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The Concept of Circular Economy in Wastewater Management along the Slovenian Coast

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Abstract
The current concept of wastewater management and treatment in the European Union complies with the requirements of Directive 91/271/EEC on urban wastewater treatment, established in 1991 with a primary focus on limiting excessive organic carbon, nitrogen, and phosphorus in treated water. At that time, the reuse of treated water was not considered. Not surprisingly, attempts were made to remove as much carbon as possible in the form of CO_2. The removal of nitrogen compounds by denitrification results in the formation of N_2, which is then released into the atmosphere. When removing phosphorus compounds, the aim is to incorporate as much phosphorus as possible from the water into the sludge of the wastewater. This also ignores the fact that treated water can be a very valuable resource. In regions, particularly those with advanced agriculture, where wastewater from treatment plants pollutes the environment, adopting an appropriate approach could address summer water shortages, reduce CO_2 emissions into the air, and reduce reliance on artificial fertilisers. The key prerequisite for any use of treated wastewater is adequate microbiological purification and the absence of hazardous substances. This paper analyses the effluent characteristics of some examples of wastewater treatment plants along the Slovenian Adriatic coast, and evaluates the possibilities of reusing the treated water. The results are correlated with the wastewater treatment efficiency data from the town of Rovinj (Croatia), which provides the reuse of treated wastewater for municipal purposes.

Keywords
Wastewater treatment, water reuse regulation, water reuse, Rovinj

1 Introduction

Climate change in much of southern Europe over recent years has led to a severe water deficit from late spring to early autumn.[1] This deficit is worsened by relatively warm winters, resulting in decreased snowfall – a crucial water supply for late spring and early summer. Additionally, the rising summer temperatures and prolonged dry periods in recent years have increased the demand for water, affecting drinking water supplies, industrial needs, and agricultural irrigation. Wastewater treated according to the specific quality standards can replenish water supplies and bridge the gap between demand and availability.[2] Regulation (EU) 2020/741, issued on May 25, 2020, by the European Parliament and Council, outlines the minimum requirements for water reuse, promoting the reuse of water.[3] It sets minimum water quality and monitoring requirements, as well as risk management provisions to ensure the safe utilisation of treated water in the context of integrated water resources management. This Regulation states that the Union's water resources are increasingly under pressure, leading to water scarcity and deterioration in water quality. In particular, climate change, unpredictable weather patterns and drought are contributing significantly to the strain on freshwater availability, arising from urban development and agriculture. By encouraging broader reuse of treated wastewater, the Regulation aims to limit extraction from surface and groundwater bodies, reduce the wastewater discharge impact, and promote water savings through multiple uses for urban wastewater, while ensuring a high level of environmental protection. The minimum requirements for water reuse, as set by this Regulation, are applicable when treated wastewater from urban WWTPs is reused for agricultural irrigation, in accordance with Directive 91/271/EEC,[4] Furthermore, water reuse for agricultural irrigation can contribute to the promotion of the circular economy by recovering nutrients from the reclaimed water and applying them to crops through fertigation techniques. It is necessary to emphasise that the Regulation prioritises the safety of the reclaimed water.

This article is confined to analysing the current situation and exploring possibilities for partially addressing the water supply shortage, especially in the Slovenian coastal area. For several years, this area has been suffering from drinking-water shortages in the summer months due to drought, significantly reducing the amount of water available to the Rižana water supply system. This reduction in available water is also reflected in the flow rates of the Rižana River.[5] The surge in the number of consumers during the peak summer tourist season substantially increases the water demand from the water supply system. For many years, the Rižana water supply system has lacked sufficient water resources during this period, leading to the purchase of water mainly from Croatia. Due to limited water sources tap water consumption has been limited, notably in the summer of 2022. Over the years, experts and politicians

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have focused on exploring alternative water sources in the Notranjska and Karst region (such as water reservoirs). However, there is minimal discussion about the potential utilisation of properly treated wastewater for specific purposes. Currently, water from the Koper Wastewater Treatment Plant is discharged into the sea[6], and water from the Piran Wastewater Treatment Plant flows into a nearby watercourse[7] before reaching the sea.

