Performance indicators for water supply management
Ruggero Ermini, Rafet Ataoui and Lydra Qeraxhiu

ABSTRACT
In the present study specific performance indicators are proposed that express the level of service of a water system subjected to varying operating conditions over time. The proposed methodology has been applied to a specific case study (Sinni water supply system in Basilicata – Italy) to demonstrate the real applicability of the proposed performance analysis that could be very useful to support the monitoring and the management activities.

Key words | performance indicators, spatial uniformity, temporal uniformity, water supply system

INTRODUCTION
The complexity of water systems, their structural evolutions, and the need to adapt them to changing conditions requires to develop approaches able to synthesize the system performance through specific parameters measured or evaluated by numerical simulations.

The use of the performance indicators (PIs) can play a key role in the process of measuring the quality of service provided by the utility, can simplify the comparison between different objectives, provide benchmarking between similar undertaking and help the decision processes involved in the planning and management phases.

With regard to the research conducted in the field of water systems, several authors (Hashimoto et al. 1982; Tang 1985; Bao & Mays 1990; Goulter 1992; Mays 1995; Tanyimboh 1993; Bos 1997; Burt & Styles 1997; Ermini 2000; Alegre et al. 2006; Atkinson et al. 2011) introduced the concepts of performance and reliability by defining specific dimensionless indicators that express quantitatively the state of different elements of the system. Similar indicators have been introduced by other authors (Levine 1982; Bos & Nugteren 1990; Weller 1991; Korkmaz & Avci 2012) that express the concepts of efficiency and adequacy in terms of leakage control and demand satisfaction.

Different concepts of efficiency are also adopted (Merriam et al. 1985; Jahromi & Feyen 2001) that express the uniformity of the demand effectively delivered, the adequacy of the service provided to the users (Clemmens & Bos 1990; Molden & Gates 1990), and the satisfaction rate of the requested demands (Coelho 1997).

In case of system failure some authors (Fiering 1982a, 1982b; Ermini et al. 1998; Todini 2000; Gunderson & Walters 2002) introduced the concept of resiliency and vulnerability to analyze the critical behaviors of the system.

To overcome some of these issues, the present paper introduces a methodology that assesses the hydraulic performance of a real water supply through the developing of a set of PIs that permit the evaluation of system responses under any operating conditions and analyze the system behaviors over time.

METHODOLOGY
The functioning of a water system is influenced by many factors, mainly those that refer to the physical characteristics inherent to each element and to the hydraulic principles that the system must fulfill. Those two factors determine the operating limits beyond which the system is not able to ensure its proper functioning.

The physical characteristics of each component of the system are generally well known and not variable; therefore, this is useful only to evaluate the endemic criticality of the various components that may restrict their normal operation. On the other hand, the hydraulic behavior varies in...
space and time depending on the scenario considered and this is useful to express the operating conditions of each single component.

The system can be in a satisfactory state only if the aforementioned characteristics meet the predefined optimal objectives; otherwise, the system fails, and therefore the extent of failure depends upon the number of elements considered and on the gap from the optimal conditions.

With regard to both mentioned aspects, dimensionless indicators (PIs) are defined in order to synthesize and analyze the main properties of the system and to make comparisons between different elements and among different management rules.

The methodology to find out the different PIs was conducted by identifying the key parameters devoted to describing the system, by introducing the mathematical expression of each specific indicator and by establishing the scenarios to be used as reference.

**Key parameters**

With reference to a generic water system, the variables that describe the state of the system are: the flows ($Q_d$) conveyed in different pipes, the energy ($H_d$) used to convey the desired flows into each pipe, the energy ($\Delta H_d$) dissipated to regulate the flow, and the flow ($Q_d$) delivered at each node. The first three parameters refer to system conveyance while the last one refers to the service provided to the users.

All mentioned variables perfectly express the hydraulic state of each component of the whole system and can be evaluated with reference to different operating conditions (scenarios) under various spatial and temporal scales and in several operating periods (irrigated, non-irrigated, water drought).

