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OPERATION AND MAINTENANCE OF BRIDGE DRAINAGE SYSTEMS ALONG THE SAVA RIVER IN BELGRADE

Summary: This paper assesses the operational performance of drainage systems on four road bridges over the Sava River in Belgrade: Branko's, Gazela, Ada Ciganlija, and Ostružnica. Field inspections identified deficiencies related to original design, subsequent modifications, ageing drainage infrastructure, structural and pavement deformations, and inadequate maintenance, all of which can significantly reduce drainage effectiveness. Particular attention is given to the Gazela Bridge, where hydraulic analysis showed that an average structural deflection of 14 cm reduces flow velocities in drainage pipes by about 10% for the 10-year design storm, increasing the potential for sediment deposition and pipe blockage. The four cases demonstrate that drainage functionality can be compromised at different stages of the bridge life cycle. The paper highlights the need for continuous inspection of structural and drainage components and performance-based maintenance.

Keywords: bridge drainage systems, drainage effectiveness, bridge maintenance, stormwater management, structural deformation, stormwater treatment

FUNKCIONISANJE I ODRŽAVANJE SISTEMA ZA ODVODNJAVANJE MOSTOVA PREKO REKE SAVE U BEOGRADU

Rezime: Rad razmatra eksploataciju sistema za odvodnjavanje na četiri mosta preko Save u Beogradu: Brankov, Gazela, na Adi Ciganliji i kod Ostružnice. Inspekcija in situ pokazala je da postoje problemi vezani za njihove prvobitne projekte, naknadne izmene, starenje infrastrukture, deformacije konstrukcije i kolovoza i nedovoljno održavanje, što sve može da smanji efikasnost odvodnjavanja. Posebna pažnja posvećena je Gazeli, gde je analiza pokazala da prosečan ugib mosta od 14 cm smanjuje brzine vode u kanalizacionim cevima za oko 10% pri 10-godišnjim kišama, što povećava taloženje nanosa i rizik od zapušavanja cevi. Primeri četiri mosta pokazuju da se funkcionalnost odvodnjavanja može narušiti u različitim fazama životnog veka objekta. Rad naglašava potrebu za kontinuiranim inspekcijama konstrukcije i sistema za odvodnjavanje, kao i održavanje u skladu sa realnim funkcionisanjem sistema.

Ključne reči: odvodnjavanje mostova, efikasnost odvodnjavanja, održavanje mostova, upravljanje kišnim vodama, deformacije mostovske konstrukcije, tretman kišnog oticaja

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1. INTRODUCTION

The criteria and requirements for the design of bridge drainage systems have evolved from treating drainage as a minor structural detail to a complex discipline [1]. Historically, bridge drainage design focused only on rapid removal of stormwater from bridge decks. Contemporary practice adopts a holistic approach that balances traffic safety, structural integrity and durability, environmental protection through runoff treatment, maintenance minimization, and architectural aesthetics [1,2,3]. This evolution is reflected in design guidance in the USA, from FHWA HEC-12 to HEC-21 and HEC-22 [4]. The UK standards (CD350, CD357, CD358) similarly prioritize structural durability and whole-life cost by integrating surface and subsurface drainage, protection of critical structural components from water and salt ingress, and rigorous maintenance requirements [5]. Serbian national design guidelines for bridge drainage were established recently, in 2012 [6], and are focused predominantly on the hydraulic performance.

The bridges over the Sava River serve as the principal transport corridors in the City of Belgrade (Figure 1). At the same time, they are located within the immediate protected zone of the Belgrade water supply source area. Consequently, storm runoff from carriageways, sidewalks, and other traffic surfaces must be controlled and, where necessary, treated before being discharged into the receiving water body. Among the existing Belgrade bridges, only the Gazela Bridge has a complete integrated storm drainage and treatment system. The objective of this paper is to present the current condition of drainage systems on the major road bridges crossing the Sava River in Belgrade, based on field inspections, identify the principal operational and maintenance issues affecting their performance, and highlight the measures required to improve their long-term reliability.

