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HYDROLOGICAL MODELLING FOR SUSTAINABLE RURAL AND URBAN LANDSCAPES IN LATVIA

Anda Bakute[1], Inga Grīnfelde[1], Marcel Groosman[2]

[1]Latvia University of Life Sciences and Technologies, Latvia
GT&O Groosman Techniek en Organisatie, The Netherlands

Abstract. Effective landscape planning requires a comprehensive understanding of how land use affects hydrological processes - especially in regions such as Latvia, where climate change, urbanisation, and fragmented hydrological data complicate decision-making. This study applies the METQ conceptual rainfall–runoff model to three representative Latvian catchments (Iecava, Pērse, and Imula), each characterised by differing forest, agricultural, and urban land use patterns. Using long-term hydrometeorological data and detailed land cover classifications, the model was calibrated and validated to simulate daily runoff dynamics and explore the influence of land use on flood risk and water balance. Results indicate that forested and semi-natural areas attenuate peak flows and enhance baseflow retention, while intensively cultivated and urbanised landscapes increase surface runoff and flood potential. Scenario simulations further reveal that even small increases in impervious area can significantly elevate peak discharge, whereas the implementation of green infrastructure can mitigate these effects. The study demonstrates that METQ provides reliable, spatially explicit hydrological insights that support sustainable land use planning, particularly in data-scarce contexts. The findings emphasise the importance of incorporating hydrological models into spatial planning and environmental assessment processes. Such integration allows planners and designers to visualise the consequences of development decisions, evaluate alternative land use configurations, and enhance landscape resilience in the face of climate change. The approach presented here offers a transferable model for landscape planning in other Baltic and Northern European regions facing similar socio-environmental challenges.

Keywords: Hydrological modelling, Sustainable landscape planning, Land use impact, Flood risk management, METQ model

Introduction

Sustainable landscape planning depends on understanding how water moves through the landscape. Hydrology connects cities, farmland, forests, and wetlands, shaping both ecological health and human safety. In Latvia, as in much of the Baltic region, climate change is disrupting this balance by altering rainfall patterns and snowmelt timing [1]. These changes are increasingly influencing river flow patterns—raising concerns about flood risks, water security, and ecosystem stability.

At the same time, urbanisation and land use change are placing additional pressure on water systems. As cities expand and rainfall intensifies, localised flooding becomes more common, especially in built-up areas with poor drainage. Vulnerable communities often suffer the most from these events. This has led to stronger policy responses, such as the EU Floods Directive (European Parliament and Council of the European Union, 2007), which requires all member states to map and manage flood risks.

In this context, planners and landscape architects must design environments that can absorb hydrological extremes and adapt to long-term change. However, Latvia's fragmented and sometimes outdated hydrological data—particularly river discharge records—limit the capacity for informed decision-making.

To fill these gaps, hydrological models offer an essential tool. They allow the simulation of river responses to different weather and land use scenarios, even in areas with limited monitoring. Conceptual rainfall–runoff models have been widely adopted to simulate catchment-scale hydrological processes under varying conditions. These models provide a flexible and interpretable means of representing runoff generation, as discussed in foundational works by Beven (2012) and Seibert (1999).

In Latvia, one such model is the METQ series. Originally created in the 1990s by Zīverts and Jauja, METQ has evolved through several versions—METQ96, METQ98, METQ2007BDOPT, and METQUL2012—each improving its accuracy and adaptability. In practice, METQ is applied from 5 km² up to 2000 km² as a single lumped/semi-distributed model. For larger basins, it is operated as a network of sub-basins with routing, which preserves scalability and performance while maintaining conceptual parsimony [15; 1; 2; 6].

Land use plays a central role in how water moves through a catchment. Latvia is roughly half forested, with the remainder made up of farmland, wetlands, and urban areas. Each land type influences hydrological responses differently. Forests tend to absorb and store water, while urban surfaces increase runoff. Wetlands act as natural sponges, and agricultural areas vary widely depending on soil management.

