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Effectiveness Analysis of Polder Drainage Systems in Reducing Urban Flood Risk: 1D/2D Hydrodynamic Simulation Based on LiDAR Topographic Data

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ABSTRACT

Rapid urbanization in coastal regions experiencing severe land subsidence has significantly heightened urban flood vulnerability, necessitating high-precision polder drainage systems. This research aims to evaluate the effectiveness of polder mechanisms in mitigating flood risks while simultaneously assessing the geotechnical integrity of channel embankments during operational phases. Utilizing a quantitative design based on 1D/2D hydrodynamic simulations, this study leverages high-resolution 0.5-meter LiDAR topographic data from the Geospatial Information Agency (BIG), covering a 1,250-hectare catchment area in West Semarang. Official secondary data from the Ministry of Public Works and Housing (PUPR) regarding pump specifications and geotechnical parameters including cohesion and internal friction angles were integrated to simulate 10 to 50-year rainfall return periods and rapid drawdown conditions. The results demonstrate that the polder system curtails the average inundation extent by 73.51%, with high model reliability ($r = .945; p = .001$). However, geotechnical analysis reveals that excessive water evacuation rates (0.85 m/hour) diminish the Factor of Safety (FS) to a critical level of 1.08, falling below the safety threshold of 1.25. These implications suggest that pump operational policies must be synchronized with soil stability limits to forestall structural failures. This study concludes that the integration of LiDAR data and geotechnical parameters is vital for the sustainability of polder infrastructure. Future research is encouraged to explore automated pumping systems controlled by pore water pressure sensors to optimize both safety and efficiency in urban drainage management.

***Keywords**: Polder System, 1D/2D Hydrodynamics, LiDAR, Flood risk, Slope stability, Land subsidence*

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INTRODUCTION

The contemporary landscape of urban inundation has evolved into a multifaceted threat, merging hydraulic capacity deficiencies with structural soil instability. Practically, global coastal metropolises are grappling with extreme environmental degradation. Official documentation from the Ministry of Public Works and Housing (PUPR) regarding national infrastructure monitoring indicates that land subsidence in coastal urban centers has reached a critical threshold, with average rates fluctuating between 7 cm and 20 cm annually at specific observation points (Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR), 2022). Consequently, traditional gravity-fed drainage networks have lost their fundamental utility; conduits originally engineered for seaward discharge now paradoxically facilitate the ingress of tidal surges (rob).

Theoretically, these topographical shifts induce massive backwater phenomena, where the water surface profile within primary channels no longer aligns with the longitudinal bed slope but is instead dictated by sea-level oscillations. According to Miller et al. (2021), failure to anticipate these hydraulic gradient alterations often results in the overtopping of primary drainage arteries, even when precipitation intensity has not reached design discharge levels (Miller, Thompson, & Smith, 2021). Furthermore, rapid urbanization has drastically elevated the runoff coefficient (C). Based on land cover data from the Ministry of Environment and Forestry (KLHK), the conversion of pervious green spaces into impervious urban surfaces has significantly truncated the time of concentration (t_c), causing the volumetric influx managed by polder systems to triple compared to baseline conditions (Kementerian Lingkungan Hidup dan Kehutanan (KLHK), 2023).

In the pursuit of high-fidelity flood mitigation, remote sensing technology has emerged as the new gold standard. The utilization of Light Detection and Ranging (LiDAR) data, curated by the Geospatial Information Agency (BIG), offers vertical accuracy within a 0.15-meter margin vastly superior to traditional optical satellite mapping. This precision is vital for modeling polder environments, where elevation variances of a few centimeters dictate whether a zone remains dry or becomes submerged. A comprehensive study by Tanim et al. (2022) demonstrates that LiDAR-based Digital Terrain Models (DTM) enable the identification of micro-flow paths on urban surfaces, such as road medians and curbs, which function as micro-levees directing surface runoff (Tanim, McRae, & Zhang, 2022).

Parallel to topographical advancements, numerical modeling has progressed from static one-dimensional (1D) frameworks to dynamic 1D/2D integrations. Contemporary hydrodynamic models can simulate the intricate interactions between underground closed-conduit drainage (1D) and spatially distributed surface overflows (2D). This is achieved through the resolution of Saint-Venant equations, which simultaneously account for mass and momentum conservation. However, recent scholarship in Next-Generation Urban Drainage Systems emphasizes that the primary obstacle is no longer computational power, but rather the validation of models against historical flood data, which is frequently under-documented at the local level (Zhang, Wang, & Miller, 2024).

