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Integrated sustainable drainage and water conservation strategy for cost-effective pluvial flood mitigation in Comoro, Dili, Timor-Leste

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ABSTRACT

Rapid urbanization, land-use conversion, and reduced infiltration capacity have intensified pluvial flooding in many tropical cities, particularly in developing regions with inadequate drainage infrastructure. This study evaluates an integrated sustainable drainage and water conservation strategy for cost-effective pluvial flood mitigation in the Kampung Baru residential area and Nicolao Lobato Roundabout, Comoro, Dili, Timor-Leste. The methodology combines field drainage surveys, Digital Elevation Model processing, watershed delineation using ArcGIS and SWAT, rainfall frequency analysis, runoff estimation, domestic wastewater discharge calculation, population projection until 2030, drainage capacity evaluation, injection well planning, and cost analysis. Design runoff was estimated for return periods of 1, 2, 5, 10, and 25 years, while existing channel capacity was evaluated using Manning's equation. The results indicate that the existing drainage system is insufficient to convey design discharge, causing recurrent inundation depths of approximately 70–80 cm with recession times of 4–6 hours during heavy rainfall events. Drainage rehabilitation alone was insufficient to fully control inundation; therefore, an integrated mitigation strategy consisting of existing channel enlargement, 18 new drainage channels, and four injection wells was proposed. The injection wells were designed to increase infiltration and support urban water conservation. The estimated implementation cost was USD 1,941,051.69 for drainage rehabilitation and new channel construction, and USD 30,701.43 for injection well development. This study highlights the importance of combining conventional drainage improvement, groundwater recharge infrastructure, and cost analysis to support sustainable and practical pluvial flood mitigation in rapidly urbanizing tropical cities.

1. Introduction

Pluvial flooding has become one of the most critical urban environmental problems in rapidly developing tropical cities, particularly in developing countries where drainage infrastructure expansion cannot keep pace with urban growth and land-use transformation. Increasing urbanization, uncontrolled settlement expansion, population growth, and conversion of permeable land into impervious surfaces have significantly altered the natural hydrological cycle and reduced infiltration capacity within urban catchments. These conditions accelerate surface runoff generation, increase peak discharge, and intensify urban inundation during high-intensity rainfall events [1, 2].

Urban flooding in tropical cities is strongly associated with inadequate drainage capacity, poor watershed management, sediment accumulation, and declining groundwater recharge areas. Conventional drainage systems designed primarily for rapid runoff conveyance are often unable to accommodate increasing discharge generated by urban expansion and extreme rainfall variability. Consequently, many urban areas experience recurrent pluvial flooding characterized by short-duration but high-intensity inundation that disrupts transportation systems, damages infrastructure, reduces environmental quality, and threatens public safety [3–5].

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Dili, the capital city of Timor-Leste, has experienced rapid urbanization over the last decade due to increasing economic activity and population concentration within the metropolitan area. As the political and economic center of Timor-Leste, Dili has become a major destination for urban migration, resulting in significant land-use conversion and increased pressure on urban infrastructure systems. One of the areas highly vulnerable to urban inundation is Comoro Village in Dom Aleixo District, particularly around the Kampung Baru residential area and Nicolao Lobato Roundabout. During heavy rainfall events, the area frequently experiences inundation depths reaching approximately 70–80 cm with flood recession durations of 4–6 hours. Major flood events occurring in March 2018 and April 2021 caused significant disruption to transportation, residential activities, and urban drainage performance [6, 7].

The recurrent inundation problem within the study area is influenced by several interacting factors, including insufficient drainage capacity, limited infiltration areas, urban surface sealing, population growth, and unsuitable drainage network configuration. In addition, the dominance of inceptisol soil within the study area contributes to low infiltration efficiency and increased surface runoff during rainfall events. These conditions indicate that conventional drainage enlargement alone may not provide sustainable long-term flood mitigation under continuing urban growth conditions [8–10].

Recent studies have emphasized the importance of sustainable drainage systems and water conservation-based approaches for urban flood mitigation. Approaches such as infiltration wells, rainwater harvesting systems, eco-drainage, sponge city concepts, and groundwater recharge structures have been increasingly implemented to reduce runoff generation while simultaneously enhancing groundwater replenishment. Unlike traditional drainage systems that focus solely on runoff conveyance, sustainable drainage approaches integrate hydrological restoration and urban water conservation within flood mitigation planning [3, 11].

Several previous studies have investigated urban drainage rehabilitation and flood mitigation using hydrological and hydraulic approaches. GIS-based watershed analysis, runoff estimation, and drainage capacity evaluation have been widely applied for identifying inundation-prone areas and designing urban drainage improvements. Other studies have demonstrated that infiltration structures such as injection wells and infiltration ponds can significantly reduce peak runoff and improve urban water balance. However, many previous studies still focus primarily on hydraulic capacity improvement without integrating sustainable water conservation principles, infiltration enhancement, and cost-effectiveness evaluation into a unified framework [12, 13].