**PIs**

Referring to the system conveyance, three PIs (Table 1) are proposed:

- the carrying adequacy index ($PI_T$) is evaluated as the ratio between the carrying capacity ($Q_{cat}$) measured or evaluated and the carrying capacity ($Q_{prog}$) requested by the project (refers to the design phase);

**Table 1 | Performance indicators of the hydraulic operation of the system**

<table>
<thead>
<tr>
<th>PIs</th>
<th>Expression</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrying adequacy</td>
<td>$PI_T = n_{cat}/n_{prog}$</td>
<td>$n$: roughness; $Q$: flow</td>
</tr>
<tr>
<td>Carrying efficiency</td>
<td>$PI_{TE} = H_{u}/H_d$</td>
<td>$H_u$: used energy; $H_d$: available energy</td>
</tr>
<tr>
<td>Regulation efficiency</td>
<td>$PI_{RE} = H_{r}/H_d$</td>
<td>$H_r$: dissipated energy</td>
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</table>

- the carrying efficiency index ($PI_{TE}$) is expressed for each homogeneous pipe by the ratio between the energy ($H_u$) used to provide the required flow and the energy ($H_d$) available in the same element;
- the regulation efficiency index ($PI_{RE}$) is expressed as the ratio between the dissipated energy ($H_r$) and the energy ($H_d$) available in the same element.

The proposed indicators (Table 1) express, respectively; the capacity of the system to convey flows equal to those supposed as design criteria, the ability of the system to employ all the energy provided to convey the flows required and the measure of the energy dissipated to settle the system flows.

The two indicators $PI_{TE}$ and $PI_{RE}$ are redundant because they are complementary, but they were defined with the aim to evaluate directly only the PI that better fits the purposes of the element considered. For this reason we evaluate carrying efficiency in pipes and regulation efficiency in valves.

Referring to the service provided to the users in each demand node, two PIs are defined:

- the adequacy of delivery ($PI_{Q,EA}$) is expressed as the ratio between the flow delivered ($Q_d$) and the flow required by users ($Q_r$);
- the exploitation rate ($PI_{Q,ES}$) is expressed as the ratio between the flow delivered ($Q_d$) and the maximum flow deliverable ($Q_{E,max}$).

The expressions of those two PIs are shown in Table 2.

All the variables introduced permit to analyze the behavior of each element and the defined indicators evaluate any criticality associated with the parameters considered in dimensionless form, thereby facilitating the comparison of different scenarios.
Several applications could be considered by varying the operational scenarios (design plan, maximum demand, minimal demand) and the corresponding values of the key parameters. In this way, it is possible to evaluate the responses of the system in different conditions, achieving a broad understanding of the behavior of each element and of the whole water system useful to support appropriate management actions.

Variability of PIs

A complex structure such a water supply system is subjected to various operating scenarios and must be able to operate adequately under any conditions. To understand the full system behavior, it is important to evaluate (Clemmens & Bos 1990; Molden & Gates 1990) how each PI varies during time (temporal uniformity) and how it varies across the entire system (spatial uniformity).

The spatial uniformity (Equation (1)) is expressed for one single scenario through the coefficient of variation (CV$_S$) of the PIs evaluated in groups of elements that make up the entire system:

$$CV_S(PI_{XX}) = \frac{\sigma_S(PI_{XX})}{\mu_S(PI_{XX})}$$

The temporal uniformity (Equation (2)) is expressed by the value of the coefficient of variation (CV$_T$) of the PIs of a specific element in different scenarios:

$$CV_T(PI_{XX}) = \frac{\sigma_T(PI_{XX})}{\mu_T(PI_{XX})}$$

CV$_T$ and CV$_S$ measure the homogeneity of the different PIs to which they refer. They synthetically express whether the PI evaluated for each component varies during time or the PI referred to a specific scenario varies along the pipeline. Both expressions are very useful to understand how the system operates and where eventually changes must be actuated.

Moreover, the values of the PIs depend both on the geometric characteristics and on the hydraulic state of the system.

Furthermore, the parameters obtained through the expressions 1 and 2 translate synthetically specific properties of the system and therefore are considered as additional PIs. More, the closer the CV is to zero, the more homogeneous are the PIs over time and space.

