6JRC/IPR/2019/OP/0394 Nature Based Solutions in Agriculture

LOT 3 TREATMENT OF WASTEWATER SLUDGE OR MANURE FROM LIVESTOCK (TSM) IN A MEDITERRANEAN ENVIRONMENT

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Contract number	no. 937798 – IPR – 2019
Subject	LOT 3 - TREATMENT OF WASTEWATER SLUDGE OR MANURE FROM LIVESTOCK (TSM) IN A MEDITERRANEAN ENVIRONMENT
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Project end date:	30.04.2020
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LIST OF ABBREVIATIONS

BM	Business Model
BOD	Biological Oxygen Demand
BTM	Benefit Transfer Methods
CAPEX	Capital Expenditures
CFU	Colony Forming Unit
COD	Chemical Oxygen Demand
CW	Constructed Wetland
DM	Dry Matter
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GEF	Global Environment Facility
IUCN	International Union for Conservation of Nature
LOD	Limit of Detection
LOQ	Limit of Quantitation
MBBR	Moving Bed Biofilm Reactor
N.A.	Not Applicable
NBS	Nature Based Solutions
NPV	Net Present Value
O&M	Operation and Maintenance
OPEX	Operating Expenditures
PE	Population Equivalent
SBR	Sequencing Batch Reactor
SLR	Sludge Loading Rate
(SD)RB	(Sludge Drying) Reed Beds
TC	Total Carbon
TN	Total Nitrogen
TP	Total Phosphorus
TVS	Total Volatile Solids
TSS	Total Suspended Solids
UNIDO	United Nations Industrial Development Organization
VAT	Value Added Tax
WEFE	Water-Energy-Food-Ecosystems (Nexus project)
WW	Wastewater
WWTP	Wastewater Treatment Plant

1 INTRODUCTION

1.1 Context

With the combined effects of population growth, economic development, and expanding cities, the pressure on water sources is increasing and will increase even further in the future. Due to water and nutrient needs and scarcity producing more crops will become even more demanding in terms of water and nutrients. With adverse effects on natural ecosystems that provide essential services (including soil and water), every aspect of resource recovery must be explored. Integrated approaches are needed while simultaneously tackling water, agriculture (nutrients), and population needs.

Nature-based solutions provide an approach, where engineered natural ecosystems can be integrated to address targeted challenges effectively and adaptively, while providing human well-being and biodiversity benefits. The challenges might include climate change, water security and pollution, food security, human health (from IUCN definition[1]).

The purpose is that wastewater treatment process can result in resource recovery for water and nutrient reuse in agriculture. Sewage sludge resulting from the wastewater treatment process is regarded as a potentially useful resource if adequately processed. Phosphorus is a critical raw material, essential as fertilizer, and non-renewable scarce natural resource with limited natural phosphate rock reserves expected to run out within the next few decades.

Sludge management, on the other hand, is highly complex and has a cost ranging from 10 to 60 % of the total operating costs of the wastewater treatment plants (WWTP), depending on the sludge treatment technology (although sludge represents only 1 % to 2 % of the treated wastewater).[2] The proper end point of the 'biosolids' is a fundamental factor for the success of a sanitation system. Nowadays, sludge management is not limited to treatment and disposal. There imperative to look at sustainable sewage sludge management, which means that "the resources intrinsic to the sludge are recycled, while pollutants are transformed or removed".[3] Nutrients recovered and recused have been neglected in many countries outside Western Europe. Wastewater treatment plant design and the lack of national strategies for sewage sludge reuse or final disposal often results in neglecting the valorization of potential useful end products. This prevents WWTP investors to decide/recommend sewage sludge treatment that comply with a circular economy principles (UN goals).

1.2 Purpose

The report aims at studying in depth a pilot case, to build a solid base of the practical feasibility, effectiveness, and limitations of NBS, to treat sludge, while recovering resources, lowering financial costs and environmental impact.

The case study evaluated, along with a literature review and results from systems in Europe, will be used for a research synthesis, aimed at assess at European scale, policy recommendations in the context of the JRC Water-Energy-Food-Ecosystems (WEFE) Nexus project.

The pilot case study presented will focus on the treatment of sludge resulting from wastewater treatment, using sludge drying reed beds running under Mediterranean climatic conditions. The study includes a description of the benefits provided by natural processes, further engineered and optimized, with well-identified input flows to meet the required effluent standards. The primary purpose of the NBS considered is

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[1] https://www.iucn.org/commissions/commission-ecosystem-management/our-work/nature-based-solutions

[2] https://www.iwapublishing.com/sites/default/files/ebooks/9781780402130.pdf

[3] http://site.iugaza.edu.ps/rkhatib/files/2015/02/Sludge-Managemant-Chapters-1-and-2.pdf

the control of nutrient surplus and other contaminants while stabilizing and mineralizing the sludge, to produce a safe resource.

The following questions and aspects will be addressed in the chapters. The geographical study area is defined in the second chapter where the pilot case is located, considering the relevant elements for up-scaling the technology to the (entire) Mediterranean region.

The third chapter offers an insight into the reed bed technology where the pilot plant is located , describes the sludge treatment process, and presents technical description of the pilot plant and of two more sludge drying reed bed systems.

The report should provide insight into the efficiency of NBS reed bed technology for sewage sludge treatment and its suitability to be used in the Mediterranean areas. The analyses of treated biosolids (product of reed beds) asserts the use of the biosolids in agriculture. Furthermore, sewage sludge management is facing increasing challenges. Nutrient recycling potential is a most relevant one, as Phosphorus contained in the sludge should not be wasted. Clearly nutrient recovery must be economically justified and feasible, which is still unachieved. On the other hand users should be more prone to direct disposal of biosolids for nutrient reuse. This behavioural change is required in order to achieve direct nutrient reuse.Thus, the practice of sludge reuse in agriculture compared to other management alternatives was considered and evaluated. A business model was prepared and evaluated on the pilot case and it does confirm the business opportunity based on circular economy principals.

2 STUDY AREA

2.1 Basic information

The pilot plant is located on the Istrian peninsula in Mirna River watershed of 220 masl on karst ground. The north-west part of Municipality borders the Natura 2000.

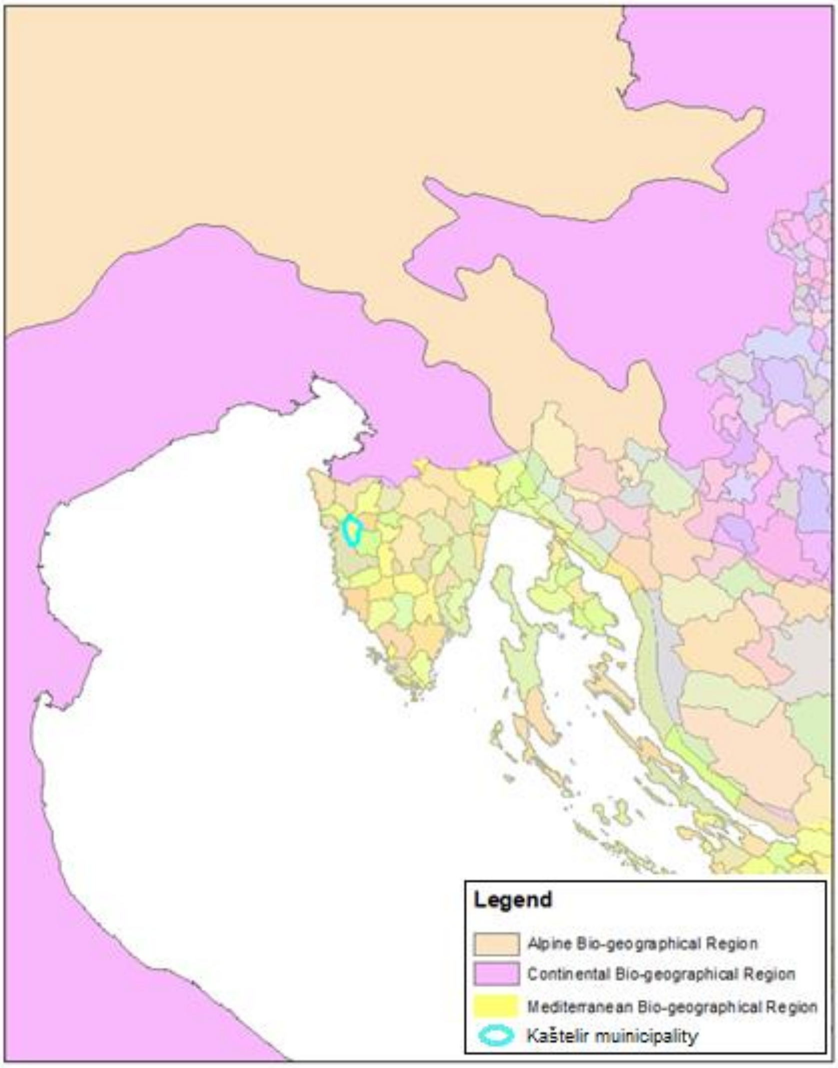

Figure 1: Kaštelir - Labinci Municipality within Croatian national border and biogeoregions[4]

The Municipality of Kastelir-Labinci is the center of the northwestern Istria. With a total area of 34 km^2, consists of 15 settlements: Babići, Brnobići, Cerjani, Deklići, Dvori, Kastelir, Kovači, Krančići, Labinci, Mekiš, Rogovići, Rojci, Roškići, Tadini and Valentići. The population is mainly engaged in small and medium-sized enterprises and agriculture. Among the economic production wine, potatoes, olive oil, honey, and vegetables are known to be of high quality. Favorable climate, a peaceful environment of low population density and, at the same time, an environment that strives for continued economic development. The region, has come a long way in the history and characteristics of which the population lived in a tumultuous geographical position.

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[4] [4] https://www.diva-gis.org/gdata

The blue Adriatic Sea lies 4 km from Kastelir and other towns that have made Istria a popular visiting destination (e.g. Poreč). Local population life is strongly linked to the sea and tourism. Over the past 10 years, there has been a significant increase in the construction of villas and holiday homes. The tourist visit in the summer increases the pressure on the environment and local capacities.

Like in the rest of Istria, tourism is a strong economic activity in the area. The Municipality Kastelir-Labinci with 1.483 inhabitants (31.12.2017)[5] in 15 settlements. According to the 2011 census report Municipality of Kastelir-Labinci had 547 private households and 758 apartments, which shows that a large number of apartments are owned by persons who do not live in the area of Kastelir-Labinci (weekenders) and that a number of residents of the Municipality have more flats and that they are partly used for tourist rental purposes[6]. Addressed WWTP treats wastewater from the municipality Kastelir – Labinci; 3 small settlements (cc. 150 inhabitants) are exempt from sewage network.

2.2 Problem description

The report presents a case study dealing with sludge drying reed beds located at the village Kastelir. In 2010, as part of the project for the protection of pollution in the coastal area, the Municipality began to build a sewage network with the establishment of a constructed wetland (CW) for wastewater treatment along with a reed beds (RBs) for sludge treatment.

Wastewater treatment plant (WWTP) Kastelir was designed for 1.900 population equivalents (PE). Since the construction in 2015 the WWTP is operating below design capacity. About 70-80 % are connected to the WWTP. The remaining 8 km of sewage system that needs to be constructed is currently in the design phase. After the sewage system is completed, WWTP Kastelir will operate with full capacity. Additionally, more than the half of households are intended for tourism and occupation is seasonal.

The WWTP in Kastelir is constructed in the industrial zone (Figure 2).

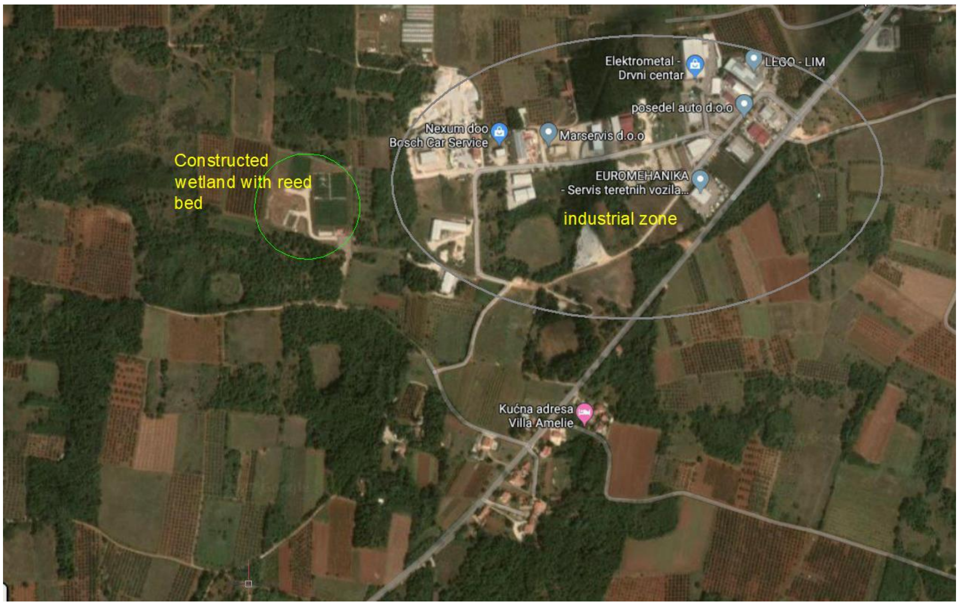

Figure 2: WWTP Kastelir location

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[5] 2011 Census. DZS. URL: https://www.dzs.hr/ (28. 11. 2019).

[6] Program ukupnog razvoja 2014. - 2020. URL: https://www.kastelir-labinci.hr/hr/dokumenti/sve/sve/Dokumenti%20i%20Akti (28. 11. 2019).

Knowledge and management of sewage sludge in the Mediterranean region have evolved, and a review of NBS practice in Kastelir (Croatia) is expected to bring useful recommendations to secure the confidence and co-operation of different stakeholders to further implement sludge drying reed beds (RBs.)

2.3 Site characteristics

2.3.1 Climate

Municipality of Kastelir belongs to the Mediterranean Biogeographical region and has a moderately warm humid climate with hot summers (Cfa). Climate is conditioned by geographical location and surface. The proximity of the sea with low relief and a pronounced edge to the northeast in the zone of Ćićarija and Učka have a great influence on maintaining the climate peculiarity of the municipality, as well as the entire Istrian region. Summers are hot, and the coldest month is January with average temperatures above zero. The area of the Municipality Kastelir-Labinci is governed by a somewhat altered Mediterranean, moderately warm rainy climate with a slightly stronger landmass impact. The area of the lower and higher hinterland of Poreština partly covers the lower and higher part of the Municipality of Kastelir-Labinci. The northern part belongs to the Mirna Valley[7].

The average rainfall in the Kastelir-Labinci Municipality is 1.070 mm annually. The driest month is July, with an average of 70 mm of rainfall. In November, the precipitation reaches its peak, with an average of 122 mm (Figure 3).

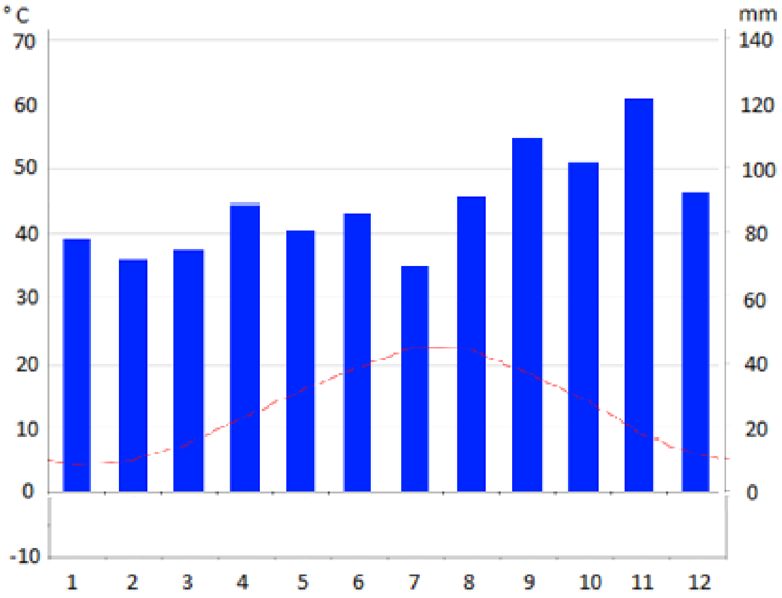

Figure 3: Climate graph of Kastelir[8]

The average annual temperature in the Municipality is 13,2 °C. June, July, August and September are the warmest months (Figure 4).

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[7] Program ukupnog razvoja 2014. - 2020. https://www.kastelir-labinci.hr/hr/dokumenti/sve/sve/Dokumenti%20i%20Akti (28. 11. 2019).

[8] Kastelir climate. URL: https://en.climate-data.org/europe/croatia/kastelir/kastelir-228118/ (15. 11. 2019).

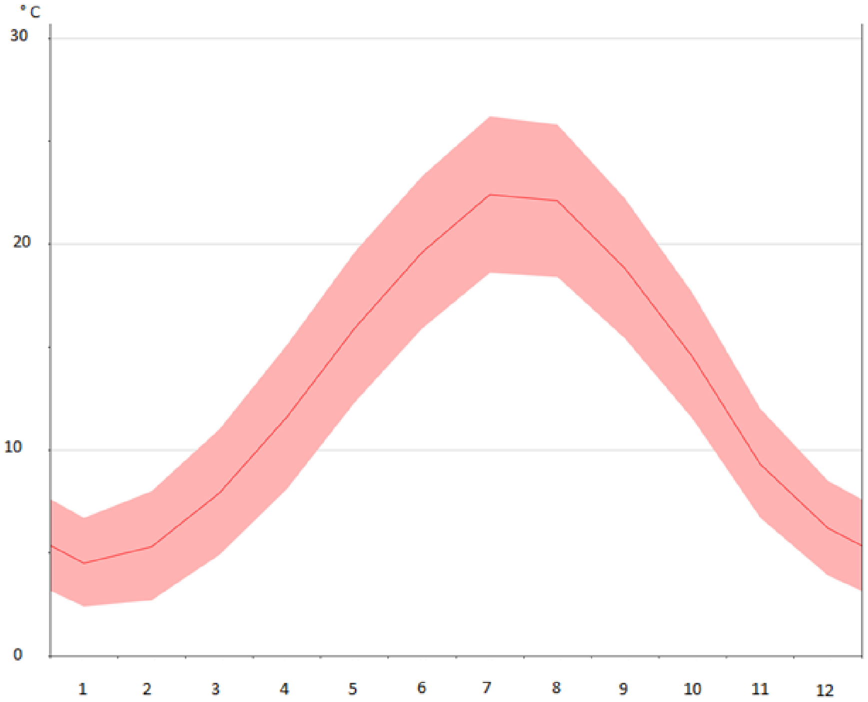

Figure 4: Temperature of Kastelir during the year[9]

Kastelir weather averages are presented in the table below.

Table 1: Kastelir weather averages by month[10]

Weather averages	1	2	3	4	5	6	7	8	9	10	11	12
Avg. T (°C)	4,5	5,3	7,9	11,6	15,9	19,6	22,4	22,1	18,8	14,5	9,3	6,2
Min. T (°C)	2,4	2,7	4,9	8,1	12,3	15,9	18,6	18,4	15,4	11,5	6,7	3,9
Max. T (°C)	6,7	8	11	15,1	19,6	23,3	26,2	25,8	22,2	17,6	12	8,5
Precipitation (mm)	79	72	75	89	81	86	70	91	110	102	122	93

2.3.2 Hydrography

The whole area is a typical karst area, mostly dominated by water shortages (no floods). The exception is one of the most important watercourses in Istria, the river Mirna with a catchment area of 536 km^2 and a length. 53 km, is the longest river in Istria. It originates 32 km east of the discharge to the Adriatic Sea, in Kotli. The upstream flows through flysch Buzetščina, has a torrential character and an extensive network of tributaries. Downstream, the canyon section of the valley, deeply carved into the limestone plain, begins with the gorge Kamena vrata. Before reclamation and regulation, Mirna regularly flooded during heavy rainfall, and at the beginning of the 20th century, the valley floor was mostly below sea level[11]. In its lower reaches, it occupies the far northern part of the Municipality. On carbonate rocks that dominate the area, large quantities of water sink into deeper parts of the underground. The mechanism of water motion through soluble rocks is impossible to determine because there are innumerable combinations, which is entirely consistent with the

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[9] Kastelir climate. URL: https://en.climate-data.org/europe/croatia/kastelir/kastelir-228118/ (15. 11. 2019).

[10] Kastelir climate. URL: https://en.climate-data.org/europe/croatia/kastelir/kastelir-228118/ (15. 11. 2019).

