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MODELIRANJE MEŠANJA VODE U REZERVOARU I STAROSTI U DISTRIBUTIVNOJ MREŽI

WATER MIXING IN RESERVOIR AND WATER AGE IN THE DISTRIBUTION NETWORK MODELLING

APSTRAKT

Rezervoari čiste vode u vodovodnom sistemu povećavaju sigurnost snabdevanja potrošača, ali mogu značajno da degradiraju kvalitet vode. Očuvanje kvaliteta vode po rezervoarskim prostorima je preduslov za očuvanje kvaliteta vode u distribucionoj mreži. Slabo mešanje po rezervoarima može dovesti do formiranja džepova sa vodom povećane starosti i negativnih posledica po zdravlje, kao i ukus i miris isporučene vode. Vreme za koje se postiže potpuno mešanje vode u rezervoaru tokom ciklusa njegovog punjenja i odnos dnevno promenjene i ukupne zapremine rezervoara su važni činioci koji utiču na promenu kvaliteta vode po rezervoarima, a samim tim i u distributivnoj mreži. Skraćivanje vremena potrebnog za potpuno mešanje tokom ciklusa punjenja i promena odnosa dnevno promenjene i ukupne zapremine rezervoara se može postići promenom nivoa uključivanja i isključivanja pumpi , promenom algoritma rada za pumpe sa promenljivim brojem obrtaja ili promenom uslova mešanja u samom rezervoaru. U ovom radu se daje pregled metoda za modeliranje mešanja vode u različitim rezervoarima i starosti vode u vodovodnoj mreži, koje su ugrađene u EPANet program. Kao primer, u radu je prikazan uticaj promene modela mešanja u rezervoarskom prostoru u gravitacionom vodovodu grada Petrovac na Mlavi.

Ključne reči: starost vode, modeliranje mešanja vode u rezervoaru

ABSTRACT

The main role of reservoirs is to store the water for periods when consumption is higher then water production, thus increasing the reliability of system. However, the water storage can also lead to water aging, and its quality reduction. Preservation of water quality at the reservoir is a prerequisite for the preservation of water quality in the distribution network. Poor mixing in reservoirs can create pockets of older water that could have negative aesthetic and public health impacts. Time achieved by fully mixing in the tank during the charging cycle and the relationship between daily water turnover and the total volume of the reservoir are the most important factors that influence the water quality change in reservoirs, and consequently in the distribution network. Shortening the time required for complete mixing during the charging cycle and the change of relation between the daily water turnover and the total volume of the reservoir can be achieved by changing the level of shut on and shut off for pumps, changing the algorithm work of variable speed pumps, or by changing the mixing conditions in the reservoir. The overview of modelling methods for water mixing in reservoirs of different type, and water aging in distribution network, built in EPANet software is presented in this paper. The impact of changes in the model of mixing in the reservoir will be presented at the case study of gravitational water supply system in the town of Petrovac na Mlavi.

Keywords: water age modeling of mixing water in the tank

1. UVOD

Starost vode je opšte prihvaćen pokazatelj kvaliteta vode. Prevelika starost vode, usled produženog vremena reakcije sa organskim materijama u vodi i na zidovima cevi može da smanji koncentraciju slobodnog hlora ili hloramina, sposobnog za dezinfekciju. Promena zakonske regulative u oblasti kvaliteta vode kojom se uzorkovanje na mestu "proizvodnje" vode zamenjuje uzorkovanjem na mestu potrošnje, nameće upotrebu hidrauličkih simulacionih modela prilikom davanja početnih procena kvaliteta vode u distributivnim mrežama

1. INTRODUCTION

Water age is widely accepted indicator of water quality. Excessive water age, due to a prolonged reaction time of the organic substances in the water and the pipe walls can reduce the concentration of free chlorine or chloramine, capable in disinfection. New legislation in the field of water quality sampling at the site of water "production" is replaced by sampling at the point of consumption, imposing the use of hydraulic simulation models in making Initial Distribution System Evaluations. By making these initial estimates, which will soon become a legal obligation of EPA's

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(Initial Distribution System Evaluations). Izradom ovakvih početnih procena, koje će uskoro postati zakonska obaveza EPA's Stage 2 Disinfectants and DBP Rule i primenom različitih "what-if" scenarija (EPA, Internet), upotreba starosti vode kao surogat parametra za procenu ukupnih trihalometana TTHMs i drugih nusprodukata dezinfekcije (DBP) postaje moguća. Povećana starost vode u rezervoarima i distributivnoj mreži ima posledice vezane za odvijanje nepoželjnih fizičkih (korozija, stratifikacija, sedimentacija, promena boje) i hemijskih procesa (raspad dezinfektanata, stvaranje nusprodukata dezinfekcije, promena ukusa i mirisa, hemijsko zagađenje), kao i njenu mikrobiološku ispravnost (razlaganje nusprodukata dezinfekcije, nitrifikacija, kontaminacija patogenima, rast biofilma) http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html).

Rezervoari su najzahtevniji elementi vodovodnih sistema i veoma je važno da se osigura očuvanje kvaliteta vode po njima, jer je to najbolja garancija kvaliteta u distribucionoj mreži. Prema ulozi koja im je dodeljena u radu vodovodnog sistema dele se na rezervoare koji "plivaju" iznad sistema i rezervoare iz koji su "utopljeni" u sistem. Tokom perioda simulacije, sa više ciklusa punjenja tokom noći u periodima male potrošnje i pražnjenja tokom dana treba obezbediti i cikluse "promene" vode po rezervoarima sa ciljem da se minimizira starost isporučene vode. Uticaj ovakvih dnevnih obrta tj. ciklusa "promene" vode po rezervoarima na kvalitet vode u njima zavisi od ukupne zapremine rezervoara, zapremine prostora za dnevno izravnanje, vremena i intenziteta punjenja i pražnjenja, položaja rezervoara u distributivnoj mreži, kao i uslova mešanja u rezervoaru. Čak i u slučajevima da je po rezervoarima obezbeđeno dobro mešanje , vreme punjenja duže od vremena potrebnog za kompletno mešanje i optimalna zapremina za dnevno izravnanje, oni mogu da predstavljaju mesta gde lako može doći do pogoršanja kvaliteta vode. Kao primer može poslužiti ne tako redak slučaj vraćanja vode koja je napustila rezervoarski prostor tokom ciklusa pražnjenja, ali nije utrošena, već se vraća u rezervoar iz koga je potekla, kada se usled smanjenja potrošnje noću podignu pritisci u sistemu i promene hidraulički uslovi tečenja.

U našoj inženjerskoj praksi je raširena upotreba EPANet simulacionog modela za modeliranje hidraulike (pritiska i protoka) vodovodnih mreža. Relativno retko se EPANet koristi da se provere i parametri kvaliteta vode, gde je starost vode prvi pokazatelj. U ovom radu se daje prikaz načina kako EPANet modelira procese mewanja vode u rezervoaru, u zavisnosti od tipa rezervoara, kao i kakav je uticaj rezervoara na starost vode u mreži. Kao primer, u radu se koristi gravitacioni vodovodni sistem grada Petrovac na Mlavi.

