HYDRAULIC EFFICIENCY OF URBAN DRAINAGE NETWORK

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Abstract

The paper presents a methodology for analyzing and computing the efficiency of urban drainage networks through the use of performance indicators. The methodology is based on system approach and describes the hydraulic behavior of each element in the network as well as the whole system. A global performance methodology has been used to define different performance indicators based on system parameters. Due to the dynamic behavior of the drainage networks, proper consideration of system operations (management policy, operating conditions) are essential for better understanding the system functioning. In order to help the decision processes, spatial and temporal distributions of the performance indicators are evaluated to express the responses of each element in the network and, to state how it affects the functioning of those that surround. All the performance indicators are assessed quantitatively and could be combined or compared to assess the overall system performance.

1. Introduction

Drainage systems constitute a significant portion of the assets in urban areas and their efficiencies have a direct impact on people’s quality of life. Their structural integrity and functional efficiency represent key strategy for the safe transfer and disposal of surface run-off and the domestic/trade discharges. The efficiencies of these systems contribute to the achievement of sustainable development in urban area and bring about different benefits: improving the quality of services provided, reducing management costs and reducing malfunctioning that cause deterioration of the networks.

Therefore, the sustainability of such assets, which interact with all the components of urban water infrastructure, is an important issue for urban water system managers. There is a need for enormous investment to meet the required services level. This could be achieved either by developing new systems or rehabilitating existing ones. Therefore, in order to maintain good services and to better drive management decisions, the authorities charged to manage these systems need to evaluate the efficiency of each elements in the networks and to determine the causes of their low performances.

Performance measurement can be regarded as techniques able to express how effectively and efficiently an urban water network guaranteed the required service in terms of both quantitative and qualitative aspects.

In the last years, several approaches have been proposed to explain the concept of performance of urban water systems, which are usually pursued by the definition of performance indicators (PIs) synthetically representing system behavior.

Referring to water supply and water distribution systems, many authors (Hashimoto *et al.,* 1982; Tang, 1985; Bao & Mays, 1990; Goulter, 1992; Mays, 1993; Tanyimboh, 1993; Bos, 1997; Burt & Styles, 1997; Coelho, 1997) express the performance by means of reliability indicators defined as an estimate of the relative frequency that an element is not in a failure state. Other authors (Levine, 1982; Bos & Nugteren, 1990; Weller, 1991; Cabrera, 1995) introduced the concept of efficiency to evaluate the level of services provided by each element. Similarly, Clemmens & Bos (1990) provided a more detailed exposition of the same concept to express adequacy and equity of water delivery. Moreover, several PIs for water systems are widely used by the International Water Association, the American Water Works Association and the World Bank (Alegre *et al*., 2006; AWWA, 2004; Yepes & Dianderas, 1996), to evaluate functional and managerial performance used as support in the decisions and planning activities. Despite its importance, the concept of performance and efficiency in urban drainage networks are not widely diffused and most of the studies conducted in this field (Guérin-Schneider, 2001; Ashley & Hopkinson, 2002; Matos *et al*., 2003) focus on the economical aspects related to the service provided and few of them analyze the hydraulic functioning of the system to assess the level of service.

Our contribution in this research field was developed in several past studies in which were considered different aspects of the performance context. Referring to water distribution networks (Ermini & Ingeduld, 2005; Ermini *et al*., 2006), to water supply balance (Ermini & Ataoui, 2011) and to water systems (Ermini, 2000, Ermini *et al.*, 2001) we introduced methodologies that express the level of service of each element and of the whole infrastructure in terms of hydraulic PIs. All the performance introduced were evaluated in terms of frequency and expressed in quantitative but dimensionless form. More recently a similar approach was extended to sewer networks (Piro *et al.*, 2011) in order to detect the criticality of a specific sewer network. All the previous studies permit to locate inefficiencies, to compare different project hypothesis and to support decision management. In this paper we upgrade the performance methodology already defined for urban drainage systems, introducing the concepts of spatial and temporal distributions in order to express how the PIs vary along the networks and during time.