[11] Zamejska Hrvaška. Ekskurzoje Ljubljanskega geografskega društva, 2008. Založba ZRC. URL: https://books.google.si/books?id=MLEsaxX_msUC&pg=PA166&lpg=PA166&dq=reka+mirna+hrvatska&source=bl&ots=fao8AqhTlo&sig=ACfU3U325s2k12Yq8Hw_W0rBwvyEfZhcYQ&hl=sl&sa=X&ved=2ahUKEwjFm7eal4PnAhWEllsKHV-1DMgQ6AEwCHoECBQQAQ#v=onepage&q=reka%20mirna%20hrvatska&f=false (10. 11. 2019).

nature of the karst and its properties. Mirna River valley is an important agricultural area, rich mainly with truffles, vineyards, olives, figs, and cherries groves.

The torrents in the Mirna River basin caused extensive damage due to soil erosion. Part of Mirna River that belongs to the Municipality of Kastelir-Labinci is regulated[12].

2.3.3 Karst

The Municipality of Kastelir-Labinci lies in the karst area of the Istrian peninsula. Karst aquifers are particularly susceptible to contamination because of very thin or absent soil, vegetation, and/or sediments enabling a rapid flow of the infiltrating water and its distribution over large distances in heterogeneous flow conditions. For these specific characteristics, the overlying layers and concentration of flow enable easy and rapid pathways to the saturated zone. Since there is little opportunity for contaminant attenuation until it reaches groundwater, spring, or well, some severe contamination problems may result from different human impacts. Karst aquifers are vital for regional and local drinking water supply. Therefore, human impacts and their effects on karst groundwater are becoming more important for the proper groundwater protection[13]. The lack of an adequate wastewater drainage and treatment system is even more pronounced, considering that the karst aquifer in the Istrian Region is extremely sensitive to surface pollution and that 70% of the area of the region is under some water protection regime. The central Istrian aquifer serves as retention recharging karts springs of the Mirna river basins[14].

Rapid propagation of pollutants in karst landscape is a limiting factor when it comes to sludge reuse, which is also one of the main reasons why local authorities have not decided where treated sludge will be disposed after the end of 1st operation cycle (2026).

2.3.4 Soil

The greater part of the Municipality of Kastelir-Labinci is formed by dolomites and limestone (from the lower Cretaceous Period), and only in the smaller, northern part of the surface of the Municipality are rudist limestones (upper Cretaceous Period). The Mirna valley is formed by sand, gravel, and clay (Holocene and Pleistocene). Terra rossa is an insoluble part of the carbonate mass, and the pebble-sand deposits of the Mirna valley are proportional to the transport power, as well as the resistance of the rocks to the mechanism of running water[15].

The most widespread soil in Istria and in the Municipality is Terra rossa on a carbonate base. Terra rossa (Italian for "red soil") is well-drained, reddish, and clayey to silty clayey soil with neutral pH conditions and is typical of the Mediterranean region. The reddish color of Terra rossa is the result of the preferential formation of hematite over goethite. This soil type typically occurs as a discontinuous layer that ranges from a few centimeters to several meters in thickness that covers limestone and dolomite bedrock in karst regions. The high internal drainage and neutral pH conditions of Terra rossa are a result of the karstic nature of the underlying limestone and dolomite. Terra rossa is also found associated with Mediterranean climates and karst

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[12] Program ukupnog razvoja 2014. - 2020. https://www.kastelir-labinci.hr/hr/dokumenti/sve/sve/Dokumenti%20i%20Akti (28. 11. 2019).

[13] Karst aquifer hazard assessment and mapping on the classical karst, 2006. Acta geographic Slovenia, 46, 2, str. 169–189. URL: https://ojs.zrc-sazu.si/ags/article/view/1240/1010 (10. 11. 2019).

[14] REGIONAL REPORT FOR THE COLLECTED INFORMATION: "REGION OF ISTRIA, CROATIA" (FINAL VERSION). TRANSNATIONAL INTEGRATED MANAGEMENT OF WATER RESOURCES IN AGRICULTURE FOR EUROPEAN WATER EMERGENCY CONTROL (EU.WATER). URL. http://www.eu-water.eu/images/Regional%20Report%20Croatia%20ENG.pdf (10. 11. 2019).

[15] Felja, I., Fontana, A., Furlani, S., Bajraktarević, Z., 2015. Environmental changes in the lower Mirna River valley (Istria, Croatia) during Upper Holocene. Geologia Croatia, 68, 3, 209-224. URL: https://www.researchgate.net/publication/283464900_Environmental_changes_in_the_lower_Mirna_River_valley_Istria_Croatia_during_Upper_Holocene (10. 11. 2019).

elsewhere in the world. Compared to most clayey soils, Terra rossa has surprisingly good drainage characteristics. This makes it a popular soil type for wine production.

2.3.4 Land use

Like all Istria, the Municipality is endowed with natural resources such as agricultural land, forested areas, and natural landscapes, especially in the Mirna River valley.

Agricultural land occupies a relatively large area. In terms of soil quality and suitability, three types of land prevail for agricultural crops: for arable crops, for meadows, and vineyards and orchards. The characteristics of soil quality and the relative fragmentation of the soil, correspond to the viticulture, fruit growing, and production of vegetable crops in an intensive mode of exploitation[16].

The Municipality agricultural area is a mosaic of agricultural land - arable land, meadows and vineyards strewn with forested areas of low oak forests, mostly privately owned.

Based on data from OpenStreetMap[17], 65 % of the total area (vineyards, orchards, olive groves, pastures, complex cultivation patterns, and land principally occupied by agriculture) falls under agricultural land. The most intensively cultivated arable land is in the Mirna River valley area. Given that the Municipality is fertile, favorable for the economy, and due to its favorable climate, it boasts numerous olive growers, winemakers, beekeepers, lavender and vegetable producers' fruits and flowers growers[18].

28 % of the area is covered with forest, and only 4 % is urban. Assessment of land use is presented in the table below.

Table 2: Land use for Kastelir-Labinci Municipality (%)

Land use	**%**
residential	4,32%
vineyards	2,64 %
orchard	13,24 %
pastures	0,53%
complex cultivation patterns	22,71%
agriculture	26,59%
forest	27,74%
shrub	2,23%

The land use is illustrated in the Figure 5 (1:50.000).

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[16] Program ukupnog razvoja 2014. - 2020. https://www.kastelir-labinci.hr/hr/dokumenti/sve/sve/Dokumenti%20i%20Akti (28. 11. 2019).

[17] OpenStreetMap data. Geofabrik GmbH. URL: http://download.geofabrik.de/europe/croatia.html (19. 6. 2020).

[18] Program ukupnog razvoja 2014. - 2020. https://www.kastelir-labinci.hr/hr/dokumenti/sve/sve/Dokumenti%20i%20Akti (28. 11. 2019).

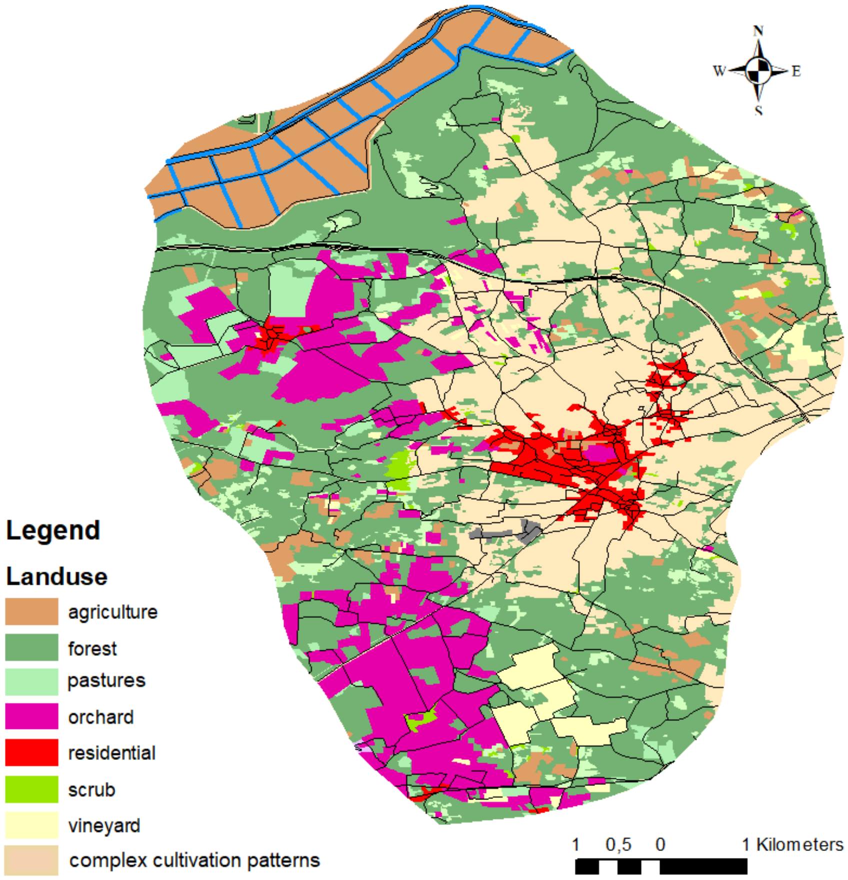

Figure 5: Land use for Kastelir-Labinci Municipality[19]

2.4 Generalizability

The coast is essential to people because it is the starting point for the economic exploitation of water bodies. Historically, settlements have been concentrated along coastal areas of seas and oceans. Coastal areas are still the most populated areas today, which have increased due to tourism.

The coastal areas have become a busier place, and demands for water, energy, food production, and other resources are increasing. Wastewater reuse is and will become more significant in water-scarce regions of the Mediterranean, and RB Kastelir sets an example of how to close the wastewater cycle on site of its origin with a cost-effective solution. The RB Kastelir is not located directly on the seacoast or on the best agricultural land. Costs of land purchase are much higher, or/and land is protected, which are important factors to consider when we address solution transferability. Specific knowledge can be gathered from the chosen case study (seasonal dynamics, land availability problems, correlation between sludge loadings and climate, treated sludge application, cost-benefit analyses), and transferred to the broader Mediterranean region thanks to a comparable territorial setting.

In addition to the case of Kastelir (Croatia), we have considered another example in the Sant Boi de Lluçanès (Spain) to evaluate the transferability of the Kastelir case to the Mediterranean context.

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[19] CLC 2018. URL: https://land.copernicus.eu/pan-european/corine-land-cover/clc2018 (10. 11. 2019).

2.4.1 Drought

The Municipality of Kastelir is facing drought in the summer. Summers of the last ten years have been extremely warm, dry or extremely dry. Analysis of historic summer precipitation series amounts, and expressed as a % of summer values (1981-2010), show that precipitation in Croatia was mostly below average[20]. Draught is the most serious problem in the Mediterranean environment, and the pilot case in Kastelir is operating under these climatic conditions. The solution might involve the provision of reclaimed water to farmers for irrigation of the nearby olive groves and/or vineyards.

2.4.3 Tourism

The village of Kastelir has a tourist season from May to the beginning of October, at which time the load on the CW plant increases by 100% and more, which affects the WWTP operation. In the Kastelir area, seasonal tourism results in double inflow loadings during the summer peak. Thus, it is a representative case for all countries in the Mediterranean region, which have been experiencing tourism growth in recent years.

2.4.4 Land problems

In addition to being an important global biodiversity hot spots[21], the Mediterranean region is among the most vulnerable areas under a multitude of pressures and threats. Approximately one-third of the Mediterranean population is concentrated along coastal zones. In hydrographic basins, rivers begin to meander and create wide valleys and creeks that represent fertile plains for agricultural production. Due to flooding, the Mirna River was regulated and reclaimed, thereby acquiring agricultural land. In such areas, tourism returns to agriculture in the form of tourist farms, cultural tourism (rich history), and cuisine.

Increasing competition for land for agriculture production and tourism development influences the placement of land-intensive technology such as reed beds in the Mediterranean. Implementation of RB in Kastelir addresses described problems.

2.4.4 Climate

Since the climate is the most important factor affecting the performance of reed beds, the focus is on the climatic characteristics of the selected case (Kastelir in Croatia). A similar example of reed beds (Sant Boi de Lluçanès in Spain) will be used to compare results. Thus, the climatic conditions of both locations are presented in the table below.

Table 3: Kastelir and Prat De Llobregat climate comparison

	Kastelir	**Prat De Llobregat**[22]
Köppen-Geiger climate classification	Cfa	Csa
annual temperature, average	13,2 °C	16,6 °C
warmest month, average	July, 22.4°C	July, 24.3 °C
coldest month, average	January, 4.5 °C	January, 9,9 °C
annual rainfall, average	1070 mm	622 mm
driest month, average	July, 70 mm	July, 24 mm
wettest month, average	November, 122 mm	October, 96 mm
wind speed, average	7,8 m/s[23]	7,9 m/s[24]

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[20] ODSTUPANJE SREDNJE MJESEČNE TEMPERATURE ZRAKA ZA LJETO 2019. Ržavni hidrometeorološki zavod. URL: https://meteo.hr/klima.php?section=klima_pracenje&param=ocjena&MjesecSezona=ljeto&Godina=2019 (10. 11. 2019).

[21] https://www.iucn.org/downloads/the_mediterranean_a_biodiversity_hotspot_under_threat_factsheet_en.pdf

[22] EL PRAT DE LLOBREGAT CLIMATE. URL: https://en.climate-data.org/europe/spain/catalonia/el-prat-de-llobregat-56990/ (13. 11. 2019).

[23] Average Weather in Kastelir. URL: https://weatherspark.com/y/75043/Average-Weather-in-Ka%C5%A1telir-Croatia-Year-Round (13. 11. 2019).

[24] Average Weather in El Prat de Llobregat. URL: https://weatherspark.com/y/47186/Average-Weather-in-El-Prat-de-Llobregat-Spain-Year-Round (13. 11. 2019).

Since the nearest weather station for Sant Boi de Lluçanès is Prat De Llobregat (Catalunya, Spain), climatic data from this station is compared to data from Kastelir. The classification of EU biogeoregions corresponds to climatic conditions. Kastelir example is representative of the Mediterranean environment.

3 TECHNOLOGY PRESENTATION

3.1 Sludge treatment in Kastelir, Croatia

3.1.1 Project background

The RB at the Municipality Kastelir – Labinci was constructed as a part of Coastal Cities Pollution Control Project. The project began in 2010 and included the construction of a sewage system for the settlements, a constructed wetland for wastewater treatment, and the sludge treatment system. Constructed wetland for wastewater treatment, with the capacity of 1.900 PE was completed in 2015. The WWTP has a secondary level of treatment (aimed at removing TSS, BOD5 and COD). Until RBs were constructed in 2016, the generated sludge was transported to the central wastewater treatment plant at Porec North. National water Agency Hrvatske vode (Croatian Waters) and founder Global Environment Facility were initiators of cost-efficient, and sustainable solution for sludge treatment. RBs technology was chosen because of its buffer capacity, constant microbiological mass, low O&M costs, integration to the landscape and aesthetic look.

The constructed wetland was fully funded through a grant agreement with the Global Environment Facility (GEF). The Project total budget was 3,5 million EUR, of which 1,6 million EUR are grants for the implementation of the constructed wetland. The project started in 2010 and ended in 2016. The construction of RB was part of this project.

Project activities:

- Elaboration of detailed technical design;
- Construction;
- Commissioning.

3.1.2 The main units of WWTP Kastelir

The treatment process in Kastelir consists of a pre-treatment, followed by biological treatment using a constructed wetland that meets the final effluent discharge standards for secondary treatment. The sludge disposal, after primary treatment is more straightforward and consists of a process of sludge homogenization and process of sludge drying.

WWTP Kastelir has three basic groups of units (Table 4), corresponding to treatment levels, and these are:

- Pre-treatment wastewater units;
- Wastewater treatment units;
- Sludge treatment unit.

Table 4: WWTP Kastelir units

Groups of units	Units	Process
Pre-treatment wastewater units	Automatic coarse screens and grit removal, Imhoff tank	Mechanical treatment Anaerobic stabilization of sludge Water/sludge separation
Wastewater treatment units	Constructed wetland (5 beds)	Biological treatment, nitrification - denitrification
Sludge treatment units	Reed bed	Sludge dewatering, mineralization and stabilization

Aerial shot of WWTP Kastelir with marked basic elements is shown in the figure below.

Figure 6: Aerial shot of WWTP Kastelir

The units of the wastewater treatment are presented in Figure 7 and described below:

- Coarse screens
    - Screening is the first operation unit.
    - Coarse screens and grit automatically remove solid materials and sand from wastewater.
- Imhoff tank
    - the suspended solids present in the wastewater are deposited and retained and to certain extend anaerobic degradation occurs, reducing the organic load to further steps in the treatment.
    - It consists of an upper chamber where sedimentation takes place, in the lower chamber, sludge is collected and digested. The sediment, which is formed, is a septic sludge that needs to be removed at regular intervals and further treated.
- Biological treatment
    - Secondary treatment takes place in constructed wetland:
        - Filtration bed (FB)

      Filtration planted bed (FB) is the first in the CW and therefore receives the highest loading. Its function is the retention (filtration) of suspended solids and others coarse particles that have passed through the Imhoff tank. The FB prevents the clogging of the rest of the CW.

        - Treatment bed (TB);

      In treatment beds (TB) intensive degradation of waste matters takes place. Plant activities assisted by O_2 diffusion ensure a satisfactory levels of oxygen thus securing an effective nitrification process therefore decrease ammonium nitrogen concentration. Within the bed combination of process, including filtration, adsorption, absorption, a remove or transform pollutants. This happens though the intervention of bacteria, filling media and plants. The result is the removal of suspended solids, organic matter, nutrients and even pathogenic bacteria.

        - Polishing bed (PB).

      The polishing bed (PB) function is to bring the final stage of wastewater treatment to further step to improve even more water quality, particularly reduces pathogen microorganisms.

- Sludge treatment:
    - Natural dewatering, mineralization, and stabilization on sludge drying reed beds.

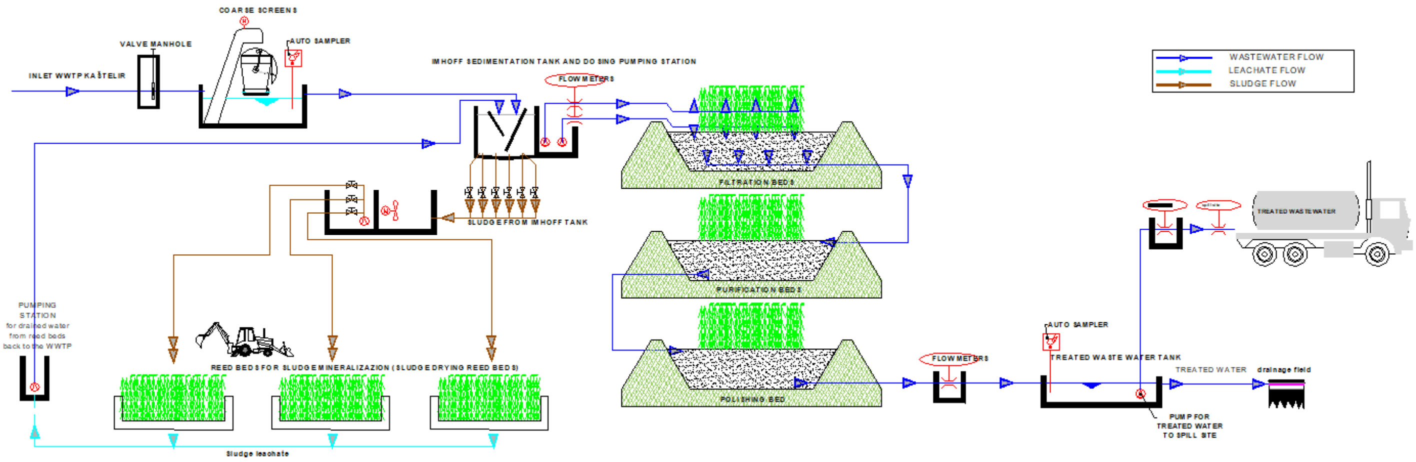

Figure 7: The process flowchart of WWTP Kastelir with natural sludge dewatering[25]*

3.1.3. Sludge drying reed beds in Kastelir

After the construction of WWTP, technological improvements were implemented as a second phase of the construction. One of these improvements was sludge drying reed beds. Sludge drying reed beds were designed as three beds for mineralisation and stabilization, but currently, only one bed has been constructed due to lack of funds, but the process is not affected since the WWTP is operating below design capacity. The remaining two beds will be built subsequently when the expected load to the WWTP reaches the design target.

Sludge drying reed bed was established to overcome sludge disposal problems. Selected technology of reed beds does not affect the first phase of wastewater treatment (WWTP) but addresses the second phase (line for sludge treatment).