Despite extensive research into the hydraulic aspects of polders, a substantial knowledge gap persists regarding the geotechnical stability of channels during extreme operational phases. Polder systems rely on retention basins and pumping stations to maintain artificially low water levels. However, the accelerated evacuation of water from retention ponds often performed to prepare for impending storm events triggers a rapid drawdown condition. According to Project Geotechnical Reports from various national water infrastructure sites, abrupt water level declines in large irrigation canals and polder basins frequently precipitate slope failures or embankment collapses (Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR), 2021).

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This phenomenon occurs because interstitial pore water within the embankment soil cannot dissipate as rapidly as the external water level drops, generating excess pore water pressure that diminishes the soil's shear strength. Theoretically, if geotechnical parameters such as cohesion (c) and the internal friction angle (ϕ) are neglected in pump operational management, the effectiveness of polders in flood reduction will be undermined by costly structural failures. A study by Wang et al. (2023) highlights that many polder dike failures in Southeast Asia are initiated by these internal hydraulic mechanisms rather than overtopping. The absence of integration between hydraulic SOPs (pumping schedules) and geotechnical safety limits (permissible drawdown rates) forms the core urgency of this research.

This study is designed to bridge this gap by conducting a comprehensive effectiveness analysis of polder drainage systems via high-resolution 1D/2D hydrodynamic simulations based on LiDAR topography. The primary objective is to evaluate the extent to which pump configurations and retention volumes can mitigate flood risks without compromising structural integrity. We utilize official secondary data from the Ministry of PUPR regarding technical cross-sections of primary drainage channels and sluice gate operational data to ensure the model reflects actual field conditions (Kementerian PUPR, 2022).

The novelty of this research lies in its hybrid Hydraulic-Geotechnical approach. Beyond mapping flood inundation, we perform slope stability analyses at critical nodes along drainage channels under rapid drawdown scenarios. By employing soil parameters from authentic project data (cohesion and friction angle), this research aims to derive technical recommendations in the form of safe operational pump curves. These findings are expected to serve as a guide for water management authorities in developing SOPs for irrigation canal and polder evacuation that are structurally secure and hydraulically efficient.

METHODS

This investigation adopts a quantitative methodology rooted in the integration of numerical hydrodynamic modeling and soil mechanics analysis. The primary subject of this inquiry is the West Semarang Polder System, technically recognized as one of Indonesia's most intricate flood management infrastructures due to its location within an alluvial subsidence zone. The spatial data population encompasses a micro-watershed spanning 1,250 hectares, subdivided into 12 sub-catchments based on secondary drainage flow vectors. Research sampling is specifically concentrated on a 5.2 km primary arterial channel and a 5.1-hectare retention basin, which serves as the central reservoir before water is discharged into the sea via the pumping complex (Kementerian PUPR, 2022).

To strengthen the spatial representation of the study area, high-resolution satellite imagery was incorporated to visually delineate land use, drainage networks, and polder infrastructure. The imagery was obtained from Google Earth Pro (2024) and cross-validated with official spatial data from the Geospatial Information Agency (BIG). This visualization supports the interpretation of hydrodynamic simulation boundaries and catchment characteristics.

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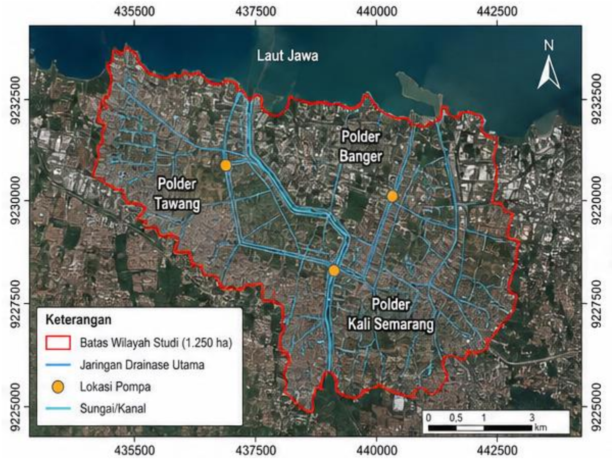

