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Designing of an Integrated Zero-Runoff Stormwater Management System for Surface Runoff Reduction in A Hospital Complex

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ABSTRAK

Konversi lahan berdampak pada berkurangnya luas daerah tangkapan air dan meningkatnya limpasan permukaan. Kebijakan Zero Delta Q (ZDQP) mengatur bahwa setiap bangunan harus mengelola air limpasan di dalam area bangunannya. Penelitian ini bertujuan untuk merancang dan menentukan efektivitas teknologi konsep zero runoff dalam pengelolaan air hujan untuk mengurangi debit limpasan. Studi ini menggunakan model pengembangan yang diadaptasi dari Richey & Klein (2005), yang diadaptasi menjadi kerangka kerja desain teknik untuk infrastruktur air (Mays, 2011). Metode pengembangan mencakup tiga tahap: penilaian lokasi, perancangan dan evaluasi hidrologi, serta validasi perancangan. Teknik pengumpulan data dilakukan melalui observasi, dokumentasi, dan wawancara. Observasi dilakukan untuk melengkapi data yang dibutuhkan dalam penelitian. Dokumentasi dilakukan untuk mengumpulkan data terkait penerapan teknologi konsep zero runoff. Wawancara dilakukan dengan Kepala Instalasi Pemeliharaan Fasilitas Rumah Sakit untuk mengetahui penerapan konsep zero runoff. Kesimpulan dari penelitian ini adalah hasil perancangan ulang menggunakan konsep zero runoff dengan menerapkan tangki air hujan, sumur resapan, bioretensi, dan perkerasan permeabel, yang secara teoritis dapat mengurangi limpasan sebesar 50,17%.

Keywords: aliran permukaan, bangunan rumah sakit, *zero runoff*

ABSTRACT

Land conversion impacts reducing the catchment area and increasing surface runoff. The *zero delta Q policy* (ZDQP) regulates that each building manages runoff water within the building area. This study aims to design zero runoff stormwater management system and assess their theoretical effectiveness based on the developmental research approach from Richey & Klein, (2005) that was adapted into an engineering design framework for water infrastructure (Mays, 2011). The methodology involves three technical stages: site assessment, hydrological design and evaluation, and design validation. Data collection techniques were carried out through observation, documentation, and interviews. Observations were made to complete the data needed in the study. Documentation was conducted to collect data related to *zero runoff concept technology* application. Interviews were conducted with the Head of the Hospital Facility Maintenance Installation to determine the application of the *zero-runoff concept*. The conclusion of this study is the result of the redesign using the *zero-runoff concept* by applying rainwater tanks, infiltration wells, bioretention, and *permeable pavement, which* theoretically can reduce runoff by 50.17%.

Keywords: land conversion, surface runoff, zero runoff system

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1. INTRODUCTION

Ambarini et al. (2026) stated that the rapid expansion of urban infrastructure and commercial development has led to a significant reduction in available open land. This pervasive land-use conversion poses critical environmental challenges, most notably by exacerbating surface runoff and accelerating soil erosion (Ekaputra et al., 2020). Franco et al. (2025) argue that replacing natural landscapes with by impervious surfaces such as asphalt pavements and expansive building roofs, the soil's inherent infiltration capacity is severely diminished, leading to a marked increase in stormwater runoff volumes. Recent empirical studies confirm that the expansion of impervious ratios directly increases total and peak runoff, fundamentally altering local hydrological cycles and escalating flood risks (Li et al., 2024).

In response to these hydrological disruptions, Government Regulation of the Republic of Indonesia Number 26 of 2008 concerning the National Spatial Plan established the Zero Delta Q Policy (ZDQP). The ZDQP mandates that the water balance within a developed region must be maintained at, or improved beyond, its pre-development state. Achieving this regulatory standard necessitates shifting from conventional conveyance-first drainage networks to sustainable, decentralized approaches such as Green Stormwater Infrastructure (GSI) (Tri et al., 2019; Seidu et al., 2025). GSI encompasses nature-based and engineered systems, designed to capture, store, infiltrate, and reuse stormwater directly at the source, thereby mitigating downstream flooding and improving urban water resilience (Fakhrudin, 2015; Franco et al., 2025; Lemieux et al., 2023; Ou et al., 2023).

Various GSI technologies can be adapted to manage runoff in urban spaces, including rainwater tanks (Khastagir & Jayasuriya, 2010), infiltration wells (Zhiqiang et al., 2021), conservation ponds (Hilla et al., 2021), rain gardens (Kasprzyk et al., 2022), rainwater catchment channels (Shadeed & Lange, 2010), permeable pavements (Zhu et al., 2021), integrated green stormwater infrastructures (Lemieux et al., 2023), and bioretention facilities (Yu et al., 2023). Furthermore, Seidu et al. (2025) emphasize that achieving multifunctionality in these infrastructure projects is increasingly recognized as a vital driver for their successful implementation and sustainability in developing regions.

Quantitative assessments strongly underscore the efficacy of these zero-runoff GSI technologies. For instance, Ardiyana et al. (2016) demonstrated that the implementation of infiltration wells and permeable pavements significantly reduced runoff discharge by 23.41% and 14.02%, respectively, while specific bioretention applications yielded a 0.1% reduction in certain contexts. More remarkably, an integrated system of rainwater tanks, infiltration wells, and rain gardens deployed in a residential area in Bali demonstrated the capacity to reduce stormwater runoff by 96.6% of the total calculated land discharge (Lestari, 2016).