Until RBs started operation in 2016, sludge generated in the WWTP Kastelir was pumped and transported to the central WWTP. After construction sludge from the primary step of the wastewater treatment process accumulates in the Imhoff tank. Every two months, the purge valve of the Imhoff tank is open, and sludge flows gravitationally to a homogonization tank. In the tank, sludge is homogenized, and subsequently pump dosed to the RB.

The sludge drying reed bed established at Kastelir was implemented using a reinforced concrete to enclose the basin. The waterproof concrete basin is resistant to wastewater corrosion, mechanical loads, UV light, air, and root growth. It is impermeable, long-lasting and prevents leaking. The surface area of the bed is 240 m^2 (12 m by 20 m). The total height (filter layer + height for sludge depositing + freeboard) of the bed is 2,6 m.

Dimensions of the RB, both the built system (SDRB 1) and the two other planned units (SDRB 2 and 3) are detailed in Table 5 below.

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[25] Municipal wastewater treatment plant Kastelir-Labinci- stage II. Detailed design - construction project. July 2015. „HIDROPROJEKT-ING“ d.o.o.

Table 5: Dimensions of RBs

Reed bed	**Width [m]**	**Length [m]**	**Area [m^2]**	**Height* [m]**
SDRB 1	12	20	240	2,6
SDRB 2	12	20	240	2,6
SDRB 3	12	20	240	2,6

* Height of filter layer + height for sludge depositing and freeboard.

The Reed beds are connected to the WWTP pipeline system. Sludge from the Imhoff tank gravitationally flows through a valve (manually opened by an operator) to the homogenization tank, where is pumped to the RB.

There is no control system for sludge dosing and draining or logging real-time data. All the operations are done manually. Operators dose sludge every 2 or 3 months, depending on the season. The period was proposed by the technological expert – LIMNOS Ltd. from Slovenia.

Sludge distribution pipes are located on both sides of the concrete basin. The sludge is filled through a fire hose from top-down (Figure 8). The solids are retain by the filter layer, while water percolates through the filter layer built form a combination of gravel, and sand. Once the water percolates, the drained water is collected by drainage pipes placed on the bottom of the bed and returned to the wastewater treatment plant for further treatment. The RB is planted with common reed (*Phragmites australis*). The technology does not require the addition of any chemicals or flocculants making the final product environmentally friendly and with the potential of reuse.

Figure 8: Sludge distribution pipe

The system of RB comprises of (Figure 9):

- **a sludge mixing tank**
- **pumping station** for sludge distribution onto reed bed;
- **sludge drying reed bed** with a surface area of 240 m^2;
- **drained water pumping station** to return drained water from RB back to WWTP.

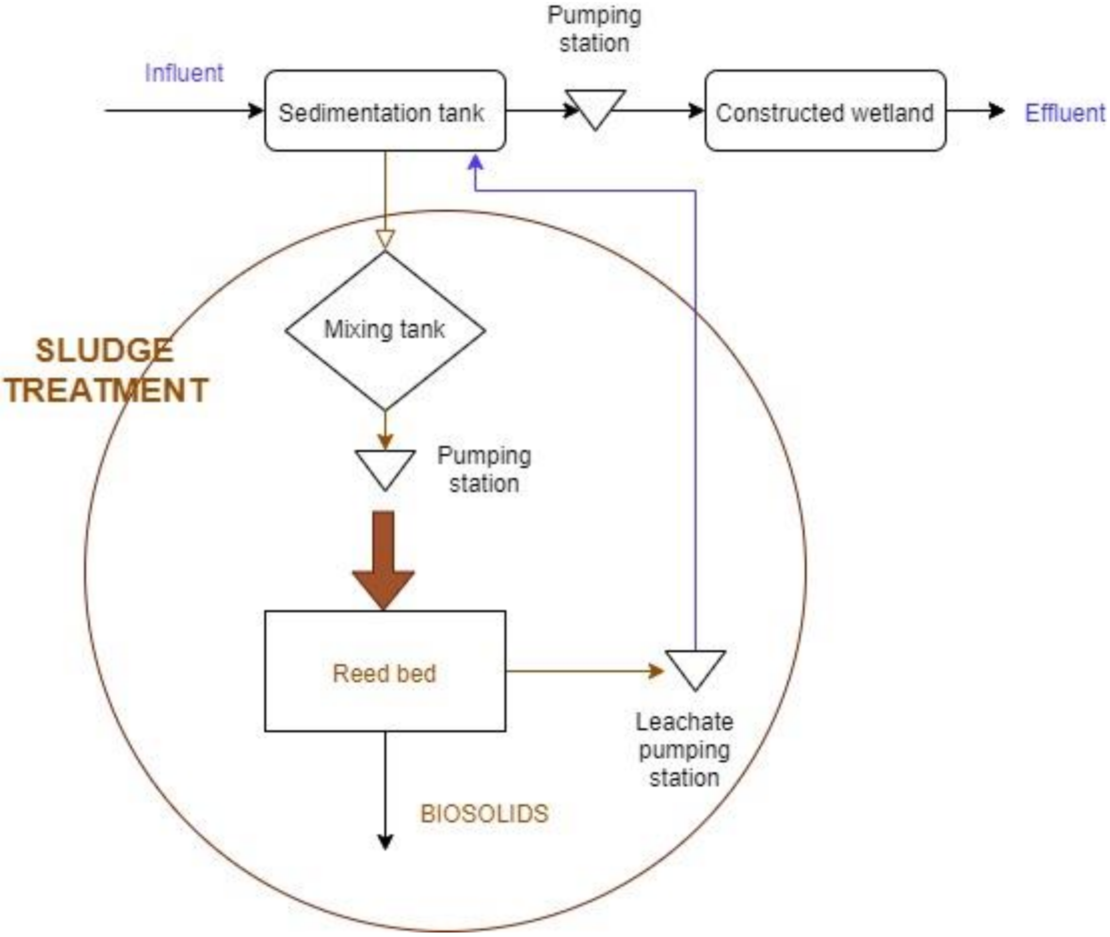

Figure 9: Flowchart diagram of operating sludge treatment in Kastelir

3.1.4 Pictures and drawings

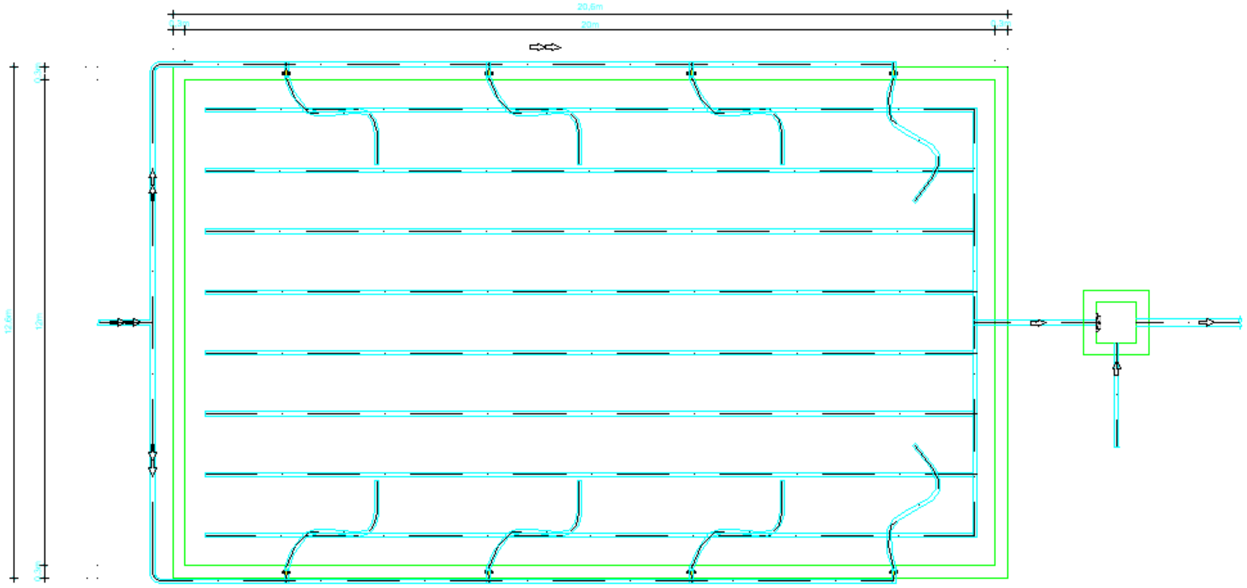

Figure 10: Floor plan of RB in Kastelir (Detailed design, 2016)[26]

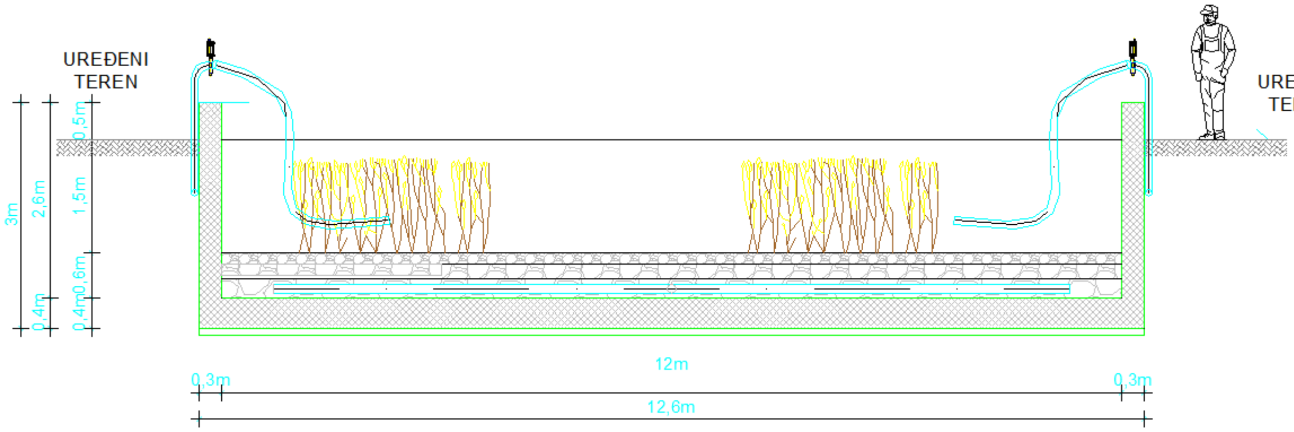

Figure 11: Cross section of RB in Kastelir (Detailed design, 2016)[27]

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[26] Final design project. Municipal wastewater treatment plant Kastelir-Labinci- stage II. 2016. HIDROPROJEKT-ING“ d.o.o.

[27] Final design project. Municipal wastewater treatment plant Kastelir-Labinci- stage II. 2016. HIDROPROJEKT-ING“ d.o.o.

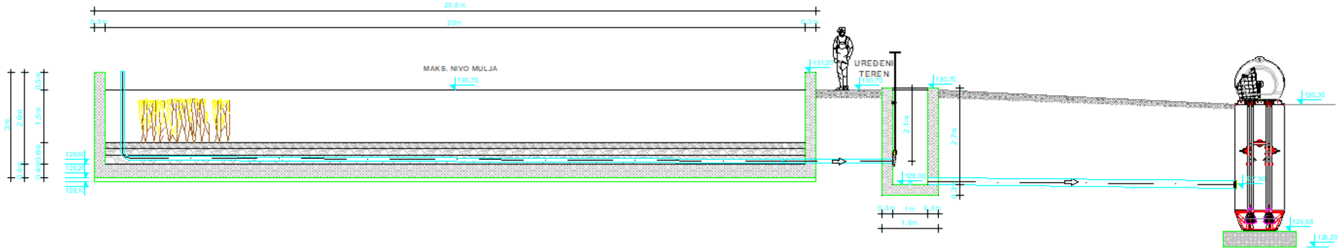

Figure 12: Longitudinal cross-section of RB in Kastelir – sludge distribution (Detailed design, 2016)[28]

Figure 13: RB (front) with one of the five beds of constructed wetland (back) in Kastelir

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[28] Final design project. Municipal wastewater treatment plant Kastelir-Labinci- stage II. 2016. HIDROPROJEKT-ING“ d.o.o.

Figure 14: Reed bed after planting of common reed in May 2016

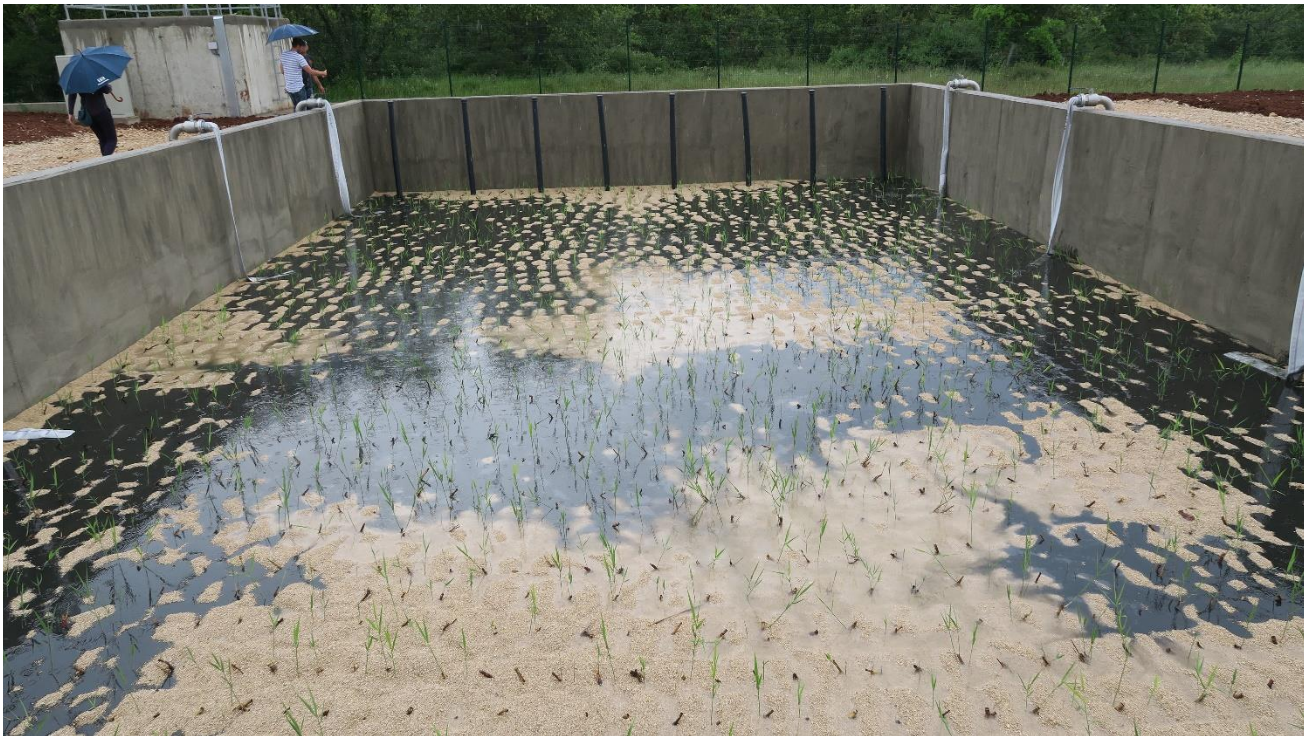

Figure 15: RB Kastelir after dosing

Figure 16: Reed bed in July 2016

3.1.5 Design parameters

The design parameters, used for the design process for the RB at Kastelir, are presented below.

3.1.5.1 Design horizon parameters

The design capacity of WWTP Kastelir is to treat 1.900 PE. The reed bed was constructed in 2016. The planning (investment) horizon is up to the year 2055.

The specific of this location is a high fluctuation of population: due to the tourist season, the population during the summer months doubles and reaches up to 1.900 PE.

3.1.5.2 Differences between design and construction

For the mineralisation and stabilization of the sludge, three beds were projected to be built at Kastelir. The total surface was 3 x 240 m^2= 720 m^2, but from 2016, only one bed has been constructed with a surface area of 240 m^2. The remaining two beds will be built later, once the load of the WWTP increases to the designed load and the first bed fills up.

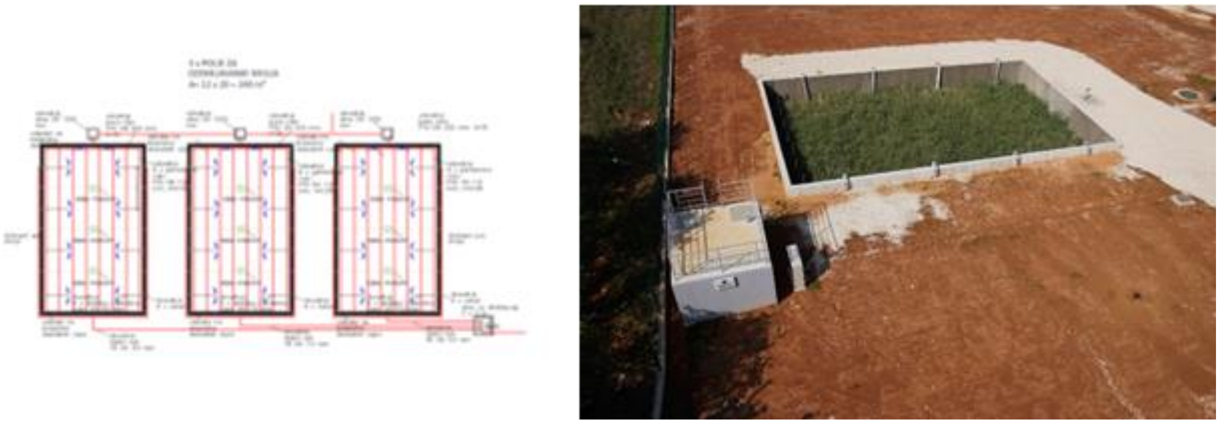

Figure 17 Floorplan of designed RBs in Kastelir (left) and the already established RB at Kastelir (right)

3.1.5.3 Sludge requirements for sludge reuse in Croatia

Management of sewage sludge in Croatia is defined by a Rulebook on the management of sludge from wastewater treatment plants when used in agriculture (Official Gazette of Croatia, No 38/08[29]). The Rulebook states the conditions that have to be met for municipal sewage sludge before reuse including quantities, volumes, frequency of application and analyses required for the sludge to be approved for specific purposes, and conditions that have to be met by the soil where the sludge is to be reused. The regulation was adopted based on the European Sewage Sludge Directive 86/278/EEC.

The Regulation defines treated sludge as a sludge that has undergone biological, chemical, or thermal treatment, long-term storage, or any other process that significantly reduces its fermentability and health hazards resulting from its use.

The Regulation also defines the limit values for treated sludge in terms of heavy metals and organic matters. Additionally it defines the maximum annual load of dry matter to be applied for agriculture use.

3.1.5.3.1 Limit values for heavy metal in sludge

In agriculture, sludge reuse is only allowed if heavy metals contents comply with the permitted concentrations. (Table 6).

Table 6: Limit values for heavy metal content of treated sludge used in agriculture

Heavy metals	Allowed heavy metal content in mg/kg of dry matter of representative sludge sample
Zn	2000
Cu	600
Cr	500
Pb	500
Ni	80
Cd	5
Hg	5

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[29] https://narodne-novine.nn.hr/clanci/sluzbeni/2008_04_38_1307.html

3.1.5.3.2 Limit values for soil to which sludge is applied

Table 7: Limit values for heavy metals concentration in soil to which treated sewage sludge is applied

Heavy metals	**Allowed heavy metal content in soil in mg/kg of dry matter of representative soil sample**		
soil pH in 1 M KCl solution	5,0	5,5	pH>6,5
Zn	100	150	200
Cu	40	50	100
Cr	50	75	100
Pb	50	70	100
Ni	30	50	70
Cd	0,5	1	1,5
Hg	0,2	0,5	1

3.1.5.3.3 Limit values for some persistent organic compounds in sludge

Table 8: Allowed content of organic pollutants in treated sewage sludge

Organic matters in sludge	**Allowed concentrations organic matters in sludge**
polychlorinated biphenyls (PCBs):	In mg/kg of dry matter of sludge
2,4,4’- trichlorobiphenyl	*0,2*
2,2’,5,5’- tetrachlorobiphenyl	*0,2*
2,2’,4,5,5’- pentachlorobiphenyl	*0,2*
2,2’,3,4,5,5’- hexachlorobiphenyl	*0,2*
2,2’,3,4,4’,5,5’- heptachlorobiphenyl	*0,2*
Polychlorinated dibenzodioxins / dibenzofurans (PCDD/PCDF)	100 ng TCDD equivalent* per kg of dry matter of sludge

**TCDD equivalent is the sum of the multiplication of the content of individual polychlorinated dibenzodioxins / dibenzofuran expressed in ng / kg and factors.*

3.1.5.3.4 Limit values for pathogens

Treated sludge intended for agriculture use needs to be stabilized in such a way that pathogenic organisms, potential causes of diseases, are removed.