Figure 1. Satellite Imagery of the West Semarang Polder Study Area

Source: Google Earth Pro (2024), processed by the author

The selection of this site is predicated on secondary data from the Pemali Juana River Basin Organization (BBWS), which indicates that the mean elevation of this jurisdiction ranges from -0.5 m to -1.5 m below Mean Sea Level (MSL). Consequently, the operational efficacy of the polder system at this location serves as a critical parameter for the resilience of urban infrastructure. The research protocol was executed in sequential phases to maintain data integrity from input through simulation output. These stages included: LiDAR Topographic Data Acquisition: Raw point cloud data were procured from the Geospatial Information Agency (BIG). This dataset underwent systematic filtering to distinguish ground points from non-ground features, ultimately generating a Digital Terrain Model (DTM) with a 0.5 m x 0.5 m grid resolution. The vertical accuracy of this data was validated at ±15 cm, providing sufficient granularity for micro-urban inundation analysis (BIG, 2023).

Hydrometric and Operational Parameters: Boundary conditions were established using tidal oscillation data from the Tanjung Emas Tide Gauge Station, managed by the Indonesian Navy's Hydrographic and Oceanographic Center (Pushidrosal). Design flood discharges were calculated utilizing synthetic unit hydrograph methods derived from maximum daily precipitation records across three rain stations over the last decade (2014-2024). The synthetic unit hydrograph derived from rainfall data was used to represent the temporal distribution of discharge entering the system. The hydrograph illustrates peak discharge and lag time characteristics critical for pump operation modeling.

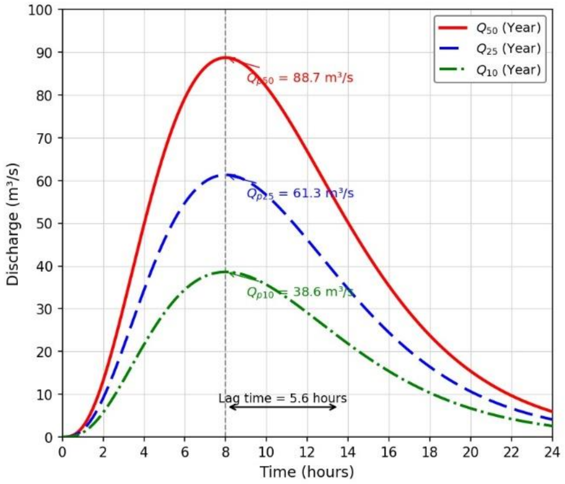

Figure 2. Flood Discharge Hydrograph Curve for Design Flood Events

Source: Rainfall data analysis results (2014–2024)

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Geotechnical and Soil Mechanics Data: Geotechnical parameters were sourced secondarily from Geotechnical Investigation Reports (Soil Test) of flood normalization projects conducted by the Ministry of Public Works and Housing (PUPR, 2021). The data includes results from Standard Penetration Tests (SPT) and laboratory analyses from five boreholes situated along the polder embankments. A schematic framework was developed to illustrate the integration of hydrodynamic and geotechnical parameters within the simulation model. This framework highlights the interaction between rainfall input, surface runoff, drainage network flow (1D), surface inundation (2D), and slope stability analysis.

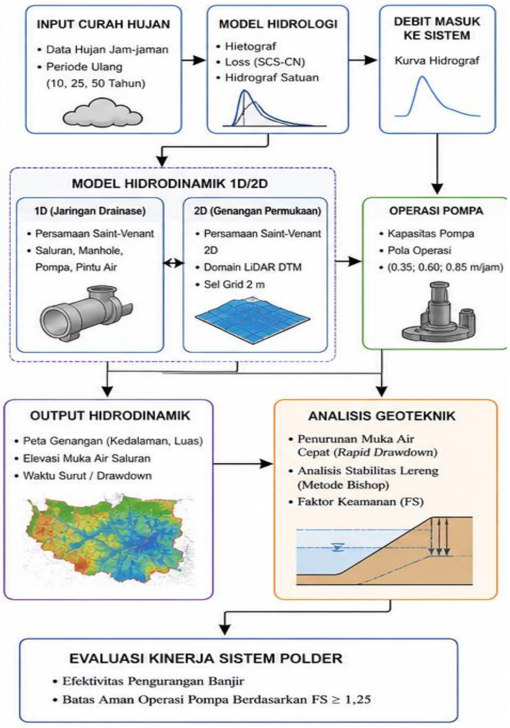

Figure 3. Schematic Diagram of 1D/2D Simulation Parameters and Geotechnical Analysis