In addition, studies addressing pluvial flood mitigation in tropical developing cities remain limited, particularly in Timor-Leste where urban drainage research and hydrological datasets are still relatively scarce. Most existing studies in the region focus mainly on flood occurrence description and drainage rehabilitation without evaluating integrated mitigation strategies involving hydrological analysis, drainage redesign, infiltration enhancement, and economic feasibility simultaneously. Therefore, this study aims to evaluate sustainable and cost-effective pluvial flood mitigation strategies within the Kampung Baru residential area and Nicolao Lobato Roundabout, Comoro, Dili, Timor-Leste. The study integrates watershed delineation, rainfall analysis, runoff estimation, drainage capacity evaluation, population projection, infiltration-based water conservation measures, and cost analysis within a comprehensive urban drainage assessment framework. The proposed mitigation strategies include rehabilitation of existing drainage channels, construction of new drainage networks, and implementation of injection wells to improve infiltration capacity and reduce inundation risk [6, 14, 15].

The novelty of this study lies in the integration of conventional drainage rehabilitation and water conservation-based mitigation within a single urban flood management framework. Unlike previous studies focusing only on drainage enlargement, this research combines hydrological analysis, GIS-based watershed assessment, drainage redesign, injection well planning, and economic evaluation simultaneously. Furthermore, the study introduces a cost-informed sustainable drainage framework specifically designed for rapidly urbanizing tropical cities with limited drainage infrastructure and groundwater recharge capacity. The integrated methodology developed in this study is expected to provide a practical reference for sustainable urban drainage planning and pluvial flood mitigation in other tropical developing cities experiencing similar environmental challenges.

2. Materials and Methods

2.1. Study area

The study was conducted in the Kampung Baru residential area and Nicolao Lobato Roundabout, located in Comoro Village, Dom Aleixo District, Dili, Timor-Leste (Fig. 1). The study area represents one of the most flood-prone urban zones in Dili due to rapid urban expansion, inadequate drainage infrastructure, reduced infiltration areas, and increasing surface runoff caused by land-use conversion.

Geographically, the study area is situated within a lowland urban environment influenced by tropical climatic conditions with two dominant seasons:

1. Rainy season occurring between November and May,
2. Dry season occurring between June and October.

During heavy rainfall events, inundation depths within the study area frequently reach approximately 70–80 cm and remain for 4–6 hours before receding. Major inundation events recorded in March 2018 and April 2021 caused significant disruption to transportation systems, residential areas, and public activities.

The study area is dominated by inceptisol soil characterized by relatively low infiltration efficiency under saturated conditions, contributing to increased surface runoff generation during intense rainfall events. Rapid urban development and increasing impervious surface coverage further intensify drainage system overload and urban inundation problems [4, 16].

Fig. 1. Location of the Kampung Baru and Nicolao Lobato Roundabout study area within Comoro Village, Dom Aleixo District, Dili, Timor-Leste.

This study integrated hydrological analysis, GIS spatial analysis, drainage capacity assessment, sustainable drainage planning, and cost evaluation [17, 18] into a comprehensive urban flood mitigation framework (Fig.2). The overall research framework consisted of:

1. Field survey and data collection,
2. Watershed delineation and spatial analysis,
3. Rainfall and hydrological analysis,
4. Runoff estimation,
5. Drainage capacity evaluation,
6. Rehabilitation and new drainage design,
7. Injection well planning,
8. Cost estimation,
9. Mitigation effectiveness assessment.

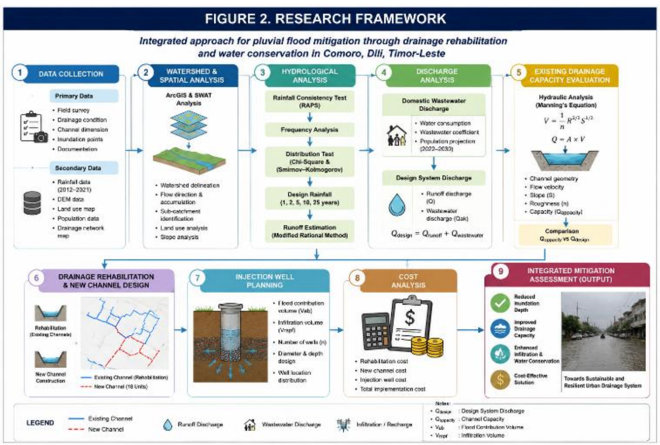

Fig. 2. Research framework integrating hydrological analysis, GIS spatial assessment, drainage rehabilitation, injection well planning, and cost evaluation for pluvial flood mitigation.

2.2. Data collection

Both primary and secondary datasets were utilized in this study. Primary data included:

- Field observations of inundation locations,
- Drainage channel conditions,
- Channel dimensions,
- Flow direction,
- Field documentation.

Secondary datasets included:

- Daily rainfall data,
- Digital Elevation Model (DEM),
- Land-use maps,
- Population data,
- Watershed maps,
- Urban drainage network information.

Rainfall data were obtained from Nicolao Lobato Rainfall Station with observation periods from 2012 to 2021.