3.1.5.3.5 Maximum annual load of dry matter in agriculture

A maximum of 1,66 tons of sludge dry matter per hectare of agricultural land is allowed to be used per year.

3.1.5.4 Wastewater characteristics

3.1.5.4.1 Wastewater origin

The wastewater origin impacts sewer and WWTP design significantly. At the Municipality of Kastelir, separate sewer systems are being build. The industrial zone is not connected to the sewer network. Currently, the only wastewaters connected to the system are the domestic wastewaters, two wineries, and two restaurants.

3.1.5.4.2 Hydraulic parameters

WWTP Kastelir does not log daily inflow on WWTP. In the project documentation[30], a specific water consumption rate of 150 liters per inhabitant per day has been used.

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[30] Final design project. Municipal wastewater treatment plant Kastelir-Labinci- stage II. 2016. HIDROPROJEKT-ING“ d.o.o.

Hydraulic parameters:

- Specific Water Consumption: 150 l/day/P.E. (including water rate of 50 l/d/PE for runoff waters);
- Daily Flow: $Q_d = 285\ m^3/d$

3.1.5.4.3 Influent wastewater loads

According to available analysis results from 13.7.2017 and 21.7.2020 (high season; full loading) and 21.4.2020 (low season), the CW efficiently removes biological oxygen demand, chemical oxygen demand, and suspended solids (Table 9 and Table 11) and meets Croatian legal requirements.

Table 9: Treatment performance of hybrid constructed wetland LIMNOWET® Kastelir, Croatia (July, 2017).

Parameter	**Influent (*mg/L*)**	**Effluent (*mg/l*)**	**Efficiency (%)**	**Legal requirement in Croatia (% removal)**
BOD_5	174	21	88	70
COD	605	5	99	75
TSS	213	23.3	89	90

Table 10: Treatment performance of hybrid constructed wetland LIMNOWET® Kastelir, Croatia (July, 2020).

Parameter	**Influent (*mg/l*)**	**Effluent (*mg/l*)**	**Efficiency (%)**	**Legal requirement in Croatia (% removal)**
BOD_5	/*	11	/	70
COD	1.226	22	98,2	75
TSS	508	2	99,6	90

Table 11: Treatment performance of hybrid constructed wetland LIMNOWET® Kastelir, Croatia (April, 2020).

Parameter	**Influent (*mg/l*)**	**Effluent (*mg/l*)**	**Efficiency (%)**	**Legal requirement in Croatia (% removal)**
BOD_5	/*	12	/	70
COD	1.835	25	98,6	75
TSS	1.248	2	99,8	90

* BOD_5 concentration on influent wasn't measured.

When discussing sludge treatment, the focus is often only on organic loading and nutrients, while other constituents that may be present in the domestic wastewater are neglected. The analyses of wastewater before deciding on treatment technology are recommended, but in reality, are not often implemented in practice. Thus, theoretical values are being used for design.

3.1.5.5 Sludge characteristics

An effective physical pre-treatment step is necessary to ensure good performance and protect the constructed wetlands. As a pre-treatment step, the sedimentation processes take place in a settling tanks, where primary sludge is generated. Primary sludge is pumped on to the reed beds.

The storage period in settling tanks has an influence on the sludge characteristics and treatment. Additionally, during the sedimentation processes while under low oxygen saturation conditions, implies that anaerobic digestion of sludge takes place. For example, as time goes by and the sludge spends longer periods in the sedimentation tank for instance weeks, months, years, or decades affects the physical characteristics to some extent the digestion state..

Table 12: TSS Influent specific loads (max. load 1.900 PE)

Parameter	Unit	*Value*
Accumulated suspended solids in Imhoff tank	g/PE*d	47,6
	kg/d	90,4
	kg/y	33.010,6

** Assuming effective primary cleaning (68% reduction in TSS parameter in Imhoff tank).*

Sludge characteristics before dosing sludge to reed beds:

- Sludge type: primary sludge
- Mostly anaerobic sludge
- Mechanical properties of sludge: fluid sludge
- Dry matter content: 2-5 %
- Sludge density very close to water: 1,02 kg/m3 (1 m^3 of sludge ≈ 1000 kg or 1 ton of sludge)

3.1.6 Process Parameters

3.1.6.1 Sludge loading rate

The most important process parameter to affect sludge drying is the dry matter loading rate. . The sludge loading rate (SLR) is expressed in kg TSS/ m^2/y. It represents the mass of solids dried on one m^2 of bed in a year.[31] The loading rate depends on climate (temperature, precipitation, humidity), and thus optimal local operating conditions need to be determined during the design phase.

The maximum calculated loading rate in Kastelir is 80 kg TSS/m^2 y.

3.1.6.2 Infiltration rate

In Kastelir, fine sand is at the top and coarse gravel at the bottom of the filter layer, enabling the efficient removal of solids from water. The height of the filter layer determines the effective volume of RBs (cc. 43 m3). Water percolates through the filter layer by gravity. The infiltration rate is expressed in m^3 of water percolating through the filter layer in one hour, divided by the filter surface area. In case fine particles of suspended solids enter the filter layer, clogging can occur.

The filtration rates through filter media in Kastelir are estimated at 0,03 m/h (very slow filtration). The infiltration rate also depends on the water saturation of the system. In general, water trickles through the system in a day or more.

3.1.6.3 Sludge loading height

A sludge loading height is defined by the sludge loading volume per surface area of the bed. Higher loading volume can lead to a higher amount of suspended solids in sludge (max kg TSS/y per surface area of reed bed), that can cause low-permeability layer of sludge and clog the system. Such a situation can occur if the loading of the beds is too fast. This will result in poor dewatering and limited reed growth and even collapse of the system. The higher the sludge loading volume, the longer the resting periods in between loading is required.

A loading volume of around 35 m^3 of sludge per one dosing is applied at the site.

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[31] https://www.un-ihe.org/sites/default/files/fsm_book_lr.pdf

3.1.6.4 Sludge loading pattern

Sludge loading has been the same since the RBs were put into operation. There was no start-up phase with reduced loading. The sludge loading pattern depends on the season.

Usual loading in Kastelir:

- during summer (touristic season): every two months;
- Rest of the year: every three months.

3.1.7 Visual examination

The sludge drying reed beds were examined in October 2019 for this study.

3.6.7.1 Sludge height

Sludge drying reed beds are in operation since June 2016. The sludge height of 24 cm was achieved in three years. The samples obtained in October 2019 revealed good dewatering capability of reed beds. The total suspended solids (TSS) content varied from 23 – 23 % (average 23,0 %). Average total volatile solids (TVS) content of sludge was 64 %.

Figure 18: Sludge height in RBs Kastelir.

3.2.7.2 Sludge distribution

The sludge distribution is uniform. Water efficiently drains from the system and there are no signs of filter clogging.

Figure 19: sludge sampling at Kastelir (October 2019).

3.2.7.3 Plant growth

The chosen plant common reed (*Phragmites australis*) has been proven to grow on sludge. There is no visible sign of nematode attack. Plant is invasive but cannot spread outside the reed bed system because the primary method of reproduction is vegetative via a vast underground rhizome network. The spreading of the reeds is disabled physically by the concrete basin and will not propagate to the adjacent zones.

Figure 20: Uniform growth of common reed in Kastelir.

Plants in Kastelir are around 2 m high. On one side of the RB, plants are smaller and less dense because, for one year, the operator tried to compost reeds from a constructed wetland in that area. Plants could not grow in the absence of light. They have removed the dried plants, but the plants in the affected area are still smaller. This growth backlog is expected to disappear within the next growing season. Replanting is not required.
Plants of the RB wilt twice a year, once due to drought (August) and at the end of the growing season (November). Plants are not harvested.

Figure 21: Common reed height in Kastelir.

3.2.7.4 Odor

Sludge stabilization (anaerobic digestion) in the Imhoff tank reduces the odor of sludge, while sludge spreading has an bad odor potential. On reed beds, layers of dosed sludge are thin and well aerated; thus there are no anaerobic conditions and odor generation.

The system in Kastelir has no odor problems. The system is located away from the urban city area, the first houses are located at a distance of 200 m. So far, no one has complained about the odor.
Clogging of the system would create anaerobic conditions, limit air supply to the system, and can cause odor emissions. Therefore, odor is one of the main alarming signs of potential system malfunctioning. The system in Kastelir has never clogged and at the current loading rate it is not expected to clog.

3.2.7.5 Water drainage

The drying process happens as the water drains from the sludge and through evapotranspiration of plants. The drained water trickles through the filter. To collect the drained water the reed beds at Kastelir was fitted with a drainage piping and drainage collection. A manhole outside serves as temporary storage, and as pumping well to send the water to the primary treatment of CW wastewater for treatment. As long as water drains from the sludge, the plants are in healthy conditions and the bed is not saturated aerobic conditions in the sludge drying bed is maintained and guaranteeing a successful and odor free process. Heavy rain events do not negatively affect hydraulic of the RBs. Rainwater trickles through the system without consequences and should not affect the processes.

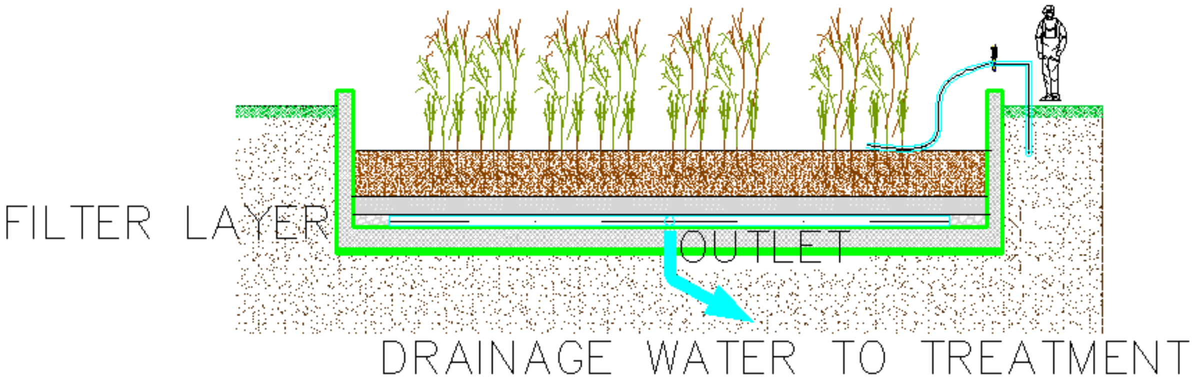

Figure 22: Schematic overview of sludge drying reed beds.

The annual amount of rainfall on the reed bed surface (257 m^3) is greater than the dosed annual sludge volume (175 m^3). The evapotranspiration of reeds reduce the volume of drained water therefore when designing an RB. The water balance must be taken into account and is a key design parameters.

3.2 Sludge treatment in Sant Boi de Lluçanès, Catalonia, Spain

To fully reflect the RBs operation and efficiency in the Mediterranean biogeographical region, another RBs in the territorial setting comparable with that of Kastelir, were assessed. The selected case for comparison is located in the Sant Boi de Lluçanès in Spain and presented in detail below. Gathered data from both cases (Kastelir and Sant Boi de Lluçanès) demonstrate the technical suitability and potential for upscaling to the entire Mediterranean region. Additionally, the comparison is relevant since the country of the establishment has economic social and environmental similarities. .

The RBs in Sant Boi de Lluçanès are presented below.

3.2.1 Basic data on WWTP

The WWTP as well as the sludge drying reed beds are located south from the urban area of Sant Boi de Lluçanès and next to the Sorreigs Stream. The closest houses are only about 300 m away from the WWTP facilities and according to the inhabitants there are not affected by odor nor noise.

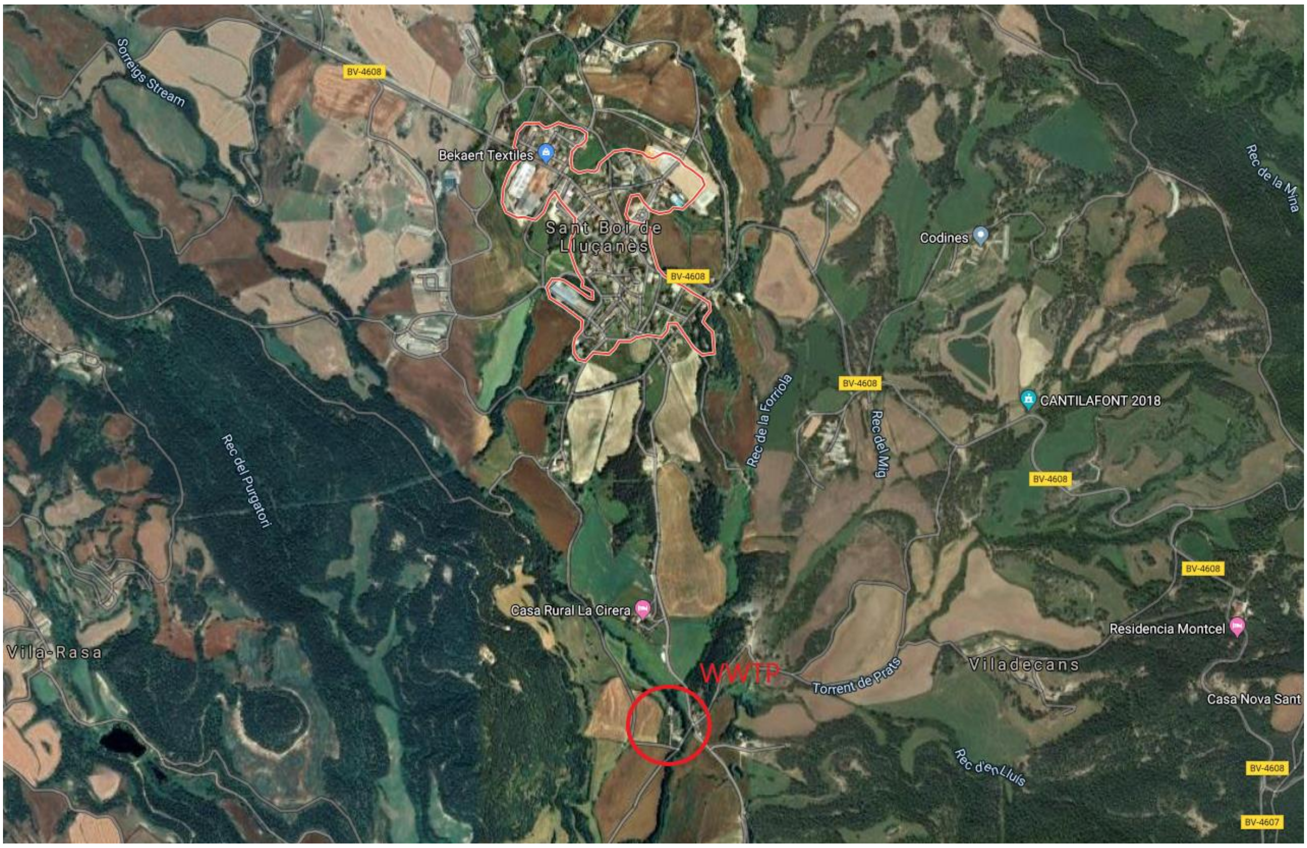

Figure 23: WWTP Sant Boi de Lluçanès, Catalonian, Spain

WWTP design capacity is 1.500 PE, although the load of the WWTP is much lower, 600 PE. The WWTP receives water through a combined sewer system that is not water tight meaning that subsurface water infiltrates to the sewer systems[32]. Regardless of the extra water, the system is robust enough to cope with the extra water. The RBs in Sant Boi de Lluçanès started to operate in winter 2006.

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[32] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

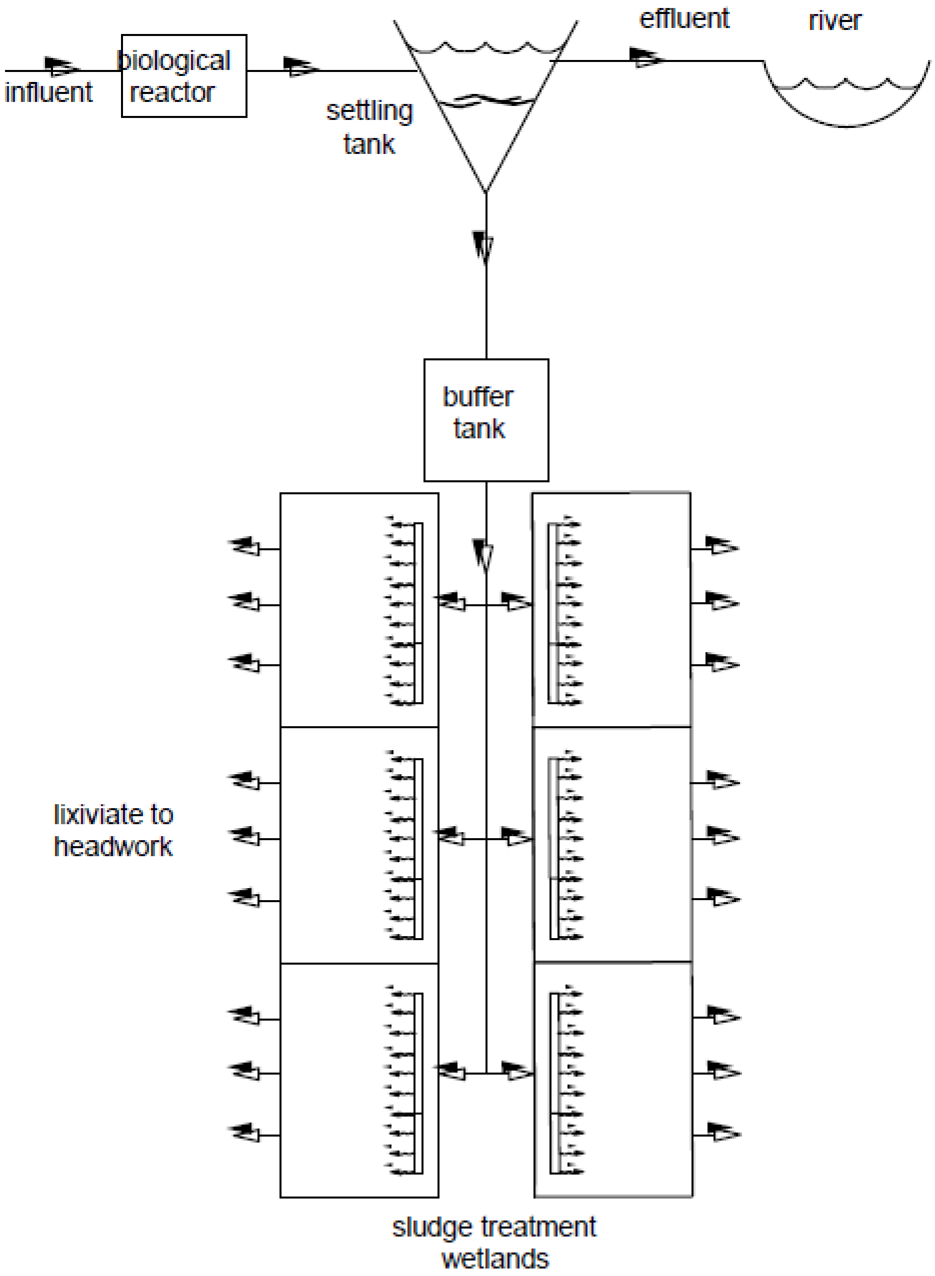

Figure 24: Schematic diagram of a sludge treatment for the treatment of activated sludge[33]

The main WWTP units are:

- Primary treatment: screening line;
- Biological treatment: two activated sludge aeration tanks, for nitrification and denitrification;
- Sludge line and treatment: sludge from the aeration tanks, where microorganisms flocks of settle down and are loaded to the reed beds.

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[33] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

Table 13: Main characteristics of the wastewater treatment plants at Sant Boi de Lluçanès[34]

Population equivalent	600 (1500 design)
Type of treatment	Extended aeration
Wastewater flow rate (m^3/d)	200-250
Sludge production (kg TS/d)	45
Sludge flow (m^3/day)	3

3.2.2 Sludge drying reed beds in Sant Boi de Lluçanès

The system consists of six reed beds. Each of them has a surface of 54 m^2, in total 324 m^2. The bed height is 1,5 m (including free board). The main characteristics of the RBs are detailed in Table 14 below.