Hydrological models help quantify these effects and offer planners insights into the potential outcomes of different land use strategies. For example, simulations can reveal how forest conservation or wetland restoration might reduce flood peaks, or how unchecked urban development could worsen surface runoff and degrade water quality.

Despite the availability of hydrological models like METQ, there is limited understanding of how varying land use conditions—from forested uplands to intensively managed lowlands—affect runoff and streamflow dynamics in Latvian river basins. The aim of this study is to demonstrate how hydrological modelling can support sustainable planning and landscape design—not only in Latvia, but in other regions of temporal climate facing similar challenges.

Materials and Methods

Study Area and Land Use Data

This study focuses on three river basins in Latvia—Iecava, Pērse, and Imula. These catchments were selected due to their contrasting land use patterns, ranging from forested to agricultural and mixed-use landscapes, which provide a representative basis for assessing land use impacts on hydrological processes. Additionally, their relevance to both rural and urban planning makes them suitable case studies for evaluating model performance under varying environmental conditions. The Iecava River basin, located in southern Latvia, is the largest of the three. Its area ranges from approximately 1,100 to 1166 km² depending on how the basin is defined. The landscape is mostly rural, with about 60 % covered by

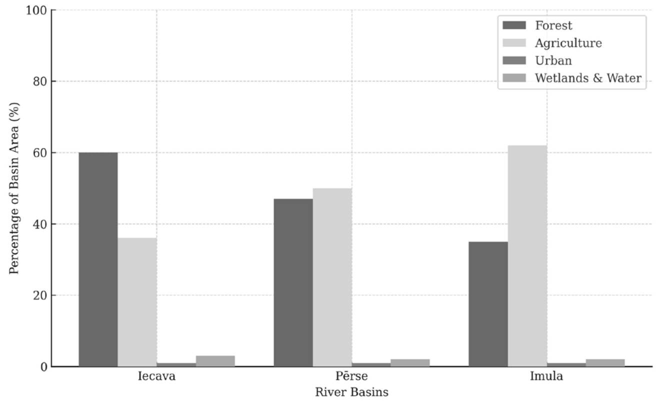

Fig. 1. Land use composition of the Iecava, Pērse, and Imula river basins.
Forest and agricultural land dominate across all basins, while urban and wetland areas represent minor proportions [created by authors, 2025]

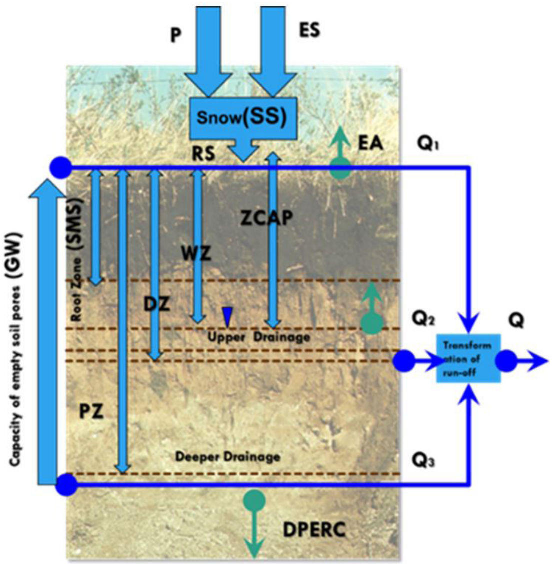

Fig. 2. Conceptual structure of the metq hydrological model [Grīnfelde & Bakute, 2017]. The model includes p- precipitation, mm/day; es- evapotranspiration from snow, mm/day; ss-snow storige, mm; rs-rain and snow melt water, mm/day; ea- evapotranspiration from the root zone, mm/day; zcap- height of capillary rise, cm; wz- depth of the groundwater level (cm); dz-depth of the upper level "drain" (cm); pz-characterises the depth of the lower level "drain"; sms- water storage in the root zone, mm; gw- capacity of empty soil pores, mm; q1- surface runoff, mm/day; q2- upper layer subsurface runoff, mm/day; q3- the base flow, mm/day ; dprec- deep percolation to the aquifers, mm/day

forest and 36 % by agriculture. Urban areas are minimal- less than 1 %—and consist mainly of the town of Iecava and a few small settlements. Wetlands and open water bodies make up the remaining land cover.