Municipal wastewater treatment plants (WWTPs) produce treated water with certain concentrations of N and P compounds (nutrients). If the wastewater undergoes appropriate treatment processes and is then used for irrigating agricultural land, the microbiological contamination would need to be eliminated. However, maintaining nutrient concentrations in the water at levels suitable for fertigation would be desirable. Managing municipal wastewater in this manner could alleviate the need for irrigation water and reduce the need for fertilisers on agricultural land.

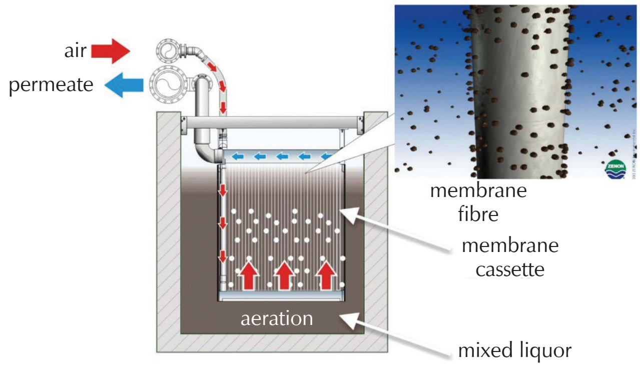

Fig. 1 – Operating principle of MBR wastewater treatment at Rovinj WWTP

Slika 1 – Princip rada MBR uređaja za pročišćavanje otpadnih voda grada Rovinja

2 Methods

In the vicinity of the wastewater treatment plants in the Slovenian coastal settlements of Koper and Piran, there are agricultural areas that require water for irrigation. To assess the potential reduction in water demand from primary sources for irrigating agricultural land on the Slovenian coast, the effects of the WWTPs in this area are examined. Annual reports on the operational monitoring of treated wastewater from 2022 were utilised to analyse the quality of treated wastewater from the WWTPs.[8,9] Data from the Statistical Office of the Republic of Slovenia[10] and literature were employed to determine the amount of water needed to supply agricultural land. The potential water demand for irrigation is analysed and compared with available discharges from the WWTPs. To determine the quality-based potential of water reuse, the available initial measurement results (sampling and laboratory analysis) of treated wastewater from the town of Rovinj, located on the Croatian coast, are presented. Rovinj has already been included in the mentioned strategy of water reuse for municipal and agricultural purposes.[3] Measurement data from the Rovinj WWTP for the year 2022 are analysed.

3 Results and discussion

In 2022, a new WWTP, capacity of 63,000 PE, based on membrane technology (membrane bioreactor, MBR), was constructed to treat the wastewater of Rovinj.[11] The estimated average daily dry discharge is 8,640 m^3/day, and the maximum hourly dry discharge is 631 m^3/h. The initial wastewater treatment includes mechanical pre-treatment, followed by an equalisation basin. Subsequently, biological treatment is planned, combined with filtration on ultrafiltration membranes, and treatment of the effluent sludge. A membrane technology with membrane modules made of ZeeWeed tubular membrane fibres immersed in separate aerated chambers[12] is proposed. The permeability threshold of the membranes used is 0.04 μm. The principle of the membranes is shown in Fig. 1.

The separation of treated water from sludge through a membrane bioreactor represents an advanced technique for wastewater treatment involving activated sludge. The membrane filtration process effectively eliminates suspended solids, bacteria, and a majority of viruses from the water. The plant's intended configuration allows for high adaptability to significant and sudden fluctuations in hydraulic and biochemical wastewater loads, such as those associated with seasonal variations, or increases in the number of residents or guests during weekends or holidays. During periods of lower loading, a large number of modules will temporarily be out of service. The good results achieved by the Rovinj WWTP, according to the JRC analysis[13], are reflected in the data of the "Report on the test series of the Rovinj WWTP".[14] The measured values are presented in Fig. 2. Microbiological analysis of the effluent from the wastewater treatment plant was conducted to detect the presence of *Escherichia coli*, *Enterococci*, *Clostridium perfringens*, and enterovirus. The analyses revealed no presence of the analysed microorganisms.