Table 14: Main characteristics of RBs in Sant Boi de Lluçanès[35]

Number of wetlands	6
Total surface area (m^2)	324
Bed surface area (m^2)	54
Nominal height for sludge accumulation (m)	0,65
Total height (m)	1,5*
Total nominal volume for sludge accumulation (m^3)	210
Sludge loading rate (kg TS/m2·year)	51
Loading pattern	2 min every 4 h

** Height of filter layer + height for sludge depositing and freeboard*

Sludge drying reed beds are enclosed as concrete basins. The bottom of the beds are lined with a waterproof membrane to seal the beds and prevent in and off infiltration of water that could pollute ground waters or add water to the beds.

The draining filter layer of the drying reed beds, is approximately 55 cm high. It consists of a bottom 30 cm deep layer Ø 1 to 3 cm gravel (and covered by a 25 cm high sand layer Ø 0.3 to 1 mm from. The beds were planted with common reed (*Phragmites australis*) with a density of 4 plants/m^2.[36]

Surrounding the beds, 3 m wide roads were established to access the beds for maintenance and emptying of the filled beds as necessary.

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[34] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

[35] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

[36] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

3.2.3 Pictures and drawings

Figure 25: Reed beds in Sant Boi de Lluçanès[37]

Figure 26: WWTP and reed beds in Sant Boi de Lluçanès[38].

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[37] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

[38] www.google.com/maps

3.2.4 Sludge loading volume

The wastewater treatment plant produces around 3 m^3/d of sludge. The loading is controlled with the pump operated by the workers. Sludge is distributed to the beds for two minutes every 4 hours, but the actual flow is not measured precisely[39].

3.2.5 Sludge loading pattern

Biological waste sludge from the corresponding WWTP is periodically spread on the beds. Sludge loading patterns during the period of the study were almost the same in the beds of Sant Boi de Lluçanès (51 kg TS/m^2 year, respectively).

Sludge loading:

- Every two days loading
- After loading ten resting days

Table 15: Loading pattern

Hours	BED 1	BED 2	BED 3	BED 4	BED 5	BED 6
Day 1	Filling	*Resting*	*Resting*	*Resting*	*Resting*	*Resting*
Day 2	Filling	*Resting*	*Resting*	*Resting*	*Resting*	*Resting*
Day 3	*Resting*	Filling	*Resting*	*Resting*	*Resting*	*Resting*
Day 4	*Resting*	Filling	*Resting*	*Resting*	*Resting*	*Resting*
Day 5	*Resting*	*Resting*	Filling	*Resting*	*Resting*	*Resting*
Day 6	*Resting*	*Resting*	Filling	*Resting*	*Resting*	*Resting*
Day 7	*Resting*	*Resting*	*Resting*	Filling	*Resting*	*Resting*
Day 8	*Resting*	*Resting*	*Resting*	Filling	*Resting*	*Resting*
Day 9	*Resting*	*Resting*	*Resting*	*Resting*	Filling	*Resting*
Day 10	*Resting*	*Resting*	*Resting*	*Resting*	Filling	*Resting*
Day 11	*Resting*	*Resting*	*Resting*	*Resting*	*Resting*	Filling
Day 12	*Resting*	*Resting*	*Resting*	*Resting*	*Resting*	Filling

3.2.6 Visual examination of

Three sampling campaigns were carried out, each one in a different season: fall 2007 and spring and summer 2008.

3.2.6.1 Sludge height

Sludge drying reed beds in Sant Boi de Lluçanès are in operation since 2006. The values of sludge height measured in each campaign are shown in Table 16.

Table 16: Sludge height

Sludge height (m)		
2007	**¼ of 2008**	**½ of 2008**
30	30	15

Examination of the sludge cores in Sant Boi de Lluçanès showed a somewhat blackish upper layer and a brownish bottom layer, suggesting a higher mineralization degree in the bottom layer. Each of these two layers extended to the half of the total sludge height.

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[39] Carlos A. Arias: Interview with WWTP operator

3.3 Efficiency

RBs efficiency of Kastelir (Croatia) and Sant Boi de Lluçanès (Spain) is determined by sludge analysis.

3.3.1 Sludge analysis from WWTP Kastelir, Croatia

Sludge analysis was performed to obtain sludge quality information. On-site sampling was done in October 2019. The samples were taken from 6 sampling points. The created sample assures homogeneity, and best represents the physical and chemical quality of sludge treated on reed beds in Kastelir.

The analyses of dry matter, total volatile solids, and TN were done by a certified laboratory of Biotechnical University of the University of Ljubljana. Standard methods were used. The results from the analysis are presented in the table below.

Table 17: Dry matter, total volatile solids, heavy metals, TP and TN results from RB Kastelir

Parameter	**Unit**	**Measured values**		**Limit values for use in agriculture**
		Sample 1	**Sample 2**	
Dry matter	mass %	22,9	23,1	
Total volatile solids	mass %	63,3	64,4	
Total nitrogen	mass %	3,5	3,7	
Total carbon	mass %	34,7	32,5	
Total phosphorous	mass %	1,3	1,2	
pH		6,65	6,8	
Cadmium (Cd)	mg/kg TS	1,1	1,2	5
Copper (Cu)	mg/kg TS	324,8	323,1	600
Nickel (Ni)	mg/kg TS	31,8	28,3	80
Lead (Pb)	mg/kg TS	90,5	87,0	500
Zinc (Zn)	mg/kg TS	1.031	1.059	2.000
Mercury (Hg)	mg/kg TS	0,42	0,42	5
Chromium (Cr)	mg/kg TS	53	45	500

Land application of of biosolids requires considering pathogen risks. Pathogen die-off in RBs is assured with resting periods of 4-6 months before biosolids harvesting. Resting period means that during the period no sludge loading occurs.

The selected site in Kastelir is in full operation, fresh sludge is regularly loaded to RBs surface. Characterization of pathogen die-off was not possible at the usual loading on RBs. Therefore, an experiment to mimic the similar conditions to the one happening under a resting period was conducted. We isolated a part of the system to stop sludge loading to a section of the system to mimic the conditions similar to the resting period (for the pathogen die-off) to take samples to asses Indicator pathogen presence

- during RBs operation and
- after seven months of resting period.

Figure 27: Set up of the pathogen test in Kastelir.

The analyses of pathogens were done by the laboratory that is certified/accredited (Faculty of Health Sciences of the University of Ljubljana). Standard methods were used.

Table 18: Pathogens results before simulated resting period (before pathogen die-off period)

Homogenous sample from following sampling points	***Escherichia coli* CFU/g**	**Coliform bacteria CFU/g**	**Enterococci CFU/g**	***Salmonella* spp. in 50 g**
Sample 1	$5{,}5*10^4$	$3{,}3*10^6$	$4{,}9*10^4$	Present*
Sample 2	$6{,}2*10^4$	$1{,}3*10^6$	$5{,}0*10^4$	Present*

* Salmonella spp. in 50 g sample after pre-enrichment is present but in very small numbers.

The set-up experiment has failed because operator loaded sludge over the expected height and flooded the isolated area. Repeating analysis of pathogens content didn’t make sense because the obtained reduction in pathogenic organisms wouldn’t be significant or reflect the pathogen die-off efficiency.

On the other hand, analyses of micropollutants were carried out, although isolation would probably improve removal of organic micropollutants due to better oxygen conditions[40]. Micropollutants were analysed twice (October 2019 and June 2020) to assess reduction/accumulation. More analysis over longer period of time with mass balances (before and after each loading) would be needed to make general conclusions on micropollutants removal efficiency on RBs in Kaštelir. The obtained results provide an overview of the variation of concentration of the micropollutants over period of 6 months.

For this assignment, 3 families of micropollutants: pharmaceuticals, pesticides, and Per- and Polyfluoroalkyl Substances (PFAS) have been analyzed. Two sets of samples were taken, in October 2019 and in June 2020, from the same place and the same day as samples for pathogens (P1, P2: Figure 27). The analyses of micropollutants were done by Dr. Pedro Carvalho, Researcher at the Department of Environmental Sciences of Aarhus University. Standard methods were used. Briefly, three samples (2 g tubes) from each isolated spot were taken, freeze and lyophilized. Two grams of dried sludge from each individual tube were combined in a larger container - one composite sample. Three replicates of this “pooled” sample were then analysed. Extraction was performed in two steps (1) water and 2) methanol by ultrasounds) and the fractions were analyzed separately by HPLC-MS/MS.

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[40] https://hal.archives-ouvertes.fr/hal-01058679/document

Compounds analyzed are representative of different substances used in Europe. That means that one specific compound can be used in Denmark or other countries but not in Croatia and vice-versa. The total amount of analyzed compounds is wide and covers reasonably the ones mostly consumed in Denmark and Germany, but that does not exclude Mediterranean countries. The number of pesticides tested is relatively small, but the compounds tested are of common use in Europe. Pharmaceuticals like diclofenac, erythromycin, clarithromycin and azithromycin are of common use and included in the EU watch list of substances of emerging concern. Among the pharmaceuticals, different compounds of the same therapeutic class are included - which covers variability among countries. For the overall concept of compound selection, one should have in mind that even for the Mediterranean countries, there might be differences in consumption patterns. The only way around this would be a truly extensive preparatory work, by looking into data on consumption/prescription - but such was outside the scope of our exploratory work and without dedicated funding resources.

It must be stressed that concentrations calculated are based on dry weight, while some publications report wet weight. This means that because analyzed sludge is dried, it might look more “concentrated” – but the overview of the concentration measured is that the levels are within the same range as if we correct for water content.

This means that the levels found are similar to “fresh” sludge and not really to mineralized sludge. To understand if the system is degrading this type of compounds, it is critical to sample and analyze again the areas that were “isolated” from fresh loadings.

Regarding the PFAS, levels measured were low. PFAS can be found in higher concentrations when some industrial inflows might mix with domestic sewage. Thus, it just tells us that no significant industrial inputs occur.[41]

The total amounts of micropollutants are presented in the tables below (Table 19 to Table 29).

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[41] Pedro Carvalho. Aarhus University

Table 19: Average value of antibiotics in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	**Azithromycin**	**Clarithromycin**	**Erythromycin**	**Roxithromycin**	**Cipro-floxacin**	**Clinda-mycin**	**Sulfadiazine**	**Sulfameth-izole**	**Sulfameth-oxazole**	**Trimetho-prim**
October 2019	115,52	4,80	<LOD*	<LOD	21,79	4,87	<LOD	17,70	<LOQ**	0,81
June 2020	<LOQ	<LOD	<LOD	<LOD	67,27	<LOD	<LOD	<LOD	<LOD	<LOD

* Limit of detection

** Limit o quantification

Table 20: Average value of blood pressure and analgesic in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	**Blood pressure**				**Antidepressant/ analgesic**						
	Atenolol	**Metoprolol**	**Propranolol**	**Sotalol**	**Carbamazepine**	**Citalopram**	**Diclofenac**	**Ibuprofen**	**Phenanzone**	**Tramadol**	**Venlafaxine**
October 2019	0,93	16,52	7,51	<LOQ	16,47	35,63	83,35	263,33	<LOD	26,70	13,21
June 2020	<LOD	<LOD	<LOQ	<LOD	<LOQ	56,59	<LOD	n.a.	<LOD	<LOD	12,73

Table 21: Average value of x-ray contrast media and angiotensin II receptor blocker in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	**x-ray contrast media**					**Angiotensin II receptor blocker**					
	Diatrizoic acid	**Iohexol**	**Iopromide**	**Iomeprol**	**Iopamidol**	**Olmesartan**	**Valsartan**	**Irbesartan**	**Eprosartan**	**Candesartan**	**Losartan**
October 2019	<LOD	<LOD	<LOD	1,82	<LOQ	5,03	193,40	42,35	40,98	<LOQ	66,66
June 2020	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOD	<LOD	22,19	<LOD	<LOD	12,84

Table 22: Average value of Immunosuppressant drug and others in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	**Immunosuppressant drug**		**Others**	
	Mycophenolic acid	**Oxazepam**	**Benzotriazole**	**Gabapentin**
October 2019	32,93	20,09	40,62	4,60
June 2020	<LOD	33,47	28,79	<LOD

Table 23: Average value of transformation products (1.) in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	Azithromycin	Clarithromycin	Erythromycin	Sulfadiazine	Sulfamethoxazole		Metoprolol		
	Azithromycin N-oxides	Clarithromycin N-oxides	Erythromycin N-oxides	Ac-Sulfadiazine	Ac-Sulfamethoxazole	AMiosX	Alpha-hydroxymetoprolol	Metoprolol acid	O-demethylmetoprolol
October 2019	<LOD	n.a.	<LOD	<LOD	<LOD	<LOD	<LOQ	<LOD	<LOD
June 2020	<LOD	<LOD	<LOD	<LOD	<LOD	n.a.	<LOD	<LOD	<LOD

Table 24: Average value of transformation products (2.) in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	Carbamazepine		
	BaQD 1-(2-benzoic acid)-(1H,3H)-quinazoline-2,4-dione	CBZ 10,11 epoxides CBZ-EPX	rac trans 10,11 (dihyro, dihydroxy) CBZ-RTN
October 2019	9,47	<LOD	5,88
June 2020	20,56	<LOD	<LOQ

Table 25: Average value of transformation products (3.) in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	Diclofenac				
	DCF 2,5 quinone imine	DCF amide	DCF benzoic acid	1-(2,6-dichlorophenyl)indolin-2,3-dione DCPID	2,6-dichlorodiphenylamine
October 2019	n.a.	1,28	<LOQ	<LOD	<LOD
June 2020	<LOD	<LOQ	<LOQ	<LOD	<LOD

Table 26: Average value of transformation products (3.) in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	Tramadol		Venlafaxine
	N-Desmethyl tramadol	**Tramadol N-oxide**	**Venlafaxin N-oxide**
October 2019	9,49	<LOD	<LOD
June 2020	<LOQ	<LOD	<LOD

Table 27: Average value of Pesticides Parents in ng/g (ng of micropollutant per g of dry sludge)

Date of sampling	Triazines		Triazoles		Carbamates				Carboxamides	Organophosphate
	Terbutryn	Irgarol	Tebuconazole	Propiconazole	Carbendazim	Pirimicarb	Azoxystrobin	Pyraclostrobin	Diflufenican	Diazinon
October 2019	2,86	<LOD	1,02	<LOD	1,36	0,21	<LOD	<LOD	<LOD	<LOD
June 2020	4,11	<LOD	3,28	<LOD	0,39	0,16	<LOD	<LOD	0,30	<LOD

Table 28: Average value of Cationic Surfactant and Pesticides Transformation products in ng/g (ng of micropollutant per g of dry sludge)

	Cationic Surfactant			**Pesticides Transformation products**		
	Benzalkonium chloride			**Diflufenican**		
	12-BAC	**14-BAC**	**16-BAC**	**AE-B**	**AE-O**	**AE-C**
October 2019	3945,78	1801,41	310,23	<LOD	<LOD	<LOD
June 2020	<LOQ	<LOQ	81,02	<LOD	0,51	<LOD

Table 29: Average value of Per- and Polyfluoroalkyl Substances (PFAS) in ng/g (ng of micropollutant per g of dry sludge)

	Per- and Polyfluoroalkyl Substances (PFAS)															
	PFPeA	**PFHxA**	**PFHpA**	**PFHxS**	**PFBS**	**PFOA**	**PFHpS**	**PFOS**	**PFNA**	**PFDA**	**PFUnA**	**PFOSA**	**PFDoA**	**PFDS**	**PFTrA**	**PFTeA**
October 2019	<LOD	<LOD	<LOD	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOD	<LOQ	<LOQ	<LOD	0,008	<LOD	<LOQ	0,013
June 2020	<LOD	<LOQ	<LOD	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOQ	<LOD	<LOD	<LOQ

3.3.2 Sludge analysis from WWTP Sant Boi de Lluçanès, Spain

Analyses of sludge from RBs in Sant Boi de Lluçanès, Spain were done in 2007, spring 2008 and summer 2008.

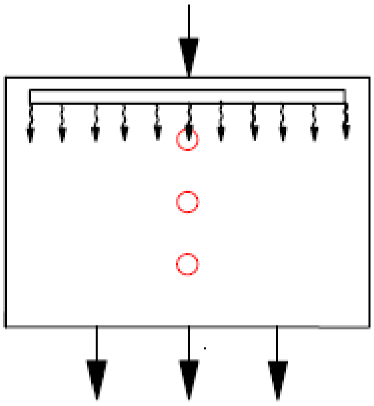

Figure 28: Sampling points in the representative drying reed beds of Sant Boi de Lluçanès.

The results from 2007-2008 are presented in the table below. All the results are within allowed limit values.

Table 30: Dry matter, total volatile solids, heavy metals, TP and TN, pH, Electrical conductivity, BOD$_d$[42]

PARAMETER	**Influent**	**Surface**	**Bottom**	**Limit values**
TS (%)	1-3	7-26	20-30	
VS (% TS)	52-67%	36-45%	32-39%	
TKN (% TS)	4.66 ± 0.05	3.08 ± 0.008 – 3,48	2.13 ± 0.014 – 2,67	
Phosphorus (% TS)	-	0.04 ± 0.01	0.10 ± 0.08	
pH	7,4	6,6-8,0	7,2-8,2	
Electrical Conductivity EC 1:5 (dS/m)	n/a	1.7- 2	1,8-2,2	
BOD$_5$ (gO$_2$/kg TS)	6.9	3.6-5.5	3.7-.4.6	
Cadmium (ppm)	0,66	0,73	0,54	5
Copper (ppm)	183	174	120	800
Nickel (ppm)	50,2	36,0	29,0	200
Lead (ppm)	51,0	46,0	33,2	500
Zinc (ppm)	609	568	425	2000
Mercury (ppm)	1,99	1,44	3,34	5
Chromium (ppm)	36,4	45,6	42,4	800

Differences in TS content between bed layers are due to dewatering processes. After each feeding event, most of water content seems to be removed rather quickly from the surface layer due to evapotranspiration and percolation processes (water content decrease from 97-99% in the inlet to 82-85% within the surface layer). After that, the sludge seems to have a slow progressive dewatering along time. The comparison of the upper and bottom sludge layers in the beds of Sant Boi de Lluçanès suggests that remaining water is progressively eliminated during storage, as sludge in depth is accumulated for a longer period. Thus, the final product is

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[42] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

sludge with moisture contents around 70-80%, which fills in the range obtained with conventional technologies, like centrifuges and belt-filter presses (Metcalf and Eddy, 2003)[43].

Moisture content of the influent sludge was reduced by 26-30% in Sant Boi de Lluçanès. Therefore, in terms of sludge dewatering, which is one of RB technology's main goals, from the studied systems are capable of achieving efficiencies similar to conventional techniques.

Table 31: Concentration of fecal bacteria indicators of the sludge samples obtained in the first sampling campaign

PARAMETER	**Influent**	**Surface**	**Bottom**
Salmonella spp. (presence/absence in 25g)	Absence	Absence	Absence
Escherichia coli (MPN/g)	1100	1100	>2400

In the same region, in Catalonia (Spain), two similar WWTPs with sludge drying reed beds operate; Alpens (400 PE, designed for 800 PE) and Seva (1500 PE). The results of sludge from these two systems from 2007/2008 are presented below.

Table 32: Dry matter, total volatile solids, heavy metals, TP and TN results from Alpens and Seva system[44]

	Alpens			**Seva**			**Limit values**
Parameter	**Influent**	**Surface**	**Bottom**	**Influent**	**Surface**	**Bottom**	
TS (%)	1-3	7-26	20-30		18-23%	11-13%	
VS (% TS)	52-67%	36-45%	32-39%	58-59%	46-51%	46-51%	
TKN (% TS)	5,85 ± 0,018 - 6,83	3,77 ± 0,012	2,72 ± 0,007	5,19 ± 0,002 - 5,08	3,75 ± 0,012 - 3,37	4,99 ± 0,019 - 4,33	
Phosphorus (% TS)	/	0,07 ± 0,05	0,11 ± 0,11	0,07 ± 0,01	0,18 ± 0,11	0,10 ± 0,03	
pH	7,2-7,5	7,4-7,9	6,7-7,6	7,3	6,9-7,3	7,2-8,2	
Electrical Conductivity EC 1:5 (dS/m)	1,4-3,8	0,8-2,3	0,6-1,9	2,1-6,7	0,5-1,1	0,7-1,0	
BOD5 (gO2/kg TS)	3,7-6,8	1,6-5,5	1,0-3,3	3,4	1,3-2,9	1,9-3,3	
Cadmium (ppm)	0,41	0,61	,65	0,76	0,9	1,0	5
Copper (ppm)	227	392	392	232	245	229,7	800
Nickel (ppm)	27,9	29,2	29,6	25	44,7	37,1	200
Lead (ppm)	30,3	49,3	54,3	60,1	80,9	79,3	500
Zinc (ppm)	348	537	565	897	789,7	622,2	2000
Mercury (ppm)	4,29	5,67	4,87	0,95	3,3	3,2	5
Chromium (ppm)	35,8	54,8	56,0	52,1	62,0	54,3	800

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[43] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

[44] E. Uggetti. Sewage sludge treatment in constructed wetland. Technical, economic and environmental aspects applied to small communities of the Mediterranean Region. 2011

Table 33: Concentration of fecal bacteria indicators of the sludge samples obtained in the first sampling campaign.