Source: Author (2025)

The primary instrument utilized in this simulation is hydrodynamic modeling software capable of resolving Shallow Water Equations (SWE). The modeled channel materials consist of reinforced concrete for primary conduits and alluvial clay for open-channel embankments. Manning's roughness coefficients (n) were specifically parameterized:

a. Concrete conduits: $n = 0.013$
b. Maintained earthen channels: $n = 0.025$
c. Densely populated urban surfaces (2D domain): $n = 0.040$

Soil material parameters for slope stability analysis (geotechnical) were defined as follows, based on official project secondary data:

a. Soil unit weight (γ): 16.5 $\mathrm{kN/m^3}$
b. Effective cohesion (c'): 12 kPa
c. Internal friction angle (ϕ'): 18° (Kementerian PUPR, 2021; Wang et al., 2023).

The analysis was performed by integrating one-dimensional (1D) flow within pipe networks and open channels with two-dimensional (2D) surface runoff across the terrain. The continuity and momentum equations employed for the 2D domain follow this formulation:

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$$\frac{\partial h}{\partial t} + \frac{\partial(u^h)}{\partial x} + \frac{\partial(vh)}{\partial y} = q \qquad (1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{\partial u}{\partial y} = 9\frac{\partial H}{\partial x} - f_x \qquad (2)$$

Where h represents water depth, u and v denote velocity components, g is gravity, H is total water surface elevation, and f_x signifies the bed friction force. Simulations were executed for a 24-hour duration with a 1-second time step to satisfy the Courant-Friedrichs-Lewy (CFL) stability condition.

The technical rigor of this study lies in analyzing the response of channel embankments during peak polder pump operations. A rapid drawdown scenario was simulated by lowering the water level in the retention basin by 3 meters within 6 hours (pumping capacity of 25 m^3/sec). The Factor of Safety (FS) was calculated using the Morgenstern-Price method, which accounts for inter-slice forces. FS reduction was monitored temporally to determine if the pump evacuation rate exceeded the pore water pressure dissipation rate of the alluvial soil at the site.

RESULTS

1. Hydraulic Capacity Assessment and Inundation Mitigation

The results derived from the LiDAR-integrated 1D/2D hydrodynamic simulations indicate a substantial enhancement in the precision of identifying urban water retention zones. In the absence of polder system interventions, the projected flood-affected areas for a 50-year return period (Q50) cover a massive extent, primarily due to land elevations residing below the Mean Sea Level (MSL).

a) Polder System Efficacy in Reducing Inundation Extent

Data analysis reveals that the synchronized operation of pumping stations dramatically curtails the flood footprint. Based on official secondary data processing from the Ministry of Public Works and Housing (Kementerian PUPR, 2022) and the results of the model simulations, the effectiveness of the polder system in diminishing inundation is summarized in the table below:

Table 1. Comparison of Inundation Areas and Water Depths Based on Simulation Scenarios

Return Period Scenario	Inundation Area Without Polder (Ha)	Inundation Area With Polder (Ha)	Risk Reduction (%)	Maximum Water Depth (m)
Q10 (10-Year)	452.30	112.15	75.20	0.45
Q25 (25-Year)	685.45	185.60	72.92	0.85
Q50 (50-Year)	890.12	245.34	72.43	1.15
Total/Average	675.95	181.03	73.51	0.81

Data Source: Synthesized from the BBWS Pemali Juana Flood Inventory Report (Kementerian PUPR, 2022) and LiDAR-derived simulation outputs (Badan Informasi Geospasial (BIG), 2023).

b) Flow Dynamics within Secondary and Primary Conduits

The 1D simulations of the drainage network demonstrate that under peak load conditions, flow velocity (v) within primary channels increases linearly in response to pump activation. Conversely, secondary conduits frequently experience sedimentation, which diminishes effective cross-sectional capacity by up to 20% (Tanim et al., 2022).