The results of most studies on the quality of wastewater treated by membrane filtration in various wastewater treatment plants have also shown that the treated water is suitable for irrigation or municipal use.[15,16] The MBR technology employed in treating the wastewater of Rovinj presents advantages over conventional particle removal methods involving settling. In addition to achieving water quality suitable for discharge into sensitive areas, bathing waters, coastal areas for shellfish and fish farming for public consumption, proper treatment of wastewater in MBR plants also allows for its reuse, especially for municipal and agricultural purposes. The advantages of MBR technology align with the concept of circular economy and wastewater management in Rovinj. There are plans to transport the treated water to the southern part of Rovinj through a pressure pipeline approximately 6,600 m in length. The water from the pumping system, with a capacity of 150 $m^3\,h^{-1}$, is further disinfected using UV rays, before utilising it for irrigation of agricultural land and green areas, recreational spaces, and the cleaning of public urban areas.[17]

The problem of water deficit in summer also confronts the inhabitants of the Slovenian coastal regions. Treated

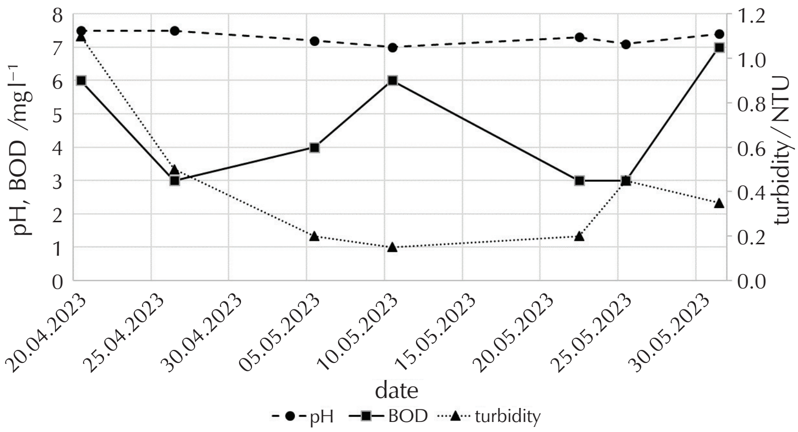

Fig. 2 – Results of the effluent analysis of Rovinj WWTP
Slika 2 – Rezultati analize efluenta uređaja za pročišćavanje otpadnih voda grada Rovinja

wastewater from the Koper WWTP flows into the Rižana River just before it reaches the sea, where public bathing areas and shellfish farms are situated. Treated wastewater from the Piran WWTP flows into the sea. In both cases, the effluent is microbiologically contaminated, which poses concerns for protecting the microbiological quality of bathing waters and shellfish farms. While this article does not address the negative impact of the microbiologically untreated effluents from the Koper and Piran WWTPs on sea quality, its primary aim is to emphasise the potential of reusing properly treated wastewater, mainly for municipal, agricultural, and industrial purposes. Further presented are the operational characteristics of the WWTPs and data on water quality at the outflow of the WWTPs, extracted from the annual reports of the WWTPs for the year 2022.

The Koper WWTP is designed to treat 84,500 PE of wastewater. It utilises SBR technology with selectors installed before the sequential basins. The selector tanks operate from anoxic to anaerobic conditions, eliminating the need for an anoxic mixing phase in the sequencing tanks. The selectors streamline the process and facilitate the biological selection of microorganisms that mainly form flocs at all loadings, but especially at loadings below the design load. UV disinfection is conducted during the bathing season (from early June to mid-September) at the outflow of the treatment plant. The treated water from the plant is discharged into the Rižana watercourse, near its mouth, into the sea. The annual report of the Koper Wastewater Treatment Plant for the year 2022[8] provides the following information on the outflow.

The Piran WWTP has a capacity of 33,000 PE. It employs SBR technology for the biological treatment stage, and there is no additional disinfection of the water at the outflow of the treatment plant. The treated water from the plant is discharged into the sea through two submarine outflows of about 3500 m in length. The annual report of the Piran WWTP for the year 2022[9] provides the following information on the outflow.