	Alpens		Seva	
Parameter	Salmonella spp. (presence/absence in 25g)*	E. coli (MPN/g)*	Salmonella spp. (presence/absence in 25g)*	E. coli (MPN/g)*
Influent	Absence	1100	Absence	4
Surface	Absence	460	Absence	<3
Bottom	Absence	460	Absence	<3

3.3.3 Conclusions from sludge analysis

3.3.3.1 Heavy metals

Analysis of sludge in Kastelir (Croatia) and Sant Boi de Lluçanès (Spain) showed that heavy metals in sludge are within allowed limits for biosolids use in agriculture. The results are in line with several other studies, which show that in general, heavy metal concentrations of biosolids are within limits for unrestricted land application[45,46,47], and remain unchanged over time[48] or slightly higher due to accumulation through years[49].

3.3.3.2 Nutrients

In Kastelir, total nitrogen varies from 3,5 to 3,7% of the mass. Total phosphorous varies from 1,2 and 1,3% of mass. In Sant Boi de Lluçanès total Kjeldahl nitrogen was 3,08 to 3,48% TS on surface and 2,13 to 2,67% TS on the bottom. The total phosphorous was 0,04% on the surface and 0,10 % on the bottom.

These TN contents are similar to the TN contents of three other plants (2,9-3,8%).[50] In Polish RBs[51] the average nutrient contents were for nitrogen from 1,0 to 10% dry matter and for phosphorus from 0,2 to 1,0% dry matter.

Nutrient availability changes along vertical profile of the RBs. Different studies have detected increasing or decreasing of the average concentration of nitrogen and phosphorus along the vertical profile. A study from China[52] describes a certain decrease in nutrient concentration (TN and TP) along the vertical profile of sludge treated in RBs, probably due to plant uptake during the growing season. While the decrease of TN and increase

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[45] Uggetti, E., Llorens, E., Pedescoll, A., Ferrer, I., Castellnou, R., García, J. (2009a). Sludge dewatering and stabilisation in drying reed beds: characterisation of three full-scale systems in Catalonia, Spain. Bioresource Technology 100 (17), 3882-3890.

[46] Nielsen, S., & Willoughby, N. (2005). Sludge treatment and drying reed bed systems in Denmark. Water and Environment Journal, 19(4), 296–305. https://doi.org/10.1111/j.1747-6593.2005.tb00566.x

[47] Nielsen, S. (2007). Sludge treatment and drying reed bed systems. Ecohydrology and Hydrobiology, 7(3–4), 223–234. https://doi.org/10.1016/S1642-3593(07)70105-2

[48] Peruzzi, E., Macci, C., Doni, S., Masciandaro, G., Peruzzi, P., Aiello, M., & Ceccanti, B. (2009). *Phragmites australis* for sewage sludge stabilization. Desalination, 246(1–3), 110–119. https://doi.org/10.1016/j.desal.2008.02.039

[49] Nielsen, S., & Bruun, E. W. (2015). Sludge quality after 10–20 years of treatment in reed bed systems. Environmental Science and Pollution Research, 22(17), 12885–12891. https://doi.org/10.1007/s11356-014-3815-6

[50] B. Gómez-Muñoz, J.D. Larsen, G. Bekiaris, C. Scheutz, S. Bruun, S. Nielsen, L.S. Jensen,
Nitrogen mineralisation and greenhouse gas emission from the soil application of sludge from reed bed mineralisation systems, Journal of Environmental Management, Volume 203, Part 1, 2017, Pages 59-67,
ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2017.07.042.

[51] Obarska-Pempkowiak, H., Tuszynska, A., Sobocinski, Z. (2003). Polish experience with sewage sludge dewatering in reed systems. Water Science & Technology 48(5), 111-117.

[52] Yubo, C., Tieheng, S., Lihui, Z., Tingliang, J., Liping, Z. (2008). Performance of wastewater sludge ecological stabilization. Journal of Environmental Sciences 20, 385-389.

of TP was detected by Pempkowiak and Obarsza-Pempkowiak[53] in sludge systems in Poland. Similar pattern was detected in Sant Boi, where TP increases at the bottom by 2.5 times, and Kjeldahl nitrogen decreases.

The results confirm that the long-term stabilization of sewage sludge causes an increase of phosphorus concentration, which is caused by the decomposition of organic matter while retaining the phosphorus. The presence of nutrients N and P indicates that the stabilized sludge in the RBs can be a valuable fertilizer[54]. The results of nutrients suggest that the final product from the treatment, because of its stabilization, may be used as a fertilizer in agriculture.

3.3.3.3 Dry matter

In Kastelir, dry matter is 23% while in Sant Boi de Lluçanès is between 20 and 30% at the bottom layer. It must be noted that these are just intermediate results. More recent results are not available.

RBs can increase the dry matter content of sludge by up to 40%[55] and can be comparatively better than products from mechanical dewatering[56]. A maximum content of dry matter (40%) has been obtained due to long time operation – dry matter content increases with depth[57].

3.3.3.4 Total volatile solids

In Kastelir TVS are 63-64% and in Sant Boi de Lluçanès are 36-45% (surface) and 32-39% (bottom).

During sludge treatment within the reed beds, a VS reduction of 25–30 % can be achieved, reaching final VS concentrations of between 40 % and 50 %. VS removal yields depend on influent sludge VS concentration. For instance, sludge from extended aeration activated sludge systems has lower VS content than from other treatments (i.e., conventional activated sludge); hence VS removal within the wetlands is lower when this type of sludge is treated. Consequently, the efficiency in terms of VS removal of the wetlands might be slightly lower than that of aerobic digestion (40–55 %) or anaerobic digestion (35–50 %)[58,59] . On the other hand, VS contents in compost are considerably higher (60–70 %) than in sludge from other treatments, including wetlands.[60]

3.3.3.5 Pathogens

The contents of pathogenic bacteria must be reduced before sludge reuse activity. Studies in RBs have shown that the number of pathogenic bacteria (Salmonella, enterococci, and Escherichia coli) in the sludge residue during a period of 3–4 months after the last loading was reduced to <2/100 g (Salmonella), <10 CFU/g (enterococci) and <200 number/100 g (E. coli). For enterococci and E. coli the reduction was approximately

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[53] Obarska-Pempkowiak, H., Tuszynska, A., Sobocinski, Z. (2003). Polish experience with sewage sludge dewatering in reed systems. Water Science & Technology 48(5), 111-117.

[54] Kominko, H., Gorazda, K., & Wzorek, Z. (2019). Potentiality of sewage sludge-based organo-mineral fertilizer production in Poland considering nutrient value, heavy metal content and phytotoxicity for rapeseed crops. *Journal of Environmental Management*, *248*(February), 109283. https://doi.org/10.1016/j.jenvman.2019.109283

[55] S. Nielsen. Sludge drying reed beds. Water Sci. Technol., 48 (5) (2003), pp. 101-109

[56] Plestenjak, Eler, K. Mihelič, R. Ferlan, M. Ogrinc, N. Krajnc, B. Vodnik, Can additional air supply enhance decomposition processes in sludge treatment reed beds? 2020. Not yet published.

[57] Obarska-Pempkowiak, H., Tuszynska, A., Sobocinski, Z. (2003). Polish experience with sewage sludge dewatering in reed systems. Water Science & Technology 48(5), 111-117.

[58] Metcalf and Eddy (2003). Wastewater Engineering: Treatment, Disposal and Reuse. McGrawHill. New York.

[59] Von Sperling and Gonçalves (2007). Sludge characteristics and production. In: Sludge Treatment and Disposal. Cleverson, Von Sperling & Fernandes Eds. IWA Publishing, London, UK, 2007.

[60] Uggetti, E., Ferrer, I., Llorens, E., & García, J. (2010). Sludge treatment wetlands: A review on the state of the art. *Bioresource Technology*, *101*(9), 2905–2912. https://doi.org/10.1016/j.biortech.2009.11.102

log 5 and log 6–7, respectively[61]. Thus, from a hygienic perspective, it is safe to recycle the biosolids to agriculture and even to other productive activities[62].

In Kastelir and Sant Boi de Lluçanès *Salmonella spp.* was present, but in small numbers. *Escherichia coli in Kastelir was 5.500 to 6.200 CFU/g, while in* Sant Boi de Lluçanès a much smaller value 1.100 MPN/g (on the surface) and >2400 MPN/g (on bottom) was measured.

Analysis of the reduction in pathogens in the sludge residue from Galten Sludge Reed Bed Plant in Denmark [63] in sludge residue samples taken 6 - 9 months after the last loading indicated that the pathogen content was reduced by approximately 6 log units based on a dry solids basis to a level corresponding to the requirements for controlled sanitation. The results are in agreement with the Danish EPA results for the storage of sludge (Environmental project number 351 regarding sanitation aspects during handing and recycling of organic waste).

Another study in Helsinge, Denmark [64] indicated that the pathogen content in the sludge residue through a period of 3–4 months after the last loading was reduced down to 2/100 g (Salmonella), 10 CFU/g (enterococci) and, 200 number/100 g (E. coli). For enterococci and E. coli, the reduction was between 5 and 6–7 log units, respectively. In the same period, the sludge residue achieved a dry solids content of approximately 20–35%.

3.3.3.6 Micropollutants

Overall, the number and type of detected compounds are in line with what is found elsewhere in Europe. Regarding the pesticides, tebuconazole and carbendazim were in similar ranges (0,1 to 10 µg/Kg) to those reported previously for sewage sludge as well[65,66]. Benzalkonium chlorides belong to the broader family of quaternary ammonium compounds, a major class of cationic surfactants, used as the ingredients in fabric softeners, antistatics, disinfectants, biocides, detergents, phase transfer agent and numerous personal care products[67]. Benzalkonium chlorides are known to sorb to sludge in wastewater treatment plants[68]. The values presently found are within the orders of magnitude previously reported (µg to mg per Kg of sludge)[69]. PFAS concentrations were lower than what is normally measured in sludge.

The higher concentration of pharmaceuticlas in sludge were measured for the antibiotic ciprofloxacin (21,79 ng/g DM in October 2019, 67,27 ng/g DM in June 2020), analgesic citalopram (35,63 ng/g DM in October 2019, 56,59 ng/g DM in June 2020), immunosuppressant drug oxazepam (20,09 ng/g DM in October 2019, 33,47 ng/g DM in June 2020) and for carbamazepine transformation product BaQD 1-(2-benzoic acid)-(1H,3H)-quinazoline-2,4-dione (9,47 ng/g DM in October 2019, 20,56 ng/g DM in June 2020). This can be due to

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[61] Uggetti, E.; Ferrer, I.; Nielsen, S.; Arias, C.; Brix, H.; Garcia, J. Characteristics of biosolids from sludge treatment wetlands for agricultural reuse. Ecol. Eng. 2012, 40, 210–216.

[62] Boyce, A.W. Pathogen levels and sludge use. Biocycle 1988, 29, 65. [Google Scholar]

[63] Nielsen, S., & Willoughby, N. (2005). Sludge treatment and drying reed bed systems in Denmark. *Water and Environment Journal*, *19*(4), 296–305. https://doi.org/10.1111/j.1747-6593.2005.tb00566.x

[64] Nielsen, S. (2007). Helsinge sludge reed bed system: Reduction of pathogenic microorganisms. *Water Science and Technology*, *56*(3), 175–182. https://doi.org/10.2166/wst.2007.491

[65] Kupper, T., et al., *Fate and removal of polycyclic musks, UV filters and biocides during wastewater treatment*. Water research, 2006. 40(14): p. 2603-2612.

[66] Chen, Z.-F., et al., *Determination of biocides in different environmental matrices by use of ultra-high-performance liquid chromatography–tandem mass spectrometry*. Analytical and bioanalytical chemistry, 2012. 404(10): p. 3175-3188.

[67] Zhang, C., et al., *Quaternary ammonium compounds (QACs): a review on occurrence, fate and toxicity in the environment*. Science of the Total Environment, 2015. 518: p. 352-362.

[68] Mulder, I., Siemens, J., Sentek, V., Amelung, W., Smalla, K., Jechalke, S., 2018. Quaternary ammonium compounds in soil: implications for antibiotic resistance development. Reviews in Environmental Science and Bio/Technology.. doi:10.1007/s11157-017-9457-7

[69] Zhang, C., et al., *Quaternary ammonium compounds (QACs): a review on occurrence, fate and toxicity in the environment*. Science of the Total Environment, 2015. 518: p. 352-362

accumulation or fresh sludge. However, the accumulated pharmaceuticals (ciprofloxacin and carbamazepine) lay in the 10-1000 ng/g DM range reported by the Mailler et al. (2018)[70].

The compounds measured in high concentrations (>100 ng/g) were cationic surfactant benzalkonium chloride and some pharmaceuticals such as azithromycin, ibuprofen and valsartan. High concentrations (>100 ng/g) for pharmaceuticals have also been found by other authors (Golovko et al., 2021[71]; Clarke and Smith, 2011[72]).

Another comparison with Lindholm-Lehto et al., 2018[73]showed that the concentrations of pharmaceuticals are higher (3x, 9x) for diclofenac (treated sludge on RBs: 83,35 ng/g; untreated solid sludge: 26 ng/g) and ibuprofen (treated sludge on RBs: 263,33 ng/g; untreated solid sludge: 29 ng/g). The observed difference is due to comparison of different type of sludge and dilution.

However, Wang et al. reported that sludge stabilization time and reed are an important factor influencing the removal efficiency of antibiotics in sludge drying reed beds. Plant roots provide growth and reproduction interface for microorganism with antibiotic degradation ability, and indirectly promote the sludge dry reed bed to remove antibiotics. Their average content of roxithromycin in raw sludge was 95,6 ng/g (dry weight). After three years of loading and one year of stabilization period, they measured roxithromycin concentration in three beds and their average concentration was 18,04 ng/g.[74] Roxithromycin was absent in sludge from reed beds in Kastelir, but this can just be due to different usages in different countries.

In October 2019 we measured the pharmaceuticals azithromycin, trimethoprim, clarithromycin, clindamycin, atenolol, metoprolol, diclofenac, valsartan and tramadol, but they were below limit of detection in June 2020. The measured concentrations (excl. valsartan) of all these compounds were in range with results in Golovko et al. research[71], where they investigated sludge at 15 locations for chemicals of emerging concern. Comparing our results to theirs, we see that the sludge from Kaštelir has lower average concentrations (<100 ng/g DM) of venlafaxine, citalopram, oxazepam and losartan.

There is not much known about the occurrence and fate of organc micropollutants during treatment of sludge with reed beds. In addition, the impact of sludge treatments on micropollutant concentrations is difficult to evaluate considering that most studies do not distinguish different types of sludge from a given sludge treatment plant; they just aimed at characterizing the contamination of raw and/or final treated sludge disregarding the type of sludge treatment.[75] The apparent accumulation of few pharmaceuticals (ciprofloxacin, citalopram, oxazepam), one transformation product (BaQD 1-(2-benzoic acid)-(1H,3H)-quinazoline-2,4-dione) and two pesticides (terbutryn, tebuconazole) may be due to resistance of these compounds to treatment coupled with dehydration process. Nevertheles, the application of fresh sludge might also be responsible by this apparent accumulation. The potential degradation of compounds in time seems to occur to more compounds than the accumulation. Lower content was detected for pharmaceuticals (clarithromycin, clindamycin, sulfamethizole, trimethoprim, atenolol, metoprolol, sotalol, diclofenac, tramadol, venlafaxine, iomeprol, olmesartan, valsartan, irbesartan, eprosartan, losartan, mycophenolic acid, benzotriazole, gabapentin) and pesticides (carbendazim, pirimicarb, 16-BAC). This could be the result of biodegradation on sludge drying reed beds, but cannot be confirmed within the limited scope of the present assessment. More

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[70] https://hal-enpc.archives-ouvertes.fr/hal-01397727/document

[71] O. Golovko, S. Örn, M. Sörengård, K. Frieberg, W. Nassazzi, F. Y. Lai, L. Ahrens: Occurrence and Removal of Chemicals of Emerging Concern in Wastewater Treatment Plants and Their Impact on Receiving Water Systems. Sci. Total Environ. 2021, 754, 142122.

[72] Clarke, B.O., Smith, S.R., 2011. Review of 'emerging' organic contaminants in biosolids and assessment of international research priorities for the agricultural use of biosolids. Environment International 37, 226-247.

[73] Lindholm-Lehto, P.C., H.S. Ahkola, and J.S. Knuutinen, Pharmaceuticals in processing of municipal sewage sludge studied by grab and passive sampling. Water Quality Research Journal, 2018. 53(1): p. 14-23.

[74] C. Wang, Y. Cui, J. Ma, A.Li, S.Li, S. Zhang: The Removal of Antibiotics in Sludge Drying Reed Bed. Advanced in Eng. Reseasrch, volume 170. https://doi.org/10.2991/iceep-18.2018.83

[75] https://hal-enpc.archives-ouvertes.fr/hal-01397727/document

samples and a complete mass balance will be needed to confirm the exact processes occurring in the sludge drying reed beds for these type of compounds.

3.8.3 RBs efficiency

There are relatively few published articles on the effectiveness of reed beds on the content of various pollutants, as the topic is new. In reviewing the literature, one can rely on a small group of experts. Most experts are primarily concerned with heavy metals and their content in the final product (biosolids) and the quality of the final product in general - whether it meets the standards for agricultural land disposal. TS and TVS were also reviewed in terms of dry matter volume, hazardous substances, and their biodegradability and mineralization, micropollutants, and pathogenic organisms.

3.9 Generalization

Presented pilot cases displayed an efficient work of reed beds in the Mediterranean biogeographical region and potential for the use of biosolids in agriculture. Principal findings for reed beds in the Mediterranean region are summarized below:

- Seasonal loading changes (e.g., tourist season) does not impact RBs efficiency;
- Every RB has to be designed according to local climate conditions. Higher temperatures and less precipitation impacts the key design parameter (TSS loading), which is directly related to required surface area of RBs. The smaller the RB area per PE – the higher the solid loading per year. Annual solid loading in Kaštelir (80 TSS kg/m^2)is higher than one evidenced in Alpine climate (up to 60 kg dry matter/m^2 in Mojkovac, Montenegro) due to warmer and drier climate
- Sludge analysis (intermediate[76] results) showed that:
    - Heavy metals in sludge are within limits for biosolids use in agriculture;
    - Valuable nutrients are present in the sludge;
    - Dry matter content is higher compared to Alpine climate conditions due to lower precipitation, more sunny days, higher temperatures, prolonged vegetation period, and higher plant water uptake.

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[76] RBs have a long operating cycle (8 and more years), thus all results of sludge analysis carried out before the end of operating cycle are not considered final.

4 COST ANALYSIS

4.1 Investment costs

Total construction costs in RB Kastelir were 262.626 €. The costs do not include project documentation.

WWTP Kastelir was 100% funded by GEF (Global Environment Facility) grant.

RBs were constructed within the WWTP Kastelir property. There were no costs of land purchasing or renting through an acquisition process. Land was free of charge and owned by the Municipality.

4.2 O&M costs

The analysis was carried out based on historical unit costs with the help of WWTP Kastelir operators. O&M costs are project-specific and cannot be transferred to another location without detailed insight.

The public utility estimated that all operating costs for the entire WWTP with a sewage network, not just RB, arise to 300 € per month. Costs include phone, water, and electricity (incl. operation of 3 sewage pumping stations).

Their estimation does not include labor costs nor final sludge disposal costs after the end of the operational cycle. They perform only urgent maintenance and replacement costs and repairs. Savings for future repairs are also not included.

Below is a consultant estimation for all O&M works related to RBs.

4.2.1 Labor costs

Only one person is operating WWTP Kastelir. The operator e visits the WWTP twice per week: every Friday and Monday. Regular site visit of WWTP includes a visit to the RB. The operator spends only a few hours a year.

The average net pay in Croatia in 2019 was 853 € and average monthly gross earnings per hour 6,70 €[77]. Estimated working hours for O&M activities of RBs Kastelir present less than 10 % of the total working hours of one operator, who is not only working on WWTP Kastelir. Thus, the labor costs for the RB operation are estimated at 1.200 €/Y.

4.2.2 Electricity consumption

Energy consumption of RB in Kastelir is expressed in costs of electric power required for sludge dosing on RB and to return drained water from RBs back to the WWTP to be treated. The pumps (3 kW) are working around 4 hours every 2 months. There is no other electrical consumption data because the system does not have any automatic control system (monitoring, sensors…).

