



Drainage Planning and Design for Light Infrastructure Using Building Information Modelling: Integrating Hydrology, Topography, and Adaptive Engineering

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Introduction

The planning and design of drainage systems for light infrastructure have become increasingly critical as climate variability, land-use pressures, and the growing interdependence of infrastructure networks intensify risks related to flooding, erosion, and groundwater fluctuations. Light infrastructure—such as access roads, small buildings, utility corridors, renewable energy installations, and distributed technical facilities—often occupies semi-natural landscapes where hydrological processes remain dominant. Even relatively minor interventions can disrupt runoff pathways, concentrate flows, alter infiltration patterns, or create localized stagnation zones. Flood hazards may arise from multiple interacting sources, including fluvial, pluvial, coastal, groundwater, utility water main bursts, and levee or dam failures (Konstantis et al., 2023). The interaction of these drivers frequently amplifies impacts, underscoring the necessity for drainage systems that are technically robust, environmentally integrated, and adaptable to uncertainty.

Infrastructure Interdependencies and Cascading Failures

Recent extreme events have demonstrated the vulnerability of infrastructure systems to cascading failures. Light infrastructure is particularly sensitive, as it typically lacks the redundancy and buffering capacity of large-scale engineered systems. Flood durations may range from hours to months, depending on soil saturation, catchment response, and local drainage capacity, and their impacts often propagate across interconnected systems. As infrastructure networks become increasingly interlinked, hazard-induced disruptions can spread through both explicit and implicit interdependencies (Yang et al., 2021). This reality elevates the importance of proactive mitigation strategies and positions drainage design as a central pillar of infrastructure resilience.

Planning Phase: Conceptual Modelling Under Data Constraints

A fundamental distinction in drainage development lies between the planning phase and the final design phase. During planning, designers usually work with limited or preliminary data, including basic topographic surveys, hydrological estimates, soil classifications, and environmental screenings. The objective is to understand the natural drainage regime, delineate catchment boundaries, identify flood pathways, and align proposed interventions with sustainable water-management principles. Early-stage modelling often begins with the creation of a three-dimensional surface representation of the site (Nair et al., 2024). However, data resolution may be coarse or incomplete, requiring conceptual hydrological models that capture essential flow behavior without yet achieving construction-level precision.

Final Design Phase: Detailed Hydraulic and Geometric Integration

The final design phase, by contrast, demands detailed hydraulic calculations, accurate geometric modelling, and full integration with all structures and utilities. This stage incorporates refined survey data, construction constraints, and field-verified conditions. In practice, final designs often diverge from planning assumptions due to earthworks, unforeseen groundwater conditions, undocumented drainage features, or third-party interventions. Iterative refinement becomes necessary as new information emerges. Light infrastructure projects, which frequently proceed in phases and evolve over time, particularly benefit from flexible design frameworks capable of accommodating such uncertainties.

The Role of Building Information Modelling (BIM)

Building Information Modelling (BIM) has emerged as a powerful tool for bridging the gap between planning and detailed engineering. Traditional two-dimensional CAD systems struggle to represent the spatial and functional complexity of drainage systems interacting with roads, trenches, foundations, and utility networks. BIM environments integrate three-dimensional terrain models, hydrological parameters, structural components, and construction sequencing within a unified digital platform. This integration enhances interdisciplinary coordination, reduces design conflicts, and supports intelligent documentation management (Li and Jing, 2019; Wei et al., 2017). Moreover, BIM has been shown to improve efficiency and reduce costs by enabling rapid scenario testing and automated updates (Chen, 2024; Wen and Wang, 2023).

Automated Watershed and Flow-Path Analysis

One of the most significant capabilities of BIM-enabled platforms is automated watershed and flow-path analysis. Catchment boundaries and runoff trajectories can be generated directly from digital terrain models, allowing designers to visualize how water traverses a site and how proposed modifications may alter flow distribution. As terrain surfaces are modified by roads, embankments, trenches, or foundations, hydrological models update dynamically. Parametric design tools enable drainage components—such as ditches, culverts, and low-water crossings—to be dimensioned using embedded formulas, ensuring that changes in slope, rainfall intensity, or catchment area automatically recalibrate hydraulic capacity.