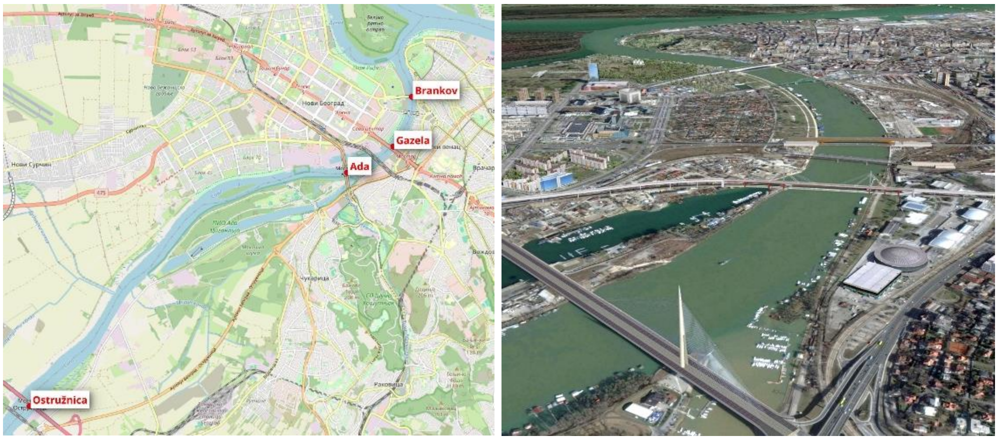

Figure 1: Bridges across the Sava River in Belgrade considered in this paper (left) and a view from the Ada Bridge toward the Gazela and Branko's Bridges (right)

2. DESIGN REQUIREMENTS FOR BRIDGE DRAINAGE SYSTEMS

Bridge drainage design is a unique engineering challenge that depends on local rainfall characteristics, wind conditions, ice formation potential, maintenance requirements, and other site-specific factors. Its primary goal is to efficiently remove surface runoff before it accumulates on the deck or enters travel lanes [1,2]. This requires proper selection of pavement slopes, inlet types and spacing, gutter spread control, and hydraulic design that ensures self-cleansing velocities in the conveyance system [1,2,4]. Hydrological design must rely on local meteorological data and appropriate design storms, with a return period of at least 10 years [4] and short durations (e.g., 5-minute intensities) that are critical for inlet capacity [1,7,8]. Since bridge decks are impervious, runoff should be computed with a runoff coefficient of 1.0, meaning that all rainfall becomes runoff [9]. Using longer storm duration (and lower average rainfall intensities) may underestimate peak runoff rates and increase the risk of ponding.

Uncontrolled runoff is a severe threat to the bridge structural integrity, acting as a primary facilitator of structural deterioration [2]. De-icing chemicals can cause rapid steel corrosion, concrete reinforcement decay, and spalling of bridge elements [10]. Therefore, drainage systems must capture and direct water completely away from vulnerable structural elements. Inlets must be positioned to intercept gutter flow before it reaches expansion joints to prevent concrete staining, chemical attacks, and cracking [2]. The piping system must also accommodate bridge deflections and expansion under traffic load and temperature changes [2]. Additionally, underdeck pipelines are typically aligned with structural lines of the bridge for aesthetic reasons.

Bridges over waterways are subject to strict environmental regulations because bridge runoff contains sediments, microplastics, heavy metals, de-icing chemicals and other pollutants [11]. Environmental considerations therefore guide the selection between open and closed drainage systems [2]. While open systems such as drainage openings through the bridge structure may be acceptable where runoff can be safely discharged, closed systems are required above sensitive waters. In such cases, collected runoff is conveyed to treatment facilities or stormwater control measures such as detention basins or infiltration trenches, where sediments and pollutants are removed before being discharged to the environment [4,12].

Operational performance is equally important. Evidence shows [2] that debris-induced inlet clogging is the most common failure point of bridge drainage systems, followed by the clogging of pipes at bends or due to undersized diameters, as well as corrosion of pipes and inlets. Even well-designed drainage system cannot perform adequately without proper maintenance. Modern practice therefore emphasizes accessible layouts, durable materials, and standardized design details that facilitate efficient inspection and cleaning throughout the bridge service life [2].