In the calculation of electricity consumption variable market unit cost for electricity of 0,1€/kWh[78] (non-household consumers[79] is applied.

The electricity costs for the RB operation are estimated to be lower than 100 €/Y.

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[77] https://www.dzs.hr/Hrv_Eng/publication/2019/09-01-01_12_2019.htm

[78] https://www.google.com/search?q=0%2C7+HRK+convert+to+€&&oq=0%2C7+HRK+convert+to+€&&aqs=chrome..69i57j33.10048j0j7&sourceid=chrome&ie=UTF-8

[79] Eurostat. 2018.

4.2.3 Monitoring costs

WWTP Kastelir does not perform sludge analysis. The plan is to carry out sludge sampling and analysis only before the final disposal decision.

The sludge analysis and soil analysis to which sludge is applied are estimated at 1.500 € per operating cycle of RBs. If the operating cycle is 10 years, the yearly costs would be around 150 €/Y.

4.2.4 Maintenance costs of mechanical equipment

From 2016 to 2020, the service of the pumps in Kastelir was not carried out due to a small number of working hours.

Maintenance of mechanical equipment and installations is estimated with the percentage of the CAPEX expenditure: 1,5 %. Activities include yearly service of the pumps or the number of operating hours.

The maintenance costs of mechanical equipment are estimated at 150 €/Y.

4.2.6 Replacement costs and repairs

Periodic investment costs and repairs are estimated from 1 to 3 % of investment costs per year. The costs include:

- replacement of the pumps after the end of the life cycle (life expectancy: 10 years)
- major repairs of concrete basin (life expectancy: 50 years)
- replacement costs repairs of piping and manholes (life expectancy: 30 years)
- replacement of filter layer (life expectancy: 30 years)
- repairs of the access road (life expectancy: 20 years)

For WWTP Kastelir, replacement costs and repairs are estimated at a maximum of 2.000 €/Y. The replacement costs increase with the age of the facility. So far, no repairs were needed for RB operation and maintenance.

4.2.7 Final disposal or reuse costs

After the end of the operating cycle, up to 408 m^3 (240 m^2 of surface area x 1,7 m of biosolids height) of sludge will be excavated and disposed to the final location or reused. Cost analysis considers biosolids use. Other options (e.g. incineration) in Istria County are not feasible at the moment.

Final disposal costs for biosolids use are estimated at 384 €/Y (optimal scenario: 40% dry matter, 40% mineralization; 26 tons per year).

4.2.8 Overview of O&M costs

Table 34: Cost analysis of RBs in Kastelir

O&M costs	**Reed beds (€/Y)**
Labor costs	1.200
Electricity consumption	100
Monitoring	150
Maintenance	2.150
TOTAL (without disposal) in €/Y:	**3.600**
TOTAL (without disposal) in €/PE/Y:	**1,89**

O&M costs	Reed beds (€/Y)
Disposal – biosolids use (€/Y)	384
TOTAL with biosolids reuse in €/Y:	**3.984**
TOTAL with biosolids reuse in €/PE/Y:	**2,10**

4.3 Tariff revenues

4.3.1 Existing water tariff

The water tariff for wastewater collection in treatment for Municipality Kastelir-Labinci is presented in the table below.

Table 35: Water tariffs paid by users[80]

Municipality Kastelir-Labinci	Household	Other consumers
Fixed fee (€/month)	2,54	3,58
Variable fee (€/m^3)	2,31	3,30

* The prices include 13% VAT

The existing tariff for wastewater treatment for households is 1,42 €/m^3 without fixed fees (1,19 €/month) but including sewage development fee (0,53 €/m^3). It should be noted that existing wastewater tariff is not covering only O&M costs of RBs, but also other related wastewater services.

Assessment of water tariff rates that would cover the operation and maintenance of sludge treatment in Kastelir is presented in the table below. Initial investment was covered with a 100 % grant, thus we assessed only the price of the tariff required for O&M activities.

The estimated needed wastewater tariff for O&M activities of RBs is 0,08 €/m^3. The estimated tariff is calculated from the estimated design water consumption (49.500 m^3/Y) and estimated O&M costs (3.984 €/Y). The RB was financed through grant, thus calculated water tariff of 0,08 €/m^3 doesn't cover financing of investment. If RB was financed through loan, the needed water tariff would be 0,26 €/m^3.

Needed wastewater tariff for O&M of RB (€/m^3) = O&M of RB (€/Y) / water consumption (m^3/Y).

The estimated yearly revenue from the wastewater treatment tariff is 70.290 €/Y (estimated water consumption (49.500 m^3/Y x existing water tariff of 1,42 €/m^3) and can cover RB O&M costs (3.984 €) for O&M with biosolids use. The public utility confirmed that WWTP Kastelir operation and maintenance is covered with revenues from wastewater tariff.

4.3.2 Cash flow analysis

4.3.2.1 Grant

Cash flows for RBs in Kastelir are:

- Cash in-flows
    - Revenues: the application of existing charges to users (1,42 €/m^3 for whole wastewater service)
- Cash out-flows
    - O&M costs

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[80] https://www.ivb.hr/media/1687/25-cjenik-opcina-kastelir-labinci.pdf

Grant and investment flows are neglected because their sum is equal to zero (grant-investment=0). Project cash-flow forecasts 30 years of RB operating life. The applied financial discount rate is 4%.

Table 36: Projection of cash-flow with grant for reed beds with biosolids reuse

Net Present Value (NPV)	**INFLOW** **NPV Revenue from wastewater tariff**	**OUTFLOW** **NPV O&M costs of RBs**
SUM 0-30 years (€):	+1.215.457	-68.897
Cash inflow – Cash outflow (€):	1.146.560	

The O&M costs of RBs present 6% of revenues from the application of existing charges to users.

4.3.2.2 Loan

A 100 % grant is not always the case, so a scenario of providing financial resources through loans was created.

Cash flows for RBs in Kastelir are:

- Cash in-flows
    - Revenues: the application of existing charges to users (1,42 €/m^3 for whole wastewater service)
- Cash out-flows
    - Investment costs: **loan**
    - O&M costs

Investment is financed through national bank (30 years, 0,7% fixed interest rate). Project cash-flow forecasts 30 years of RB operating life. The applied financial discount rate is 4%.

Table 37: Projection of cash-flow with loan for reed beds with biosolids reuse

	INFLOW	**OUTFLOW**
SUM 0-30 years (€):	**Water charges:** +1.215.457	**Loan repayments:** -319.910 **O&M costs:** -68.897
TOTAL:	1.215.457	-388.807
Cash inflow – Cash outflow (€):	826.650	

The outflow costs of RBs present 32% of revenues from the application of existing charges to users. The needed water tariff to cover O&M of RB would with financing through loan increase from 0,08 €/m^3 (grant) to 0,26 €/m^3 (loan).

4.3.3 Tariff and affordability analysis

The prices of water, drainage, and tariffs are determined in the Decisions on the price of water services for public water supply and drainage (with the consent of the municipalities and cities) and decisions on fees for development (drainage and Istria water communities), the Law on Waters, the Law on Financing of Water Management, the Law on VAT[81].

Regulations for determining the amount of water charges in Croatia [82]:

- Water contribution

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[81] https://www.ivb.hr/centar-za-potrosace/cijena-vode/

[82] https://www.voda.hr/hr/zakoni-propisi-vodne-naknade

- Regulation on the amount of water contribution (Official gazette (OG) 78/2010, 76/2011, 19/2012, 151/2013, 83/2015 and 42/2019)
    - Ordinance on the calculation and collection of water contributions (OG 107/2014)
- Compensation for water management
    - Regulation on Fees for Water management (OG 82/2010, 108/2013)
    - Ordinance on the calculation and payment of water management fees (OG 83/2010, 126/2013)
- Water usage fee
    - Regulation on the amount of water use charges (OG 82/2010, 83/2012, 10/2014)
    - Ordinance on the calculation and payment of water use fees (OG 84/2010, 146/2012)
- Water protection fee
    - Regulation on the amount of water protection fee (OG 82/10, 83/12, 151/2013)
    - Ordinance on the calculation and payment of water protection fees (OG 83/10, 160/2013)

According to the Water Services Act (OG 66/2019)[83], the price of water, including the price of water services, development fee, water use fee, and water protection fee, shall not exceed 3% of the net disposable annual household income. Tariffs should ensure that all community members have access to these services without placing a significant burden on their household expenditures.

Existing water tariffs in Kastelir-Labinci are applied for the analysis. The average disposable income per household was 12.918 € in 2018, while average equivalent disposable income amounted to 7.262 €.[84].

The following table provides affordability analysis calculated from the average equivalent and disposable household income and estimated water consumption.

Table 38: Affordability analysis for Kastelir-Labinci

Household income[85]	*Household water consumption	Affordability index
Average equivalent disposable income per household: 7.262 €	146 m^3/Y or 340 €/Y	4,68%
Average disposable income per household: 12.918 €	146 m^3/Y or 340 €/Y	2,63%

*4 people, 100 l/PE/day

The share of expected income spent on water bill is less than 3 % of average disposable household income and, therefore, affordable. However, when comparing the water bill with the average equivalized disposable income, the water bill is not affordable anymore. The value indicates that water is not affordable for people living below the "at-risk-poverty threshold". The at-risk-of-poverty threshold for a household consisting of two adults and two children younger than 14 was 8.280 € per year[86].

The social price (variable part in €/m^3) is 40% lower compared to full price for water services paid by users who are not socially endangered.[87] Cost difference is usually reimbursed to the supplier by the local government. Subsidized water consumption (consumer pays social price) in the "household water-use" category is evident in 0,5% of the consumers in the entire area of Istrian water system operation[88]. Here it

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[83] https://narodne-novine.nn.hr/clanci/sluzbeni/2019_07_66_1286.html
[84] https://www.dzs.hr/Hrv_Eng/publication/2019/14-01-01_01_2019.htm
[85] https://www.dzs.hr/Hrv_Eng/publication/2019/14-01-01_01_2019.htm
[86] https://www.dzs.hr/Hrv_Eng/publication/2019/14-01-01_01_2019.htm
[87] https://www.ivb.hr/media/1136/opci-uvjeti-poslovanja-odluka-o-cijeni-vodnih-usluga.pdf
[88] Hilda Sirotić Labinjan. ISTARSKI VODOVOD d.o.o.

must be noted that Municipality Kaštelir-Labinci is only one out of 27 Municipalities which are included in this statistic.

4.3.4 Sources of financing

Kastelir-Labinci Municipality was able to access an international grant because waste and wastewater pollution has been identified as a major threat to the protection of the Dinaric Karst Aquifer System. It provides essential and precious ecosystem services and supports the development of the country's economy[89]. Untreated wastewater discharge carried the risk of environmental degradation, along with serious economic consequences for tourism.

Grants are rarely an option for most communities, but it was the best financial instrument for the Kastelir village.

In case the Municipality of Kaštelir-Labinci could not receive a grant for WWTP, they would need to assure funds from the municipal budget or take a loan and repay it through the application of charges to users. The Municipality of Kastelir-Labinci is a smaller municipality with an annual budget of less than one million €[90]. Their funds for investments are limited, and they already had to take the bank loan to construct the second phase of the sewerage network. They used an instrument for pre-accession assistance (IPARD funds).

The village Kastelir is 15 km away from the city of Poreč but excluded from plans to connect on central WWTP and could not be part of the EU Poreč project (project worth more than 66 million €[91]). Under the current financial perspective, the agglomeration is too small (below 2.000 PE) for direct access to European funds. Currently, the EU is only co-financing larger wastewater investment projects.

4.4 Net present value

The accumulated sludge in the Imhoff tank (mechanical treatment before CW) has to be desludged regularly. In case RB was not constructed, the sludge would need to be pumped out and transported to central WWTP. As shown below, the sludge volume changes significantly if different scenarios of dry matter content are adopted. Imhoff tank can generate 628 m^3 of sludge per year with 3 % solids content. That would on a yearly basis require 79 slurry tankers with a capacity of 8 m^3 and cost 6.320 €/Y. The estimated price for one pumping and transport to the central WWTP is 80[92] €/8 m^3 of sludge.

Table 39: Different scenarios of accumulated sludge in Imhoff tank (1.900 PE)

% of dry matter content	Accumulate sludge (m^3/Y)	Estimated costs (€/Y)
2	942	9.440
3	628	6.320
4	471	4.720
5	377	3.760

Ranking of different sludge handling scenarios is presented in the Table 40. The calculation of NPV takes into account following:

- The average economic life of the project assets (time horizon) is assumed to be 30 years;
- Initial investment costs (capital costs);
- Operational and maintenance costs;
- The real discount rate applied is 4%.

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[89] https://www.thegef.org/project/adriatic-sea-environmental-pollution-control-project-i

[90] https://www.kastelir-labinci.hr/dokumenti/proracun/sve/1

[91] http://odvodnjaporec.hr/projekti/projekt-porec/

[92] Public utility MARTINELA. Price based on the costs of emptying the household septic tanks.

Table 40: Comparison of different sludge handling scenarios

Sludge treatment + disposal	NPV O&M	NPV Investment	NPV Total	Ranking
Reed beds + biosolids use	-68.897	-262.626	-388.807	2
*Sludge pumping and transport to the central WWTP (3% dry content)			-109.286	1

*The costs don't include costs of sludge treatment and handling on central WWTP.

The results showed that total costs in the RBs over a period of 30 years sums up to 388.807 €. In this specific case, sludge pumping and transport to the central WWTP Poreč would be a much cheaper option. It must be emphasized here that investment costs in RB Kastelir were higher because works required mechanical excavation in the ground of IV. (decays rocks) and V. (medium hard wall) category.

The technical basis of feasibility (pre-investment) study are conceptual solutions. The document addresses all variants that would be economically, financially, technically, and environmentally feasible with concerning identified objectives. All criteria, not only the financial aspect, impact the decision-making process. Because WWTP Poreč refused to accept sludge from WWTP Kastelir, the Municipality didn't have other more feasible options at that time. The quest for a sustainable solution was imminent.

In the decision-making process, the financial criteria impacting selection of reed beds for treatment of sludge from small WWTP (below 2.000 PE) over other options (transport of the sludge to the central WWTP) are:

- WWTP capacity – impacting sludge volume;
- Technology – affecting sludge volume, sludge characteristics and sludge storage capacity;
- Distance (km) and topography from small WWTP to the centralized WWTP - impacting the costs of transport;
- Vehicle ownership (does public utility owns vehicles and also use them for other services or has to order a service for sludge pumping);
- WWTP ownership – if both small and central WWTP falls under the same public service, the in-house costs are usually cheaper than external costs charged to a client from another municipality.
- Costs of transportation and other fees;
- CAPEX and OPEX of sludge treatment;
- Potential revenues derived from biosolids use.

Choosing the best option is case-specific, and generalization can lead to mistakes. Thus, it is difficult to draw conclusions under what conditions it would be no longer financially viable to transfer sludge from small to central WWTP. However, it can be concluded for Kastelir that if the price of sludge transfer would increase for 3,6 times (285 €/8 m^3 instead of 80 €/8m^3), the investment would be than justified from the financial point of view.

At the moment O&M costs of public utility for the whole WWTP (not only RB) with sewerage system are much lower (3.600 €/Y) than estimated O&M costs for RB (3.984 €/Y) because this study also takes into the account labor costs, replacement cost and biosolids reuse. Public utility is not having this kind of cost at the moment.

4.5 Generalization

Presented cost analysis is case-specific, and all prices apply to Croatia and not for other Mediterranean countries. The presented cost methodology is transferable, but with use of case-specific prices. Below a regional diversity of prices around the Mediterranean region is shown.

Labor costs

Presented labor costs based on pilot case in Croatia. When transferring this data to the Mediterranean region, it must be considered that hourly earnings can vary from 2,19 €/hour in Albania to 14,94 €/hour in France (Table 41).

Table 41: Median gross hourly earnings in countries of Mediterranean Region.

Country	Median gross hourly earnings in €/hours, all employees (excluding apprentices), 2014[93]
Albania	2,19[94]
BiH	4,54[95]
Croatia	4,90
Cyprus	8,35
France	14,94
Greece	8,00
Italy	12,49
Malta	8,48
Montenegro	3,42
Spain	9,83

Water tariff

Water tariffing is a complex topic as it depends on multiple local parameters like tax level, water sources, length of network per inhabitant, receiving water, etc. It is generally regulated through a public body, either an official regulator or the local government.[96] Below a snapshot of the current situation in the EU member countries with average prices of water per m^3 is presented. Prices are useful in evaluating the global diversity of prices across Europe.[97] Comparison of water bills requires careful interpretation.

Table 42: Average price of water tariffs around the Europe [98] (countries in Mediterranean region)

Country	Drinking water network length per capita (m)	Average residential consumption (L/cap/d)	Wastewater network length per capita (m)	Average price of water tariff (€/m^3)
Croatia	7,8	150	14	1,98
Cyprus	6,55	149	5,63	2,9
France	15	143	6	3,92
Greece	6,61	150	4,46	1,40
Italy	5,8	245	4,7	1,5
Malta	5,6	79,36	3,83	3,32
Spain	4,8	139	3,54	1,78

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[93] https://ec.europa.eu/eurostat/statistics-explained/index.php/Wages_and_labour_costs#Gross_wages.2Fearnings

[94] https://balkaneu.com/salaries-albania-drastic-gap-minimum-maximum-pay/

[95] https://tradingeconomics.com/bosnia-and-herzegovina/wages

[96] http://www.eureau.org/resources/publications/1460-eureau-data-report-2017-1/file

[97] http://www.eureau.org/resources/publications/1460-eureau-data-report-2017-1/file

[98] http://www.eureau.org/resources/publications/150-report-on-the-governance-of-water-services-in-europe/file

4.8 Conclusions of the cost analysis

Cost analysis conclusions based on pilot case in Kastelir:

- Construction costs of RB amounted to 138 €/PE without project documentation. The cost of investment is higher than costs of comparable investments (two reed beds in Mojkovac (2.500 PE) were 55 €/PE for 900 m^2; one reed bed in Kastelir (1.900 PE) was 138 €/PE for 240 m^2).
- Estimated operational and maintenance costs (labor, energy consumption, monitoring, regular and periodic maintenance) of RBs are 1,9 €/PE per year without biosolids reuse and 2,1 €/PE per year with biosolids reuse.
- At the moment, all operating costs for the entire WWTP and sewage network, not just RB, arise to 1,9 €/PE per year without labor costs and final sludge disposal costs.
- Ranking options (sludge treatment on RB with biosolids use to alternative of sludge pumping and transport to the central WWTP) by NPV showed that sludge transfer to central WWTP would be a cheaper option. However, one must not forget that sludge transfer to central WWTP was not a feasible option at that time. Only feasible alternative options should be adequately considered in the feasibility analysis.
- Comparing sludge treatment on reed beds to sludge transfer to central WWTP showed that the price of sludge collection and transport would need to increase for 3,5 times that investment in reed beds would pay off financially due to high investment costs.
- The existing wastewater tariff (1,42 €/m^3) covers all wastewater costs in the municipality. In this Study, calculated wastewater tariff needed for RBs should be set at 0,08 €/m^3 to cover OPEX of RBs with biosolids use. In case Municipality of Kastelir - Labinci would not get the 100% non-refundable grant and should take the loan to finance implementation of RB, the needed water tariff would needed to be higher arising to 0,28 €/m^3 to cover CAPEX and OPEX of RBs with biosolids reuse.
- Cost analysis emphasized following aspects when deciding whether implement RBs:
    - Sludge quantities;
    - CAPEX and OPEX of all feasible sludge management alternatives with long-term perspective;
    - Potential revenues from biosolids land application.
- The obtained results are case-specific and do not reflect the situation of the whole Mediterranean region.
- The approach used for cost analysis is transferrable, but not the used units and prices. Cost assessment also demonstrated vulnerability related to specific conditions and expert judgment.

5 DIRECT AND INDIRECT BENEFITS

Direct and indirect benefits of RB Kastelir were assessed by the **unit value transfer method.**

DIRECT BENEFITS:

- Reduced sludge volume – quantified in %;
- Changes in operation (lower O&M costs) - quantified in avoided costs in €/Y;

INDIRECT BENEFITS (assessed with low, medium, or high):

- Education and promotion;
- Aesthetic value;
- Well-being;
- Tourism sustainability and development;
- Biodiversity;
- Biosolids use.

In addition, indirect benefits were also assessed through quantitative information summarized based on the mean value of all the data collected (see Table 43).