Reference scenarios

Different conditions can be easily considered by changing the threshold values adopted in the expressions of PIs:

- in design conditions, in order to assess the state of the system with reference to the default project hypothesis;
- in particular operating conditions (plan, irrigation, no irrigation, etc.), in order to assess the ability of the system to respond in different situations;
- in critical conditions (water drought, exceptional demands, malfunctions, emergencies, etc.), in order to assess the ability of the system to cope with exceptional situations.

In all conditions, the PIs allow to assess the degree of response guaranteed by the system and by each individual element, and thus permit to obtain information about the real and potential problems that restrict the system’s ability to operate properly.

APPLICATIONS

The proposed methodology has been applied to a specific case study, the ‘Sinni’ water supply system in the Basilicata region (Italy), which is particularly representative of the complexity of the water supply system. As shown in Figure 1, the system considered has a total length of about 65 km along the Ionian Sea in the Basilicata region. The system ensures the delivery of water resources in 21 demand nodes for drinking, irrigation and industrial purposes as well as ensuring the water supply for the Puglia region. The Sinni system is managed by EIPLI through a remote sensing plant that monitors continuously the operating conditions in each node.
The Sinni system is fed by gravity and delivers flows to different reserve tanks. The whole pipeline is made of five sections (DN3000 mm) disposed in series but disconnected from each other by means of coupled towers; thus each section begins and ends with a tower that fixes the hydraulic boundary conditions of the section itself. Between each couple of towers a specific flow-regulating valve is installed that sets the values of the flows according to the water demands.

The proposed methodology is applied considering seven scenarios, three referring to non-irrigated periods and four referring to irrigated periods. All the scenarios consider real functioning conditions and express the flows delivered and conveyed to the users.

In Table 3 are reported the flows delivered, referring to different conditions. $Q_{RP}$ are the hypothetical delivery flows stated by the project referring to both irrigated and non-irrigated periods, $Q_E$ are the real measured flows delivered in different conditions (scenarios) and $Q_{E\text{ max}}$ are the maximum flows delivered in the considered scenarios.

**Performance estimation**

The concerned management authority (EIPLI) has provided all the data referring to operating conditions measured during several years. Particularly, they have provided the flow delivered ($Q_{RP}$) in all nodes, the flow conveyed ($Q_{ij}$) in any pipe, and the ground water level ($H_{ij}$) in every tower. All the data were collected through the monitoring activities. The state of the system was assessed evaluating the different PIs previously introduced, for each scenario, and analyzing separately each element (pipe, node and tower).
The hydraulic analysis of the system was carried out considering separately each section. As already mentioned, the Sinni system is made of five sections hydraulically separated through towers, then each section has fixed boundary conditions (flows and water level) that affect their own hydraulic behaviors. Hydraulic simulations were applied only to evaluate the equivalent roughness of each section.

Based on the mentioned key parameters, the PIs were evaluated to synthetize the dynamic behaviors of the system and to identify the most critical conditions (operating conditions closer to the threshold).

Carrying adequacy

The carrying adequacy of the system was obtained by comparing the theoretical value of the equivalent roughness adopted during the design phase, and the one deduced experimentally according to the flows and the piezometric heads collected through the activity of remote control.

In particular (Table 1), the value of the indicator (PIₚ = 0.85) obtained for the current case study indicates a carrying adequacy lower by 15% compared with the one assumed in the design phase. Therefore, the maximum flow rate conveyable by the system does not meet the desired design conditions and eventually it could affect water demands.

Carrying efficiency and regulation

Considering the normal operation of the system represented by the values of the key parameters measured in stationary conditions, the PIs that express the carrying efficiency (PIₑₑ) and the regulation efficiency (PIᵣₑ) were evaluated considering separately homogeneous elements (pipe, towers) and seven different scenarios (related to irrigated and non-irrigated periods) in order to compare similar situations among themselves. Similar situations mean that we consider situations related to the same period (irrigated or non-irrigated).