Although there is extensive documentation on zero-runoff GSI technology, the current literature reveals a critical research gap regarding its implementation. First, previous studies have largely focused on residential watersheds, urban open spaces, or city-scale planning (e.g., Lestari, 2016; Ou et al., 2023), and thus fail to address the complex operational challenges, high imperviousness ratios, and strict spatial constraints that characterize high-density institutional and critical public facilities. Second, although individual technologies have been extensively studied, there is a significant lack of research on how these systems can be optimized simultaneously within an integrated design framework specifically tailored to hospital complexes, environments where uninterrupted public services, strict sanitation standards, and severe land constraints limit the implementation of conventional green open-space infrastructure.

To address these missing gaps, this study investigates the hydrological impacts of implementing an advanced zero-runoff conceptual design within a hospital complex. As critical public infrastructure, healthcare facilities have a profound responsibility to adopt environmentally sustainable practices. Evaluating the efficacy of zero-runoff systems in this specific setting will elucidate, the potential for runoff mitigation ultimately providing an adaptable framework for sustainable stormwater management that can be adopted by similar institutional buildings.

2. METHODOLOGY

2.1. Research Sites

The study was conducted in a hospital in mid-Indonesia, a tropical country. Geographically, the hospital building is located between 110° 57' 33.70'' and 110° 42' 6.79'' East Longitude and 7° 32' 17.00'' and 7° 49' 32.00'' South Latitude. The results of the soil permeability test at the site showed that the Permeability coefficient was 1.297×10^{-4} cm/s, indicating that the soil is coarse sand (Wang et al., 2021).

The hospital building is divided into three buildings. Building A is the main building, which has seven floors and Emergency Installation and Laboratory facilities. Building B, which functions as Medical Education and Research (MERC), has three floors, while building C has a Power House, Ground Water Tank (GWT), and Pump Room. This hospital stands over 3 hectares with the percentage breakdown of land cover types is presented in Table 1. The open area consists mainly of vacant land behind the hospital, which is earmarked for future hospital expansion.

Table 1. Land Cover Types

Land Cover Type	Area	Persentage
Main Building	5,389.349 m^2	18%
MERC Building	570.206 m^2	2%
Mosque Building	328.986 m^2	1%
Paving	895.755m^2 m^2	3%
Asphalt	5,530.376 m^2	18%
Section C Buildings	421.320 m^2	1%
Open area	17,495 m^2	57%
Total	30,631,117 m^2	100%

The GSI technologies already in place at the research site include a rainwater collector that captures 12.96% of runoff and permeable pavement that absorbs 0.07% of runoff.

2.2. Research Stages

This research initially adopted the generic developmental research framework proposed by Richey & Klein (2005), which consists of planning and product development, product evaluation, and product validation. However, to ensure the methodology aligns robustly with civil and environmental engineering practices, the implementation of these developmental stages was adapted and renamed to correspond with the water resources engineering design framework (Mays, 2011). While the fundamental logic of developmental research remains, the stages applied in this study are specifically translated into three engineering-focused phases, as shown in Figure 1: Site Assessment (adapting the *planning and product development* stage): this involves collecting required data, testing the consistency of rain data, analysing rainfall intensity and runoff discharge; Hydrological Design and Evaluation (adapting the *product evaluation* stage): this encompasses the engineering sizing of zero-runoff technologies, and evaluating the theoretical reduction in runoff discharge against national standards; Design Validation (adapting the *product validation* stage): this involves rigorous validation of the proposed engineering design by water resources and environmental experts using the Delphi method to ensure technical feasibility.

2.3. Site Assessment Stage

The design and development stage involves several data, namely: rainfall data between 2010-2019 from four rain stations around the site, topographic maps to determine the elevation of the land, site plan in the form of detailed engineering design, groundwater level data, and soil permeability coefficient from laboratory test results.

The rainfall data needs to be tested for consistency before being used in analysis. The consistency test in this study uses the Rescaled Adjusted Partial Sums (RAPS) method. The data can be considered consistent if the calculated Q < critical Q for a certain amount of data and a certain level of confidence as shown in Table 2. A consistency test can be done using the following equation (Kamiana, 2011):

$$Sk^* = \sum_{i=1}^{k}(\text{Yi-}\overline{\text{Y}})$$

$$\overline{\text{Y}} = \frac{\sum \text{Yi}}{\text{N}}$$

$$Sk^{**} = \frac{\text{Sk*}}{\text{Dy}}$$

$$\text{Dy2} = \sum_{i=1}^{N}\frac{(\text{Yi-}\overline{\text{Y}})^2}{\text{N}}$$

$$Q = \left|\text{Sk}^{**}\right|\text{maks}$$

with:

Sk * : Cumulative Value of Deviation from the Average Value
Yi : i-th Rain Data
$\overline{\text{Y}}$: Average Rain Data
N : Number of Data
Sk ** : RAPS Value
Dy = Standard Deviation