Table 1
Data used in the study

No	Data Type	Source	Purpose
1	Rainfall data	Nicolao Lobato Station	Hydrological analysis
2	DEM data	GIS database	Watershed delineation
3	Drainage dimensions	Field survey	Capacity evaluation
4	Land-use map	Spatial database	Runoff analysis
5	Population data	Government statistics	Wastewater estimation
6	Drainage network map	Local authority	Drainage analysis

2.3. GIS-based watershed delineation

Digital Elevation Model (DEM) data were processed using ArcGIS and SWAT (Soil and Water Assessment Tool) to delineate the urban drainage watershed and identify runoff flow patterns (Fig. 3). Spatial analysis included:

- Watershed boundary delineation,
- Flow direction analysis,
- Flow accumulation analysis,
- Drainage network extraction,
- Slope analysis,
- inundation point identification.

The GIS-based analysis was used to identify sub-catchment characteristics contributing to runoff concentration within the urban drainage system [3, 6, 16].

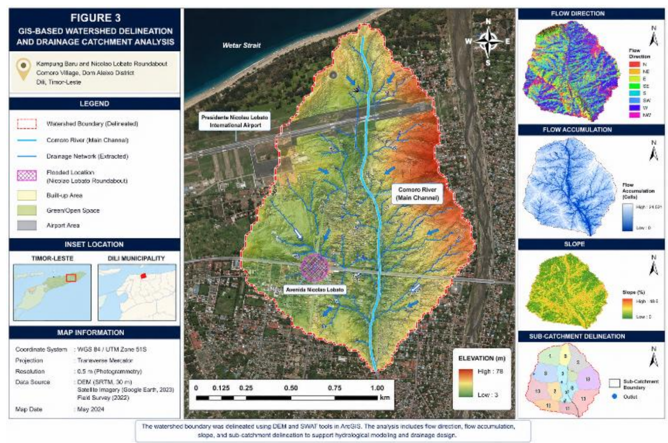

Fig. 3. GIS-based watershed delineation and drainage catchment analysis for the Kampung Baru urban drainage system.

2.4. Hydrological analysis

Hydrological analysis was conducted to estimate design rainfall and runoff discharge for various return periods. Rainfall consistency testing was performed using the Rescaled Adjusted Partial Sums (RAPS) method to evaluate data reliability prior to frequency analysis [19–21]. Design rainfall estimation was conducted using frequency distribution methods followed by distribution suitability testing using Chi-Square test, and Smirnov–Kolmogorov test. Runoff discharge was calculated for return periods of 1 year, 2 years, 5 years, 10 years, and 25 years. Runoff estimation was conducted using the modified Rational Method considering:

- Runoff coefficient,
- Rainfall intensity,
- Watershed area,
- Concentration time,
- Storage coefficient.

2.5. Population projection and wastewater discharge analysis

Population projection was conducted to estimate future domestic wastewater discharge within the drainage catchment area until 2030. Population growth estimation was performed using the geometric projection method. Domestic wastewater discharge was estimated based on projected population, daily water consumption, and wastewater generation coefficients. The wastewater discharge component was incorporated into the total drainage system discharge calculation [3, 6, 16].

The hydraulic performance of the existing drainage system was evaluated using Manning's equation to determine channel conveyance capacity. The analysis considered : 1). channel geometry, 2). flow velocity, 3). hydraulic radius, 4). channel slope, 5). and roughness coefficient. The drainage capacity was compared with the design discharge to identify channels requiring rehabilitation or redesign.

Table 3
Parameters used in drainage capacity analysis

Parameter	Description
B	Channel width
H	Water depth
A	Flow area
R	Hydraulic radius
S	Channel slope
n	Manning roughness coefficient

Channels unable to convey design discharge were classified as hydraulically insufficient and prioritized for rehabilitation.

Drainage rehabilitation was conducted by enlarging dimensions of existing channels that were unable to accommodate the design discharge. In addition, new drainage channels were designed to improve runoff conveyance and reduce inundation accumulation within critical urban areas. The rehabilitation and new drainage planning (Fig. 4) were developed based on:

- Hydraulic capacity requirements,
- Runoff accumulation patterns,
- Field drainage conditions.

With a total 18 new drainage channels, and several rehabilitated existing channels were proposed as part of the integrated flood mitigation strategy.