Table 1 – Parameters at the outflow of the Koper WWTP in 2022
Tablica 1 – Parametri vode na izlazu iz postrojenja za pročišćavanje otpadnih voda Kopra u 2022. godini

Koper WWTP for the year 2022	Value
Number of residents	51,756
Annual volume of treated wastewater	4,917,420,000 m^3
Suspended solids concentrations	1.7 to 19.0 $mg\,l^{-1}$
NH_4^+ concentrations	0.8 to 8.3 $mg\,N\,l^{-1}$
N_{tot} concentrations	2.3 to 20.0 $mg\,N\,l^{-1}$
P_{tot} concentrations	0.30 to 1.75 $mg\,P\,l^{-1}$
COD	10 to 73 $mg\,O_2\,l^{-1}$
BOD	3 to 9 $mg\,O_2\,l^{-1}$
No. *Escherichia coli*	11 to 727 cfu/100 ml (from early June to mid-September)
No. Intestinal *Enterococci*:	9 to 170 cfu/100 ml

Table 2 – Parameters at the outflow of the Piran WWTP in 2022
Tablica 2 – Parametri vode na izlazu iz postrojenja za pročišćavanje otpadnih voda Pirana u 2022. godini

Piran WWTP for the year 2022	Value
Number of residents	14,290
Annual volume of treated wastewater	2,363,798,000 m^3
Suspended solids concentrations	5.5 to 65.0 $mg\,l^{-1}$
NH_4^+ concentrations	1.0 to 5.9 $mg\,N\,l^{-1}$
N_{tot} concentrations	4.0 to 13.7 $mg\,N\,l^{-1}$
P_{tot} concentrations	0.56 to 1.46 $mg\,P\,l^{-1}$
COD	11 to 95 $mg\,O_2\,l^{-1}$
BOD	8 to 29 $mg\,O_2\,l^{-1}$
Presence of microorganisms is not controlled	

The data on the composition of treated wastewater in the Koper[8] and Piran[9] WWTPs for 2022 are similar to the data in their other annual reports for the period 2015–2022. Both the Koper and Piran WWTPs exhibit shortcomings in providing adequate microbiological treatment, leading to microbiologically polluted water at the outflow of the WWTPs. The measured values in 2022 for suspended solids, COD, total nitrogen, and total phosphorus are presented in Figs. 3–6.

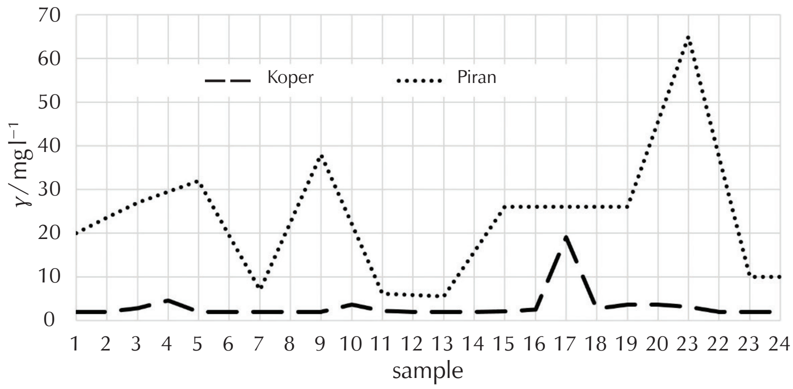

Fig. 3 – Concentrations of suspended solids at the Koper and Piran WWTPs in 2022

Slika 3 – Koncentracije suspendiranih tvari na uređajima za pročišćavanje otpadnih voda u Kopru i Piranu u 2022.

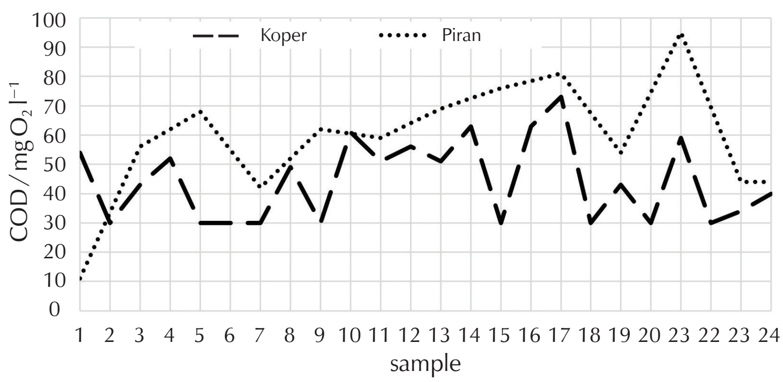

Fig. 4 – COD values at Koper and Piran WWTPs in 2022

Slika 4 – KPK vrijednosti na uređajima za pročišćavanje otpadnih voda u Kopru i Piranu u 2022.