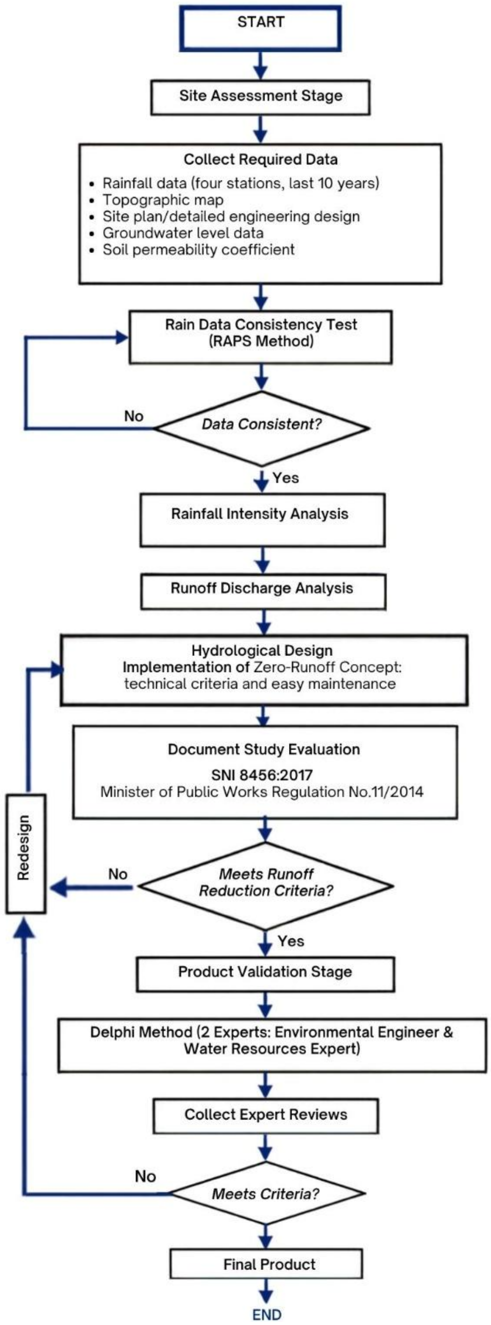

Figure 1. Research Stages

Table 2. Critical Q (Kamiana, 2011)

N	Critical Q / √N		
	90%	95%	99%
10	1.05	1.14	1.24
20	1.10	1.22	1.42
30	1.12	1.24	1.46
40	1.13	1.26	1.50
50	1.14	1.27	152
100	1.17	1.29	1.55
≈	1.22	1.36	1.63

Rain intensity is the volume of rain that occurs per unit of time (Nurhapni & Burhanudin, 2011). The amount of rainfall intensity is influenced by the concentration-time (tc) of the runoff flow in the area. The intensity of rainfall can be calculated using the Monobe formula (Kamiana, 2011):

$$I = \frac{R24}{24} \times (24/\text{tc})^{2/3}$$

with;
I : Rain Intensity (mm/hour)
R 24 : Daily Rainfall (mm)
tc : Time of Concentration (hours)

Runoff discharge is when the rainwater that falls on a catchment area exceeds the infiltration capacity of the area. The infiltration capacity that has been fulfilled will then drain the water into the basins on the ground surface (Frans & Nesimnasi, 2020). Because the total catchment area of the hospital is relatively small (< 50 Ha), the Rational Method is highly suitable and widely accepted as a standard approach for preliminary institutional drainage sizing. The runoff discharge can be calculated using the following equation (Kamiana, 2011):

$$Q = 0.002778 \times C \times I \times A$$

with:
Q : Runoff discharge (m^3 /second)
C : Runoff coefficient (according to standard)
I : Rain intensity (mm/hour)
A : Area of drainage (Ha)

2.4. Hydrological Design and Evaluation Stage

The product evaluation stage assesses the technical performance and regulatory compliance of the proposed Zero-Runoff Green Stormwater Infrastructure (GSI) design. In alignment with the Zero Delta Q Policy (ZDQP) mandated by Government Regulation No. 26 of 2008, the "zero runoff" objective in this study is evaluated based on a combination of peak discharge reduction (Q_{red}) and runoff volume retention (V_{ret}).

2.4.1. Rationale for Technology Selection and Optimization

Before sizing, the specific GSI technologies were selected based on the stringent spatial constraints of the hospital environment. Traditional large-scale surface retention ponds are unfeasible due to land scarcity. Therefore, the design was optimized prioritizing decentralized, land-efficient systems. Rainwater Tanks (RWT) was selected to leverage the massive existing rooftop catchment area without consuming ground space, optimizing non-potable water reuse. Infiltration Wells was selected for their vertical subsurface optimization, bypassing highly compacted topsoil to directly inject runoff into deeper permeable layers, bounded only by structural safety distances from building foundations. While, bioretention & Permeable Pavement was selected for the remaining available open spaces and light-duty parking areas, respectively, providing dual functions of pollutant filtration and aesthetic landscaping, optimized for areas away from heavy ambulance traffic.

2.4.2. Evaluation Parameters and Quantitative Targets

Peak Discharge Reduction (Q_{red}): Assesses the mitigation of peak surface runoff discharge exiting the hospital complex. The quantitative target is to attenuate peak flow toward pre-development levels (Q_{post_GSI} to Q_{pre}).

Runoff Volume Retention (V_{ret}): Measures the total volumetric storage and infiltration capacity provided by the integrated GSI system. The target is to capture and retain the incremental runoff volume generated by site development ($\Delta V = V_{post} - V_{pre}$) within the property boundary.

2.4.3. Calculation Procedure

The total volumetric retention capacity (V_{total}) is calculated as the combined sum of all integrated GSI facilities:

$$V_{total} = V_{RWT} + V_{wells} + V_{bioretention} + V_{permeable}$$

with:
Rainwater Tanks (V_{RWT}*):* Cumulative storage volume of installed holding tanks.
Infiltration Wells (V_{wells}*):* Calculated based on structural storage and soil infiltration rate:

$$V_{wells} = N\left(\frac{\pi}{4}d^2h + A_{side}.k.t\right)$$

where N is the number of wells, *d* is inner diameter, *h* is effective depth, *k* is soil permeability coefficient (cm/s), and *t* is infiltration duration.
Bioretention & Permeable Pavements (V_{bio}, V_{perm}*):* Calculated from media porosity (n), layer thickness (d_m), and surface ponding depth (d_p).

The net percentage reduction in peak surface discharge achieved by the proposed GSI layout is calculated using

$$Q_{reduction}(\%) = \frac{Q_{existing} - Q_{post-GSI}}{Q_{existing}} 100\%$$

2.4.4. Standard and Regulatory Compliance Verification

The physical dimensions, infiltration rates, and storage volumes determined during the calculation procedure are cross-checked against standard technical specifications in:

1. SNI 8456:2017 (Indonesian National Standard for Rainwater Infiltration Wells and Trenches) for minimum infiltration dimensions and soil permeability requirements.
2. Regulation of the Minister of Public Works No. 11/PRT/M/2014 regarding Rainwater Management in Buildings and Land.
3. Published empirical GSI performance studies to verify structural feasibility under high-density site constraints.