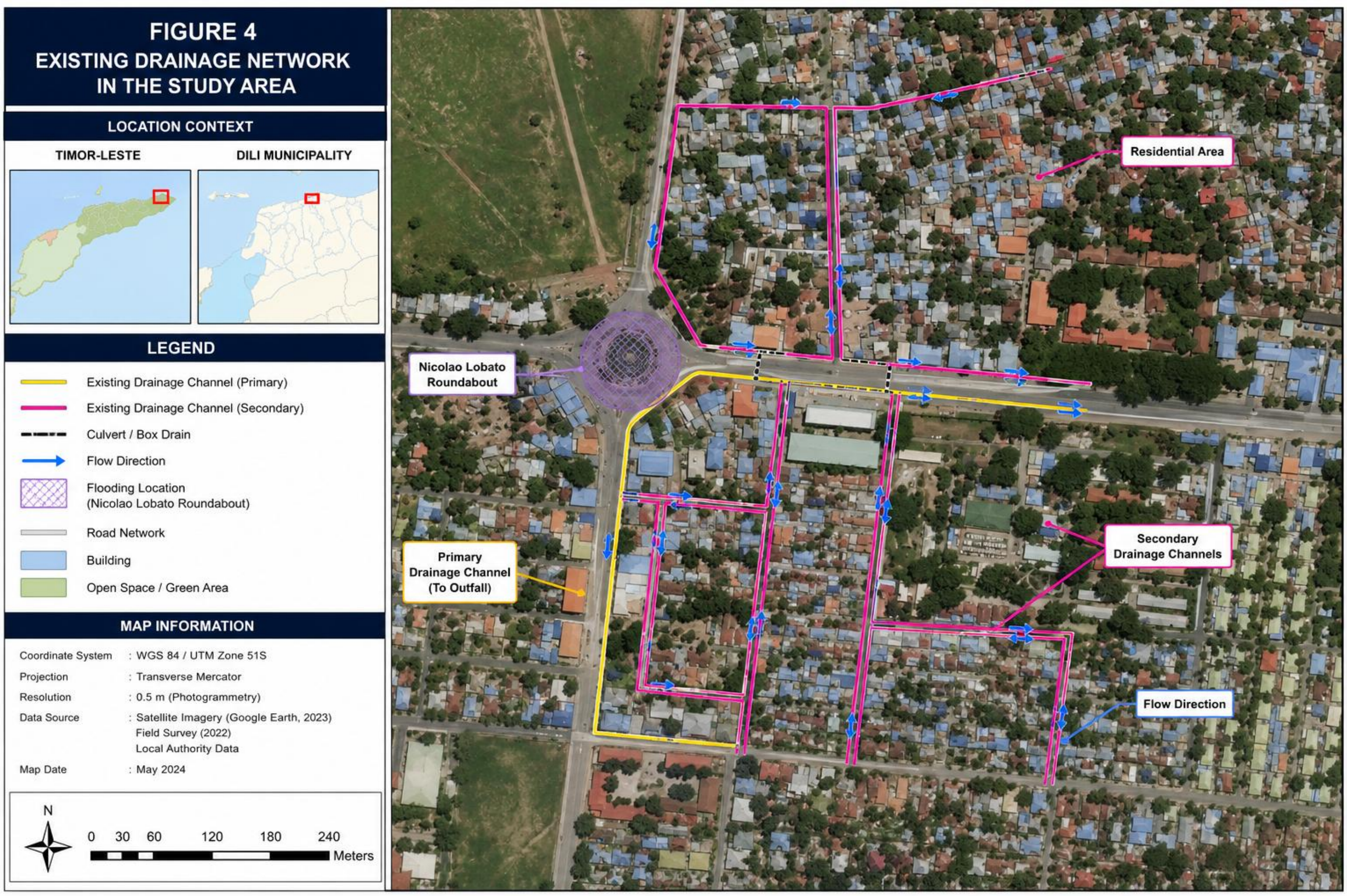

Fig. 4. Location of existing drainage rehabilitation and proposed new drainage channels within the study area.

2.6. Injection well planning and cost analysis

Injection wells were designed as part of the water conservation-based flood mitigation approach to enhance infiltration and reduce surface runoff. The number and dimensions of injection wells were determined based on flood contribution volume, infiltration capacity, groundwater depth, and effective rainfall duration. The volume of infiltrated water was estimated considering:

- Well geometry,
- Soil permeability,
- Infiltration area.

Boundary conditions were defined using discharge hydrographs obtained from hydrological analysis [6, 14, 15].

The injection wells were distributed near inundation-prone locations and critical drainage channels to maximize runoff reduction effectiveness. For the cost analysis was conducted to estimate the total investment required for drainage rehabilitation, new drainage construction, and injection well implementation. The analysis included:

- Excavation work,
- Concrete structures,
- Drainage construction,
- Injection well materials,
- Supporting infrastructure costs.

The estimated implementation costs were evaluated to assess the practicality and economic feasibility of the proposed mitigation measures.

Table 4

Summary of proposed mitigation measures

Mitigation Measure	Quantity
Existing channel rehabilitation	Several channels
New drainage channels	18 units
Injection wells	4 units

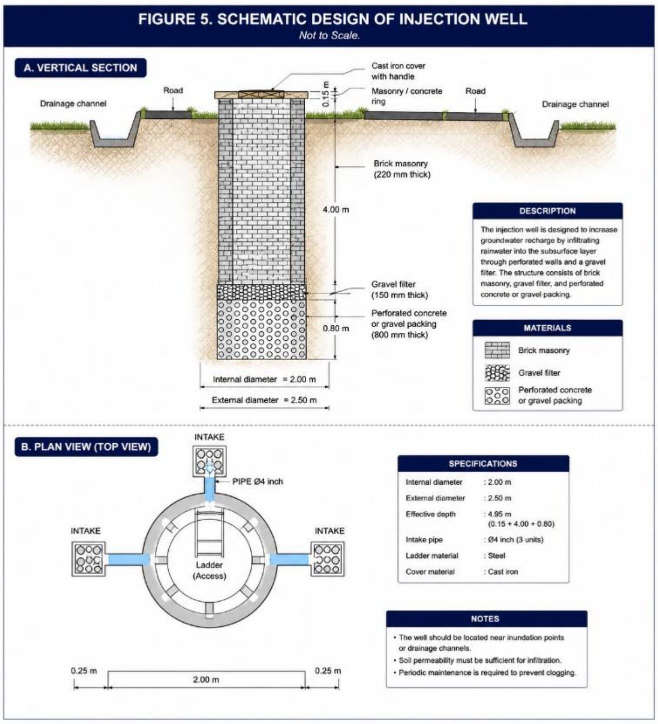

Fig. 5. Conceptual design and spatial distribution of proposed injection wells for urban water conservation and runoff reduction.