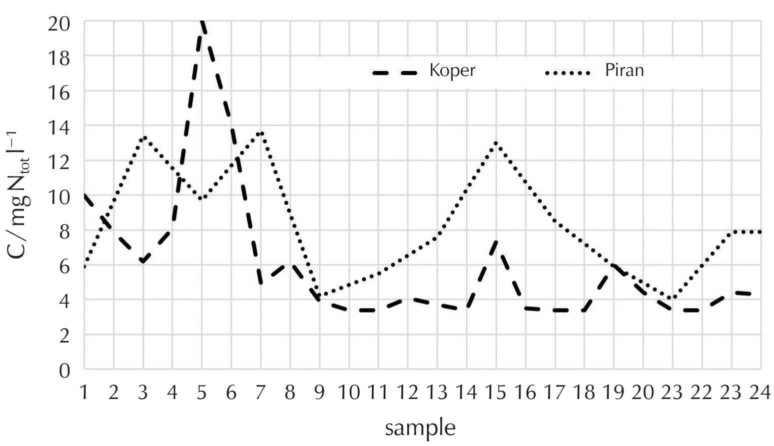

Fig. 5 – N_{tot} concentrations at the Koper and Piran WWTPs in 2022

Slika 5 – N_{tot} koncentracije na uređajima za pročišćavanje otpadnih voda u Kopru i Piranu u 2022.

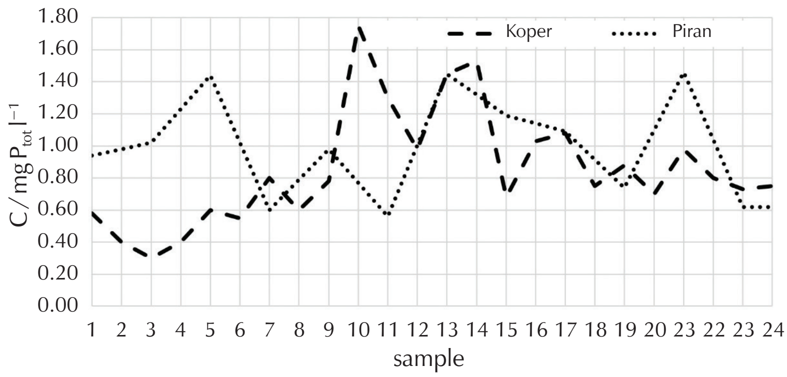

Fig. 6 – P_{tot} concentrations at the Koper and Piran WWTPs in 2022
Slika 6 – P_{tot} koncentracije na uređajima za pročišćavanje otpadnih voda u Kopru i Piranu u 2022.

The diagrams (Figs. 3–6) reveal that the water quality from the existing wastewater treatment plants in Koper and Piran fails to meet the reclaimed water quality criteria for agricultural irrigation[17], which could otherwise be utilised for municipal purposes or for irrigation of surrounding agricultural land. The populated area serviced by the Koper and Piran WWTPs encompasses agricultural land, mainly vineyards and orchards. Given the prolonged dry periods in summer, there is an increased demand for irrigation in these areas. According to the Statistical Office of the Republic of Slovenia[10], in 2022, 4,955 ha of land were irrigated, consuming 3,443,000 m^3 of water. This implies an average of 695 m^3/ha used for irrigation of agricultural land in 2022, a calculated value several times lower than the irrigation water consumption obtained in practice for certain crops. *Pintar* and *Matajc*[18] state that 3,329 m^3/ha of water was used for irrigation in the considered areas in 2001.

A similar approach to the reuse of treated wastewater from the city of Rovinj could be applied to wastewater from the Slovenian coastal WWTPs of Koper and Piran. In the area of municipal systems, where the studied WWTPs of Koper and Piran are located, water consumption exhibits considerable variations throughout the year, peaking during the summer months as a monthly average. In 2022, the average flow at the Koper WWTP was 156 $l\,s^{-1}$, with a maximum weekly average of 233 $l\,s^{-1}$.[8] For the same period, the average flow at the Piran WWTP was 75 $l\,s^{-1}$ with a maximum weekly average flow of 115 $l\,s^{-1}$.[9] Considering the intensive irrigation season lasting 3 to 4 months and the surge in water consumption during summer, it is assumed that nearly half of the treated water out of the total annual WWTPs output could be utilised for irrigation. Consequently, the amount of treated water during the irrigation season would likely suffice for irrigating the surrounding agricultural lands and meeting the year-round municipal needs of the communities.