2.5. Product Validation Stage

To demonstrate the efficacy of the proposed Zero-Runoff Green Stormwater Infrastructure (GSI) design, the validation stage integrates a quantitative hydrological comparison of pre- and post-implementation conditions with a structured expert validation using the Delphi method

2.5.1. Quantitative Hydrological Comparative Assessment

The quantitative validation compares pre-development baseline conditions and post-GSI mitigated conditions across three primary hydrological metrics:

Peak Discharge Attenuation (ΔQ):

Evaluates peak surface runoff existing the hospital complex before development ($Q_{existing}$) and after GSI implementation (Q_{post_GSI}):

$$\Delta Q = Q_{\text{existing}} - Q_{\text{post\_GSI}}$$

Volumetric Runoff Reduction ($V_{reduction}$):

Calculates net volume retained and infiltrated on-site (V_{RWT} + V_{wells} + $V_{bioretention}$ + $V_{permeable}$) relative to total generated runoff volume.

2.5.2. Expert Delphi Validation Framework

Following quantitative calculation, the technical feasibility and empirical performance of the proposed design were evaluated using the Delphi validation method involving two domain experts: an environmental engineer (focusing on sanitary, maintenance, and spatial integration within healthcare settings) and a water resources engineer (focusing on hydrological modeling accuracy, structural sizing, and ZDQP regulatory compliance).

The experts evaluated the design across two iterative rounds based on four core criteria:

1. Quantitative Target Achievement: Sufficiency of $Q_{reduction}$ to meet Zero Delta Q Policy (ZDQP) standards.
2. Engineering & Structural Viability: Adequacy of storage volumes, soil infiltration rates (k), and overflow provisions.
3. Hospital Site Compatibility: Spatial feasibility, safety, and non-interference with healthcare operations and sanitary protocols.
4. Maintenance & Operational Resilience: Long-term functionality, clogging prevention, and ease of maintenance.

Consensus was established when evaluation scores reached a minimum threshold of 80% agreement across all criteria.

3. RESULT

3.1. Rain Data Consistency Test

The results of the rain data consistency test using Rescaled Adjusted Partial Sums (RAPS) are shown in Table 3, and the value of $Q/\sqrt{n}$< probability value is obtained. These results show that the rain data from the four stations are all consistent.

Analytically, the $Q/\sqrt{n}$ values obtained for all four stations (0.53–0.65) fall well below the critical threshold of 1.05, indicating that none of the records contain significant inhomogeneities such as station relocation, instrument change, or observation error. This result is important beyond simply confirming data quality: it justifies pooling the four stations to derive the design rainfall depth (R24) used in Section 3.2 without first having to correct or discard any series, so that the resulting rainfall intensity and, subsequently, the runoff discharge in Sections 3.2 and 3.3 can be considered representative of the actual hydrological condition of the catchment rather than an artefact of inconsistent measurement.

Table 3. Rain Data Consistency Test

Num	Station	$Q/\sqrt{n}$	Probability Value	Result
1	A	0.56	1.05	Consistent
2	B	0.65	1.05	Consistent
3	C	0.53	1.05	Consistent
4	D	0.56	1.05	Consistent

3.2. Rainfall Intensity Analysis

The process of adding zero runoff technology to the design of the hospital area needs to pay attention to the results of the hydrological analysis. The results of this analysis aimed to determine the intensity of rain that occurs in the area. Calculation of rainfall intensity can use the formula below:

$$I = \frac{\text{R24}}{24} \times (24/\text{tc})^{2/3}$$

$$I = \frac{102.638}{24} \times \left(\frac{24}{4}\right)^{\frac{2}{3}}$$

$$I = 15.321\text{mm/hour}$$

The calculation results of the planned rainfall intensity are 15.321 mm/hour. The results of this analysis are further used to calculate runoff in the hospital area.

The intensity equation shows that I is inversely proportional to tc raised to the power of 2/3, so the moderate concentration time (tc = 4 hours) estimated for this catchment already tempers the peak intensity relative to a faster-draining site, yet the resulting design intensity of 15.321 mm/hour is still high enough, sustained over several hours, to generate a meaningful volume of runoff from the largely paved hospital area. Practically, this means the design has to attenuate a sustained rather than momentary rainfall input, which is why the zero-runoff design developed in Section 3.4 relies on storage-based measures (infiltration wells, bioretention, and rainwater tanks) capable of holding water over the duration of the storm rather than a single fast-draining component alone.

3.3. Runoff Discharge Calculation

The amount of runoff that occurs in the hospital area needs to be known for further design development using zero runoff technology that allows it to be used in the area. The calculation of runoff discharge is as follows:

$$Q = 0.002778 \times C \times I \times A$$

$$Q = 0.002778 \times 0.411 \times 15.321 \times 3.0631$$

$$= 0.0536\, m^3/s$$

The runoff value will be the basis for implementing zero runoff technology in hospital redesign.

The runoff coefficient used in the calculation (C = 0.411) reflects the mixed land cover of the hospital site, combining impervious roofs and pavement with the remaining green area; a value closer to 1.0 would indicate a fully paved catchment, while the moderate value obtained here shows that part of the site still has infiltration capacity that the zero-runoff design can be built upon. The resulting discharge of 0.0536 m^3/s represents the volume of water that would leave the site uncontrolled under existing conditions; because Indonesian zero-runoff regulations require this discharge to be attenuated on-site rather than passed to the surrounding drainage network, this value becomes the design target that the combination of infiltration wells, bioretention, and rainwater tanks in Section 3.4 must be sized to offset.