2.7. *Integrated mitigation assessment.*

The integrated mitigation assessment was conducted to evaluate the effectiveness of the proposed sustainable drainage and water conservation measures in reducing pluvial flood inundation within the Kampung Baru residential area and Nicolao Lobato Roundabout. The assessment integrated hydrological analysis, drainage capacity evaluation, runoff reduction estimation, infiltration enhancement, and cost considerations into a comprehensive urban flood mitigation framework [19–21]. The mitigation strategy developed in this study consisted of three major components:

- Rehabilitation of existing drainage channels,
- Construction of new drainage channels,
- Implementation of injection wells as infiltration-based water conservation infrastructure.

The evaluation process compared the hydraulic performance of the existing drainage system with the proposed post-mitigation condition. Existing drainage channels were first analyzed to determine their hydraulic insufficiency relative to the design runoff discharge generated under various rainfall return periods. Channels unable to safely convey runoff were classified as critical drainage segments requiring rehabilitation or redesign.

The rehabilitation assessment focused on increasing drainage conveyance capacity through enlargement of channel dimensions, improvement of hydraulic flow continuity, and reduction of local hydraulic bottlenecks. The comparison between existing and proposed drainage dimensions is summarized in Table 5, which shows that several drainage channels required substantial enlargement to safely convey the design runoff discharge and reduce overflow potential within inundation-prone urban areas.

The integrated mitigation approach was not limited to conventional drainage enlargement alone. Injection wells were incorporated into the mitigation framework to improve infiltration capacity and restore part of the natural hydrological response within the urban catchment. The injection wells were strategically distributed near major inundation locations and overloaded drainage channels to maximize runoff reduction effectiveness and groundwater recharge potential. The mitigation effectiveness assessment included:

- Comparison of existing and rehabilitated drainage capacity,
- Reduction in runoff accumulation,
- Decrease in inundation potential,
- Improvement of hydraulic flow distribution,
- Enhancement of groundwater infiltration.

Table 5

Existing and proposed drainage channel dimensions in the study area

Channel ID	Existing Width (m)	Existing Depth (m)	Proposed Width (m)	Proposed Depth (m)	Hydraulic Condition
CH-01	1.20	1.00	1.80	1.60	Rehabilitated
CH-02	1.00	0.90	1.60	1.50	Rehabilitated
CH-03	1.30	1.10	1.90	1.70	Rehabilitated
CH-04	1.10	1.00	1.70	1.50	Rehabilitated
CH-05	1.40	1.20	2.00	1.80	Rehabilitated
CH-06	New Channel	-	1.50	1.50	Proposed
CH-07	New Channel	-	1.60	1.60	Proposed
CH-08	New Channel	-	1.80	1.70	Proposed
CH-09	New Channel	-	1.70	1.60	Proposed
CH-10	New Channel	-	1.50	1.40	Proposed

Hydraulic improvement performance was evaluated by comparing the design discharge with the drainage channel conveyance capacity before and after rehabilitation. Channels that previously experienced overflow conditions under design rainfall scenarios were reassessed after dimension enlargement and integration with new drainage channels.

Table 6

Integrated mitigation assessment results for pluvial flood reduction

Mitigation Measure	Existing Condition	Post-Mitigation Condition	Expected Improvement
Drainage capacity	Insufficient hydraulic capacity	Increased conveyance capacity	Reduced overflow risk
Inundation depth	70–80 cm	< 20 cm	Significant flood reduction
Flood recession time	4–6 hours	1–2 hours	Faster drainage performance
Surface runoff	High runoff concentration	Reduced runoff accumulation	Improved flow distribution
Infiltration capacity	Low infiltration	Increased groundwater recharge	Better water conservation
Drainage network coverage	Limited channel network	Expanded drainage connectivity	Improved runoff conveyance
Groundwater recharge	Minimal recharge	Enhanced recharge through injection wells	Improved urban hydrological balance
Flood-prone locations	Multiple inundation points	Reduced inundation hotspots	Improved urban resilience
Environmental sustainability	Conventional drainage only	Integrated sustainable drainage	Long-term flood mitigation
Economic feasibility	Recurrent flood losses	Cost-effective mitigation strategy	Sustainable infrastructure investment

The infiltration contribution from injection wells was evaluated based on infiltrated runoff volume, soil permeability conditions, effective infiltration area, and rainfall duration. The integrated infiltration system was designed to reduce direct surface runoff entering the drainage network, thereby decreasing peak discharge within critical drainage sections.

In addition to hydraulic and hydrological performance, this study also incorporated cost analysis into the mitigation assessment framework. The economic evaluation considered construction costs associated with drainage rehabilitation, new drainage construction, excavation works, concrete structures, and injection well implementation.