3. BRIDGES ACROSS THE SAVA RIVER IN BELGRADE AND THEIR DRAINAGE SYSTEMS

3.1. BRANKO’S BRIDGE

Branko's Bridge has a drainage system with an unsatisfactory level of performance. Surface runoff is collected through a series of relatively small openings within the bridge structure, each with a diameter of 12 cm (Figure 2). However, long-term pavement deterioration, including rutting, potholes, localized depressions, and surface irregularities, significantly impedes runoff concentration toward the curbs and the drainage inlets. As a result, water accumulates and spreads over the pavement during intense rainfall and is splashed by passing vehicles, adversely affecting traffic safety and driving conditions. An additional problem is its relatively small cross slope, which prevents part of the runoff from being effectively directed toward the drainage openings.

Figure 2: Drainage openings in the structure of the Branko’s bridge and pavement deformations prevent effective drainage even during relatively moderate rainfall events

The unrestricted discharge of runoff through the openings is therefore highly inefficient. Furthermore, based on the authors' experience with the Gazela Bridge, it can reasonably be assumed that this drainage practice contributes to corrosion and deterioration of the underside of the bridge structure. It can therefore be concluded that detailed inspections and comprehensive rehabilitation of the bridge drainage system are required.

3.2. GAZELA BRIDGE

The Gazela Bridge is the only bridge across the Sava River in Belgrade where an integrated runoff collection and treatment system was implemented during the bridge rehabilitation between 2010 and 2012 [13]. Prior to rehabilitation, the bridge experienced numerous problems associated with uncontrolled stormwater discharge, deterioration of drainage components, and progressive degradation of structural elements caused by water and the dissolved aggressive substances. Figure 3 (left and centre) illustrates the condition of the underside of the bridge deck near the drainage outlets before rehabilitation, while Figure 3 (right) shows a curb inlet grate on the bridge deck. Uncontrolled runoff carrying pollutants are washed from the pavement (including oils, grease, and de-icing chemicals) and flow over the bridge structure, contributing to corrosion and deterioration of its steel elements (Figure 4).

Figure 3: Components of the Gazela Bridge drainage system (drainage openings, outlets, and inlet grates) prior to the 2012 rehabilitation

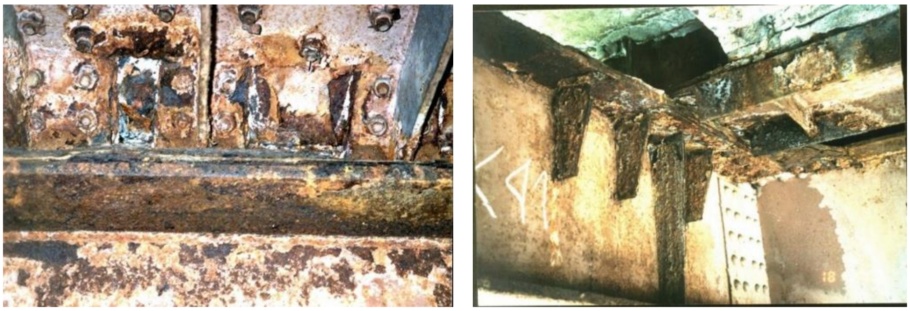

Figure 4: Condition of the Gazela Bridge structure resulting from corrosion of the steel box girders prior to the 2012 rehabilitation

As a part of the rehabilitation works, high-capacity drainage inlets with openings in both curb and pavement were installed for efficient stormwater collection (Figure 5, left). Their hydraulic capacity had previously been thoroughly tested under laboratory conditions [7]. A dedicated pipeline system was constructed to convey runoff to a treatment facility (Figure 5, right), together with an emergency response system designed to prevent the discharge of heavily contaminated runoff in the case of accidental pollution (see also section 5). To satisfy aesthetic requirements, visible stormwater drainage pipes were designed with a uniform diameter of 300 mm along the entire pipeline length and were installed parallel to the edge of the bridge deck using both horizontal and vertical anchors [13].

However, operational experience has shown that even modern drainage systems require continuous maintenance. More than a decade of service upon the rehabilitation, drainage inlets and expansion joints are subject to deformation, while sediment accumulation within the treatment filters has reduced their hydraulic capacity and treatment efficiency (Figure 5).