Stage 2 Disinfectants and DBP Rule and applying various "what-if" scenarios (EPA, Internet), use of water age as a surrogate parameter for the assessment of total trihalomethanes TTHMs and other by-products of disinfection (DBP) becomes possible. Increased water age in reservoirs and distribution network has consequences related to the conduct of unwanted physical (corrosion, stratification, sedimentation, changing color) and chemical processes (dissolution of disinfectants, disinfection byproducts creation, changes in taste and smell, chemical pollution), as well as its microbiological correctness (decomposition of disinfection byproducts, nitrification, contamination by pathogens, biofilm growth) http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html).

Reservoirs are the most demanding elements of water supply systems and it is very important to ensure the preservation of water quality in them, because that is the best guarantee of the distribution network quality. Based on the role that they were given in the operation of the water supply system they are divided into reservoirs that "float" above the system and the reservoirs that are "sunk" into the system. During the simulation period, with more charging cycles at night during periods of low consumption and discharge during the day, the cycles should provide a "change" of water in the reservoirs in order to minimize the age of delivered water. Impact of such daily trades i.e. cycles of "change" in water reservoirs on water quality in them depends on the total volume of the reservoir, the volume of space for daily equalization, time and intensity of charging and discharging, the position of the reservoir in the distribution network, as well as the mixing conditions in the reservoir. Even in cases when the reservoirs have ensured good mixing, charging time is longer than the time required for complete mixing and the optimum volume for daily equalization, they can represent a place where can easily lead to a deterioration of water quality. As an example can serve not so rare backflow which left the reservoir area during the discharge cycle, but not consumed, it is returned to the reservoir from which it originated, when due to reduced consumption at night pressures elevate in the system and hydraulic conditions of flow are changed.

In our engineering practice is widespread use of EPANET simulation model for hydraulic modeling (pressure and flow) of water supply networks. Relatively rarely EPANET uses to check the water quality parameters, where the water age is the first indicator. This paper gives an overview of EPANET modeling of the processes of water mixing in the reservoir, depending on the type, and the impact of reservoir on the water age in the network. As an example, the paper uses a gravity water supply system of the city of Petrovac na Mlavi.

2. VREME POTREBNO ZA KOMPLETNO MEŠANJE U REZERVOARU I STAROST VODE U DISTRIBUTIVNOJ MREŽI

Za određivanje vremena potrebnog za potpuno mešanje po rezervoarima potrebno je poznavanje energije dolaznog mlaza i dimenzija rezervoara. Postoji više empirijskih formula kojima se može sračunati ovo vreme (Rossman i Grayman, 1999).

Jedna od najčešće korišćenih, dimenziono ispravnih empirijskih formula je:

$$\tau_m = \frac{K * H^{\frac{1}{2}} * D^{\frac{3}{2}}}{M^{\frac{1}{2}}} \quad (1)$$

gde je:

$K = 5 - 9$ - bezdimenziona konstanta koja zavisi od definicije vremena potrebnog za kompletno mešanje

$\tau_m(s)$ - vreme potrebno za kompletno mešanje

$H(m)$ - nivo vode u rezervoaru

$D(m)$ - prečnik rezervoara

$M = Q * v = \frac{4}{\pi} * \left(\frac{Q}{d}\right)^2$ - fluks dolaznog mlaza (2)

$d(m)$ - prečnik dovodnog cevovoda

Modeliranje starosti vode kao ukupnog vremena koje provodi segment vode u distributivnoj mreži se u EPANet-u zasniva na primeni Lagranžovog transportnog algoritma i praćenju "*sudbine*" segmenta određene starosti duž cevovoda i mešanja sa drugim segmentima različite starosti u čvorovima mreže, tokom dovoljno kratkih intervala vremena koji mogu da verno prikažu vreme putovanja kroz cev i povećanje starosti vode u takvom intervalu (slika 1).

"Nova" voda koja dospeva u mrezu iz "neiscrpnih" izvora (čvorovi u kojima Π kota ne zavisi od potrošnje) ima starost 0 i ona se tokom putovanja kroz mrežu meša sa vodom različite starosti. U slučaju kada se raspolaže sa hidraulički kalibrisanim modelom, EPANet omogućava automatsko modeliranje starosti vode, bez upotrebe drugih empirijskih koeficijenata. Starost vode se tretira kao parameter kvaliteta čiji rast odgovara hemijskoj reakciji stepena 0 sa koeficijentom brzine reakcije $k = 1\frac{gm}{lit/s}$, što znači da se u svakoj sekundi proteklog vremena starost svakog segmenta vode koja nije napustila distributivnu mrežu povećava za 1 sekund.

2. TIME REQUIRED FOR COMPLETE MIXING IN THE RESERVOIR AND WATER AGE IN THE DISTRIBUTION NETWORK

To determine the time required for complete water mixing in reservoirs it is needed to have the knowledge of the energy of the incoming stream and the dimensions of the reservoir. There are a number of empirical formulas that can calculate this time (Rossman and Grayman, 1999).

One of the most commonly used, dimensionally correct empirical formula is:

$$\tau_m = \frac{K * H^{\frac{1}{2}} * D^{\frac{3}{2}}}{M^{\frac{1}{2}}} \quad (1)$$

where:

$K = 5 - 9$ - dimensionless constant that depends on the definition of the time required for complete mixing

$\tau_m(s)$ - time required for complete mixing

$H(m)$ - water level in the reservoir

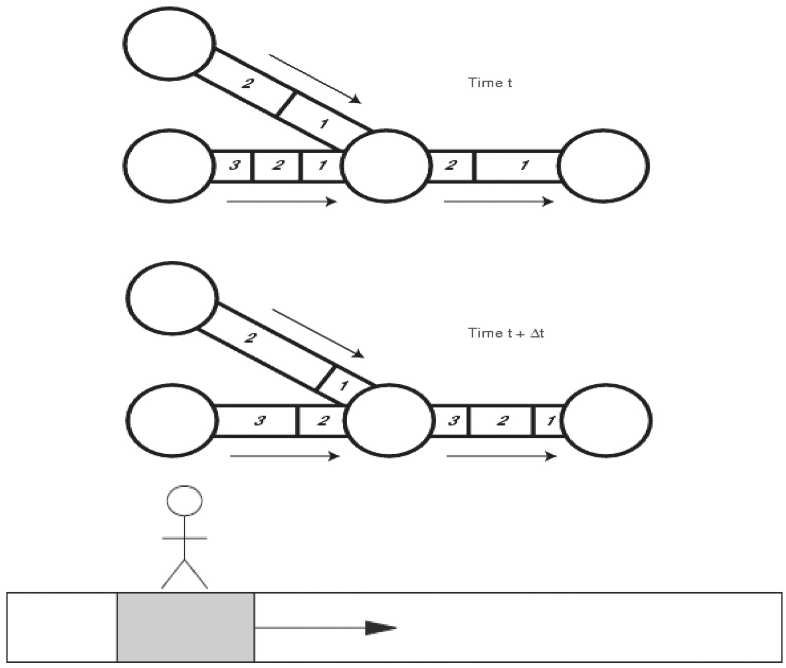
$D(m)$ - diameter of the reservoir

$M = Q * v = \frac{4}{\pi} * \left(\frac{Q}{d}\right)^2$ - flux of the incoming stream (2)