3.4. Hospital Area Planning and Development by Implementing Zero Runoff Technology

Zero runoff concept technology to reduce runoff considers existing land's availability. The availability of land in the hospital area is in the front area of the main building (section A) and the side area of the main building (section A), which can be planned for additional bioretention. The MERC building area (section B) and the mosque building area can also be used to add a Rainwater Tank to accommodate rainwater that falls on the roof of the building. The added zero runoff concept technology is infiltration wells, bioretention, and rainwater tanks. The planning scheme can be seen in Figure 2. The selection of zero runoff concept technologies (ZRO) is based on technical criteria and pays attention to easy maintenance. The selection of selected ZRO technologies can be seen in Table 4.

Table 4. ZRO Technology Selection

No	ZRO Technology	Runoff water retention type	Reason
1	Infiltration wells	Storage and impregnation types	Can accommodate significant surface runoff Quite flexible placement
2	Bioretention	Storage type and impregnation type	Functions as a component of the regional landscape It can be combined with absorption holes or infiltration wells
3	Rainwater Tank	Storage type	Easy manufacture and maintenance The stored water can be used.

Table 4 shows that the three technologies were deliberately selected to complement rather than duplicate one another: infiltration wells and bioretention both provide storage together with impregnation into the soil, whereas the rainwater tank relies on storage only. This distinction is analytically significant because it determines where each technology is effective—infiltration wells and bioretention reduce runoff by returning water to the ground and are therefore placed where land and soil conditions allow, while the rainwater tank does not depend on soil infiltration and can instead be placed under roofed structures such as the MERC and mosque buildings where open land for infiltration is unavailable. Combining the three therefore allows the design to address both the land-limited and roof-dominated parts of the site, rather than relying on a single retention mechanism that could only be applied partially across the hospital area.

3.4.1. Infiltration Wells

Infiltration wells were used because the depth of the groundwater table at the study site was 5.8 m. The requirements of Indonesian standard (SNI 8456:2017) state that infiltration wells can be used if the groundwater depth is more than 2 m. Rainwater infiltration wells planned to be applied in the hospital area are uniform with type III. Type III is a rainwater infiltration well with a concrete block wall. The diameter of the infiltration well is 1 meter with a depth of 3 meters. The planned infiltration wells are 55 units. The location of infiltration well placement is planned in the area with the lowest elevation while considering the criteria for distance to other buildings/objects. The details of the infiltration well can be seen in Figure 3.

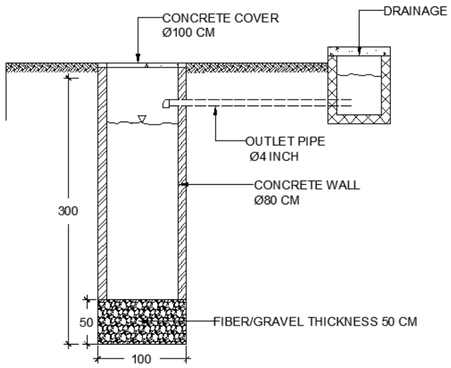

Figure 3. Infiltration Wells Details

Sizing the infiltration wells at a 1 m diameter and 3 m depth, well within the 5.8 m groundwater depth measured on site, keeps the base of each well safely above the water table as required by SNI 8456:2017, so infiltration is not impeded by saturated soil; placing the 55 units at the lowest-elevation points of the site further ensures that runoff is intercepted by gravity flow before it can leave the area, which is consistent with this technology contributing the largest single share of the runoff reduction achieved in Section 3.5.

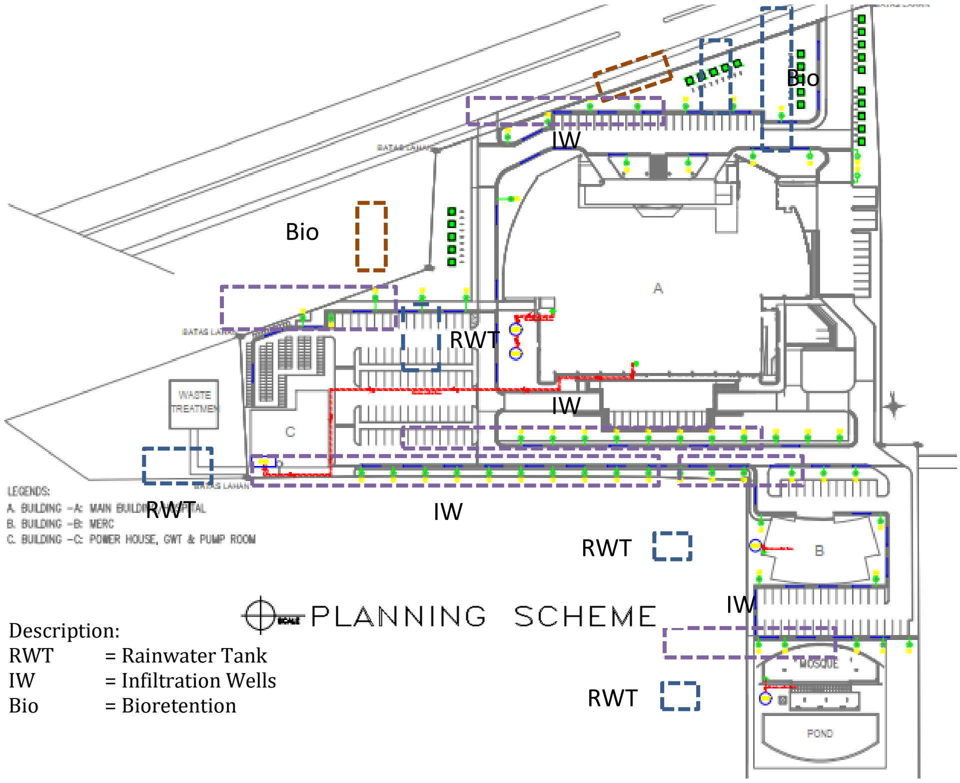

Figure 2. Zero Runoff Concept Technology Planning Scheme

3.4.2. Bioretention

Bioretention implemented in the hospital area will have the same structure and dimensions, measuring 2 m x 2 m x 1 m. Cover crops used are plants that live in waterfront areas. The planting media uses humus soil with a layer of soil thickness of 70 cm. The sand layer for filtering media is 10 cm thick. The sand used is silica sand. The last layer is a layer of gravel with a thickness of 20 cm. The number of bioretention implemented is 20 units. The location of the bioretention placement is in a green open area to reduce runoff and add to the *landscape*'s beauty. Details of bioretention can be seen in Figure 4.