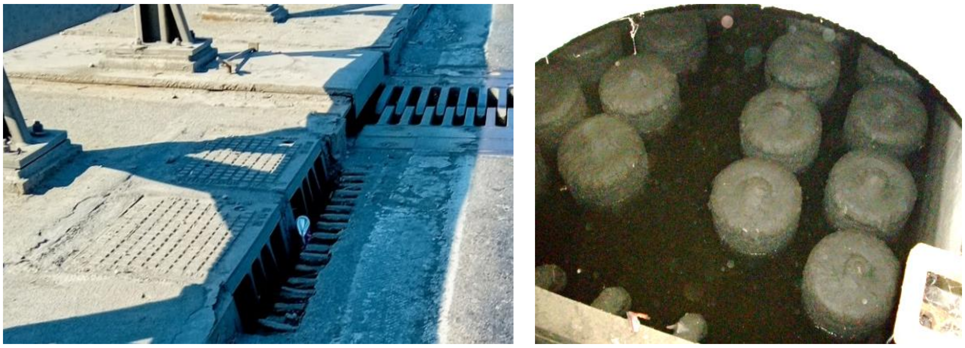

Figure 5: Gazela Bridge 12 years after the rehabilitation: deformed drainage inlets and expansion joints (left); sediment-clogged filters in the stormwater treatment facility (right)

3.3. ADA CIGANILIJA BRIDGE

The drainage system of the Ada Ciganlija Bridge was designed using the experience gained from previous bridge drainage projects. However, unlike the rehabilitation of the Gazela Bridge, the hydraulic capacity of the drainage inlets was not verified through laboratory testing. Instead, inlet capacities were estimated on the basis of previously obtained experimental data.

Immediately before the bridge was opened to traffic, modifications were introduced that were not compatible with the originally designed drainage system. Specifically, New Jersey concrete barriers were installed to improve traffic safety. However, this intervention left the drainage inlets on the opposite side of the barriers from several traffic lanes, preventing runoff from those lanes from reaching the inlets. Consequently, the drainage system is unable to collect runoff from the full width of the bridge deck as originally intended. Moreover, even the remaining functional inlets have not been adequately maintained, further reducing the overall efficiency of the drainage system (Figure 6).

Figure 6: Unmaintained drainage inlets on the Ada Ciganlija bridge

During operation, additional deficiencies have been observed in several components of the drainage system, particularly the pipes, pipe connections, clamps, and anchor supports (Figure 7). These problems may be attributed, at least in part, to insufficient care in the procurement, quality control and installation of drainage system components, including drainage inlets, pipes, pipe supports, and associated fittings. As a result, the quality and long-term performance of the installed components were not adequately verified. These observations highlight the importance of rigorous supplier selection, quality assurance during procurement and construction, and regular inspection and maintenance of the entire drainage system throughout its service life.

Figure 7: Unsatisfactory condition of drainage system components on the underside of the Ada Ciganlija Bridge structure

3.4. OSTRUŽNICA BRIDGE

Engineering designs for the Ostružnica Bridge included an integrated system for the collection, conveyance, and treatment of surface runoff, incorporating facilities for protection against accidental pollution events. However, the system was not implemented in its entirety because the investor and contractor modified the originally designed and approved technical solution during construction. Consequently, the drainage system was not completed in accordance with the original design concept, and the bridge currently lacks several components intended to ensure environmental protection and pollution control.

4. OPERATIONAL PROBLEMS – THE EXAMPLE OF THE GAZELA BRIDGE

The operational problems on the Gazela Bridge result both from deterioration accumulated before rehabilitation, when the bridge lacked an adequate drainage system, and from the issues that emerged during the post-rehabilitation operation. Before rehabilitation, decades of uncontrolled runoff containing de-icing chemicals and traffic-related pollutants accelerated corrosion and material degradation of both the steel and reinforced-concrete structural elements.

