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Contribution to study of the dependability of a drinking water system

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Abstract

In order to ensure better availability of water resource to different users, we undertook a dependability study of system for drinking water supply. A real case study was done on the water supply network in the city of El Hadjarin Algeria. We started from the site modelling, which provided a calculation of a Hydraulic Criticality Index (*HCI*) in order to prioritize the importance of pipes in the network. Once the indices were calculated, a modelling procedure of reliability block diagram was applied. The objective was to study and analyse the existing network to measure the water availability problems and try to provide viable solutions. An action on the structural aspect and hardware may be required in order to ensure better availability of water and make the system more reliable. Spatial modelling is also proposed to be able to monitor different parts of the network where problems may occur.

Key words: *dependability, hydraulic system, hydraulic criticality index (HCI), reliability block diagram, spatial interpolation*

INTRODUCTION

In spite of the hydrological availability, Algeria suffers from the unavailability of drinking water due to the high demand for this important element which entails a constraint on the comfort level of the population especially if one takes into account the rapid population growth [MOZAS, GHOSN 2013]. The projection of drinking water networks and the application of inappropriate methods are in the most of time studied locally and not globally which lead to a dysfunction of the whole [BOUKHARI, DJEBBAR 2011]. Several factors may be the cause of this dysfunction. Among which, we cite: the expansion of the urban area with the maintenance of the infrastructure of pipes, the water sheeting and pressure accessories [MOZAS, GHOSN 2013]. We propose to study a meth-

odology to be applied in the case of deficiency of a network for drinking water supply according to BOUMELITA *et al.* [2014]. We have undertaken an application on a real case and we have sufficient data: case of the city of El Hadjar. The supply network of drinking water to the city of El Hadjar is very complex. To approach the analysis of this problem, we try to deal with a case of fairly simple but representative study of the operation mode of the entire network. The proposed study area covers the drinking water supply of 300 housing sector of El Hadjar city.

In the other hand, the recurrent unavailability of this vital resource poses an acute problem. In order to achieve viable solutions, calculation of hydraulic criticality index (*HCI*) of each tube of the site is essential to measure the impact of the unavailability of a given pipe on the overall operation of the network (cf. MA-

GHEZZI [2008] and NAFI [2006]). Therefore, a hydraulic model of the site was established using Epanet tool (version 2), which allows the network simulation of the hydraulic behaviour and perform all the flow and pressure measures envisaged, regardless of the time that we position.

For recall, dependability is a generic concept. These main concepts are: reliability, availability, maintainability and safety [DJEBABRA 2006; KHALFAOUI 2003; MEGDICHE 2004]. According to the dependability methods (for example: reliability block diagram [MALHOTRA, TRIVEDI 1994], Artificial Neural Network [MEMON *et al.* 2011]), our choice is oriented to the worm modelling reliability block diagram because this method is widely used in this study field. It allows to model the different components of system for drinking water supply for 300 housing sectors in order to calculate their reliability and availability. We start by the modelling procedure, then we propose to make structural and physical improvements to ensure better availability of water and make the system more reliable.

To predict unknown values for any type of geographic data, spatial interpolation is used [CHINTA 2014; COULIBALY, BECKER 2007; DREŠKOVIĆ, DUG 2012; FIRDAUS, TALIB 2014; HAO, HANG 2013; KEBLOUTI *et al.* 2012; TAIEB, HAMDI 2014]. The use of HCI measurements were performed using Geographic Information System (GIS) for a model mapping, which provides the ability to monitor various points where problems may occur. The purpose of spatial modelling is to locate areas that cause problems such as: high pressure, pressure drop, low flow velocity and hydraulic criticality indices with high values which are treated in this paper.

DESCRIPTION OF THE STUDY AREA

It's interesting to notice that the city of El Hadjar is the fourth most populous town in the state of Annaba in Algeria. It is located for 7.43° to 7.44° East lon-

gitude and for 36.47° to 36.49° North latitude (Fig. 1). According to the general census of population and housing in 2013, the population of the municipality of El Hadjar is estimated at 41,941 inhabitants. The city covers 63 km^2 , with a density of 593.08 people by km^2 .