In contrast, the Pērse basin, located in the hilly uplands, has a more balanced mix of forest and agriculture. Forests cover around 47 % of its 329 km^2 area [2]. Meanwhile, the Imula basin, situated in the lowlands, is more intensively cultivated, with 62 % of its 263 km^2 area used for farming. This variation provides a valuable testbed for examining how different land uses affect hydrological behaviour.

For modelling purposes, land use was grouped into six categories:

- **Urban** (buildings, roads, infrastructure)
- **Agriculture (**fields and pastures)
- **Forests** (broadleaf, coniferous, and mixed types)
- **Wetlands** (bogs and marshes)
- **Water bodies** (rivers and lakes)

Each category was mapped and quantified in square kilometres, then used to define the parameters of the model's hydrological response units (HRUs). Forest areas were assigned higher infiltration and evapotranspiration values, while urban zones were modelled with reduced absorption and higher runoff rates. This configuration allowed the model to accurately represent the spatial heterogeneity of land cover and its influence on runoff. Figure 1 shows the proportion of each land use type in the three study basins.

Hydrological Model: METQ

The METQ model, originally developed by A. Zīverts in collaboration with I. Jauja in the early 1990s, is a conceptual hydrological model designed to simulate daily streamflow based on rainfall, snowmelt, evapotranspiration, and soil storage processes [15].It was specifically formulated for the hydrological conditions of Latvia and has since been extended through multiple versions—each improving its capacity to represent different land use and climate scenarios.

In this study, the METQ2007BDOPT version was applied, which includes a semi-automatic calibration module [2].The model also incorporates parameter extensions introduced in METQUL2012, including a dedicated urban hydrological response unit [6], allowing the simulation of spatially differentiated runoff behaviour.

The model represents the hydrological cycle using a series of storage compartments for snow, soil moisture, and groundwater. Snow accumulation and melt are simulated using a temperature-index method. Rainfall or snowmelt first infiltrates the soil, up to a maximum storage capacity. When the soil is saturated, excess water generates surface runoff (Q1). Water that infiltrates further contributes to subsurface flow (Q2) and groundwater baseflow (Q3).

Figure 2 illustrates the model's structure, showing how inputs are transformed into streamflow components.

Key model parameters include:

- **ALFA** (soil porosity),
- **ZCAP** (capillary rise),
- **CMELT** (snowmelt rate).

These parameters were adjusted based on land use and soil type. For example, sandy forest soils were given higher ALFA values, while clay-rich agricultural soils received higher ZCAP values to reflect greater moisture retention. Urban areas were modelled with lower infiltration and storage capacity, consistent with observed behaviour in similar contexts [6].

Data and Calibration

Hydrological and meteorological data were obtained from the Latvian Environment, Geology and Meteorology Centre. Discharge data came from gauging stations at Iecava–Dupši, Imula–Pilskalni, and Pērse–Ūsiņi. Simulations were run over long-term periods (30–50 years), divided into calibration (e.g., 1960–1990) and validation (e.g., 1991–2015) phases.