The inclusion of economic evaluation allowed identification of mitigation strategies that are not only hydraulically effective but also financially feasible for implementation within rapidly developing urban areas with limited infrastructure budgets.

The integrated mitigation assessment demonstrated that combining conventional drainage rehabilitation with water conservation-based infiltration measures provides more sustainable flood mitigation performance compared with traditional drainage enlargement approaches alone (Table 6). The proposed system reduces surface runoff concentration while simultaneously supporting groundwater recharge and improving urban hydrological balance.

Furthermore, the integrated framework developed in this study provides a practical decision-support approach for urban flood management in tropical developing cities experiencing rapid land-use change, increasing impervious surfaces, inadequate drainage infrastructure, and declining infiltration capacity. The methodology can also be adapted for other urban catchments facing similar pluvial flooding and urban drainage challenges.

3. Results and discussion

3.1. Watershed characteristics and urban drainage conditions

The GIS-based watershed delineation revealed that the Kampung Baru drainage catchment is characterized by highly urbanized land cover with dense residential settlements, limited open spaces, and increasing impervious surface areas. Rapid urban expansion within Comoro Village has significantly altered the natural hydrological response of the area, resulting in increased surface runoff generation and reduced infiltration capacity [14, 22, 23].

The watershed analysis demonstrated that runoff generated within the catchment rapidly concentrates toward the Nicolao Lobato Roundabout due to the local topographic configuration and inadequate drainage connectivity. The flow accumulation analysis further indicated that several secondary drainage channels discharge directly into overloaded primary drainage systems, creating hydraulic bottlenecks during high-intensity rainfall events.

As shown in Fig. 1, the study area is located within a densely populated urban zone adjacent to critical transportation infrastructure, including the Nicolao Lobato International Airport corridor. The limited drainage space, combined with uncontrolled urban growth, contributes significantly to recurrent pluvial flooding within the catchment area.

The GIS spatial analysis presented in Fig. 3 demonstrates that several sub-catchments within the watershed contribute substantial runoff toward the central inundation zone. The flow direction and accumulation analyses confirm that runoff concentration is strongly controlled by urban surface sealing and drainage network limitations.

3.2. Rainfall characteristics and hydrological analysis

Rainfall analysis using daily rainfall data from 2012–2021 indicated that the study area experiences high rainfall intensity during the wet season, particularly between November and May. Frequency analysis results showed increasing design rainfall values with longer return periods, indicating substantial flood potential within the urban drainage system during extreme rainfall events.

Hydrological calculations using the modified Rational Method demonstrated that the existing urban catchment produces high runoff discharge due to:

- Low infiltration capacity,
- Dense urban settlements,
- High runoff coefficients,
- Inadequate drainage conveyance.

The runoff coefficient within the study area was relatively high because the watershed is dominated by impervious urban surfaces such as roads, buildings, and paved residential areas. In addition, the dominance of inceptisol soil contributes to limited infiltration efficiency during intense rainfall events.

The hydrological analysis also revealed that population growth and urban expansion significantly increase wastewater discharge entering the drainage system. Population projection results estimated continued growth until 2030, indicating increasing future pressure on the urban drainage infrastructure. The combined effect of surface runoff and domestic wastewater discharge substantially increases hydraulic loading within the drainage channels, particularly during peak rainfall periods.

3.3. Existing drainage capacity evaluation

The hydraulic evaluation of the existing drainage network indicated that many drainage channels within the study area are hydraulically insufficient to convey the design runoff discharge. Several channels experience overflow conditions due to inadequate channel dimensions, sediment accumulation, limited drainage connectivity, and poor hydraulic continuity.

As illustrated in Fig. 4, the existing drainage network consists of primary and secondary drainage channels with varying dimensions and hydraulic capacities. Field observations showed that several drainage channels were partially blocked by sediment deposition and urban waste accumulation, further reducing conveyance efficiency.

The comparison between design discharge and existing drainage capacity demonstrated that several drainage segments operate beyond their hydraulic limits during rainfall events with return periods exceeding 5 years. This condition explains the recurrent inundation depth of approximately 70–80 cm observed during major rainfall events in March 2018 and April 2021.

The Nicolao Lobato Roundabout area was identified as the most critical inundation hotspot because it receives concentrated runoff from multiple upstream drainage channels while simultaneously experiencing insufficient outlet capacity.

3.4. Drainage rehabilitation and new channel planning

The drainage rehabilitation analysis demonstrated that enlargement of existing channels alone was insufficient to fully mitigate urban inundation within the study area. Therefore, an integrated drainage improvement strategy involving both rehabilitation of existing channels and construction of new drainage channels was developed. The proposed rehabilitation focused on increasing channel width and depth to improve hydraulic conveyance capacity. Several critical channels required significant dimensional enlargement to safely accommodate the design discharge generated under the selected return period scenario.

As presented in Table 5, the proposed drainage dimensions substantially increase channel capacity relative to existing conditions. The rehabilitated channels are expected to reduce overflow frequency and improve runoff conveyance efficiency within densely populated residential zones. In addition to rehabilitation, 18 new drainage channels were proposed to redistribute runoff more effectively and reduce flow concentration near critical inundation locations. The new drainage channels were strategically designed to improve connectivity between secondary and primary drainage systems [20, 21, 25].