$d(m)$ - diameter of the inlet pipe

Modeling of water age, as the total time that a segment of water spends in the distribution network, in EPANET is based on the use of Lagrange transport algorithm and monitoring of "*fate*" of a certain age segments along the pipeline and mixing with other segments of different ages in the network nodes, for a sufficiently short time interval that can faithfully represent time travel through the pipes and increasing of the water age in that interval (Figure 1).

"New" water that enters the network from the "*inexhaustible*" sources (nodes where Π elevation is independent of consumption) has an age 0 and it is while traveling through the network mixes with water of different ages. In the event that has a calibrated hydraulic model, EPANET provides automatic modeling of water age, without the use of other empirical coefficients. Water age is treated as a quality parameter which corresponds to the growth of the chemical reaction degree 0 with the coefficient of the reaction rate $k = 1\frac{gm}{lit/s}$, which means that in every second of elapsed time water age of each segment that has not left distribution network is increased by 1 second.



Slika 1. Primena Lagranževog transportnog algoritma u određivanju starosti vode
Figure 1: Application of Lagrange transport algorithm in water age determination

U početnom trenutku proračuna starosti vode, svaka cev u mreži se sastoji od jednog segmenta čija je starost ista kao početna starost vode u uzvodnom čvoru. Tokom vremena simulacije povećava se veličina najuzvodnijeg segmenta vode koji *"dolazi"* kroz cev, a istovremeno, i to za istu vrednost smanjuje veličina najnizvodnijeg segmenta koji *"odlazi"* iz cevi, bez promena na međusegmenima vode. Pretpostavka da po rezervoarima dolazi do kompletnog mešanja vode u ciklusu punjenja je uobičajna za uslove eksploatacije sa dnevnim izravnanjem i dovoljnim fluksom mlaza na dovodu. U ciklusu punjenja starost vode u rezervoaru predstavlja starost mešavine koja se dobija od već prisutne zapremine vode i novopridošle zapremine vode u rezervoaru i ova vrednost predstavlja *"uzvodni granični uslov"* za određivanje starosti vode kod potrošača (u ciklusu pražnjenja rezervoara).

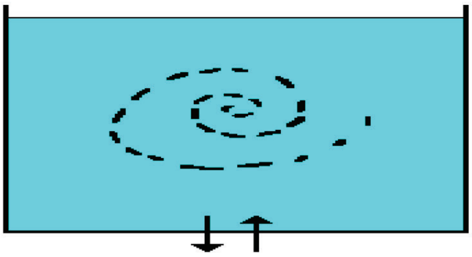
Za modeliranje procesa mešanja u rezervoaru u EPANet-u postoje sledeće opcije:

a. *model kompletnog mešanja* - slika 2 . Ovo je najjednostavniji model koji ne zahteva obračun dopunskih parametara, važi pretpostavka da se starost novopridošle i vode iz rezervoara *trenutno* ujednačavaju
b. *model sa ulazno-izlaznom i glavnom zonom* u rezervoaru - slika 3. Ovaj model mešanja deli ukupnu zapreminu rezervoara na ulazno-izlaznu i glavnu zonu. Novopridošla voda se doprema u ulazno-izlaznu zapreminu i kompletno meša sa njenim sadržajem, a posle popunjavanja ove prve zone rezervoara, novopridošla voda preliva u drugu zonu, gde se potpuno meša sa vodom iz druge zone. Pražnjenje rezervoara počinje pražnjenjem prve zone, a količina nedostajuće vode se dopunjava iz druge zone. Fizički posmatrano, ulazno-izlazna zona može da simulira *"kratki spoj"* u toku vode kroz rezervoarski prostor, a glavna zona *"mrtvu zonu"*. Odnos između zapremina prve i druge

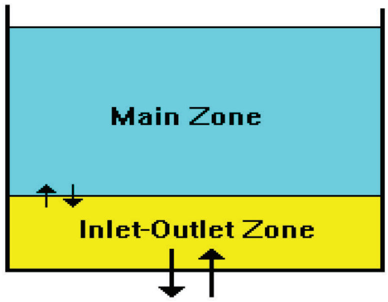
In the initial time of water age calculations, each pipe in the network consists of a single segment whose age is the same as the starting water age in the upstream node. During the simulation time is increased the size of the most upstream water segment, which "enters" through the pipe, and at the same time, for the same value is reduced the size of the most downstream segment that "*leaves*" the pipe, with no changes in intermediate water segments. The assumption that the reservoirs have complete water mixing during the charge cycle is a common in terms of exploitation with daily equalization and sufficient inlet stream flux. In the charge cycle water age in the reservoir is the age of the mixture that comes from the already-present water volume and newly arrived water volume in the reservoir and this value is the "*upstream boundary condition*" for determining the water age in consumer (in the cycle of reservoir emptying).

For the modeling of the mixing process in the reservoir in the EPANET there are the following options:

a. *Model of complete mixing* - Figure 2. This is the simplest model that does not require calculation of additional parameters; the assumption is that the age of the newly arrived and the water in the reservoir are currently equalized.
b. *Model with inlet-outlet and the main zone in the reservoir* - Figure 3. This mixing model divides the total volume of the reservoir to the inlet-outlet and the main zone. Newly arrived water is being delivered to the inlet-outlet volume and is completely mixed with its contents, and then after filling the first zone of reservoir, the newly arrived water overflows into the second zone, where it is fully mixed with water from other areas. Reservoir emptying starts by emptying the first zone and the amount of the missing water is supplemented from other zones. Physically speaking, the inlet-outlet zone can simulate a "*short circuit*" in the water flow through the reservoir area and the main zone is "*dead zone*". The relationship between the volume of the first and second zone sets the user.
c. *FIFO (first in-first out) model* (volume of water that first comes to reservoir, the first leaves this volume) – Figure 4. It is used for modeling the breaking chambers of water supply systems with equal inflow and outflow, which means that there is no spare capacity and water mixing during its stay in the reservoir, and additional modeling parameters are not need.