Model calibration combined manual parameter tuning with semi-automated optimisation. Parameters were constrained using available land use and soil data. Performance was

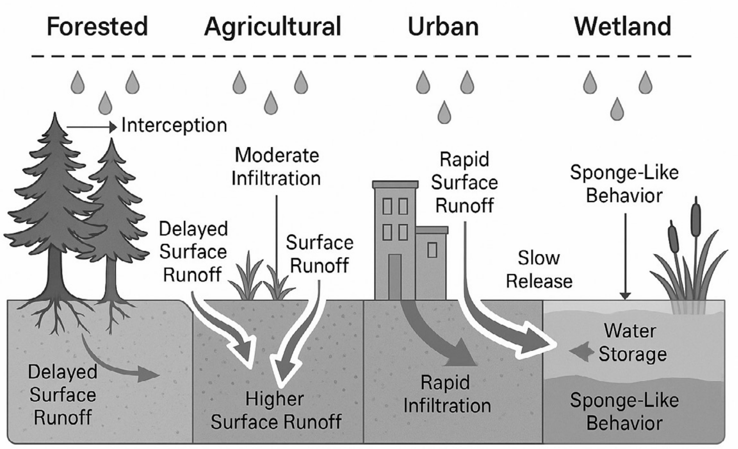

Fig. 3. Conceptual illustration of runoff generation under different land uses. Forested and wetland areas delay and reduce runoff, while agricultural and urban surfaces accelerate surface runoff due to reduced infiltration and increased imperviousness [created by authors, 2025]

evaluated using standard metrics:

- **Nash–Sutcliffe Efficiency (NSE);**
- **Pearson correlation coefficient (r);**
- **Bias.**

Typical NSE values ranged from 0.65 to 0.75, with r values near 0.8 - indicating reliable performance [2].

To explore future land use impacts, scenario simulations were also conducted. These tested how changes in urbanisation or green infrastructure might affect runoff and flood peaks. The results of these scenarios are discussed in subsequent sections.

Results

Model Performance and Runoff Simulation

The METQ model was successfully calibrated for the Iecava, Pērse, and Imula catchments, producing a good agreement between simulated and observed daily streamflow.

Land use differences among the catchments, shown in Figure 2, underpinned variations in runoff dynamics. Model performance met established thresholds for conceptual models (Moriasi et al., 2007; Gupta et al., 2009). The Nash–Sutcliffe Efficiency (NSE) ranged from 0.65 to 0.70, and Pearson correlation coefficients (r) were between 0.75 and 0.85. These values indicate a satisfactory level of predictive reliability.

While the model occasionally underestimated sharp peak flows during intense rainfall, seasonal patterns—such as spring snowmelt and summer low flows—were reproduced with accurate timing and magnitude. These underestimations are consistent with known limitations of lumped conceptual models in representing fine-scale urban runoff dynamics.

The calibration process revealed that key model parameters were closely linked to landscape characteristics. For example:

- In the Iecava basin, dominated by forests and sandy soils, higher soil porosity (ALFA) supported infiltration and delayed runoff.
- The Pērse basin, with heavier clay soils, showed higher capillary rise (ZCAP), indicating saturation-excess runoff tendencies.
- In the agriculturally dominated Imula basin, compacted soils and lower infiltration rates led to a faster and more pronounced surface runoff response.

These findings confirm the model's capacity to reflect how land use and soil properties shape catchment hydrology.

Influence of Land Use on the Hydrological Regime

Model outputs and parameter sensitivity analysis confirmed that land use exerts a clear influence on catchment-scale hydrology.

Forested catchments, such as Iecava and Pērse, exhibited attenuated hydrographs with delayed peaks and more sustained baseflows. These effects reflect the known buffering role of forest ecosystems, which promote infiltration and evapotranspiration [14].

By contrast, the Imula basin, with over 60% of land in cultivation, generated quicker runoff responses. Rainfall in this basin was converted more rapidly into direct runoff (Q1) and shallow interflow (Q2), particularly due to reduced infiltration capacity and increased surface drainage—common in intensively managed agricultural landscapes.

Urban areas, although covering less than 1% of basin area, had a disproportionate impact on runoff. Urban hydrological response units (HRUs) generated rapid surface flows during storm events, producing earlier and steeper hydrograph peaks [6].