The proposed drainage network also improves hydraulic continuity and minimizes localized ponding within road intersections and residential areas. The integrated drainage system was designed considering:

- Runoff concentration patterns,
- Land-use conditions,
- Hydraulic slope, and urban spatial constraints.

3.5. Injection well planning and water conservation performance

The implementation of injection wells represents one of the major novelties of this study because the mitigation strategy does not rely solely on conventional drainage enlargement. Instead, the study integrates infiltration-based water conservation measures into urban flood mitigation planning. The injection wells were designed to reduce direct surface runoff, increase groundwater recharge, improve infiltration capacity, and support sustainable urban hydrological balance.

Based on hydrological calculations, four injection wells were required to reduce excess runoff volume within the study area. The proposed injection wells were distributed near critical inundation zones and overloaded drainage segments to maximize infiltration effectiveness. The conceptual design and structural configuration of the proposed injection wells are presented in Fig. 5. The design includes gravel filters, perforated infiltration sections, intake pipes, and reinforced structural walls to support infiltration efficiency and long-term operational performance.

The integration of injection wells within the urban drainage system provides several advantages:

- Reduction of runoff entering drainage channels,
- Enhancement of groundwater recharge,
- Reduction of flood recession time,
- Improvement of environmental sustainability.

Compared with conventional drainage approaches, the proposed infiltration-based system provides a more sustainable long-term flood mitigation strategy under continuing urbanization conditions [24].

3.6. Integrated mitigation performance assessment

The integrated mitigation assessment demonstrated that the combined implementation of drainage rehabilitation, new drainage construction, and injection wells significantly improves hydraulic performance within the study area. As summarized in Table 6, the proposed mitigation system substantially reduces inundation depth, decreases flood recession duration, and improves drainage conveyance capacity. The integrated system also enhances groundwater recharge and reduces direct runoff concentration entering the drainage network [16, 26, 27].

The post-mitigation condition indicates that inundation depth can be reduced from approximately 70–80 cm to less than 20 cm under the design rainfall scenario. In addition, flood recession time decreases from 4–6 hours to approximately 1–2 hours after implementation of the proposed mitigation measures.

The integration of sustainable drainage and water conservation principles represents a significant improvement compared with traditional urban drainage systems that focus only on rapid runoff conveyance. The proposed framework improves both hydraulic efficiency and environmental sustainability simultaneously.

3.7. Cost analysis and practical implications

Economic analysis indicated that the total estimated implementation cost for drainage rehabilitation and new drainage construction was approximately USD 1,941,051.69, while the estimated cost for injection well construction was approximately USD 30,701.43. Although the proposed mitigation system requires substantial initial investment, the long-term benefits associated with reduced flood damage, improved urban functionality, enhanced groundwater recharge, and increased environmental sustainability justify the implementation cost.

The integration of cost analysis within the mitigation framework represents another important contribution of this study because many urban drainage studies focus only on hydraulic performance without considering implementation feasibility. Furthermore, the methodology developed in this study provides a practical framework for sustainable pluvial flood mitigation in rapidly urbanizing tropical cities experiencing:

- Increasing impervious surfaces,
- Declining infiltration capacity,
- Recurrent urban flooding,
- Inadequate drainage infrastructure.

The integrated GIS-based and hydrological approach developed in this study can also be adapted for other tropical urban catchments facing similar environmental and infrastructure challenges [28, 29].

4. Limitations

Although this study provides important contributions to sustainable urban drainage and pluvial flood mitigation in tropical cities, several limitations should be acknowledged when interpreting the results and applying the proposed mitigation framework.

First, the hydrological analysis relied primarily on rainfall observations obtained from a single rainfall station, namely the Nicolao Lobato Rainfall Station, covering the period from 2012 to 2021. The limited spatial distribution of rainfall monitoring stations may not fully represent spatial rainfall variability across the entire urban catchment, particularly during localized extreme rainfall events. Consequently, uncertainty may still exist in the estimation of design rainfall and runoff discharge.

Second, the Digital Elevation Model (DEM) used for watershed delineation and spatial analysis was derived from medium-resolution topographic data. Although sufficient for general drainage and runoff analysis, higher-resolution topographic datasets such as LiDAR would improve the accuracy of flow accumulation analysis, micro-topographic representation, and inundation mapping within densely urbanized environments.

Third, the drainage capacity evaluation was conducted using one-dimensional hydraulic calculations based primarily on Manning's equation and channel conveyance analysis. Complex urban hydraulic interactions such as localized backwater effects, road overtopping, subsurface flow interactions, and two-dimensional surface flow propagation were not fully represented within the analysis framework. Therefore, some local inundation behavior may not be completely captured by the current modeling approach.

Fourth, the study focused mainly on structural and hydrological mitigation strategies, including channel rehabilitation, new drainage construction, and injection well implementation. Non-structural flood mitigation measures such as urban flood early warning systems, community-based drainage management, land-use regulation, and environmental governance were not included in the analysis.

Fifth, sediment accumulation and solid waste blockage within urban drainage channels were identified during field observations; however, detailed sediment transport simulation and long-term drainage maintenance evaluation were not incorporated into the study. In reality, sedimentation and waste accumulation can significantly reduce hydraulic performance and alter the long-term effectiveness of drainage infrastructure.