The exceptionally high traffic volume of approximately 200,000 vehicles per day, including heavy trucks and buses, inevitably contributes to structural deformation. This is a permanent challenge for stormwater drainage even after rehabilitation, since bridge deflections periodically reduce drainage efficiency. Although the rehabilitation reduced the vertical displacement at the crown of the central steel span from more than ±50 cm before to approximately ±14 cm (Figure 8), these deformations continue to significantly affect drainage both on the bridge deck pavement and in the pipeline. On the pavement, bridge deflection decreases the longitudinal roadway slope, resulting in lower surface flow velocities toward the inlets and greater water depths during storms. Consequently, traffic safety is adversely affected by an increased risk of hydroplaning.

The drainage pipes undergo the same deformations as the bridge structure as they were installed parallel to the edge of the bridge deck to satisfy aesthetic requirements. This reduces the pipeline gradient, particularly near the crown of the central span where it is already relatively small, possibly decreasing below the minimum required for self-cleansing flow conditions. Hydraulic analyses for a 10-year return period design storm [14] showed that the average bridge deflection of 14 cm reduces flow velocities in the drainage pipes by approximately 10%. This can impair sediment transport and promote progressive sediment deposition, reduce hydraulic capacity and increase the risk of pipe blockage.

Field inspections have also shown that structural deformations increase maintenance requirements and can significantly impair the long-term performance of bridge drainage systems [14]. Inlets located near the bridge crown are particularly susceptible to clogging and mechanical damage. When the inlets are unable to collect runoff at their full design capacity, flow velocities in the downstream pipes may fall below self-cleansing levels, leading to sediment deposition and pipe blockage. These processes further reduce system performance and increase maintenance demands. These problems can be mitigated through regular inspections and, where necessary, high-pressure cleaning of inlets and pipes. Pipes in critical sections may be mounted on rollers or other flexible supports to accommodate bridge deflections to a certain extent [15].

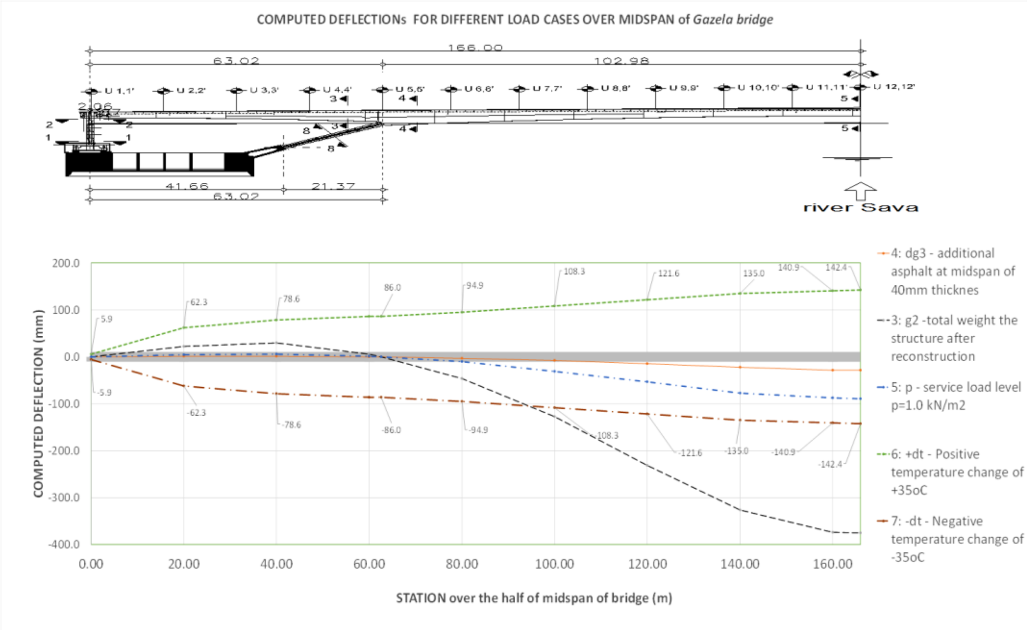

Figure 8: Deflections of the left half of the Gazela Bridge obtained from a structural model developed on the basis of field measurements [14]

5. BEYOND BRIDGE DRAINAGE: INTEGRATED STORMWATER MANAGEMENT

The Gazela Bridge reconstruction shows how a bridge drainage system can provide benefits beyond protecting the bridge structure and ensuring safe traffic conditions. Instead of conveying runoff directly to the sewer system or the receiving water body, the project adopted an integrated stormwater management approach combining runoff collection, treatment, retention, controlled infiltration, and reuse in line with the requirements for good status of recipients as provided by EU Water Framework Directive [16]. This concept was motivated by the limited capacity of the existing sewer network and the bridge location within the protected zone of the Belgrade water supply wells on the Sava River banks. The drainage system was therefore designed to minimize environmental impact while contributing to sustainable urban water management.