Figure 3 provides a conceptual illustration summarising these observed differences in runoff generation mechanisms associated with forested, agricultural, urban, and wetland land uses.

As shown, forested and wetland areas effectively delay runoff through interception, infiltration, and sponge-like water storage. Conversely, agricultural and urban landscapes exhibit accelerated runoff due to reduced infiltration and higher surface imperviousness.

To evaluate the hydrological implications of potential land use changes, scenario simulations were conducted. These indicated that:

- A 5–10 % increase in urbanised land could raise peak discharges by up to 15% in the Iecava and Imula basins.
- The implementation of green infrastructure (e.g. retention ponds, permeable pavements) could reduce peak flows by 5–8 % [16].

These results are summarised in Figure 4 and underline the importance of incorporating land use impacts into flood risk and spatial planning strategies.

Discussion

Integrating Hydrology into Landscape Planning

This study has demonstrated that conceptual hydrological models such as METQ are valuable tools for linking catchment-scale hydrological processes with landscape planning practice. Model calibration with detailed land use data provided quantitative evidence of how variations in Latvian landscapes influence runoff response.

Importantly, the findings illustrate that identical rainfall inputs can produce markedly different runoff outcomes depending on land cover. Forested zones in the Iecava basin, for instance, consistently moderated flood peaks more effectively than agricultural or urban areas. These results reinforce the hydrological significance of forest conservation in landscape planning [14].

Therefore, planners should prioritise preserving forests, riparian buffers, and wetlands to enhance flood mitigation and improve

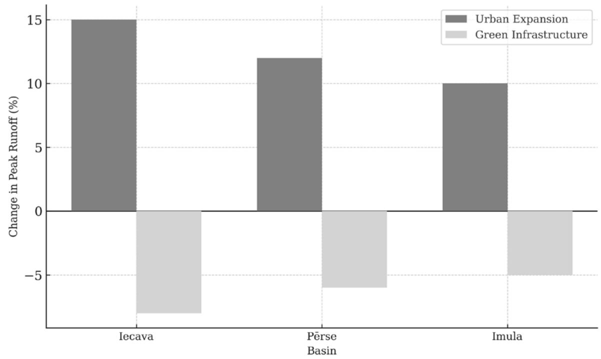

Fig. 4. Simulated changes in peak runoff under urban expansion (+10% impervious area) and green infrastructure implementation.
Values represent relative change in peak discharge for the Iecava, Pērse, and Imula river basins [created by authors, 2025]

water retention. In urban contexts, green infrastructure - such as bioswales, rain gardens, and permeable surfaces - offers a cost-effective and ecologically sound strategy for mitigating increased run off. Based on the modelling evidence, it is recommended that hydrological impact assessments become a standard component of land conversion projects, especially where deforestation or urban expansion is proposed

Rural–Urban Coordination

The results also underscore the need for better coordination between rural and urban land use planning. Hydrological processes do not adhere to administrative boundaries: surface runoff generated in upstream rural areas can affect downstream urban flood risk, and vice versa.

Restoring forest cover in headwaters or maintaining wetlands in agricultural zones may yield more sustainable outcomes compared to investments in large-scale downstream flood infrastructure. Likewise, poor urban stormwater practices can influence stream baseflow and nutrient loads in rural areas.

Catchment-scale planning offers a solution to these interconnected challenges [12]. The METQ model proved useful for simulating these interactions and can serve as a decision-support tool to promote cross-boundary planning cooperation.

Climate Resilience and Land Use

Projected climate changes for Northern and Eastern Europe - including increased winter precipitation, earlier snowmelt, and more frequent extreme rainfall events—are expected to amplify hydrological risks [8; 4]. These risks are particularly acute in areas where natural buffering features have been degraded or removed.

The modelling results confirm that land use significantly shapes hydrological response, making it a critical lever for climate resilience planning. Forests and wetlands provide low-regret adaptation benefits by absorbing stormwater and delaying runoff. In this context, strategic landscape management - guided by model-informed scenario analysis - should become a central pillar of local and regional adaptation efforts.