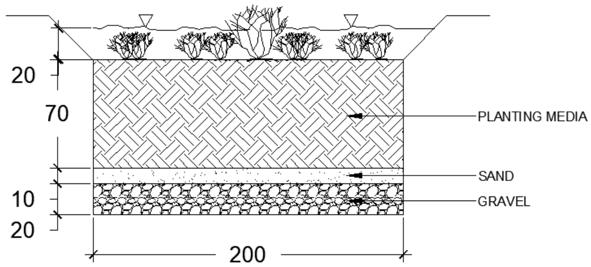

Figure 4. Bioretention Details

Each bioretention cell has a design volume of 2 m × 2 m × 1 m (4 m^3), giving the 20 planned units a combined design volume of roughly 80 m^3; because this volume is layered with humus soil, sand, and gravel rather than left as open storage, its function is primarily to slow and filter runoff as it infiltrates rather than to hold a large free volume of water, which is consistent with its comparatively modest 12.97% share of the total runoff reduction reported in Table 5 relative to the infiltration wells.

3.4.3. Rainwater Tank (RWT)

The rainwater tank mechanisms are (1) rainwater falling on the roof of the building will be channelled through the *floor drain* to the gutter, (2) the gutter will then be channelled to filtration to filter rainwater from dirt, (3) filtered rainwater will be channelled into the gutter. RWT tendons use pipes, and (4) rainwater that has been collected can be distributed using pipes for purposes such as watering plants or *hydrants*. The RWT mechanism can be seen in Figure 5.

Rainwater tank designed in the simulation in this research devided into two categories. The first one is groundwater tank with capacity 3900 liters. Two units of this tank placed in building A. Second, two units of groundwater tanks with a capacity of 2000 liters are placed in building B.

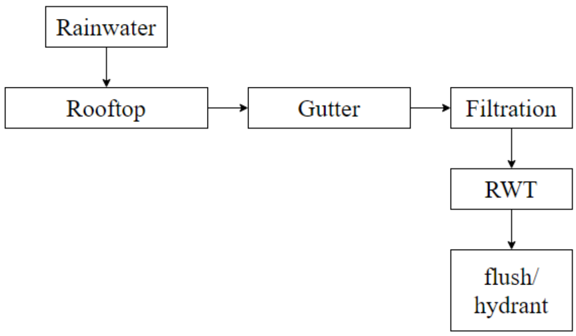

Figure 5. RWT Mechanism

Table 5. Zero-Runoff Reduction Recapitulation of the Developed Technology

ZRO Technology	Existing		Re-Design development		The result		
	Quantity /area	Infiltration discharge (m^3/s)	Quantity/ area	Infiltration discharge (m^3/s)	Number/area	Infiltration discharge (m^3/s)	%
Rainwater Tank (RWT)	1 unit	0.0069	4 units	0,000819	5 unit	0,0078	14,49
Infiltration wells	-	-	55 units	0,0121	55 unit	0,0121	22, 64
Bioretention	-	-	25	0,0069	25	0,0069	12,97
Permeable pavement	1105,113 m^2	3.6583 x 10 -5	-	-	1105,113 m^2	3,6583 x 10-5	0,07

The four planned rainwater tanks together provide about 11.8 m^3 of storage (two 3,900-litre units on building A and two 2,000-litre units on building B); because this capacity is fixed by tank volume rather than by the surrounding soil, the RWT contribution to runoff reduction depends mainly on how frequently the tanks are emptied between storms, which is a practical limitation the infiltration-based measures do not share.

3.5. Runoff Discharge Reduction After Application of Zero Runoff Technology

After determining the zero-runoff technology that can be added to the redesign of the hospital area, then analyzing the runoff reduction after the addition of the application of zero runoff technology, the results of the recapitulation of runoff reduction after the addition of the application of zero runoff technology can be seen in Table 5.

The results of redesigning the hospital area obtained the application of zero runoff technology in the form of rainwater tanks, infiltration wells, and bioretention generate the runoff reduction of 50.17%. Ranking the contributions in Table 5 shows that infiltration wells account for the largest share of the reduction (22.64%), followed by the rainwater tanks (14.49%) and bioretention (12.97%), while the retrofitted permeable pavement contributes only marginally (0.07%). This pattern is analytically consistent with the design logic developed in Section 3.4: infiltration wells were both the most numerous measure (55 units) and the only one placed directly at the lowest, most hydrologically active points of the site, so they intercept the largest volume of runoff, whereas the permeable pavement's contribution is limited because it was already part of the existing condition and no additional area could be converted to it in the redesign. Combined, the three added technologies bring the site from an uncontrolled discharge of 0.0536 m^3/s down by 50.17%, which indicates that the zero-runoff concept meaningfully mitigates, though does not entirely eliminate, surface runoff from the hospital area; achieving full elimination would require either enlarging the infiltration well network beyond the current 55 units or converting additional impervious surfaces to permeable pavement, both of which are constrained here by the limited open land available on site. These results also suggest that the design's overall performance depends most heavily on the continued function of the infiltration wells, so long-term maintenance of these wells against sediment clogging is likely to be the most critical factor in sustaining the 50.17% reduction achieved in this study.