Sixth, the injection well performance assessment was based on theoretical infiltration calculations and soil permeability assumptions without long-term field infiltration testing or groundwater monitoring. Actual infiltration performance may vary depending on:

- Soil compaction,
- Seasonal groundwater fluctuations,
- Sediment clogging,
- Maintenance conditions.

Seventh, the cost analysis conducted in this study focused primarily on initial construction and infrastructure implementation costs. Long-term operational costs, maintenance requirements, rehabilitation cycles, and future infrastructure adaptation costs under continued urban growth conditions were not comprehensively evaluated.

Another limitation of this study is the absence of climate change projections within the hydrological assessment. Future increases in rainfall intensity, extreme precipitation frequency, and urban heat effects associated with climate change may substantially alter runoff characteristics and drainage system performance within the study area. Incorporating climate change scenarios into future urban flood modeling would improve the long-term reliability of drainage planning.

Finally, this study focused specifically on the Kampung Baru and Nicolao Lobato Roundabout urban catchment area within Comoro, Dili. Although the methodology developed in this research can be adapted to other urban environments, the hydraulic conditions, urban morphology, soil characteristics, and infrastructure constraints may differ significantly across other tropical cities.

Despite these limitations, the integrated framework developed in this study still provides a practical and scientifically grounded approach for evaluating urban drainage performance, designing sustainable flood mitigation infrastructure, and integrating water conservation principles into pluvial flood management in rapidly urbanizing tropical regions. Future studies are recommended to incorporate high-resolution hydrodynamic modeling, climate change projections, long-term monitoring, smart drainage systems, and socio-economic analyses to further improve sustainable urban flood mitigation strategies.

5. Conclusion

This study evaluated sustainable and cost-effective pluvial flood mitigation strategies in the Kampung Baru residential area and Nicolao Lobato Roundabout, Comoro, Dili, Timor-Leste, through the integration of hydrological analysis, GIS-based watershed assessment, drainage capacity evaluation, injection well planning, and economic analysis. The results demonstrate that rapid urbanization, increasing impervious surfaces, inadequate drainage infrastructure, and limited infiltration capacity are the primary factors contributing to recurrent urban inundation within the study area.

The hydrological analysis revealed that the existing drainage network is hydraulically incapable of safely conveying runoff generated during moderate to extreme rainfall events. Several drainage channels were identified as critical hydraulic bottlenecks due to insufficient dimensions, sediment accumulation, and limited network connectivity. These conditions resulted in recurrent inundation depths of approximately 70–80 cm with flood recession durations reaching 4–6 hours during intense rainfall events.

The drainage rehabilitation assessment showed that enlargement of existing channels alone was insufficient to fully mitigate pluvial flooding within the study area. Therefore, an integrated mitigation strategy consisting of rehabilitation of existing drainage channels, construction of 18 new drainage channels, and implementation of four injection wells was developed. The proposed mitigation system significantly improves hydraulic conveyance capacity, reduces runoff concentration, enhances infiltration performance, and supports groundwater recharge within the urban catchment.

The implementation of injection wells represents one of the major contributions of this study because the proposed mitigation framework incorporates water conservation principles into urban flood management. Unlike conventional drainage systems that focus solely on rapid runoff conveyance, the proposed system simultaneously reduces inundation risk and improves urban hydrological balance through infiltration enhancement and groundwater recharge.

The integrated mitigation assessment demonstrated substantial improvements in drainage system performance after implementation of the proposed measures. Inundation depth was significantly reduced, flood recession time became shorter, and hydraulic flow distribution within the drainage network improved considerably. The proposed mitigation strategy also provides environmental benefits through increased infiltration capacity and improved urban water conservation performance.

Economic evaluation indicated that the estimated implementation cost for drainage rehabilitation and new drainage construction is approximately USD 1,941,051.69, while injection well implementation requires approximately USD 30,701.43. Although the proposed system requires considerable infrastructure investment, the long-term benefits associated with reduced flood damage, improved urban resilience, groundwater recharge enhancement, and environmental sustainability justify the implementation cost.

The novelty of this study lies in the integration of sustainable drainage rehabilitation, infiltration-based water conservation infrastructure, hydrological analysis, GIS spatial assessment, and cost evaluation within a single urban pluvial flood mitigation framework. Unlike many previous studies that focus only on drainage enlargement or runoff conveyance, this study combines hydraulic improvement and groundwater recharge strategies simultaneously to support more sustainable urban flood management.

Overall, the integrated methodology developed in this study provides a practical and transferable framework for sustainable pluvial flood mitigation in rapidly urbanizing tropical cities experiencing increasing flood risk, declining infiltration capacity, and inadequate urban drainage infrastructure. The framework can also serve as a reference for future urban drainage planning and water conservation-based flood mitigation strategies in other developing tropical regions facing similar environmental challenges.

CRediT authorship contribution statement

Jacob Coa: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vishal R. Panse:** Writing – review & editing, Investigation. **Alok Shukla:** Methodology, Investigation, Formal analysis, Writing – review & editing, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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