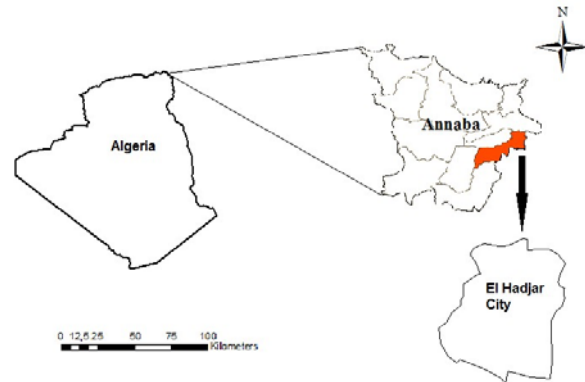


Fig. 1. Location of the study area (El Hadjar city in Algeria); source: own elaboration

MATERIALS AND METHODS

HYDRAULIC MODELING OF THE CASE STUDY

In the case of drinking water supply system of El Hadjar, calculating the HCI is essential. Also, a network modelling was conducted for purposes of hydraulic simulations. The network consists of 598 pipes, 631 consumer nodes, 98 valves, 3 tanks: two storage tanks are powered from the Chaïba treatment station (located in Sidi Amar city where this latter is located in the north-west of El Hadjar city) which is the principal provider resources. The water stored in these tanks, supplies a third elevated tank by a pumping station, and then distribute it to consumers and to two water covers: one feeds the Atoui sector (which is located south of the city El Hadjar) and the other 300 housing sectors that is the subject of our work (Fig. 2).

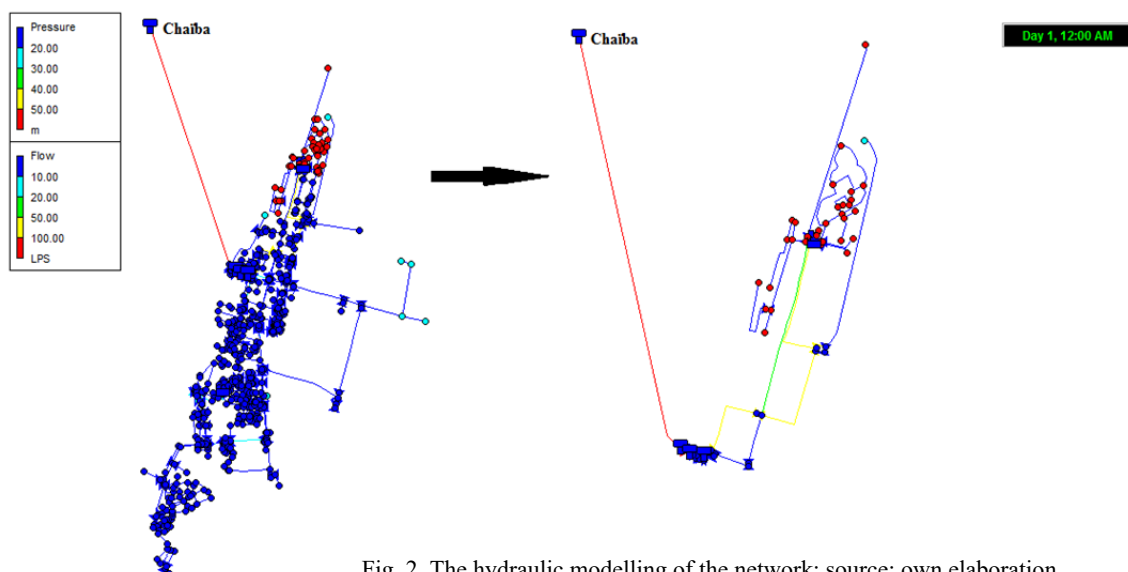


Fig. 2. The hydraulic modelling of the network; source: own elaboration

CALCULATION OF HYDRAULIC CRITICALITY INDEX (HCI)