4. DISCUSSION

Building planning using the zero-runoff concept is a plan that requires the designed building to reduce runoff water discharge to the disposal system aligning with the Zero Delta Q Policy (ZDQP) (Indonesia, 2008). The planning step begins with calculating runoff in the hospital area and then designing integrated GSI to mitigate the generated runoff (Tri et al., 2019). Based on the quantitative hydrological analysis results, the existing unmitigated peak discharge (Qexisting) in the hospital environment is 0.0536 m3/sec. When rainfall and irrigation water exceed the infiltration capacity of the heavily compacted hospital soil, surface runoff increases, rapidly flowing into the open water system and escalating urban flood risks (Zhu et al., 2019; Heinen et al., 2022). As recently highlighted by Sabut et al. (2026), this disruption of the natural hydrological cycle in urbanized areas is further amplified by climate change-induced intense rainfall events, making the strategic integration of Stormwater Control Measures (SCMs) essential for restoring natural hydrological responses and mitigating pluvial flooding.

By redesigning the hospital area with an integrated combination of infiltration wells, rainwater tanks (RWT), permeable pavements, and bioretention, this study achieved a theoretical peak discharge reduction of 50.17%, lowering the post-development discharge (Qpost_GSI) to 0.0267 m3/s. This 50.17% peak reduction aligns well with global empirical syntheses of GSI performance. A global meta-analysis by Huq et al. (2026) established that decentralized Low Impact Development (LID), another term for GSI, strategies reduce peak runoff by an average of 42% (ranging from 15% to 75%) globally, with a specific mean reduction of 39% (95% CI: 32%–46%) across tropical climate zones. While this significant reduction successfully increases on-site storage capacity and temporary retention, achieving absolute pre-development conditions (complete zero runoff) remains highly challenging due to the massive impervious footprint of the hospital. Therefore, the implication of these findings suggests that in high-density institutional settings, the zero-runoff paradigm functions practically as a strategy for maximum feasible peak flow attenuation and volume retention rather than absolute zero discharge (Yasa et al., 2020).

While traditional GSI like large retention ponds suits sprawling environments, dense hospital complexes require a fundamentally different approach. The implementation of surface-oriented nature-based solutions is limited primarily by severe spatial and institutional constraints rather than technical design (Sun et al., 2026). In hospitals, land use is fiercely contested by critical infrastructure and emergency access, while overlapping health regulations complicate facility management. Therefore, decentralized zero-runoff GSI systems are a practical necessity—not just a technical preference—to bypass the spatial and governance deadlocks associated with conventional large-scale ponding (Sun et al., 2026).

4.1. Infiltration Well

Infiltration well were selected as a primary zero-runoff technology because they efficiently utilize vertical subsurface space, making them highly effective for reducing runoff in land-scarce areas. In this study, the infiltration wells have contribution in reducing runoff by 22.64% of the total runoff. This dominant contribution is due to their ability to bypass compacted surface soils and directly inject runoff into deeper soil layers with higher permeability coefficients, which is highly consistent with the site-specific hydrological conditions of the hospital area. Previous studies similarly emphasize that infiltration wells offer significantly higher efficiency for high-volume rapid absorption than surface-level permeable pavements (Zhiqiang et al., 2021) and are highly effective for groundwater conservation (Wahyuningtyas et al., 2011). As emphasized by Huq et al. (2026), subsurface-oriented infiltration techniques are vital in urbanizing catchments because they directly restore natural infiltration pathways disrupted by extensive surface sealing. However, while they provided the highest reduction, their deployment was restricted. The mandatory structural safety distances between the wells and critical hospital building foundations strictly limited the total number of units that could be installed, preventing even higher reduction rates comparable to residential studies (Kuala, 2017; Elokpere et al., 2022).

4.2. Bioretention

Bioretention is part of a zero-runoff GSI technology that can be applied to reduce runoff. This bioretention filters and absorbs rainwater that falls to the ground into the bioretention media (Sadewa et al., 2019). Bioretention designed in this study contributes to a reduction in runoff of up to 12.97%. The performance of a bioretention system is directly related to its design parameters: the surface area, the storage depth for ponding, and the specific composition of the filtration media. The designed bioretention has several layers; the top layer is a cover crop that catches rainwater runoff. The second layer is the planting medium in the form of humus soil that can provide water and keep plants growing. The third layer is sand, which filters water from the substances it carries. The use of silica sand in the bioretention layer is intended because silica sand is very often used for water filtration (Sadewa et al., 2019). The last layer consists of stone or gravel. The last layer consists of stone or gravel. This configuration is particularly vital in hospital environments where surface runoff may carry higher concentrations of complex urban pollutants. This aligns with findings synthesized by Sabut et al. (2026), which confirm that SCMs like bioretention cells are highly effective in removing up to 90% of pollutants, underscoring their critical role in improving urban water quality alongside runoff volume reduction.

However, the 12.97% reduction is lower than the 26.89% to 26.93% reduction reported in previous studies (Andajani & Hidayat, 2019). This variance is primarily caused by strict spatial constraints. Optimal bioretention requires expansive surface areas to maximize volume capture. In the hospital complex, available green open space is severely limited by critical infrastructure, paved access routes, and emergency zones, which inherently constrained the maximum allowable surface area and storage depth of the bioretention basins, thus limiting their total volumetric contribution.

