to 15–30%, but one of them is filled to 50%. This well is unique because it is located in the northern area, which is not in the accumulation zone, so it is different from the other highly filled wells, which are located in the accumulation area. This condition indicates that there is a source of erosion in the area near to this well. The source of erosion or sediment is presumably from anthropogenic activity, such as building construction or gardening. A study from a peri-urban area in southern Brazil has also mentioned that changes in natural conditions and land cover by anthropogenic activities can lead to accelerated erosive processes (Costa et al., 2018).

Figure 8. Channel for final runoff disposal directly to the river.

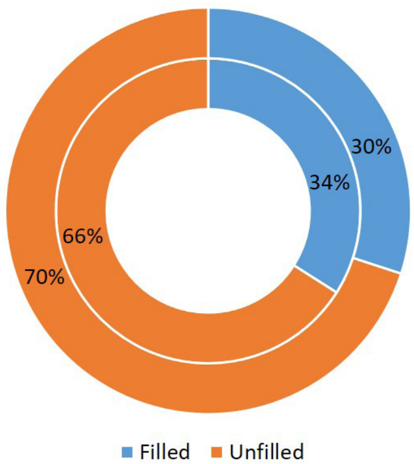

Figure 9. Comparison of the proportion of wells filled by sediment. Non-significant differences between the infiltration wells in yards (inner graph) and those on roads (outer graph).

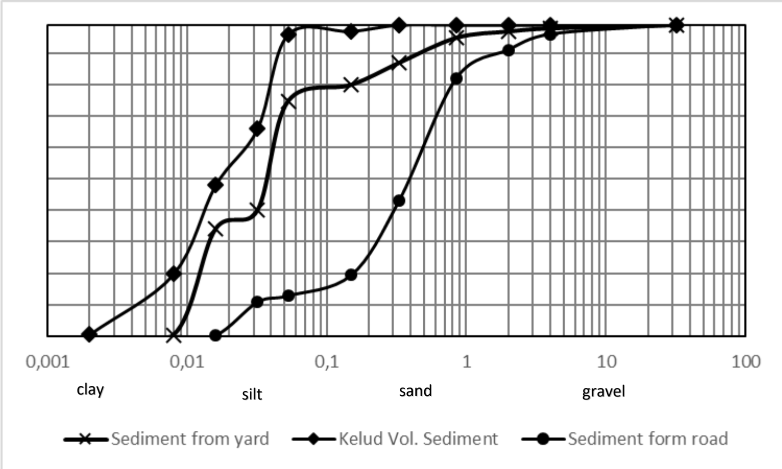

Figure 10. Comparison of cumulative size of sediment from roads and yards. Kelud volcanic ash measured for comparison with the two other sample types (particle size distribution in mm)

The infiltration wells on roads and in yards are distinct from each other in terms of grain size characteristics (Fig. 10). In yards, infiltration wells are mostly filled with silty and loamy sediment, with low proportions of sandy material. The wells on roads are also dominated by silty and sand loam material, but also contains 15–45% of sandy material. Another study on urban catchment has also shown that most of the grain sediment in such areas is dominated by silt and sand particles (Kellner & Hubbart, 2018). This is indicated in two phenomena: first, that runoff on roads is more erosive than in yards, and sediment in yards has a finer grain size; and second, that sandy material leads to infiltration wells filling up more easily due to its coarse grains and low porosity. Besides, this finding also tends to be different from the other location in urban areas. The infiltration wells in the Banteng area have collected coarser material (average: 0.1–1mm) than shown for a selected area of Christchurch (average: 0.06–0.1mm) (Charters et al., 2015).

The infiltration wells filled with sandy sediments are considered to be still able to infiltrate water because of their high permeability. In contrast, those filled with silt and loam are considered to have poor infiltration ability. Furthermore, the functioning of the wells filled with volcanic ash could be impaired. The very fine-texture of volcanic ash in infiltration can lead to sediment compaction when there is water addition from runoff since volcanic ash has high potency for uses in aggregate or lightweight concrete (Lemougna et al., 2018). This process will result in the formation of an impermeable layer inside the wells and decrease their effectiveness for groundwater recharge. Another factor that can reduce the effectivity of an infiltration well is the groundwater table rising and reaching the bottom of the well (Locatelli et al., 2017). However, we assume that the groundwater table is not affecting the infiltration wells in the Banteng area, as the groundwater table depth is >2m. Therefore, the best way to retain the efficiency of the infiltration wells is maintenance through rejuvenation, by dredging out the sediment load.

5. Conclusion

The infiltration wells in the research area form an effective system for runoff drainage; however, the urban sediment transported by the runoff could lead to problems with the infiltration wells. Most of the wells are filled up to at least 25% of their capacity by urban sediment. The sediment gathered in the wells mostly consists of loam, followed by sand, gravel, and clay. The comparison of filled and unfilled wells does not depend on the location of the wells, but the sediment grain is dependent on this factor. The sediment from roads is coarser than from yards. Fine-grained sediment in the infiltration wells, such as volcanic ash or silty sand, can cause inefficiency as it can form an impermeable layer. Because the infiltration well is old enough, it needs to be cleaned regularly or renewed, at least once every five years.

Acknowledgments

This research was funded by a research grant from Graduate School, Universitas Gadjah Mada (UGM). Thanks are also addressed to the students of UGM's Environmental Geography Department, as well as to Ms. Sri Lestari for his help in filed collecting data The authors also convey gratitude to the Laboratory of Environmental Hydrology and Climatology of the Faculty of Geography for their help in the sampling and sediment analysis.

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