The first step is to analyse the operation of the hydraulic system through the calculation of the pressures and requests under Epanet software and for desired time intervals. A failure is injected on a pipe (translated with the closure of the pipe) leading to recalculate the pressures and requests. The consumption at the node will be a function of the comparison of the pressure levels before and after the unavailability of the pipe. The values of *HCI* are between 0 and 1. The higher value is close to 1, the pipe is more important in the network (ref. MAGHEZZI [2008], NAFI [2006]). The calculation of *HCI* conducts to measure the unavailability impact of the particular conduct *j*, on the network operation. It is obtained using the following equation:

$$HCI_j = \frac{\sum Nodes_i (Demand_i - Consumption_i)}{\sum Nodes_i Demand_i} \quad (1)$$

Where: *Nodes_i* = the *i* number of the network consumption node; *j* = $\overline{1,p}$ = the set of pipes network; *i* = $\overline{1,n}$ = the set of nodes network; *p* = the number of pipes in the network; *n* = the number of nodes in the network.

From the current situation, we notice that this index is calculated for a current population number. In the future, we expect that the need for drinking water is increased according population growth. In this case, we will make increases network nodes demand in the numerical simulation procedure and after we will recalculate the *HCI*. Extrapolating the density, this index grows only naturally (see the Fig. 3 where this concept is clearly explained in the diagram). From this, we try to propose different solutions by addressing the structural aspect and bringing a redundancy in the most vulnerable pipes. These results allow us to have a clear and significant variation of this index (Fig. 3).

MODELING BY RELIABILITY BLOCK DIAGRAM (RBD)

It is known that the reliability method is a logical block of diagram representation of system operation. The system components are modelled by blocks connected by arcs in the sense that there is a path in the graph between the input and the output in order to ensure that system will be functional [CABAU 1999]. Reliability can be expressed by an exponential law. It is used for the useful life period that is to say for λ constant. Its expression is given by the following equation:

$$R(t) = e^{-\lambda t} \quad (2)$$

The reliability of a set of *n* components mounted in parallel is expressed by:

$$R(t) = 1 - \prod_{i=1}^n (1 - R_i(t)) \quad (3)$$

If the *n* components are in series, the resulting reliability becomes:

$$R(t) = \prod_{i=1}^n (1 - R_i(t)) \quad (4)$$

The availability calculation is done by the following equation:

$$A(t) = \frac{\mu}{\lambda + \mu} + \frac{\lambda}{\lambda + \mu} e^{-(\lambda + \mu)t} \quad (5)$$

Where: *t* = the time in hour; λ = the failure rate; μ = the repair rate.

The availability calculation principle of a set of *n* components mounted in parallel or in series is the same as the reliability.

As part of the network modelling, we focus on the pipes, tanks (also the water tank) and pumps (Fig. 4). The water tank (denoted T_300H) distributes water to the 300 housing sectors of El Hadjar city. If a problem occurs on a pump, the water service decreases and a spare pump is then added. The calculation of hydraulic criticality index of each pipe allows prioritize