Collected through a closed drainage network, runoff is treated in a StormFilter® unit, which removes suspended solids, hydrocarbons, heavy metals, and other traffic-related pollutants [15]. To protect the sensitive groundwater source from accidental contamination, a SWERM® emergency diversion unit redirects heavily polluted runoff to a containment facility. After treatment, a portion of the runoff is discharged to the municipal sewer system, while the remaining water is conveyed to a retention and infiltration facility within the alluvial aquifer of the Sava River (Figure 10). Treated water infiltrates into the aquifer under controlled hydraulic conditions, while a part of the harvested water may be reused for non-potable purposes such as irrigation of urban green areas and street cleaning.

This example demonstrates that bridge drainage systems can function as sustainable urban water infrastructure rather than a simple conveyance system. With appropriate treatment technologies, hydrogeological investigations, hydraulic modelling, and long-term water quality monitoring, controlled infiltration of treated runoff can contribute to groundwater recharge while reducing pollutant loads discharged into receiving waters and relieving pressure on urban sewer systems. The Gazela Bridge therefore represents an example of a multi-functional bridge drainage system that integrates structural protection, traffic safety, environmental protection, stormwater treatment, water reuse, and sustainable urban water management. It also demonstrates the importance of considering the entire urban water cycle during the design of bridge drainage systems, especially in environmentally sensitive areas or water supply protection zones.

(a) (b) (c)

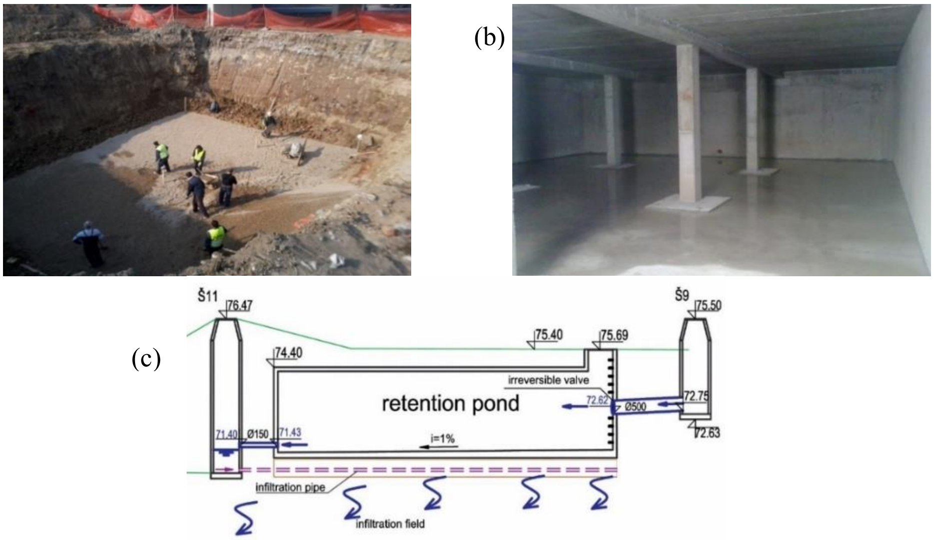

Figure 10: Retention pond as a receiving body for the Gazela Bridge drainage system: (a) during construction, (b) during operation, and (c) cross section showing redirection to the sewer system and the infiltration system [15]

6. DISCUSSION AND CONCLUSIONS

Assessment of drainage systems on the four Belgrade bridges demonstrates that their present performance reflects original design choices, subsequent modifications, structural and pavement deformation, deterioration of drainage components, and maintenance practices. The observed deficiencies therefore cannot be attributed to inadequate maintenance alone; the cases rather illustrate how the intended hydraulic performance of a bridge drainage system can progressively deteriorate during its service life.