Extending the Role of Hydrological Modelling

Although this study focused on runoff quantity, land use also influences water quality, particularly through agricultural nutrient runoff. While METQ was not used here for modelling water quality, its conceptual design allows for potential integration with nutrient transport modules.

Such a coupling would support multi-objective planning, enabling assessment of both flood reduction and water quality benefits from measures such as wetland restoration or reduced tillage.

Future work should explore these opportunities, aligning with calls for integrated hydrological–ecological modelling in planning practice [16; 12].

Model Limitations and Planning Implications

As with all conceptual models, METQ involves simplifications. Its spatial generalisation limits its ability to simulate detailed urban drainage infrastructure, such as culverts or stormwater tanks [7]. Furthermore, scenarios extending beyond calibration conditions introduce parameter uncertainty.

Land cover data must also be regularly updated to ensure modelling accuracy. The growing availability of high-resolution satellite imagery—particularly through EU platforms such as Copernicus—offers practical solutions for this.

Despite these limitations, the METQ model provides robust, interpretable outputs that can inform strategic planning. Used appropriately, it enables decision-makers to explore sustainable land use configurations and visualise the hydrological impacts of development.

Conclusion

This study has demonstrated that effective landscape planning in Latvia—and across comparable Baltic contexts - depends on a clear, integrated understanding of catchment-scale hydrological processes.

By applying the METQ conceptual hydrological model to three contrasting river basins, the influence of different land use configurations on runoff generation, peak flows, and water balance was evaluated.

The model was successfully calibrated using long-term observational data, achieving satisfactory predictive performance across rural, forested, and agriculturally dominated catchments. These results confirm METQ's suitability as a decision-support tool for sustainable land use planning, especially in regions with incomplete hydrological records.

Forested and semi-natural areas were shown to moderate surface runoff, support infiltration, and sustain baseflows, while intensively cultivated and urbanised landscapes were found to accelerate runoff and produce elevated peak discharges. Even minor expansions in impervious surfaces resulted in disproportionate impacts on flood dynamics. Conversely, the implementation of green infrastructure measures—such as retention ponds and permeable pavements—was associated with measurable reductions in peak flows.

These findings reinforce the importance of preserving forests, wetlands, and floodplains as natural buffers and of integrating green infrastructure into urban design. They also highlight the value of hydrological modelling in assessing land use trade-offs and supporting evidence-based planning.

Hydrological impact assessments, supported by models such as METQ, should be integrated into spatial planning processes, especially when evaluating significant land conversion proposals. This would ensure that the hydrological consequences of development are understood and mitigated in advance, reducing long-term risks to both communities and ecosystems.

Maintaining accurate and current input datasets—particularly land cover, meteorological, and streamflow data—is critical for continued model reliability. Open-access platforms such as Copernicus should be leveraged to ensure that modelling remains up to date and responsive to landscape change.

The need for interdisciplinary collaboration between hydrologists, landscape architects, planners, and engineers is emphasised. Although hydrological models can be technically complex, their outputs can be effectively translated into actionable guidance for policy and design. When used collaboratively, models such as METQ enable more resilient, multifunctional landscapes that balance ecological integrity, flood protection, and human development.

This study demonstrates that conceptual hydrological modelling provides a practical and scientifically grounded framework for guiding sustainable land use decisions in Latvia. The approach and insights presented here are relevant not only to national planning efforts but also to broader regional challenges across the Baltic and Northern Europe. Integrating hydrology into landscape architecture will be increasingly essential to support the development of resilient and sustainable landscapes under intensifying climate and land use pressures.