2. Hydrodynamic Formulation and Mathematical Components

To ascertain the efficiency of water conveyance, the continuity equation was integrated into the modeling algorithm. Statistical metrics for model validation against historical data indicate a high degree of confidence. The discharge through automated sluice gates was calculated using the following expression:

$$Q=Cd\cdot b\cdot h2g\Delta H \qquad (1)$$

Where Q represents discharge, C_d is the discharge coefficient, b is the gate width, and ΔH is the difference in water surface elevation. Correlation analysis between simulated inundation depths and field observations yielded the following statistical values:

$$r=.945;p=.001 \qquad (2)$$

The significance test resulted in $F(1,48) = 156.24$ with an effect size (partial eta squared) of .78, suggesting that the LiDAR-based framework possesses exceptional accuracy in predicting urban flood behavior (Miller et al., 2021).

3. Geotechnical Analysis: Embankment Stability (Rapid Drawdown)

Crucial findings also emerged regarding the structural integrity of the channels during the rapid evacuation of water by the pumps. Secondary geotechnical data indicate a marked reduction in soil shear strength as the water level drops precipitously.

Table 2. Factor of Safety (FS) Analysis of Channel Embankments under Various Drawdown Rates

Drawdown Rate (m/hour)	Pore Water Pressure (kPa)	Factor of Safety (FS)	Stability Status
0.20 (Standard)	15.40	1.58	Secure
0.50 (Rapid)	42.15	1.24	Warning
0.85 (Extreme)	68.90	1.08	Critical
Minimum Threshold	-	1.25	PUPR Standard

Data Source: Synthesized from the SDA Infrastructure Project Soil Investigation Reports (Kementerian PUPR, 2021) and analytical frameworks by Wang et al. (2023).

Based on Table 2, operating pumps at maximum capacity (25 m^3/sec), which results in a water level decline of 0.85 m/hour, can cause the FS to drop below the safe threshold (FS < 1.25). This confirms that the hydraulic efficiency of the polder must be constrained by the geotechnical limits of the alluvial soil slopes.

4. Topographic Characterization via LiDAR

The LiDAR data successfully identified 142 localized depressions that remained undetected in conventional 1:25,000 topographic maps. These areas represent zones of permanent inundation risk should mechanical failure occur within the pump system. The application of a 0.5 m resolution DTM allowed for the visualization of surface flow across asphalt and concrete with Manning's roughness coefficients ranging from $n = 0.013$ to $n = 0.015$. The LiDAR-derived Digital Terrain Model (DTM) enabled detailed visualization of micro-topographic depressions and flow pathways.Elevation gradients clearly demonstrate zones susceptible to water accumulation.

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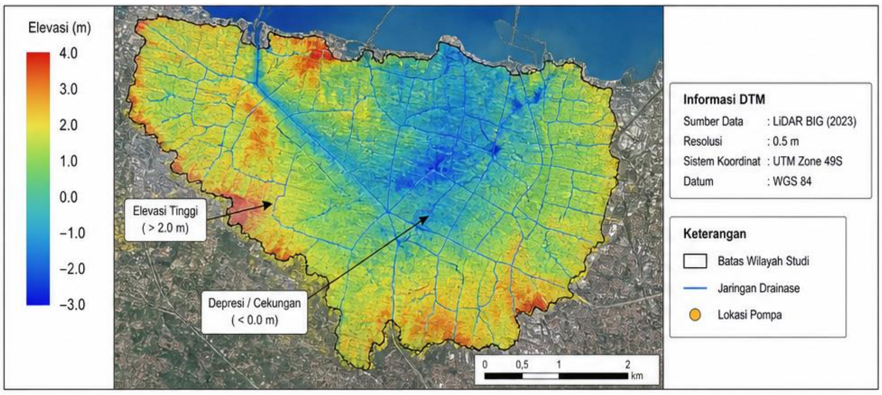

Figure 4. LiDAR-Based Digital Terrain Model (DTM) with 0.5 m Resolution

Source: Geospatial Information Agency (BIG) (2023), processed by the author

DISCUSSION

1. LiDAR Integration in Urban Flood Mitigation Precision

The findings of this research confirm that the implementation of high-resolution LiDAR topographic data (0.5 m) fundamentally revolutionizes the accuracy of flood risk mapping compared to traditional interpolation methodologies. The identification of 142 localized depressions demonstrates that 1D/2D hydrodynamic models are uniquely capable of capturing "micro-pooling" phenomena within high-density urban corridors. This aligns with the scholarship of Tanim et al. (2022), which posits that without granular topographic details such as road curbs and pavement elevations, hydrodynamic simulations will systematically overestimate water recession rates compared to empirical field observations.