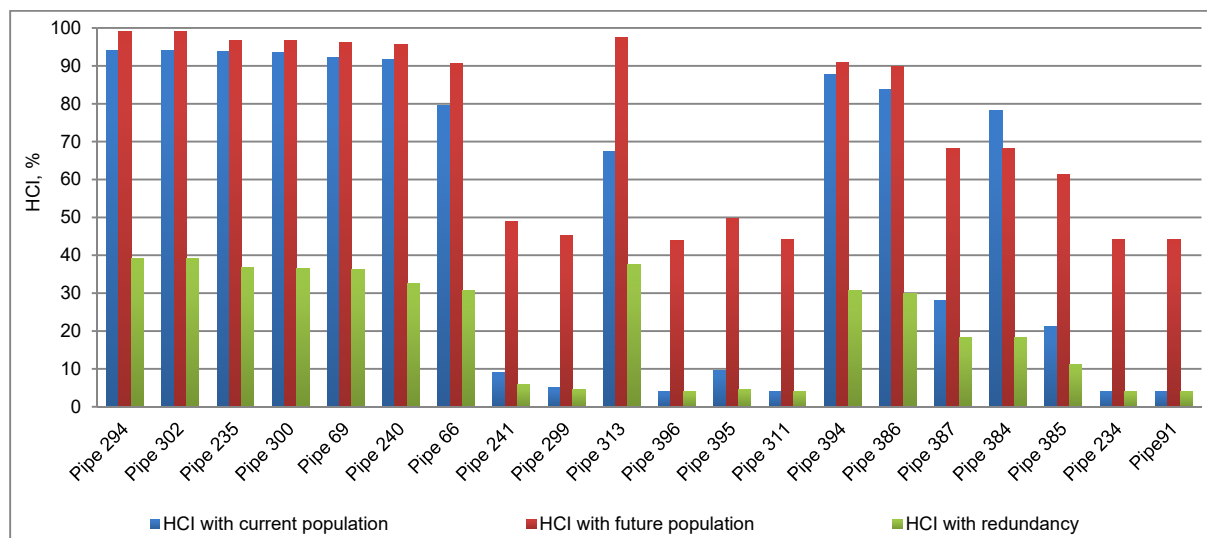


Fig. 3. The hydraulic critically index (*HCI*) values of some network behaviour: current, future and with redundancy; source: own study