Furthermore, the performance of soil-based infiltration systems, such as bioretention, is heavily reliant on the structural integrity and organic composition of the underlying soil matrix. Recent findings by Prajith et al. (2026) in the *Journal of Hydrologic Engineering* demonstrate that undisturbed, organically rich forested soils maintain significantly higher infiltration reliability and resilience against surface flow generation compared to degraded or deforested soils. Their application of the Green-Ampt infiltration model highlighted that soils with robust organic matter and root structures exhibit near-zero runoff probability during low-to-moderate rainfall events. Within the context of this study, the heavy soil compaction resulting from construction activities in the hospital area significantly limits natural infiltration capacity. This underscores the critical necessity of engineered bioretention media—specifically the incorporation of humus and silica sand—to artificially restore the high-permeability and retention characteristics typically observed in undisturbed natural environments (Prajith et al., 2026).

4.3. Rainwater Tank

Rainwater Tanks (RWT) are highly advantageous in constrained hospital sites because they directly utilize the massive existing roof catchment area without consuming additional ground space. Data from the Central Bureau of Statistics of Indonesia (2021) shows that the most significant rainfall in the research site reached 463 mm in November. The RWT simulated in this study was able to reduce runoff by 14.49%. This reduction is a direct function of the relationship between the expansive roof catchment area and the calculated tank capacity. While the proposed tank capacity is sufficient for average and moderate storm events, peak rainfall scenarios (like the November maximum) necessitate robust overflow management, where excess volume is safely routed to the municipal drainage or adjacent infiltration wells to prevent structural failure. Beyond runoff mitigation, the captured water presents significant reuse potential as part of a holistic zero-runoff strategy. RWT implementation reduces reliance on municipal groundwater extraction (Lestari, 2016), as the stored runoff can be utilized to meet the hospital's high daily non-potable water demands, such as landscape irrigation, toilet flushing, and maintenance washing (Khastagir & Jayasuriya, 2010).

4.4. Permeable Pavement

Permeable pavement is a sustainable urban drainage system used to infiltrate and absorb rainwater runoff to minimize runoff volume. The permeable pavement simulated in this research contributed a marginal runoff reduction of only 0.07%. While previous research proves that replacing standard asphalt with permeable pavement significantly reduces surface runoff and filters automotive pollutants (Bean et al., 2007), its contribution in this specific redesign is exceptionally low due to severe site constraints and limited implementation area. Due to the structural limitations of porous pavement materials, they cannot withstand the heavy, high-frequency loads of ambulances, supply trucks, and operational healthcare vehicles. Consequently, its deployment was strictly confined to small, light-duty staff parking areas (Boogaard et al., 2014). Furthermore, the heavily compacted subgrade beneath the existing hospital parking lots restricts the underlying soil infiltration capacity, preventing the pavement from achieving the high-volume reductions observed in broader urban or residential applications.

4.5. Limitations and Future Directions

While the proposed design successfully demonstrates a 50.17% reduction in runoff, this study relies on the Rational Method for baseline discharge estimation. While effective for preliminary sizing, this static method cannot fully capture the dynamic temporal routing of storm events. Additionally, as noted by Sabut et al. (2026), existing design approaches often ignore future rainfall variability driven by climate change. To strengthen the scientific evaluation of these zero-runoff concepts, future research should integrate advanced continuous hydrological simulation models, such as the Storm Water Management Model (SWMM) or HEC-HMS, and consider future climate scenarios to ensure long-term resilience (Sabut et al., 2026). Furthermore, in-situ field monitoring of the installed infrastructure is highly recommended to empirically validate these theoretical reduction percentages under operational hospital conditions.

5. CONCLUSION

The simulation of implementing an integrated zero-runoff concept within a constrained hospital area successfully reduced the existing surface runoff by 50.17%, lowering the peak discharge from 0.0536 m^3/s to 0.0268 m^3/s. This reduction was achieved through the site-specific application of infiltration wells (22.64% reduction), rainwater tanks (14.49%), bioretention (12.97%), and permeable pavements (0.07%). Regarding the Zero Delta Q Policy (ZDQP), while fully maintaining post-development runoff at or below absolute pre-development conditions is highly challenging due to the massive impervious footprint of the healthcare facility, the proposed design successfully maximizes on-site retention. It significantly attenuates post-development runoff, bringing the discharge levels substantially closer to pre-development baselines and fulfilling the regulatory intent of mitigating excess overflow into municipal drainage systems.

Beyond the numerical reduction, the primary scientific contribution of this study is an evidence-based framework for sustainable stormwater management tailored to hospital areas rather than a generic application of green infrastructure. Two implications follow from the results. First, the technology-by-technology breakdown shows that runoff mitigation performance in land-constrained institutional sites is driven disproportionately by infiltration-based measures over storage-only measures: infiltration wells alone contributed nearly as much reduction as the other three technologies combined, suggesting that future zero-runoff designs for similarly dense sites should prioritize available groundwater-compatible land for infiltration before allocating remaining area to bioretention or permeable pavement. Second, the study demonstrates that a combined consistency-testing, intensity-analysis, and technology-sizing methodology can be transferred to other high-density, highly regulated institutional environments, offering a replicable procedure rather than a site-specific result alone.

These findings also point to several directions for future research. The present results are derived from simulation and design-storm calculations rather than field-measured performance; longitudinal monitoring of the constructed system under actual rainfall events is needed to validate the simulated 50.17% reduction and to assess how infiltration well performance degrades over time due to sediment clogging, which this study identifies as the most likely factor limiting long-term effectiveness. Future work should also evaluate system performance under storm events exceeding the design return period, incorporate projected rainfall intensity shifts under climate change scenarios, and assess the water-quality treatment function of bioretention and rainwater harvesting components alongside their quantity-reduction role. Finally, a lifecycle cost-benefit comparison across the four technologies would help translate the relative-effectiveness ranking identified here into practical guidance for other hospitals and public facilities considering similar retrofits, and comparative studies across facilities with different imperviousness ratios would help determine how transferable the infiltration-well-dominant strategy found here actually is.

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