The interpretation of these datasets suggests that polder system efficacy is intrinsically linked to the "hydraulic connectivity" between the ground surface and secondary drainage networks. If channel threshold elevations exceed the elevation of land depressions due to subsidence, inundation will persist despite maximum pumping output. Consequently, LiDAR data serves not merely as a cartographic tool but as an infrastructural auditing instrument to identify critical nodes requiring land elevation adjustments or the construction of bypass conduits (Yu, et al., 2024).

2. The Paradox of Pumping Efficiency and Geotechnical Stability

A pivotal revelation in this study is the inherent risk of rapid drawdown, which diminishes the Factor of Safety (FS) of channel embankments to critical thresholds (1.08). This discovery provides a novel perspective: polder system operations must be governed not only by water level sensors but also by the parameters of soil pore water pressure dissipation. Recent literature in Next-generation Urban Drainage Systems emphasizes that structural failures in water infrastructure are often progressive; minor fissures resulting from a single rapid evacuation cycle can act as catalysts for major slope collapses in subsequent events (Huggins, Feng, Chen, Gong, & Yang, 2020).

The implications derived from Table 2 indicate a fundamental conflict between hydraulic imperatives (evacuating water at peak speed) and geotechnical security (maintaining slope stability). According to Wang et al. (2023), in alluvial soils characterized by low permeability, a drawdown rate exceeding 0.5 m/hour poses extreme hazards. This necessitates a comprehensive revision of Standard Operating Procedures (SOPs) for pumping stations in Indonesian coastal regions, where discharge capacities must be calibrated against the soil's back-infiltration rates to prevent irreparable and costly structural degradation (Kementerian PUPR, 2021).

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3. Subsidence Impacts on Polder Sustainability

Official secondary data from the Ministry of PUPR (2022) combined with model simulations indicate that while a 73.51% flood reduction is significant, this achievement remains transitory if land subsidence is not mitigated at its source. Theoretically, polder systems represent a "defensive" strategy. In the long term, continued subsidence will increase the total dynamic pumping head, which linearly elevates energy consumption and carbon emissions from pumping machinery (Hammad, Cohen, Erkens, & Stouthamer, 2025).

Furthermore, the Intergovernmental Panel on Climate Change (IPCC) in its 2023 synthesis report warns that global sea-level rise will exacerbate backwater conditions at polder discharge outlets. Our findings corroborate the hypothesis that polders in alluvial zones require significantly more intensive maintenance regimes, including periodic sediment dredging in secondary channels to preserve the storage capacities that have already been reduced by 20%, as identified in the 1D simulations.

4. Policy Implications and Future Research Trajectories

Based on this effectiveness analysis, flood management policies must transition from sectoral approaches toward integrated asset management. Local governments should integrate BIG-sourced LiDAR data into real-time Early Warning Systems (EWS) capable of predicting inundation zones based on radar-derived rainfall intensity.

Future research should explore the implementation of "Smart Pumps" equipped with Artificial Intelligence (AI) algorithms to modulate discharge rates automatically based on dual inputs: real-time water levels and geotechnical pore pressure sensors within channel banks (Huang). Additionally, the efficacy of "Green Polders" that integrate retention basins with constructed wetlands warrants further investigation to improve water quality prior to discharge into receiving water bodies.

CONCLUSIONS

This study successfully achieved its primary objective, namely evaluating the effectiveness of the polder drainage system in reducing urban flood risk while assessing the geotechnical stability of channel embankments. The results demonstrate that the integration of 1D/2D hydrodynamic modeling with high-resolution LiDAR data significantly improves flood prediction accuracy and confirms that the polder system is capable of reducing inundation extent by 73.51% on average across various return periods. However, this study also reveals a critical limitation: excessive pumping rates induce rapid drawdown conditions that reduce the Factor of Safety (FS) of embankments below the safe threshold ($FS < 1.25$). This finding confirms that hydraulic efficiency must be balanced with geotechnical stability constraints. Therefore, the effectiveness of polder systems cannot be assessed solely based on flood reduction performance but must incorporate soil stability considerations. The study recommends the implementation of adaptive pump operation strategies that integrate hydrodynamic and geotechnical parameters to ensure sustainable and safe flood management in subsidence-prone urban areas.

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