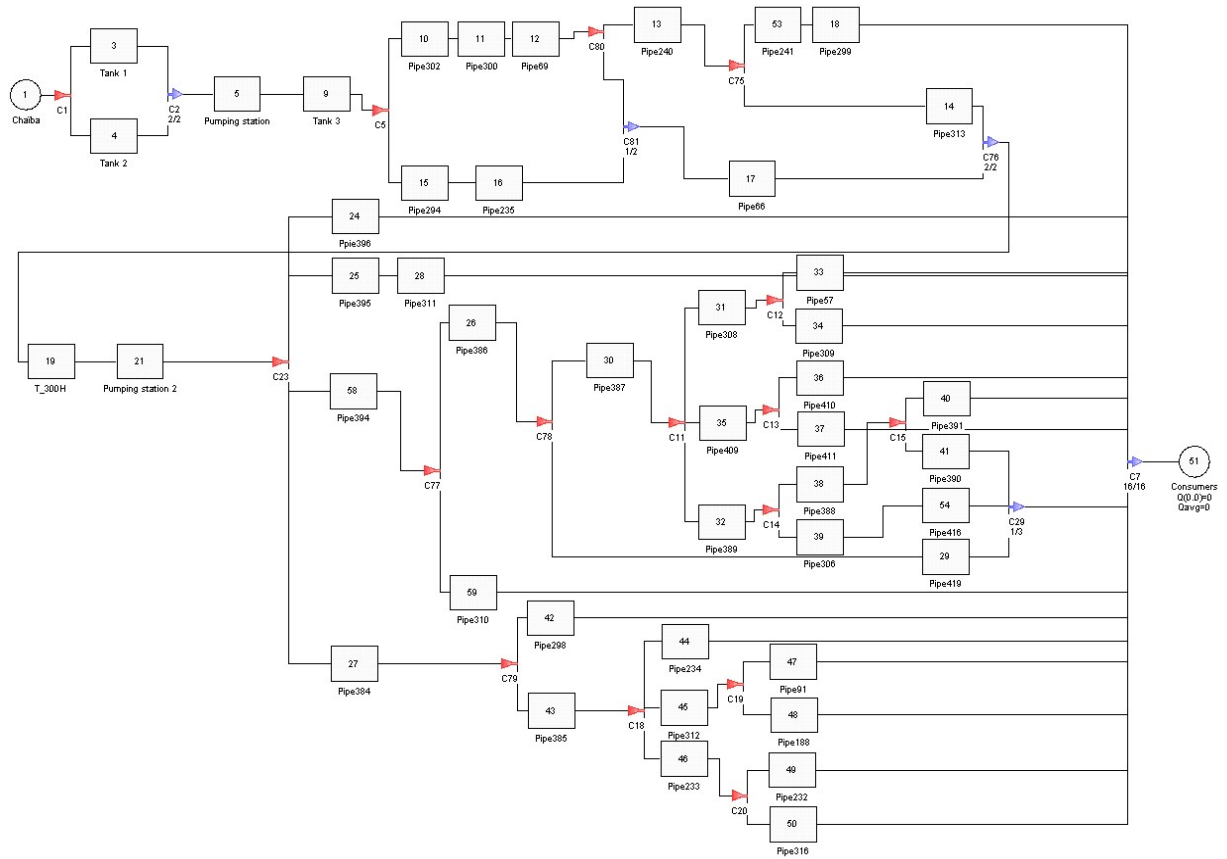


Fig. 4. Reliability Block Diagram network without redundancy; source: own elaboration

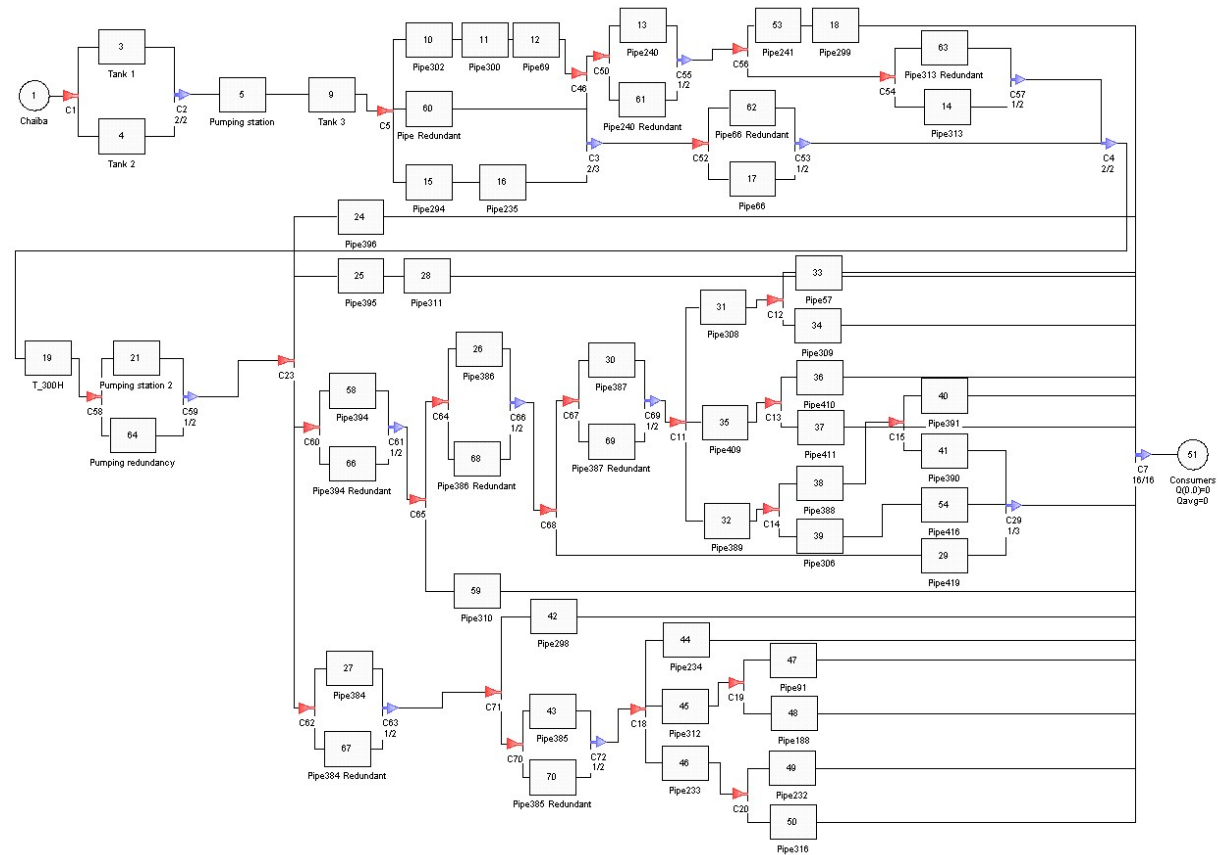


Fig. 5. Reliability Block Diagram network with redundancy; source: own elaboration

pipes according to their importance in the network. We also propose to make redundancies from pipes where the index of criticality is higher for ensuring the availability of various network devices (Fig. 5).