Slika 2. Model kompletnog mešanja
Figure 2: Model of complete mixing

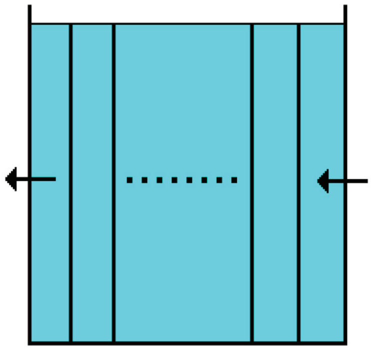


Slika 3. Model mešanja sa ulazno-izlaznom i glavnom zonom
Figure 3: Model of mixing with inlet-outlet and the main zone

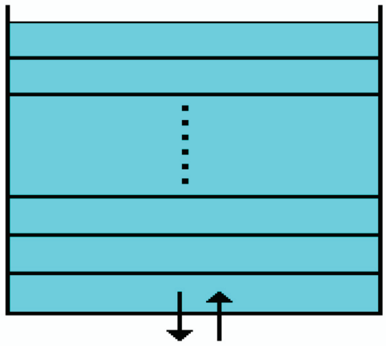
zone zadaje korisnik.

c. *FIFO (first in-first out) model* (zapremina vode koja prva dolazi do rezervoara, prva napušta ovu zapreminu) – slika 4 .Primenjuje se za modeliranje prekidnih komora vodovodnih sistema kod kojih su jednaki dotok i oticaj, ovo podrazumeva da nema rezervne zapremine i mešanja vode tokom njenog boravka u rezervoaru, a za modeliranje nisu potrebni dopunski parametri.

d. *LIFO (last in-first out) model* (zapremina vode koja poslednja dolazi do rezervoara, prva napušta ovu zapreminu) – slika 5. Primenjuje se za modeliranje vodotornjeva kod kojih postoji jedan dovodno-odvodni cevovod na dnu rezervoarskog prostora, sa relativno malom energijom dolaznog mlaza. Tokom boravka vode u ovakvom rezervoaru nema mešanja između čestica vode, one se gomilaju jedna iznad druge, a za modeliranje nisu potrebni dopunski parametri.



Slika 4. Model FIFO
Figure 4 FIFO Model



Slika 5. Model LIFO
Figure 5 LIFO Model

3. MERE ZA SMANJIVANJE STAROSTI VODE U REZERVOARIMA

Srednja starost vode po rezervoarima prvenstveno zavisi od odnosa zapremine vode koja se obrne u dnevnom ciklusu punjenja i pražnjenja i ukupne zapremine rezervoara (slika 6).

Naime, sa povećenjem % zapremine dnevnog obrta vode u rezervoaru u odnosu na ukupnu zapreminu vode, smanjuje se srednja starost vode u rezervoaru. Naime, ako zapremina dnevno promenjene vode u rezervoaru iznosi 20%/dan, srednja starost vode bi po pravilu trebalo da iznosi 5 dana. Međutim, ako nema dobrog mešanja ili postoje *"kratki spojevi"* u toku vode kroz rezervoarski prostor, rezervoar može sadržati vodu čija starost značajno prevazilazi 5 dana. Ovakvo

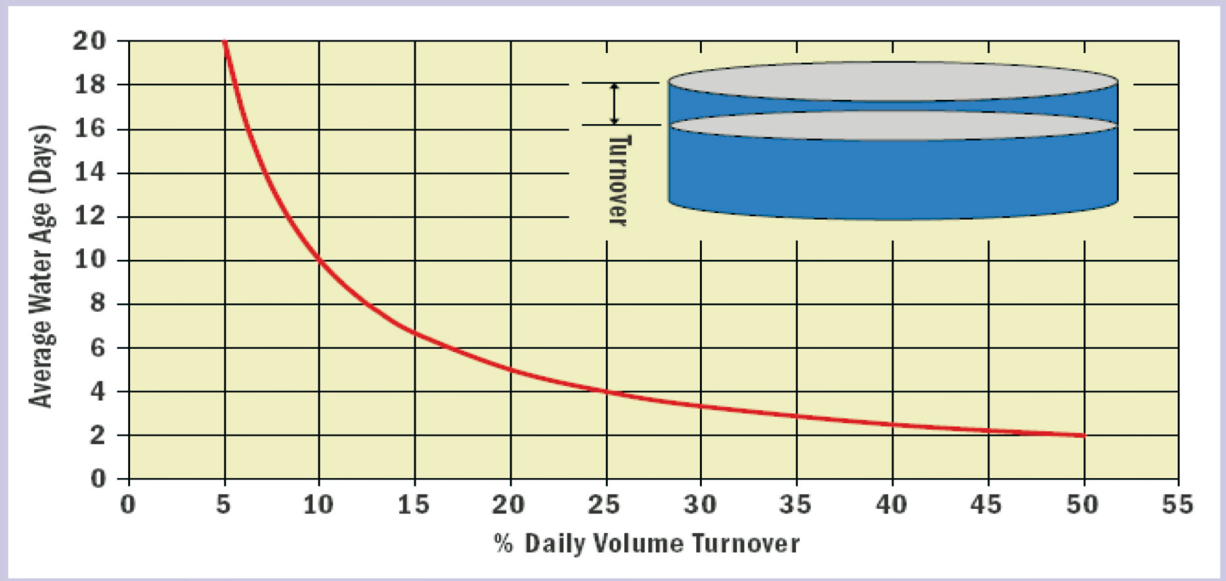
d. *LIFO (last in-first out) model* (volume of water that last comes to reservoir, the first leaves this volume) – Figure 5. It is used for modeling the water towers where there is an inlet-outlet piping system at the bottom of the reservoir area, with relatively low energy of the incoming stream. During the water stay in this reservoir there is no interference between the water particles, they are piling on top of each other, and do not need additional modeling parameters.

3. MEASURES FOR WATER AGE REDUCTION IN THE RESERVOIRS

Average water age in the reservoirs primarily depends on the ratio of daily volume turnover and total volume of the reservoir (Figure 6).

Namely, by increasing the % of daily volume turnover in the reservoir in relation to the total water volume reduces the average water age in the reservoir. Specifically, if the volume of daily turnover in the reservoir is 20% / day, the average water age should be 5 days. However, if there is no good mixing, or there are "*short circuits*" in the water flow through the reservoir area, the reservoir may contain water whose age significantly exceeds 5 days. Such a local increase in the water age can lead to many water quality problems such as increasing temperature, loss of residual chlorine, the occurrence of disinfection by-products, the growth of biofilms and pathogens.

Real water age in the reservoirs is largely dependent on the conditions of mixing and engineering practice says you should keep in mind that the time required for complete mixing is less than the time during re-



Slika 6. Odnos srednje starosti vode u rezervoaru i odnosa zapremine dnevnog obrta i ukupne zapremine rezervoara (%) u slučaju " idealnog" mešanja

Figure 6 Ratio of Average Water Age and ratio between daily volume turnover and total volume of the reservoir (%) in the case of "ideal" mixing

lokalno povećanje starosti vode može dovesti do brojnih problema sa kvalitetom vode kao što su povećanje temperature, gubitak reziduala hlora, pojava nusprodukata dezinfekcije, rast biofilma i patogena.