The evaluation of the mentioned PIs (Table 4) denotes that:
in all pipes $PITE$ varies between 0.03 and 0.37 (in non-irrigated period), and between 0.09 and 0.65 (in irrigated period), thus indicating that the system works in conditions quite different from the design ones;  
- the system flow regulations provided by towers 2 and 3 have high regulation efficiency indicators ($PIRE$ between 0.19 and 0.67), with greater values observed in the non-irrigated scenarios.

The Sinni water system reveals poor efficiency conditions for all the scenarios and almost everywhere, only the middle part of the pipeline (pipe 4–4b) exploits the real conveying capacity of the system to face the irrigation water demands concentrated in that area (see Table 5).

The carrying efficiency in the downstream section (pipe 4b–5) is fairly constant because one of the main goals of the system is to convey flows from the Sinni dam to the Puglia region to meet potable and industrial needs.

### Adequacy of delivery and exploitation rate

As reported in Table 5, by comparing the flow delivered ($Q_{RP}$) imposed at the design phase and the flow delivered ($Q_E$) at each node in various scenarios, the values of the PIs referring to the adequacy of delivery and to the exploitation rate were obtained.

In the non-irrigated scenarios, the system provides delivery flows greater than those fixed by the original design plan, whereas the opposite happens in the irrigated periods. Only nodes 3 and T5 show $PI_{Q,EA}$ greater than 1 in the irrigated period.

The trends of the adequacy of delivery ($PI_{Q,EA}$) also highlight the redundant adequacy of the nodes 2/A, 3 and UP, especially in the non-irrigated scenarios. This denotes the changes in managing policy imposed to meet the increasing demand for drinking water and to deal with the reduction of the growth rate in the irrigated areas.

The maximum flows delivered correspond to the irrigated period, where substantial increases of the exploitation rates were observed. For each node, the $PI_{Q,ES}$ are almost stable during homogeneous periods (irrigated or non-irrigated), confirming that the system performs mainly seasonal regulations.

### Spatial and temporal uniformity of the PIs

The spatial or temporal uniformity of the different PIs synthetically expresses whether the PI evaluated for each component varies during time or the PI referred to a specific scenario varies along the pipeline. Both the two evaluations are very useful for understanding how the system operates and where criticalities occur.

**Figure 2** shows the spatial uniformity ($CV_s$) and the temporal uniformity ($CV_T$) obtained referring to the indicators related to the flow conveyed by the pipe. **Figure 2** (left) reports the values of $CV_s$ for both carrying efficiency and regulation efficiency evaluated for the whole system in...
## Table 5: Adequacy of delivery and exploitation rate