Each bridge illustrates this differently. At Branko's Bridge, the open drainage concept contributes to structural deterioration, while pavement deformation prevents effective runoff concentration toward the drainage points. At Ada Ciganlija Bridge, installing New Jersey barriers just before opening the bridge to traffic altered original design and blocked runoff from several traffic lanes. At Ostružnica Bridge, an integrated system for runoff collection, conveyance, treatment and accidental-pollution protection was designed but was not fully implemented. These cases demonstrate that the drainage functionality can be compromised not only during operation but also during construction through design changes or incomplete implementation.

The Gazela Bridge provides an example of the interaction between structural behaviour and drainage performance. Although rehabilitation improved the drainage system and eliminated uncontrolled discharge, structural deformation continues to affect both deck drainage and the drainage pipeline. Pipes installed parallel to the bridge deck follow structural movements. For the 10-year design storm, an average bridge deflection of approximately 14 cm was found to reduce flow velocities in the drainage pipes by about 10% [14], impairing sediment transport and increasing the risk of pipe blockage. Similarly, the bridge deck deflection reduces the longitudinal pavement slope and consequently surface flow velocities while increasing water depth which raises the risk of hydroplaning. Inlets near the bridge crown are particularly vulnerable because deformation can reduce their intended capacity to intercept runoff, further decreasing flow velocities and promoting sediment deposition. This case therefore shows that structural deformation ultimately increases the maintenance requirements, despite the adequacy of the system under the original design conditions.

The Gazela Bridge clearly demonstrates that integrated drainage and treatment systems need continued post-construction attention. A decade after rehabilitation, deformed drainage inlets, damaged expansion joints and sediment-clogged treatment filters have been observed. Maintenance must therefore go beyond just removing debris from inlets and include systematic inspection of components affected by structural movement and cleaning of treatment units. Cutting maintenance budgets for bridge drainage systems undermines the substantial investment made in their design and construction.

Because the Gazela Bridge lies within the protected zone of Belgrade's water-supply source, the system combines closed runoff collection with treatment, emergency diversion for accidental pollution, retention and controlled infiltration, and reuse of treated water. This shows that bridge drainage can support wider urban water management system when the environmental sensitivity is considered at the design stage. However, environmental performance of such a system depends on maintaining the hydraulic and treatment functions throughout the service life.

Overall, the four bridges indicate that the long-term drainage performance is a life-cycle issue rather than just a design problem. Functionality can be lost through inadequate original design, modifications introduced during construction or operation, incomplete implementation, structural and pavement deformation, deterioration of components, clogging and sediment accumulation, and insufficient maintenance. Although these failure mechanisms differ, they lead to the same outcome: the operating conditions of the drainage system may no longer correspond to the hydraulic and environmental conditions assumed during design.

Based on the experience from the four bridges, the following conclusions can be drawn:

1. The present condition of bridge drainage systems is the result of their entire service history, since drainage performance may be compromised at different stages, from design and construction to operation and maintenance.

2. Structural deformation can measurably affect the hydraulic performance of bridge drainage. For the Gazela Bridge, an average deflection of approximately 14 cm was found to reduce flow velocities in the drainage pipes by about 10% for the 10-year return period design storm [14].

3. Changes to the system configuration can invalidate an otherwise adequate drainage concept, as demonstrated by the Ada Ciganlija and Ostružnica bridges, implying that drainage functionality needs to be verified after construction and after any subsequent modification.

4. Maintenance requirements should be based on observed hydraulic and structural performance. The Gazela case shows that inspection should cover not only inlet and pipe clogging but also deformation and damage of drainage components and sediment accumulation in treatment facilities. Maintenance measures such as high-pressure cleaning and the use of supports capable of accommodating structural movement may be required [14,15].

5. In environmentally sensitive locations, bridge drainage should be treated as part of integrated water management. The Gazela drainage system demonstrates the potential for combining runoff collection, treatment, emergency pollution control, retention, controlled infiltration and water reuse. However, its long-term environmental benefits depend on maintaining the hydraulic and treatment performance of the system.

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