Prava starost vode po rezervoarima u velikoj meri zavisi i od uslova mešanja, a inženjerska praksa govori da treba voditi računa o tome da vreme potrebno za potpuno mešanje bude manje od vremena tokom koga se puni rezervoar (kako ne bismo došli u situaciju da se potrošačima isporučuje voda neopravdano povećane starosti). Ovim se takođe predupređuje pojava džepova loše izmešane vode čija starost raste pri svakom ponavljanju ciklusa punjenja i pražnjenja rezervoara (Rossman i Grayman, 1999) .

Iskusne službe održavanja vodovoda se sa ovim problemima bore na različite načine povećavajući dnevni obrt vode u rezervoaru isticanjem, promenom nivoa uključivanja-isključivanja pumpi, promenom režima rada pumpi sa promenljivim brojem obrtaja i slično.

Prema preporukama iz literature (Rossman i Grayman, 1999) , važi sledeće:

$$\frac{\Delta V}{V} \geq \frac{9 * d}{V^{\frac{1}{3}}} \qquad (3)$$

gde je

$\Delta V(m^3)$. - zapremina vode dodata tokom perioda punjenja rezervoara

$V(m^3)$ - minimalna rezervna zapremina u rezervoaru

$d(m)$ - prečnik dovodnog cevovoda

Osim dnevnog obrta vode u rezervoaru, najvažniji

servoir charging (in order to prevent distribution of water with unreasonably increased water age). This also prevents the emergence of pockets of poorly mixed water with age increasing with each repetition of the charging and emptying cycle (Rossman and Grayman, 1999).

Experienced waterworks maintenance services are struggling with these issues in different ways, increasing the daily water turnover in the reservoir, changing the level of on-off pump, changing the pumps with variable speed, etc.

According to the literature (Rossman and Grayman, 1999), the following is applied:

$$\frac{\Delta V}{V} \geq \frac{9 * d}{V^{\frac{1}{3}}} \qquad (3)$$

$\Delta V(m^3)$ - volume of water added during filling the reservoir

$V(m^3)$ - minimum reserve volume in the reservoir

$d(m)$ - diameter of the inlet pipe

In addition to the daily water turnover in the reservoir, the most important parameters that determine the quality of mixing in the reservoir are the reservoir volume, energy and orientation of the inlet stream and the diameter of the inlet pipe, the geometry of the reservoir area and the temperature difference between the inlet and the water already in the reservoir (Olson and DeBoer, 2013). In practice, the following methods are used to reduce the water age in the reservoir space:

1. LEVEL REDUCTION to which it provides the pump operation when filling the tank, i.e. increase in daily water turnover in the reservoir, or % of reser-

parametri od kojih zavisi kvalitet mešanja u rezervoaru su zapremina samog rezervoara, energija i orijentacija ulaznog mlaza i prečnik dovodnog cevovoda , geometrija samog rezervoarskog prostora i razlika u temperaturi između dotoka i vode koja se već nalazi u rezervoaru (Olson i DeBoer, 2013). U praksi se koriste sledeći postupci za smanjivanjivanje starosti vode u rezervoarskom prostoru :

1. SNIŽENJE NIVOA DO KOGA je predviđeno da rade pumpe prilikom punjenja rezervoara tj. povećanje dnevnog obrta vode u rezervoaru, odnosno % rezervoarskog prostora predviđenog za dnevni ciklus punjenja i pražnjenja u cilju izravnavanja časovnih neravnomernosti u potrošnji u odnosu na ukupno raspoloživ rezervoarrski prostor.
2. OPTIMIZACIJA RADA PUMPI SA PROMENLJIVIM BROJEM OBRTAJA - umesto da se broj obrtaja pumpi vezuje za održavanjem konstantnog pritiska u nekom kontrolnom čvoru mreže on se vezuje za davanje konstantnog proticaja. Na ovaj nacin se obezbeđuje veći dnevni obrt vode u rezervoaru, smanjuje starost vode. Moguća je i primena kombinovanih rešenja gde bi se broj obrtaja pumpi kontrolisao u skladu sa nivoom u rezervoaru npr. sprorije punjenje prve polovine zapremine raspoložive za dnevni obrt i brže punjenje drugog dela zapremine.
3. UPOTREBA REGULACIONIH VENTILA kojima se mogu u slučajevima prstenastih mreža mogu menjati pravci iz kojih se pune rezervoarski prostori, kao i pravci pumpanja u distributivni system. Kao primer može primena 2 regulaciona ventila sa daljinskom kontrolom iz sistema za prečišćavanje, kojima bi se omogućilo da se ciklusi punjenja i pumpanja centralnog gradskog rezervoara iz oba pravca prstenaste mreže zamene ciklusom punjenja sa jednog i pumpanja u drugi "krak" prstenaste mreže.

Slika 7. Primeri ugradnje opreme za pasivno ili aktivno mešanje
Figure 7: Examples of installation of equipment for passive or active mixing

4. PROMENA UPRAVLJAČKIH PRAVILA koja dovodi do promene pravaca kretanja vode u vodovodnoj mreži, pumpanje u distribuciju umesto u rezervoar, poništavanje upravljačke veze između rezervoara i PRV (ventila za održavanje pritiska) u slučaju da ovako upravljanje dovodi do stagnacije vode u nekoj zoni, naizmenični rad pumpnih stanica.
5. SMANJIVANJE UKUPNE ZAPREMINE REZERVOARA
6. Rekonstrukcije rezervoara i instaliranja opreme za pasivno ili aktivno mešanje njegovog sadržaja – slika 7

voir space for the daily cycle of charge and discharge in order to level the hourly imbalances in consumption relative to total available reservoir space.

2. OPTIMIZATION OF PUMPS WITH VARIABLE SPEED - rather than pump speed is associated with maintaining a constant pressure in a control node which attaches to provide a constant flow. In this way it provides a higher daily water turnover in the reservoir, reducing water age. It is possible to use the combined solution which would control the pump speed in accordance with the level in the reservoir, for example slow charging of the first half of the volume available for daily turnover and faster charging of the second part of volume.
3. USAGE OF CONTROL VALVES which can, in the case of ring networks, change directions of the pump charging, as well as directions for pumping into the distribution system. An example is the application of two control valves with remote control from the water treatment system, which would allow the cycles of filling and pumping of the central city reservoirs in both directions of the ring network to be replaced with the cycle of filling and pumping from one to the other "branch" of the ring networks.
4. CHANGE OF CONTROL RULES, which leads to changes in direction of movement of water in the network, pumping into distribution instead of the reservoir, reset of the control connection between the reservoir and PRV (valve for pressure maintenance) in the event that such management leads to stagnation of water in some areas, alternating operation of pump station.
5. REDUCTION OF TOTAL RESERVOIR VOLUME
6. Reconstruction of the reservoir and installing equipment for passive or active mixing of its contents - figure 7

4. MATHEMATICAL MODEL OF THE WATER SYSTEM PETROVAC AND ANALYSIS OF THE PETROVAC RESERVOIR IN TERMS OF THE WATER AGE IN THE SYSTEM

Public water supply at Petrovac was built in 1973 and reconstructed in 2007 - 2010. Primary source of municipal water supply system is a karst spring "Šetonje" near the village; alternatively, an additional source during the low-water period is a Malo Laole in the alluvium of the river Mlave, near the village of Malo Laole.