<table>
<thead>
<tr>
<th>Pipes</th>
<th>Nodes</th>
<th>Irrigated</th>
<th>Non-irrigated</th>
<th>(Q_{\text{P}})/(Q_{\text{RP}}): Adequacy of delivery (PIQ,EA)</th>
<th>(Q_{\text{E}}/Q_{\text{max}}): Exploitation rate (PIQ,ES)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Non-irrigated 1 2 3</td>
<td>Irrigated 4 5 6 7</td>
</tr>
<tr>
<td>2–3</td>
<td>1/A</td>
<td>470</td>
<td>100</td>
<td>Non-irrigated</td>
<td>388</td>
</tr>
<tr>
<td></td>
<td>1/B</td>
<td>100</td>
<td>20</td>
<td>Irrigated 92</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>1/C</td>
<td>360</td>
<td>72</td>
<td>Non-irrigated</td>
<td>403</td>
</tr>
<tr>
<td>2/A</td>
<td>1,500</td>
<td>305</td>
<td>1,174</td>
<td>Irrigated 1.53</td>
<td>1.23</td>
</tr>
<tr>
<td>2/B</td>
<td>610</td>
<td>124</td>
<td>449</td>
<td>Irrigated 0.55</td>
<td>0.74</td>
</tr>
<tr>
<td>2/UP</td>
<td>120</td>
<td>24</td>
<td>0</td>
<td>Non-irrigated</td>
<td>1,059</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>805</td>
<td>160</td>
<td>Irrigated 362</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>3/A</td>
<td>500</td>
<td>99</td>
<td>Irrigated 362</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>3/B</td>
<td>605</td>
<td>120</td>
<td>Irrigated 446</td>
<td>0.61</td>
</tr>
<tr>
<td>UP</td>
<td>500</td>
<td>100</td>
<td>343</td>
<td>Irrigated 2.23</td>
<td>2.00</td>
</tr>
<tr>
<td>4–4b</td>
<td>4</td>
<td>1,600</td>
<td>320</td>
<td>Irrigated 1,475</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1,340</td>
<td>270</td>
<td>Irrigated 517</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1,715</td>
<td>350</td>
<td>Irrigated 840</td>
<td>0.93</td>
</tr>
<tr>
<td>4b–5</td>
<td>7/A</td>
<td>1,845</td>
<td>370</td>
<td>Irrigated 599</td>
<td>0.17</td>
</tr>
<tr>
<td>7/B</td>
<td>1,180</td>
<td>250</td>
<td>761</td>
<td>Irrigated 0.55</td>
<td>0.60</td>
</tr>
<tr>
<td>7/C</td>
<td>300</td>
<td>50</td>
<td>305</td>
<td>Irrigated 0.90</td>
<td>3.24</td>
</tr>
<tr>
<td>7/D&quot;</td>
<td>250</td>
<td>50</td>
<td>212</td>
<td>Irrigated 2.00</td>
<td>0.85</td>
</tr>
<tr>
<td>7/D&quot;</td>
<td>200</td>
<td>40</td>
<td>207</td>
<td>Irrigated 1.03</td>
<td>1.02</td>
</tr>
<tr>
<td>T5</td>
<td>4,580</td>
<td>6,500</td>
<td>6,576</td>
<td>Irrigated 0.74</td>
<td>0.75</td>
</tr>
</tbody>
</table>
different conditions (scenarios). Figure 2 (right) shows the CV_T of the carrying efficiency evaluated during time for each section of the system.

The lower the CV is (approaches zero), the more homogeneous are the corresponding indicators and, therefore, the greater is the number of elements that have the same level of performance.

In particular, for the Sinni water system (Figure 2, left), poor uniformity was detected when looking to the functioning of the whole system (CV_S vary between 0.6 and 0.98) according to the results of Table 4, in which the PITE varies considerably for all sections. The uniformity of the carrying efficiency increases as the conveying capacity increases (the lower CV corresponds to the scenario number 6 that conveys the larger flows). The regulation efficiencies have a good and stable uniformity (CV_S range between 0 and 0.2) for all the considered periods. Looking to the temporal uniformity (Figure 2, right) all sections show limited changes (CV_T vary between 0 and 0.4) of the carrying efficiency during each period and a consistent behavior of the downstream portion of the system (4b-5) that conveys potable water to the Puglia region.

Considering the spatial uniformity (CV_s) of the service provided to the users (Figure 3, left), all the indicators decrease moving from the non-irrigated period (1–2–3) to the irrigated period (4–5–6–7), as shown in Table 5.

Looking to each delivery node (Figure 3, right), the temporal uniformity of the adequacy of delivery (PI_{Q,EA}) shows an uniformity almost generalized in the irrigated scenarios (CV_T less than 0.3), while for non-irrigated scenarios a spread variation of CV_T occurs and the CV_T rise up to 0.8.

**CONCLUSIONS**

The proposed paper introduces a methodology that allows the assessment of the performance of each component and of the entire water system, based mainly on specific key
parameters that describe the hydraulic behavior and the physical characteristics of the infrastructure.

A specific case study is investigated in order to show how the proposed PIs permit to analyze different criticalities of the system infrastructure, improve the knowledge of system behavior, and allow the comparison between different scenarios. The results obtained provide a good support in the monitoring and management phases, and can guide choices in a more conscious manner to fulfill any other objectives.

In fact, the use of the proposed PIs allows to evaluate synthetically the state of the system with respect to predefined configurations and operating hypothesis in order to analyze different operating conditions, assessing for each one of them the expected responses useful to improve the knowledge of the system behavior.

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