4 Conclusion

This research indicates that the amount of water discharged daily from the Koper and Piran WWTPs roughly equals the amount of drinking water consumed from the Rižana water supply system. To enable the reuse of water from the Koper and Piran WWTPs, regular quality controls of the wastewater inflow to the WWTPs should be implemented to detect the presence of hazardous substances. Furthermore, these facilities should be upgraded to ensure adequate microbiological quality of the water for reuse. An effective risk management strategy should proactively identify and manage risks, incorporating the concept of producing reclaimed water with specific quality requirements for particular uses.[5] Upgrading the WWTPs could involve introducing membrane treatment for wastewater and, if necessary, additional UV disinfection. Properly treated wastewater has the potential to replace 50–80 % of the total water demand from other sources. If water from the WWTPs is exclusively used for irrigating agricultural land, the rate of nutrient removal would not be as important. This would also reduce the need to add nutrients through artificial or natural fertilisers. However, such an approach is hindered by current legislation that sets discharge limits for WWTPs.

On the other hand, new legislation encourages water reuse. The Regulation on Minimum Requirements for the Reuse of Water for Agricultural Irrigation[5] came into effect in June 2020, applicable from June 26, 2023. This Regulation aims to promote and facilitate water reuse in the EU, covering not only agriculture, but also permitting EU member states to use reclaimed water for industrial, municipal, and environmental purposes.

List of abbreviations
Popis kratica

EU – European Union
– Europska unija

MBR – membrane bioreactor
– membranski bioreaktor

SBR – sequential batch reactor
– slijedni šaržni reactor

UV – ultraviolet
– ultraljubičasto

WWTP – wastewater treatment plant
– uređaj za pročišćavanje otpadnih voda

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SAŽETAK

Koncept kružnog gospodarstva u gospodarenju otpadnim vodama duž slovenske obale

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Postojeći koncept upravljanja i pročišćavanja otpadnih voda u Europskoj uniji udovoljava zahtjevima Direktive 91/271/EEZ o pročišćavanju komunalnih otpadnih voda. Godine 1991. glavni je cilj bio da pročišćena voda ne smije sadržavati prekomjerne količine organskog ugljika, dušika i fosfora. U to vrijeme ponovna uporaba pročišćene vode nije razmatrana. Ne iznenađuje činjenica da se pokušalo ukloniti što je moguće više ugljika u obliku CO_2. Pri uklanjanju dušikovih spojeva denitrifikacijom nastaje N_2, koji se ispušta u atmosferu. Pri uklanjanju fosfornih spojeva cilj je ugraditi što više fosfora iz vode u mulj otpadnih voda. Zanemaruje se činjenica da pročišćena voda može biti vrlo vrijedan resurs. U područjima posebice s razvijenom poljoprivredom, gdje voda iz uređaja za pročišćavanje otpadnih voda zagađuje okoliš, odgovarajućim bi se pristupom mogla riješiti nestašica vode ljeti te smanjiti emisija CO_2 u zrak i potreba za umjetnim gnojivima. Najvažniji uvjet za svaku uporabu pročišćene otpadne vode je odgovarajuće mikrobiološko pročišćavanje i odsutnost opasnih tvari. Za neke primjere uređaja za pročišćavanje otpadnih voda duž slovenskog dijela jadranske obale analizirane su karakteristike efluenta i ocijenjena je mogućnost ponovne uporabe vode iz uređaja za pročišćavanje otpadnih voda. Rezultati analize uspoređeni su s podatcima o učinkovitosti pročišćavanja otpadnih voda grada Rovinja, u kojem je predviđena ponovna uporaba pročišćene otpadne vode u komunalne svrhe.

Ključne riječi
Pročišćavanje otpadnih voda, uredba o ponovnoj uporabi vode, ponovna uporaba vode, grad Rovinj

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