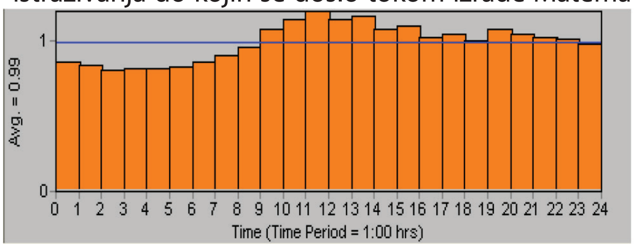
4. MATEMATIČKI MODEL VODOVODNOG SISTEMA PETROVCA I ANALIZA RADA REZERVOARA PETROVAC SA ASPEKTA STAROSTI VODE U SISTEMU

Gradski vodovod u Petrovcu na Mlavi je izgrađen 1973. godine, a rekonstruisan tokom 2007. - 2010. godine. Osnovno izvorište gradskog vodovoda predstavlja karstno vrelo *"Šetonje"* u blizini istoimenog naselja, a alternativno, dopunsko izvorište u malovodnom periodu je Malo Laole u aluvionu reke Mlave, na profilu sela Malo Laole.

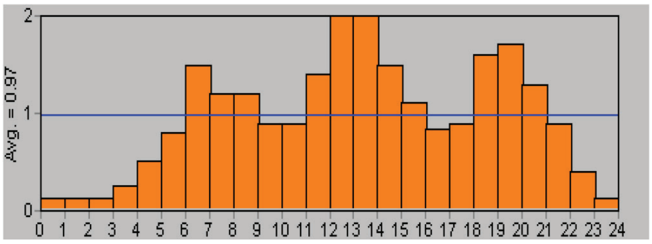
Kapitalni objekti u postojećem sistemu vodosnabdevanja su: PPV Šetonje instalisanog kapaciteta Q = 80 L/s i magistralni gravitacioni cevovod ukupne dužine L= 9.471 m od PPV Šetonje do rekonstruisane PS "Malo Laole" sa merno-regulacionim blokom kojim se reguliše kapacitet gravitacione deonice, rekonstruisana PS "Malo Laole", crpilištem zapremine 75 m³ i tri pumpna agregata tipa P8C/5/20/3C Q = 20 L/s , H = 47 m, N = 22kW, magistralni potisni cevovod PE 100, NP 10 ϕ400 мм L = 9620 m od rekonstruisane PS "Malo Laole" do rezervoara PETROVAC, dvokomorni poluukopani rezervoar PETROVAC zapremine V= 1.500 m³ i gravitacioni dovodni cevovod PE 100, NP 10 ϕ315 мм L = 640 m od rezervoara PETROVAC do distributivne mreže u Petrovcu.

Ukupna potrošnja u danu maksimalne potrošnje je raspoređena između potrošačkih čvorova. Prilikom izbora potrošačkih čvorova korišćeni su rezultati istraživanja do kojih se došlo tokom izrade Matematičkog modela vodovodnog sistema grada Petrovca na Mlavi – Idejni projekat, VODING – 92 - Beograd 1996.god, kao i dijagrami časovnih neravnomernosti za pojedine kategorije potrošača, preuzeti iz istog projekta. Prema ovoj dokumentaciji, postoje tri kategorije potrošača: gradsko stanovništvo, seosko stanovništvo i industrijski potrošači. Dijagrami časovnih neravnomernosti korišćeni u hidrauličkom proračunu za gradsko stanovništvo i seosko stanovništvo su prikazani na slikama 8 i 9.

Za potrebe ovog rada izvršeno je uprošćenje realne



Slika 8. Dijagram časovnih neravnomernosti za gradsko stanovništvo
Figure 8 Diagram of hourly imbalances for urban population



Slika 9. Dijagram časovnih neravnomernosti za seosko stanovništvo
Figure 9 Diagram of hourly imbalances for rural population

Capital facilities in the existing water supply system are: PPV Šetonje with installed capacity of Q = 80 L / s and the gravity main pipeline with a total length L = 9.471 m from the PPV Šetonje to the reconstructed PS "Little Laole" with measuring and regulating block regulating the capacity of the gravitational section, reconstructed PS Malo Laole with wellfield capacity of 75 m³ and three pumping units P8C / 5/20 / 3C Q = 20 L / s, H = 47 m, N = 22kW, the main pressure line PE 100, NP 10 ϕ400 mm L = 9620 m from the reconstructed PS Malo Laole to the reservoir PETROVAC, dual-chamber half-buried tank PETROVAC with volume V = 1.500 m³ and a gravity feed pipeline PE 100, NP 10 ϕ315 mm L = 640 m from the reservoir PETROVAC to the distribution network in Petrovac.

Total consumption in the day of maximum consumption is distributed between the consumer nodes. When selecting the consumer nodes were used research results that were obtained during the development of a mathematical model of the water system of the town of Petrovac - Preliminary design, VODING - 92 - Belgrade in 1996, as well as diagrams of hourly imbalances for certain categories of consumers, taken from the same project. According to the documentation, there are three categories of customers: urban population, rural population and industrial customers. Diagrams of hourly imbalances used in the hydraulic calculation for the urban population and the rural population are shown in Figures 8 i 9.

For the purposes of this work was done simplification of real water supply network (Figure 10) so that the entire main supply is replaced with a gravity section (without PS Malo Laole), and a primary source Šetonje and alternative source of Malo Laole with a node that has a sense of inexhaustible sources of supply for the entire distribution network. Reservoir Petrovac is a node 2, with all 4 options for mixing water in it. This eliminates the effect of the pumping station and pumping regimes on water quality parameters (which can be substantial) and allows the monitoring of changes in the water age caused by a change in the way of the mixing.

Average age of the water is determined by the maximum current consumption by all nodes and using all 4 possible ways of modeling the mixing process in vodovodne mreže *(slika 10)* tako što je kompletan magistralni dovod zamenjen gravitacionom deonicom (bez PS "Malo Laole"), a osnovno izvorište Šetonje i alternativno izvorište Malo Laole jednim čvorom koji ima smisao neiscrpnog izvora snabdevanja za celu distributivnu mrežu. Rezervoar Petrovac je čvor 2, sa sve 4 opcije za mešanje vode u njemu. Ovim se eliminiše uticaj crpilišta i režima pumpanja na parametre kvaliteta vode (koji može biti veoma značajan) i omogućava se praćenje promena u starosti vode čiji je uzrok samo promena načina mešanja u rezervoaru.