The modelling by the reliability block diagram of the 300 housing sector network is carried out in Figure 4 through blocks which represent all the infrastructures of this network. We note the water source indicated as input to the outlet that represents consumers. In the Figure 5, the HCI calculation makes it possible to prioritize the pipes according to their importance in the network. So, we try to make material and structural redundancies (pump, pipes) at the level of the blocks that represent the pipes where their values of HCI are very high.

SPATIAL MODELING

The spatial interpolation estimates the value of a variable in a site from the values of the same measured variable in neighbouring points [LAURENT 2007; 2008; ZANINETTI 2005]. The use of the *HCI* measures is performed using Geographic Information System (GIS) to model mapping. This latter is dedicated to defined the index values, estimate their impact on customers and show the spatial variation of *HCI* in the area of El Hadjar city. We will have the ability to monitor various points where problems are likely to appear, therefore the location areas that are problematic (*HCI* has higher values).

The spatial interpolation techniques are generally divided into two categories: deterministic and stochastic methods [COULIBALY *et al.* 2007]. We tested in this article the inverse method of distance and kriging [FIRDAUS, TALIB 2014].

METHOD OF INVERSE DISTANCE WEIGHTING (IDW)

The method of inverse distance is a deterministic method. It assigns for each rain gauge an inverse distance weighting between it and the point to be estimated. We attribute to each site S_i retained a weight inversely proportional at a distance between this site and the point to be estimated x_0 . Thus, the estimate unmeasured x_0 is expressed in this way [TAIEB *et al.* 2014] by:

$$\hat{Z}(x_0) = \sum_{i=1}^n \lambda_i Z(x_i) \quad (6)$$

Where: n = the number of measured values; $Z(x_i)$ = the measured at the location S_i ; λ_i = the weight of the measured value in the i^{th} location; $\hat{Z}(x_0)$ = the estimated value at x_0 location.

METHOD OF ORDINARY KRIGING

Ordinary Kriging method is a statistical method that takes place in two stages [CRESSIE 1993]. The first is the exploratory analysis which allows to be familiar with the data and to clarify the choice of the

model, and to state it. The second step concerned the choice of the form of the deterministic trend for the hope of $Z(s)$, the variogram analysis and then the cross-validation.

$$Z(s) = \mu(s) + \delta(s) \quad (7)$$

Where: $\mu(s)$ = deterministic structure for the expectation of $Z(s)$, depending on the location of the observations; $\delta(s)$: normal random function of zero mean, variance of homogeneous and does not present spatial dependence structure.

CROSS VALIDATION

Cross-validation was used to determine the most appropriate interpolation technique in the city of El Hadjar. This involves removing a known point of the data set and operates the remaining points to estimate the removed value. Once the estimate is calculated, it can be compared with the actual value which has been initially removed from the set of sampling data. This procedure is repeated for all sample values available [HAO, HANG 2013].

The error of the spatial interpolation by ordinary kriging method is lower than that of inverse distances. We could say that the interpolation by ordinary kriging for this case is more optimal than IDW (Tab. 1).

Table 1. Comparison of IDW and Kriging

Interpolation method	IDW determinist	Ordinary Kriging
Percentage error	5.58	2.99

Source: own study.

RESULTS AND DISCUSSION

We have created cartography by the ARCGIS 9.3 tool in the system (UTM zone 32 Datum WGS 84). The objective of this study is to establish a risk map which defines the spatial variation of hydraulic criticality index (*HCI*). For this, we define firstly the current critical state of the study area based on the *HCI* values of network pipes (see Fig. 6a). We note that the values of *HCI* on the network nodes are increasing; which explain a strong demand for resource (Fig. 6b). The approach taken to reduce this index is the application of redundancies at the most critical pipes. This approach led to the diagram presented on the Figure 6c, where we see a decrease in hydraulic criticality index.