2. Methodology

2.1. Definition of system objective

The system performance can be measured only in terms of well defined objectives or system conditions. To evaluate how well a drainage network is functioning, and to make decisions about designing or rehabilitating a system, decision makers need to become aware of the efficiency. The purpose of efficiency assessment is to achieve an effective system performance by providing a relevant feedback to the management in determining whether the performance is satisfactory and, if not, which and where corrective actions need to be taken in order to remedy the situation. Systems objectives could be defined in terms of integrity, costs, hydraulic behavior, customer satisfaction, environmental impacts and so forth. But, in the present study we focus our objective on the hydraulic behavior because it constitutes the most important constraint for the system and contributes to the achievement of the other objectives.

2.2. *Choice of system parameters*

A comprehensive analysis of a drainage system would require the determination of several hydraulic parameters that have a direct impact on the fulfillment of system objective and express any operating conditions. The key parameters that we consider in the hydraulic analysis of urban drainage system are defined in terms of flow, which may refer to either: flow velocity, filling capacity and outflow volume. In fact, the optimal hydraulic conditions may occur if the flows velocities prevent both solids deposition and high scour, the filling capacity must grant free surface flows and no overflows should take place.

Urban drainage systems are generally networks which convey rainwater to one or more terminal points where it is treated and/or discharged to the environment; sometimes there are combined sewers networks in which rainwater and wastewater are conveyed together. In both cases, it is well known that rainfall regime, might heavily affect the hydraulic behavior of the network. In general, there are basically two categories of rainfall, recorded (real) rainfalls and synthetic (not real) rainfall. The use of real rainfall data enables to know the network responses in preset condition, however, synthetic rainfall is used to test the network ability to provide good functioning in hypothetical conditions in order to drive the best design choices. Regardless of the method used, rainfall measure copes with the system objective previously defined.

Apart from the parameters considered, it is important to take into account the whole geometry of the networks that also affect the hydraulic behavior (for detailed analysis, see Piro *et al*., 2011).

2.3. *Definition of efficiency measurement*

Efficiency measures should be related to the system parameters and should be quantitatively measurable or predictable.

In this paper, as already introduced for water distribution networks and sewer networks (Ermini & Ingeduld, 2005; Ermini & Ingeduld, 2010), the performance measurement suggested is expressed as:

$$f_{x,i} = \frac{T - \sum t_i\{x \notin [x_{min}; x_{max}]\}}{T} = \frac{t^*}{T} \quad (1)$$

where,
T: time of simulation (24h);
$\sum ti$: total time during which threshold values are not satisfied (h);
x_{min}, x_{max}: threshold values.

That varies from zero to one and evaluates the frequencies of occurrences of the values that matching the optimal conditions. As fx,i approaches one, the element behavior becomes more efficient. For each element (node, link) of the network, the threshold values (x_{min}, x_{max}) could be defined. Independently from the parameters and from the operating scenario considered, the expression (1) is able to express the different performance indicators described later.

2.4. Evaluation of the performance indicators (PIs)

Based on expression (1) and considering the previous mentioned key parameters (flow velocity, filling capacity and outflow volume), the efficiency of any elements in the drainage network is assessed using the following performance indicators:

- **Velocity index *(I_v)***, that expresses the occurrence of flow velocity into the range v_{min}-v_{max}:

$$I_V = \frac{t^*}{T} \tag{2}$$

where,
t* represents the total time during which the flow velocity is within the range v_{min}-v_{max} and T is the total time of simulation.

- **Filling index (I_φ)**, likewise to the previous index it evaluates the occurrence of filling capacity satisfying the hydraulic constraints:

$$I_\varphi = \frac{t^*}{T} \tag{3}$$

where,
t^* represents the total time during which the filling capacity is within the range φ_{min}-φ_{max} and T is the total time of simulation.