Srednja starost vode je određivana u danu maksimalne potrošnje po svim čvorovima i uz primenu sva 4 moguća načina modeliranja procesa mešanja u rezervoaru (u slučaju primene mešanja sa 2 zone, zapremina ulazno-izlazne zone iznosi 50% ukupne zapremine rezervoara) u slučajevima ugradnje različitih ventila na dovodu i za hipotetički slučaj rada bez rezervoara :

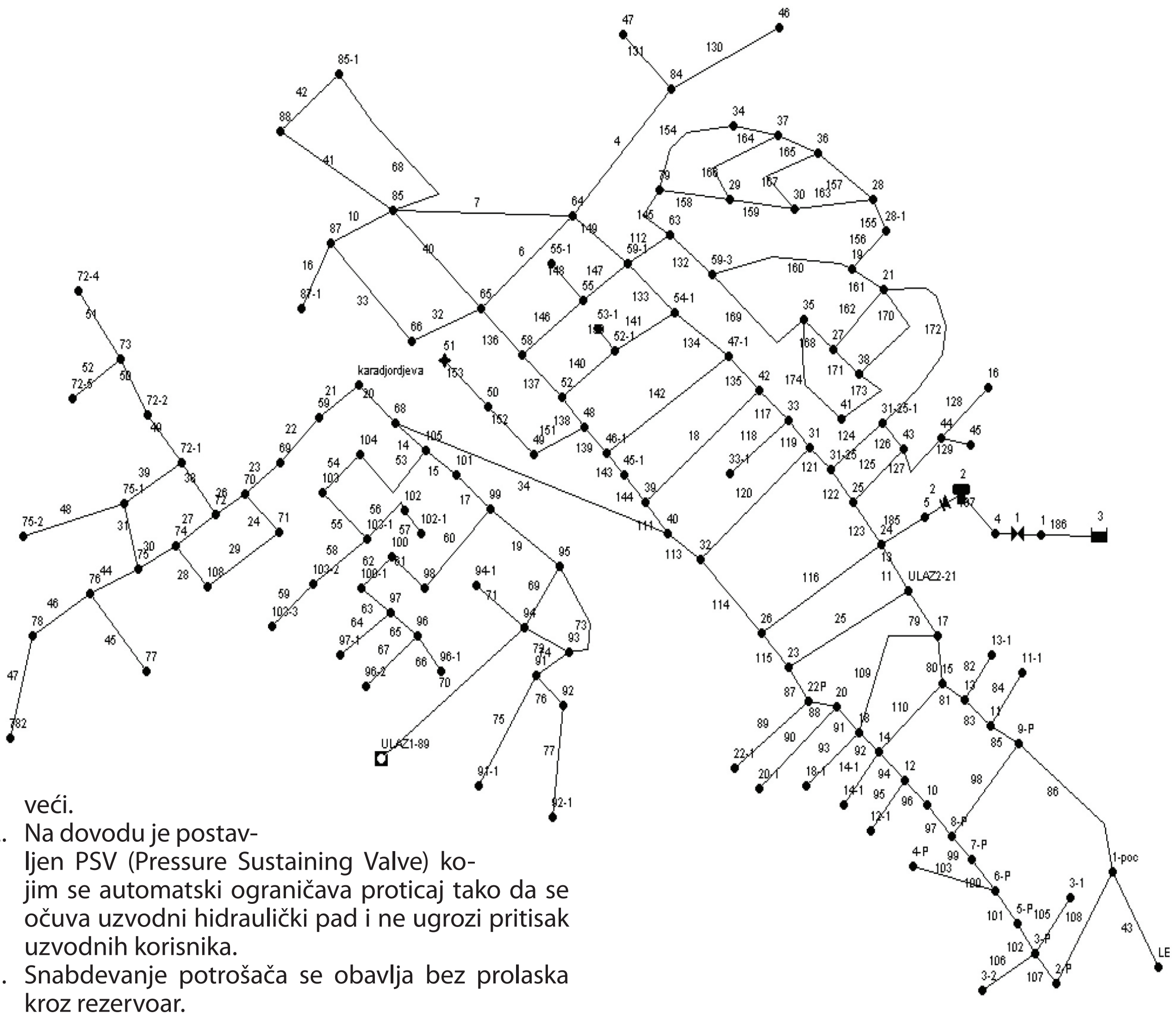
1. Na dovodu je postavljen FCV (Flow Control Valve) koji ograničava proticaj na unapred zadatu vrednost koja je u ovom slučaju jednaka srednjoj potrošnji u danu maksimalne potrošnje. Ugradnja ovog ventila ne znači da se neće ostvarivati manji proticaji od zadatog, ali znači da se neće ostvariti veći.
2. Na dovodu je postavljen PSV (Pressure Sustaining Valve) kojim se automatski ograničava proticaj tako da se očuva uzvodni hidraulički pad i ne ugrozi pritisak uzvodnih korisnika.
3. Snabdevanje potrošača se obavlja bez prolaska kroz rezervoar.

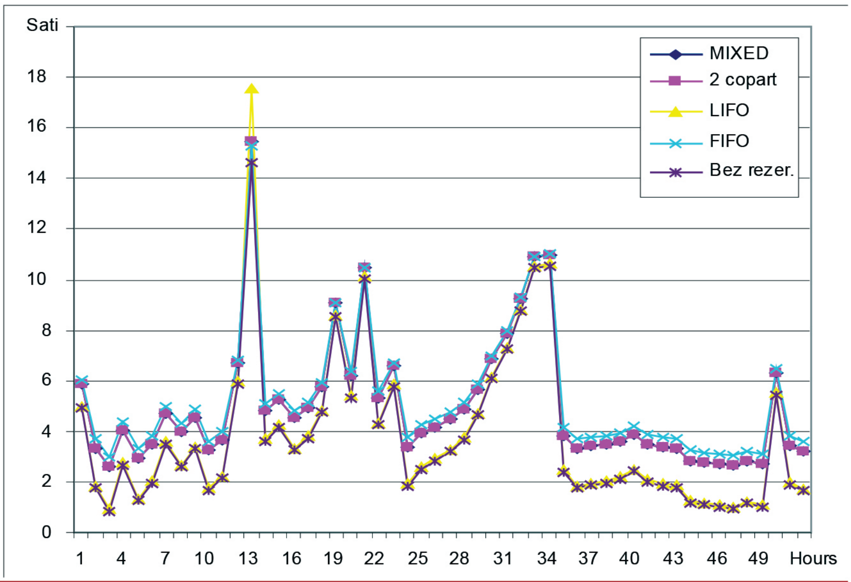
the reservoir (in the case of application of the mixing zone 2, volume of inlet-outlet zone is 50% of the total volume) in the case of installation of various inlet valves and the hypothetical case of operation without the reservoir:

1. FCV (Flow Control Valve) is set at the inlet, which limits the flow to the preset value, which in this case is equal to the average consumption in the day of maximum consumption. Installation of this valve does not mean that it will not pursue discharges less than a given, but it does mean that they will not achieve higher.
2. PSV (Pressure Sustaining Valve) is placed at the inlet, which automatically limits the flow so as to preserve the upstream hydraulic decrease and not to jeopardize the pressure of upstream users.
3. Supplying of consumers can be done without using the reservoir.