Hydrological and Hydraulic Methodologies

Despite advances in modelling environments, hydrological and hydraulic calculations remain fundamental. For small catchments, the Rational Method is widely used to estimate peak discharge, with regional adaptations reflecting local climatic and regulatory conditions (Koutsoyiannis, 2011). Runoff coefficients depend on soil type, land cover, and slope characteristics and must be calibrated to local standards (Asare-Kyei et al., 2015). Time of concentration is commonly determined using empirical relationships such as those proposed by Giandotti (1934), Kirpich (1940), or the California Culverts method (1942), often adopting conservative values to reflect worst-

case conditions. Rainfall intensity is derived from intensity–duration–frequency (IDF) curves, maximum daily rainfall data, and frequency coefficients. Hydraulic design of channels and culverts typically relies on Manning’s equation to determine flow velocity, hydraulic radius, and conveyance capacity, ensuring safe passage of design flows without erosion, overtopping, or structural instability.

Erosion, Infiltration, and Soil Stability

Erosion and infiltration processes are particularly significant for light infrastructure, which frequently disturbs soil cover and vegetation. Compacted surfaces and temporary construction works can increase runoff rates and accelerate soil loss, while altered soil structure may reduce infiltration capacity. Predictive tools such as the Revised Universal Soil Loss Equation (RUSLE) and infiltration models like Horton’s equation support evaluation of sediment transport and infiltration dynamics. Mitigation measures—including vegetated swales, check dams, erosion control blankets, and controlled discharge systems—help preserve geomorphological stability and environmental performance.

Data Limitations and Progressive Refinement

A recurring challenge in early-stage planning is incomplete or inconsistent topographical data, particularly concerning upstream catchments. Limited survey coverage can obscure potential external water contributions, increasing uncertainty in runoff estimation. While approximate terrain data may support conceptual design, detailed surveys are indispensable prior to construction. Inadequate early-stage information can lead to significant redesign once accurate field data become available, emphasizing the importance of progressive data refinement.

Regulatory and Geographic Variability

Regulatory and geographic variability further influence drainage methodologies. Jurisdictions with stringent water-management frameworks require comprehensive modelling and strictly prohibit adverse impacts on neighboring properties, often necessitating high-precision design from the outset. In regions with more flexible regulatory environments, conceptual-level data may initially suffice, though final engineering still demands rigorous hydraulic verification. Designers must therefore adapt their analytical depth and documentation standards to local requirements while maintaining technical integrity.

Adaptive and Resilient Drainage Design

Perhaps the most important principle in contemporary drainage design is adaptability. Even with advanced digital tools and detailed hydrological modelling, unforeseen conditions frequently emerge during construction and operation. Unexpected water accumulation, altered ground levels after earthworks, undocumented drainage obstructions, inaccurate infiltration assumptions, or utility relocations can necessitate iterative redesign. Continuous feedback between field observations and digital models enables progressive optimization and strengthens system resilience.

Conclusion

In summary, effective drainage planning and design for light infrastructure require a holistic, data-driven, and adaptive methodology integrating hydrological analysis, topographical modelling, soil assessment, and interdisciplinary coordination. BIM technologies provide a powerful platform for unifying these components, supporting simulation, conflict detection, and iterative refinement throughout the project lifecycle. Nevertheless, the ultimate performance of drainage systems depends on accurate site data, region-specific hydrological methods, regulatory compliance, and ongoing field validation. As climate change intensifies hydrological extremes and infrastructure networks become increasingly interconnected, robust and adaptive drainage strategies will remain essential for safeguarding the functionality, durability, and resilience of light infrastructure systems.

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