- **Flood index (I_{vol})**, that expresses the occurrence of node overflowing:

$$I_{vol} = 1 - \frac{V_{flood}}{V} \quad (4)$$

where,

V_{flood} is the outflow volume that occurs and V is the total volume of water that flows through the node.

All the performance indicators (I_x) are dimensionless and measure the efficiency for each element (node, link) in the network in different operating conditions. They could be combined to assess the overall system performance or could be used to compare different situations (elements or networks).

2.5. Temporal and spatial distribution of the PIs calculated

Drainage networks like the other urban water systems are subjected to various operating conditions that change over time. Nevertheless, an optimal condition occurs only if a set of the surrounding elements have homogeneous performance indicators, otherwise the elements that are deficient can affect the behavior of the others and in this situation the system may fails.

As already introduced for water supply systems (Ermini & Ataoui, 2011) a comprehensive analysis of the performance could be represented by the m * n matrix in which are plotted the performance indicators evaluated in n spatial element and in m different time.

$$D = \begin{bmatrix} I_{11} & I_{12} & \cdots & I_{1j} & \cdots & I_{1n} \\ I_{21} & I_{22} & \ldots & I_{2j} & \ldots & I_{2n} \\ \vdots & \vdots & & \vdots & & \vdots \\ I_{i1} & I_{i2} & \ldots & I_{ij} & \ldots & I_{in} \\ \vdots & \vdots & & \vdots & & \vdots \\ I_{m1} & I_{m2} & \cdots & I_{mj} & \cdots & I_{mn} \end{bmatrix} \quad (5)$$

where,

I_{ij} = performance indicators at element i (node, link..) and time j (scenario j). i and j refer to the spatial and temporal positions of the elements, and vary from 1 to m and from 1 to n, respectively.

The rows of the matrix represent the different components that constitute the whole drainage network, and the columns define specific operating conditions in which the performance indicators are assessed.

Based on the synthetic form of the matrix, the spatial and the temporal distribution of the performance indicators are evaluated by the coefficient of variation of each single row and of each single column.

In fact, the spatial distribution expresses the system ability to provide homogeneous service for all the elements (*m*) in one specific operating condition (one single scenario *j*). It is expressed by:

$$CV_j(PI_{ij}) = \sigma_j(PI_{ij}) / \mu_j(PI_{ij}) \quad (6)$$

where,

CV_j is the coefficient of variation of PI_{ij}, σ and μ are the standard deviation and the average of the PI_{ij}, and j defines the scenario.

However, the temporal distribution expresses the ability of the i^{th} component to provide homogeneous in different scenarios. It is expressed by:

$$CV_i(PI_{ij}) = \sigma_i(PI_{ij}) / \mu_i(PI_{ij}) \quad (7)$$

where,

CV_i is the coefficient of variation of PI_{ij}, σ and μ are the standard deviation and the average of the PI_{ij}, and i defines the component.

In the expression (6) and (7), as the values of CV approaches zero, the system behavior is becoming more uniform over space and the response of the considered element is more homogeneous over time.

Calculating the spatial and temporal distribution of the performance indicators, it is possible for each scenario and for any element to evaluate the matrices $S = [CV_1,...,CV_n]$ and $T = [CV_1,...,CV_m]$, respectively. Thus, the S matrix shows the system behavior and allows evaluating the criticality degree associated to each scenario. However, the T matrix expresses the criticality of each element.

3. Conclusions

The introduction of a quantitative measurement of the performance indicators, allows to express the efficiency provided over time by each element of the drainage network.

A hierarchy approach is presented that permits performance analysis at different spatial and temporal scales in order to introduce some synthetic indices that summarize the expected level of service of each component and of the whole system.

Applying this approach, it will be straightforward to localize at a given time and space the critical elements/components in the network that affect system functioning, and determine the impact of their low performance on the overall system performance. Thus, decision makers will potentially gain insight into the performance of drainage system, as well as information on the impacts of system elements on improving the whole system performance, and finally they will be able to prioritize the investments in particular elements on the basis of the performance results.

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