Obtained results are shown in the diagrams 11 and 12.

Slika 10. Uprošćeni model vodovodne mreža grada Petrovac na Mlavi
Figure 10 A simplified model of water supply network of the city of Petrovac Na Mlavi





Slika 11. Srednja starost vode u slučaju primene FCV na ulazu u rezervoar (različiti modeli mešanja) i bez rezervoara
Figure 11 Average water age in the case of applying the FCV at the inlet of the reservoir (different mixing models) and without reservoir

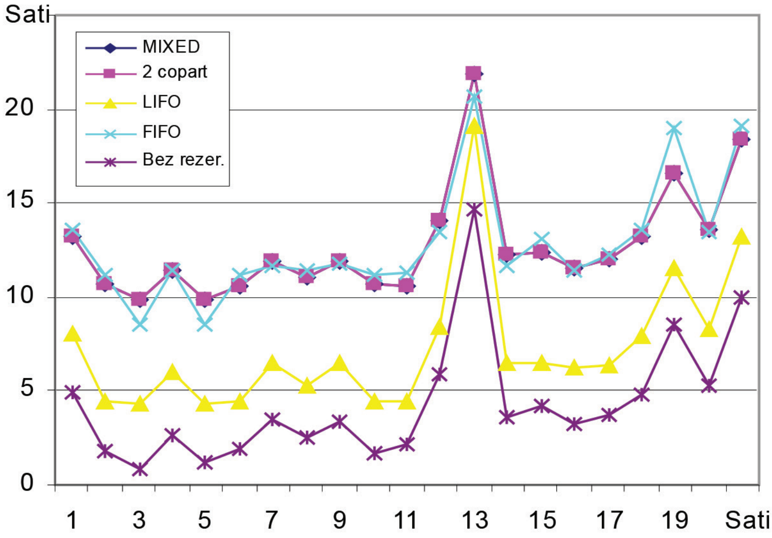
Dobijeni rezultati su prikazani na dijagramima 11 i 12.

Prema rezultatima modeliranja može se zaključiti sledeće:

1. Najmanja srednja starost vode po svim čvorovima sistema se ostvaruje u slučaju kada se mešanje u rezervoaru ostvaruje po LIFO modelu mešanja uz primenu FCV na dovodu.
2. Rezultati primene modela kompletnog mešanja, modela FIFO i rezervoara sa ulazno-izlaznom i glavnom zonom daju približno istu starost vode i u slučaju primene FCV ili PSV na dovodu
3. U slučaju primene PSV na dovodu do rezervoara dobijaju se veće srednje starosti vode, bez obzira na primenjeni model mešanja i to usled promene režima punjenja i realno manjeg dnevnog obrta vode u rezervoarskom prostoru
4. Najveća srednja starost vode po svim čvorovima sistema se ostvaruje u slučaju kada se mešanje u rezervoaru ostvaruje po FIFO modelu mešanja uz primenu PSV na dovodu.

ZAKLJUČAK

Modeliranje kvaliteta vode u distributivnim mrežama treba uvesti u praksu projektovanja i eksploatacije vodovodnih sistema i to preko hidrauličkih simulacionih modela distributivne mreže, jer se samo tako može dobiti prava slika o prostornoj i vremenskoj promenljivosti starosti vode u sistemu. Do interesantnih za-



Slika 12. Srednja starost vode u slučaju primene PSV na ulazu u rezervoar (različiti modeli mešanja) i bez rezervoara
Figure 12 Average water age in the case of applying the PSV at the inlet of the reservoir (different mixing models) and without reservoir

According to the results of modeling, the following can be concluded:

1. Lowest average water age at all system nodes is achieved when the mixing is achieved by the LIFO mixing model, using FCV inlet.
2. Results of applying the model of the complete mixing, FIFO model and reservoirs with inlet-outlet and the main zone give approximately the same water age and in the case of the application of FCV or PSV at the inlet.
3. Application of PSV at the inlet of the reservoir obtains higher average water age, regardless of the applied model of mixing and due to the change of charge regime and really small daily water turnover in the reservoir area.
4. Highest average water age at all system nodes is achieved when the tank mix ing achieves the FIFO model using PSV inlet.

CONCLUSION

Modeling of water quality in distribution networks should be introduced in the design and operation of water supply systems and through hydraulic simulation model of the distribution network, as the only way to get a true picture of the spatial and temporal variability of the water age in the system. Interesting conclusions regarding the dependence of the averaključaka vezanih za zavisnost srednje starosti vode u distributivnoj mreži od načina mešanja vode u rezervoaru i dinamike njegovog punjenja i pražnjenja se došlo sprovođenjem veoma ograničene analize na modelu. Premda je vrednost ovako dobijenih rezultata ograničena, važno je izvršiti njihovo povezivanje sa ranije sprovedenim empirijski dokazanim preporukama, kako bi se u budućnosti radilo sa kalibrisanim matematičkim modelima vodovodnih mreža. Sa druge strane sprovođenje ovakvih analiza je dragoceno u određivanju obima i procedura po kojima bi se sprovodila eksperimentalna istraživanja vezana za kvalitet vode.

ge water age in the distribution network by way of mixing water in the reservoir and the dynamics of the charging and discharging, were obtained using the very limited model analysis. Although the value of the obtained results is limited, it is important to make their connection with the previously conducted empirically proven recommendations to the future working with calibrated mathematical models of water supply networks. On the other hand, the implementation of such analysis is valuable in determining the scope and procedures by which it conducted experimental research related to water quality.

ZAHVALNOST

Rezultati istraživanja modeliranja kvaliteta vode spregnuti sa hidrodinamičkim modelima mešanja po rezervoarima i ranije sprovedenim eksperimentalnim istraživanjima prezentovani u ovom radu su delom finansirani u okviru naučnog projekta Ministarstva prosvete i nauke Republike Srbije broj TR 37010 “Sistemi za odvođenje kišnih voda kao deo urbane i saobraćajne infrastrukture”.

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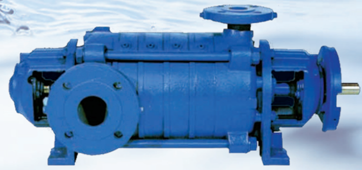

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