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Authors

Anda Bakute, Mg.geogr., Researcher, hydrologist is a researcher at the Latvia University of Life Sciences and Technologies, Institute of Landscape Architecture and Environmental Engineering. Her academic and research activities are focused on hydrology, water management, and environmental modelling, with a particular emphasis on the conceptual hydrological model METQ and its application in river basin studies. Her research supports the advancement of sustainable water management and the integration of hydrological modelling into environmental decision-making processes. E-mail: anda.bakute@lbtu.lv
ORCID ID: https://orcid.org/0000-0001-6275-0227

Inga Grīnfelde, Ph.D., Mg.paed. Associated professor, Expert in hydrology, Academic and research experience for more than ten years, currently working at the Institute of Landscape Architecture and Environmental Engineering, Latvia University of Life Sciences and Technologies. Her main research interests include air pollution, soil contamination, and environmental quality assessment.
E-mail: inga.grinfelde@lbtu.lv
ORCID ID: https://orcid.org/0000-0002-3220-1777

Marcel Groosman, MSc TU Delft, Managing Director, GT&O Groosman Techniek en Organisatie, The Netherlands. He is a managing director and senior technical consultant. He has over fifty years of professional experience in technical project management, environmental engineering, and sustainable infrastructure development. His expertise covers energy-efficient technology implementation, and organizational optimization for industrial and municipal projects. Marcel has led and coordinated numerous international collaborations focusing on green technology innovation, circular economy solutions, and sustainable resource use.
E-mail: mgroosman@zonnet.nl

Kopsavilkums

Efektīva ainavu plānošana prasa padziļinātu izpratni par to, kā zemes izmantošana ietekmē hidroloģiskos procesus, īpaši Latvijā, kur klimata pārmaiņas, urbanizācija un nepilnīgi hidroloģiskie dati apgrūtina lēmumu pieņemšanu. Pētījumā izmantots konceptuālais hidroloģiskais modelis METQ, lai analizētu trīs Latvijas upju baseinus – Iecavas, Pērses un Imulas, kas atšķiras pēc mežu, lauksaimniecības un pilsētu teritoriju proporcijas. Modelis kalibrēts un validēts, izmantojot ilgtermiņa hidroloģiskos un meteoroloģiskos datus, lai modelētu diennakts noteci un novērtētu zemes izmantošanas ietekmi uz plūdu risku un ūdens bilanci. Rezultāti parāda, ka mežaini un daļēji dabīgi apgabali samazina virszemes noteci un aiztur plūdus, savukārt intensīvi apstrādātas un urbanizētas teritorijas palielina plūdu risku. Pat neliels necaurlaidīgo virsmu pieaugums ievērojami palielina noteces maksimumus, bet zaļā infrastruktūra – lietus dārzi, caurlaidīgi segumi, dīķi – spēj mazināt šos efektus. Pētījums pierāda, ka METQ modelis sniedz ticamus, telpiski diferencētus hidroloģiskus datus, kas ir noderīgi ilgtspējīgai teritoriju plānošanai un klimata riska pārvaldībai. Modelēšanas rezultāti uzsver nepieciešamību saglabāt mežus, purvus un piekrastes buferzonas, kā arī iekļaut hidrologisko analīzi teritoriju attīstības plānos. Autori iesaka hidroloģiskās ietekmes novērtējumus integrēt kā obligātu daļu teritoriju plānošanas un zemes izmantošanas veida maiņas projektos, nodrošinot līdzsvaru starp ekosistēmu funkcijām, plūdu aizsardzību un ekonomisko attīstību. Pētījums apliecina, ka hidroloģiskā modelēšana ir praktisks un zinātniski pamatots rīks ilgtspējīgas ainavu plānošanas nodrošināšanai Latvijā un citos Baltijas reģiona kontekstos. Šī pieeja palīdz stiprināt ainavu noturību pret klimata pārmaiņām, nodrošina ūdens resursu ilgtspējīgu izmantošanu un atbalsta starpdisciplināru sadarbību starp hidrologiem, ainavu arhitektiem, plānotājiem un inženieriem.