On the set of Figure 6, we clearly observe the occurrence of critical areas representing risk of developing problems for higher *HCI*. Areas become denser, thus increasing *HCI* depending on the increasing requirement in water resource. However, by applying pipes redundancies with higher *HCI*, we see a decrease in the critical density, hence the decrease of *HCI* even with critical conditions.

The diagrams presented on Figures 7 and 8 were simulated to achieve the reliability and availability of

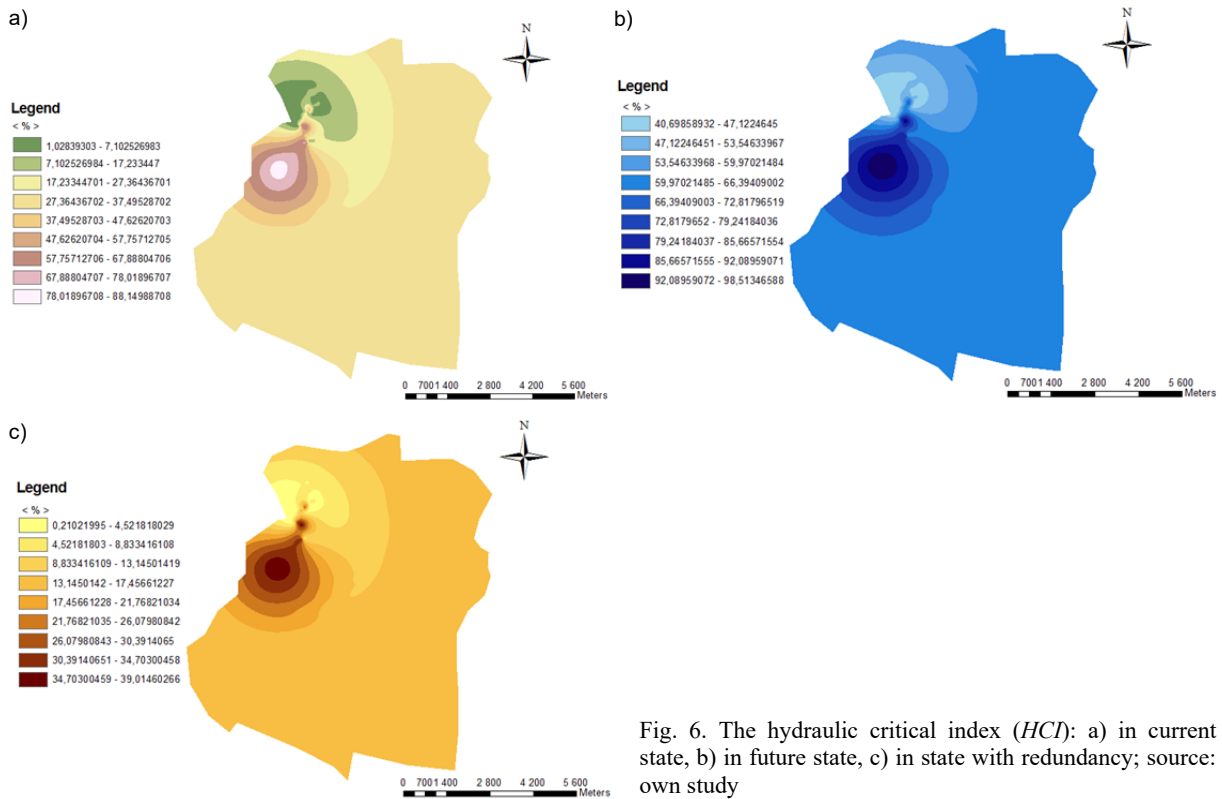


Fig. 6. The hydraulic critical index (HCI): a) in current state, b) in future state, c) in state with redundancy; source: own study

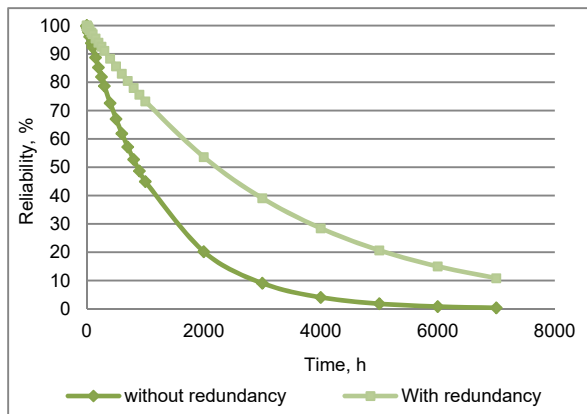


Fig. 7. Reliability of the system; source: own study

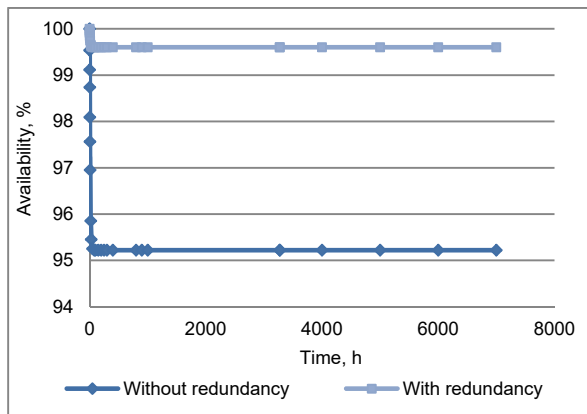


Fig. 8. Availability of the system; source: own study

the network; in the present case and with redundancy. The software tool is used GRIF (Fr. GRaphiques Interactifs pour la Fiabilité).

Starting from a maximum value, the curve decreases exponentially as shown by the Figure 7.

The Figure 8 shows the availability variation of the system over time. This decreasing availability over time to a fixed value is called asymptotic availability. For modelling by block reliability diagram without redundancy, the asymptotic availability tends to the value of 95.22%. After the integration of hardware redundancy model, the asymptotic availability is 99.60%. After comparison between the reliability of curve (also availability) with and without redundancy, we note that there is an improvement of the network reliability (availability) at the redundancy modelling.

CONCLUSIONS

The drinking water system must meet a supply waiting all parts of the city. To ensure the availability of sufficient water to all customers, we have emphasized the role of a dependability study of the hydraulic systems operation through a reliability diagram modelling by block. To do this, we find that the criticality indices can be improved through new structural and material provisions in case of deficiency of a network. Through spatial interpolation we have the ability to locate areas that pose problems to access to more proven solutions.

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Wkład w badania nad niezawodnością systemów wodociągowych

STRESZCZENIE

Celem zapewnienia lepszej dostępności różnym użytkownikom do zasobów wody podjęto badania nad niezawodnością systemu doprowadzania wody pitnej. Przykładem była sieć wodociągowa w mieście El Hadjarin w Algierii. Prace rozpoczęto od modelowania, co umożliwiło obliczenie krytycznego wskaźnika hydraulicznego (ang. hydraulic criticality index – *HCI*) w celu ustalenia priorytetu funkcji rurociągów w sieci. Po obliczeniu wskaźników zastosowano procedurę modelowania blokowego diagramu niezawodności. Celem badań było przeanalizowanie stanu istniejącej sieci, określenie problemów z dostępnością wody i zapewnienie rozwiązań możliwych do realizacji. Działania o charakterze organizacyjnym oraz inwestycyjnym mogą być niezbędne, aby zapewnić lepszą dostępność wody i uczynić system bardziej niezawodnym. Proponuje się także wykonanie modelu przestrzennego sieci, aby umożliwić monitorowanie różnych części sieci systemu.

Słowa kluczowe: *blokowy diagram niezawodności, interpolacja przestrzenna, krytyczny wskaźnik hydrauliczny (HCI), niezawodność, system hydrauliczny*