5.1 Direct benefits

5.1.1 Reduced sludge volume

RB Kastelir is dimensioned to achieve 40% mineralization and 40% dry content. This means that on RBs we pump around 18.850 TSS kg/Y of which 40 % is turned into CO_2 through microbiological activity, while 11.310 TSS kg/Y remains on the reed bed. Estimated volume reduction is above 90%.

5.1.2 Changes in operation

Since RB in Kastelir was constructed, there is no longer a need to pump the sludge out of the Imhoff tank and transfer it to the central WWTP for further treatment. It is estimated that under full capacity operators would need to pump the sludge out of the Imhoff tank at least 5 times per year and the costs of collection and transfer would amount to 6.320 €/Y. The costs of further treatment[99] on a central WWTP are not included.

Considering how much public utility spends for O&M activities of the whole system consisting of CW and RB (3.600 €/Y), the estimated costs of collection and transfer (6.320 €/Y) to the central WWTP are considered to be significant.

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[99] The acceptance fee of sludge on central WWTP varies. For example, in Slovenia WWTP Ribnica (6.000 PE) charges 7 €//m3 of sludge.

5.2 Indirect benefits

WWTP Kastelir was needed to protect public health and to prevent contamination of water sources. The solution contributes to the well-being of all residents and prevents the degradation of the environment; thus, people feel more secure. Residents accepted technology, and no complaints on WWTP's behalf were filed to local authorities.

The implemented NBS for wastewater and sludge treatment (CW plus RB) has the following advantages over more conventional WWTPs (e.g., SBR - sequencing batch reactor):

- Less intensive technology (less energy consumption, no added chemicals);
- Low-cost technology (lower O&M costs);
- Better integration in the landscape (landscape attractiveness);
  WWTP Kastelir is aesthetically pleasing – it merges harmoniously with surrounding green areas (vineyards, olive groves). In addition, CW and RB have the same visual appearance (same vegetation) therefore is integrated into the landscape.
- Greenspace supports biodiversity and can deliver various ecosystem services.
  Even though the operator didn`t notice any animals in RB, invertebrates are usually present on RBs. The height (2,6 m) of RB walls above the terrain level may be the reason for the system's lower biodiversity.

Since RB is constructed, it is no longer necessary to collect, transport, and dispose of sludge at central WWTP a few times per year, which reduces traffic, noise stress, air pollution, and gas emissions. All this positively impacts tourism. There are no evidenced economic losses linked to the dissatisfaction of tourist-related to the environment. The potential impact of the latest coronavirus outbreak may weaken tourism, but is not expected to alter RB performance (lower loading during tourist season should not affect RB efficiency).

In terms of education and promotion of NBS, the pilot case in Kastelir becomes a well-known example of NBS combining wastewater and sludge treatment. Project gained recognition when an article[100] was published in the Journal of Croatian Waters[101] and another article[102] in the Journal of the Croatian Association of Civil Engineers[103]. Since then, WWTP Kastelir is being used for the promotion of CW and RB among various stakeholders. The engineering consultants mostly organize the field visits but very much supported by the Municipality of Kastelir-Labinci and public utility. The local government is always willing to share their experience of implementation and operation of WWTP Kastelir. In recent years there were more than 10 study visits through which RB technology was presented to more than 50 expert participants.

Regarding biosolids use, RB in Kastelir will produce 469 tons (calculated from the RB volume) of stabilized sludge per operating cycle. Taking into account a maximum content of dry matter (40%) obtained by the sludge treatment on RB and a criteria for biosolids land application (1,66 tons of sludge dry matter per hectare), the produced biosolids could be applied to 113 ha (1,33 km^2) of agricultural land. The municipality of Kastelir-Labinci has enough agricultural area for local use of biosolids. They have 4,5 km^2 of vineyards or 0,5 km^2 of olive groves, etc. At the end of every operating cycle, RB can supply 25% of vineyards in the municipality with soil amendment. Their impact on the local supply of fertilizers is estimated to be low.

The WWTP Kastelir enables safe reclamation of treated wastewater. After the last treatment step (polishing bed) water is collected in a 285 m^{3}a reservoir. Water is available to the farmers to be used for irrigation of olive trees, vineyards or any other crop.

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[100] Šuljić Brajčić A. 2017. No. 219. ISSN 1330-321X. UDK 6281

[101] https://www.voda.hr/hr/casopisu-hrvatska-vodoprivreda

[102] Stanković. D. 2017. https://doi.org/10.14256/JCE.2062.2017)

[103] http://www.casopis-gradjevinar.hr/

The CW is designed to achieve secondary level of treatment, thus nutrients (nitrogen and phosphorus) remain in the reclaimed wastewater. The treated wastewater reuse could reduce the use of fertilisers for the plantations nearby. However, the main driver for wastewater reuse wasn't to close the loop of nutrients, but to mitigate water scarcity during the summer months. The water volume available for irrigation is around 41.400 m^3 per growth season (May to November). The applied water dose is from 500 to 2.500 m^3/ha per season for irrigation of olive trees[104]. The reclaimed water and according to the water need balances of the vineyards and olive trees, could be potentially used for irrigation of 17 ha or 83 ha respectively although water usage depends on precipitation deficit, soil properties, meteorological parameters, and has to be determined for each production grove separately.

Even though the WWTP has been in operation since 2016, the use of reclaimed wastewater has never been practiced by local farmers, probably due to low social acceptance. Project was well-technologically planned and implemented, but the perception of end-users and public regarding the use of "wastewaters" has not changed. Local authorities are still not addressing this problem and controversy around wastewater and biosolids reuse remains and will not change unless the socialization of the use of recovered resources happens.

The costs of wastewater reuse are equal to costs of secondary treatment. According to public utility, operating costs of all wastewater infrastructure in the Municipality is to 300 € per month (vegetation season: 7 months x 300 €/month = 2.100 €). The costs of freshwater for irrigation would be much higher (cc 41.400 m3 x 1 €/m3 =.41.400 €).

Constructed wetlands (CWs) have proven to be an effective treatment alternative for the removal and inactivation of pathogen indicators in wastewaters. Pathogen removal efficiencies of 4 log units (99.99%) have been reported by multiple authors employing a different constructed wetland designs and technology. Vymazal (2005) presented removal efficiencies and first-order aerial rates recorded for different CW systems in-use at the time of the study, for 4 different indicator organisms. Removal efficiencies up to 2 log units (99%) were observed with the highest removal rates observed for hybrid systems, followed by HSSF, and lastly FWS systems[105]. In addition, experiment conducted by Arias et al. (2003) showed that indicator bacteria are also removed effectively by vertical flow constructed wetland systems in spite of the short residence time of the water. The first-stage vertical flow beds removed about 1.5 log-units of total coliforms, 1.7 log-units of faecal coliforms and 0.8 log-units of faecalstreptococci[106].

According to Shingare et al, the average log reduction in hybrid CW was found to be 3.14 log CFU/100 ml for *E. Coli* (EC), 3,80 log CFU/100 ml for Fecal coliform (FC), 3,24 log CFU/100 ml for Fecal streptococci (FS), and 3,39 log CFU/100 ml for total coliform (TC)[107]. Performance that can also be expected in WWTP Kastelir.

If NBS (CW) is not to be used, the alternative solution to would be a WWTP based on activated sludge processes followed with a disinfection step. This implies higher CAPEX, OPEX and the increase of the level of training of the workers.

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[104] Podgornik, M., Bandelj, D.: Deficitni princip namakanja oljčnih nasadov v Slovenski Istri (Deficit irrigation principles applied to olive orchard in Slovene Istria), 2015. URL: https://doi.org/10.14720/aas.2015.105.2.17 (accessed 20 Oct 2020)

[105] K. P. Weber, R. L. Legge : Pathogen Removal in Constructed Wetlands. In Wetlands: Ecology, Conservation & Restoration; Russo, R. E., Ed.; Nova Science, 2008.

[106] Arias CA, Cabello A, Brix H, Johansen NH (2003b) Removal of indicator bacteria from municipal wastewater in an experimental two-stage vertical flow constructed wetland system. Water Sci Technol 48:35–41

[107] R. P. Shingare, P. R. Thawale, K. Raghunathan, A. Mishra, S. Kumar: Constructed Wetland for Wastewater Reuse: Role and Efficiency in Removing Enteric Pathogens. Journal of Environmental Management. Academic Press September 15, 2019, pp 444–461.

The water reuse could indirectly support the development of tourism industries [108] and rural communities and businesses in the Municipality.

5.2.1 Rapid indirect benefit indicators assessment

Table 43 presents quantitative information summarized based on the mean value of all the data collected. Values indicating higher benefits relative to the mean are color-coded in blue and values indicating lower benefits relative to the mean are coded in red. In most cases, a "yes" value indicates higher benefits and appears in blue, while a no value indicates lower benefits and appears in red.

Table 43: Quantitative, qualitative and narrative indirect benefit indicators[109]

Indirect	**Summarize the Indicators**		**Site**
Benefit	**Indicators**		**WWTP Kastelir with RBs**
Scenic Views	3.2 How Many Benefit?	Number of homes within 150 m of site	0
		Number of homes within 100 m of site	0
		Weighted number who benefit within 150 m	0
		Are there roads or trails within 100 m of site?	No
	3.3.A Service Quality	Aesthetic features or characteristics?	Yes
	3.3.B Scarcity	NBS or water within 200 m (number or %)	0
	3.3.C Complements	Natural land use types within 200 m (types)	9
	3.3.D Preferences	Will people find it aesthetically pleasing?	Yes
Environmental Education	3.2 How Many Benefit?	Education institutions within 800 m of site	0
	3.3.A Service Quality	Features/habitat/wildlife of education interest?	Yes
	3.3.B Scarcity	Wetlands/RBs within 800 m of the site	0
	3.3.C Complements	Educational facilities or infrastructure on the site?	Yes
	3.3.D Preferences	Will people prefer characteristics of the site?	Yes
Recreation	3.2 How Many Benefit?	Number of homes within 530 m of the site	17
		Are there bike paths within 530 m of the site?	Yes
		Are there bus stops within 530 m of the site?	NA
		Number of homes within 0 to 800 m of the site	18
		Number of homes within 0,80 to 10 km of the site	NA*
	3.3.A Service Quality	Total area of green space around the site, ha	400
	3.3.B Scarcity	green space in ha within 1 km of the site	89
		green space in ha within 1,6 km of the site	245
		green space in ha within 20 km of the site	260.00
	3.3.C Complements	Infrastructure supporting recreational activities?	No

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[108] EU-level instruments on water reuse, Final report to support the Commission's Impact Asessment, prepared by Amex Foster Wheeler Environment & Infrastrucure UK Ltd. IEEP, ACTeon, IMDEA and NTUA, October 2016

[109] Assessing the Benefits of Wetland Restoration: A Rapid Benefit Indicators Approach for Decision Makers, US EPA/600/R-16/084, July, 2016

Indirect	**Summarize the Indicators**		**Site**
Benefit	**Indicators**		**WWTP Kastelir with RBs**
	3.3.D Preferences	Are there additional features on the site?	No
Bird Watching	3.2 How Many Benefit?	Number of homes within 500 m of the site	2
		Are there roads or trails within 500 m of the site?	Yes
	3.3.A Service Quality	Will the site support rare or unique species?	Yes
	3.3.B Scarcity	NA	NA*
	3.3.C Complements	Supporting habitat on site?	Yes
	3.3.D Preferences	Will people be interested in birds at the site?	No
Biosolids reuse	3.2 How Many Benefit?	Number of agriculture lands within 5 km of the site	694
	3.3.A Service Quality	What is the service quality	Good
	3.3.B Scarcity	Is there need for soil amendment?	Yes
	3.3.C Complements	Are they willingness to pay for biosolids?	No
	3.3.D Preferences		NA

Legend: BLACK = No entry; **GREY** = NA; **BLUE** = Above Average/YES*; **RED** = Below Average/No* (*reverse for scarcity)[110]

*NA Not Available

The numbers and answers in the above table were compared to the values collected and analyzed in "Assessing the Benefits of Wetland Restoration: A Rapid Benefit Indicators Approach for Decision Makers"[111] made by Environmental Protection Agency of United States.

The indicators, part of indirect benefits groups, illustrates the results summary:

- Site WWTP Kastelir is not visible to people, so most scenic views indicators are colored in red;
- Environmental education indicators show high potential;
- Recreation indicators are high, but the site doesn't support recreational activities;
- RBs supports some bird species, but WWTP cannot be used for bird-watching even though the site is accessible and close to the village;
- Biosolids indicators are high, but the willingness to pay for biosolids is low.

In can be concluded that the table above shows the village population has some indirect benefits enabled by the RBs.

5.3 Conclusions of the benefits

Direct benefits conclusions based on pilot case in Kastelir:

- Municipality of Kastelir - Labinci reduced sludge volume for more than 90%.

- Solution replaced sludge disposal at the central WWTP for further treatment. The avoided costs of sludge transported in slurry tankers are 6.320 €/Y. The avoided costs are significant considering how much public utility spends for O&M activities of the whole system consisting of CW and RB (3.600 €/Y).

Indirect benefits conclusions based on pilot case in Kastelir:

- Ensuring proper wastewater and sludge treatment is protecting community health and environment, especially vulnerable underground water sources in the karst region.
- Kastelir has been experiencing tourism growth in recent years, and preserved environment is a basis for sustainable tourism development. NBS efficiently manages flow variations without significantly impacting the O&M costs.
- Local authorities accepted the whole concept of NBS for wastewater treatment (CW + RB) to optimize and reduce energy input and O&M costs. Even though RB have higher capital costs, they tend to have lower operating costs. The Municipality was in the interest to implement low-cost technology; the GEF grant covered capital costs;
- The implementation of NBS preserved landscape attractiveness and scenic views. NBS is placed among vineyards and olive groves.
- Implemented NBS created attractive green space, which supports biodiversity and delivers ecosystem services.
- Avoided sludge transfers of slurry tankers to central WWTP reduced local traffic, noise stress, air pollution, and gas emissions.
- WWTP Kastelir became a promotional pilot case for NBS for wastewater and sludge treatment in the Region. More than 10 study visits were organized, and RB technology presented to more than 50 participants.

  One of the most important benefits of RBs is possible reuse of biosolids. RB in Kastelir will produce 469 tons of biosolids per operating cycle, which can be applied to 113 ha. A yearly limit of 1,66 tones of dry matter per hectare is being used as criteria for calculation of agricultural area required for biosolids land application.

6 IMPLEMENTATION CHALLENGES

6.1 Innovative technology

RB in Kastelir is the first-ever constructed NBS for sludge treatment in Croatia. Since then, three more RBs have been constructed (Čakovec, Mrkopalj, Ravna Gora) and up to ten are planned to be built in the next few years. In Croatia, RBs are no longer perceived as novel technology but as an effective alternative to mechanical dewatering of raw sludge.

The central WWTP refused to accept sludge from CW Kastelir; thus authorities were looking for the alternative, which could solve the problem locally and for many years. Only technologies with the possibility of long-term sludge storage came into consideration. They accepted the proposed solution with open hands.

What action was needed:

- Technology presentation by the RB expert;
- Field visit (demonstration) was organized for local and national authorities, which included visiting RBs abroad and discussing with the operator.

Another challenge was related to the treatment technology. RB next to the CW presented novelty for Balkan Mediterranean Region. The engineers faced capacity challenges related to technological specifications.

As with any other wastewater technologies (SBR, MBBR, etc.), NBS technologies also require expert knowledge and specialization. Therefore, it was crucial to involve in the project NBS experts and not just "traditional" engineers. The technological design done by RB experts covered the following area of work:

- Description of treatment technology;
- The main elements of the treatment process;
- Hydraulic and technology calculations;
- Loading scenarios;
- Selection of plants;
- Selection and testing of substrate;
- Maintenance and operation.

Here it should be noted that characteristics of sludge from the Imhoff tank differ from the excess sludge from conventional WWTP (more volatile solids). Thus, WWTP Kastelir additionally mixes sludge before loading it to bed. The required surface area of the system is defined by the maximum TSS load (kg TSS/Y) depending on the climate conditions. In the Mediterranean Region, loadings on RBs can be higher than in Northern countries (Austria, Denmark, Germany), where most RB systems are built. Analyses of micro-location conditions and its impact on process parameters (e.g., mineralization rate) are a task of NBS engineer.

What action was needed:

- Inclusion of NBS expert in the project;
- Collaboration with Slovenian experts – a foreign company with experience with the design of RBs;
- Consultation with Danish expert;
- Collaboration of engineers of various disciplines (civil engineer, RB process design engineer, mechanical engineer, electrical engineer, etc.);
- Cooperation between the designer and the construction contractor during final design preparation.

6.2 Seasonal variation in RB

Seasonal variation presents a challenge for all WWTP. Kastelir is a tourist village characterized by seasonal load. This required special attention is focusing on the effect on the RB operation. Special attention was paid to ensuring stability over seasonal differences (plant drying during low season or overloading during high season).

What action was needed:

- Analyses of pollution and hydraulic loadings;
- Impact assessment on the RB operation;
- Multi-year load proposal and operational plan.

The loading pattern in Kastelir takes into account:

- Volume of accumulated sludge in Imhoff tank;
- Time required for anaerobic stabilization of sludge;
- Seasonal variation;
- Weather.

6.4 Financing and funding

The Municipality of Kastelir-Labinci did not experience any difficulty with financing and funding for the establishment of RBs in Kastelir. Kastelir was one of the areas to be addressed among the priority pollution hotspot sites, as identified by UNEP-MAP in 2003 and then confirmed by the World Bank study in 2011. Project addressed untreated wastewater discharges, which could seriously affect tourism (industry contributes 28% of GDP in the region), the pillar of the local economy.[112] Thus, investment decisions (initial investment) were made top-down with the Ministry's initiative, which was looking at the whole picture. The project was fully funded through a grant agreement by the Global Environment Facility (GEF). The Municipality of Kastelir-Labinci actively supported all the actors involved in project realization. Operational expenditures of RBs are covered by the water tariff and do not financially burden the Municipality. In their opinion, the applied solution is cost-efficient and financially acceptable for the Municipality.

What action was needed:

- Willingness of Municipality to cooperate with project initiator (Croatian Waters);
- Coordination on multiple levels of government;
- Perform administrative processes on time (spatial planning, building permit, tender, etc.).

6.5 Construction

The largest construction company led the construction of RBs at that time in Croatia (Viadukt d.d.). Their wide experience with construction projects and the inclusion of technological supervision assured that RB was constructed well.

What action was needed:

- Work was trusted to the experienced construction company;
- Technological supervision was included in the project.

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[112] https://www.thegef.org/project/adriatic-sea-environmental-pollution-control-project-i

6.6 Commissioning, operation and maintenance

After completion of construction works, all the project partners (Croatian Waters, Municipality, public utility Martinela Ltd and project consortium) arranged the date for RB commissioning. Trial operation, training, and know-how transfer were not part of the project. Thus, O&M Manual was discussed during commissioning in the presence of a technological expert.

What action was needed:

- Commissioning at the presence of key stakeholders (investor or initiator, WWTP owner, WWTP operator) and project consortium team (incl. lead process engineer);
- Elaboration and discussion of O&M manual;
- Transfer of key messages - poor maintenance and operation can result in poor performance of the system.

Fortunately, there were no operational issues due to limited know-how transfer during commissioning. However, based on our experiences, it would be better also to have:

- trial operation and process optimization – including monitoring;
- proper O&M training;
- dissemination activities.

6.7 Future challenges

6.7.1 Biosolids use in agriculture

In Croatia, national legislation allows the use of biosolids in agriculture since 2008, when the Ministry of Construction and Physical Planning passed the Rulebook on the management of sludge from wastewater treatment plants, when sludge is used in agriculture (Official Gazette of Croatia, No. 38/08[113]). Then in 2019 Ministry for agriculture accepted another Rulebook on the protection of agricultural land from pollution (Official Gazette of Croatia, No. 71/2019[114]), which doesn`t allow the use of sludge on food production crops to protect agricultural land from contamination and degradation. Both regulations are in force and exclude each other.

The Municipality of Kastelir has not yet decided what it would do with biosolids at the end of the operational cycle. At the beginning of the project, they expressed interest in using biosolids as a soil amendment on vineyards and olive groves, which grow in the vicinity of WWTP Kastelir. However, karst terrain and landscape sensitivity of the area may have a significant impact on the final decision. In karst area, polluted waters can travel quickly to and through the sub-surface[115], thus self-cleaning capacities are reduced guideline[116] currently in force, forbids use of treated sludge on karst field soil, shallow or skeletal karst soil. It also prohibits sludge use on:

- grasslands and pastures used for grazing livestock;
- areas on which fodder plants are grown at least two months before harvest;
- soil on which fruit and vegetable plantations grow, except for fruit trees;
- soil intended for the cultivation of fruit and vegetables which may be in direct contact with the ground and which can be eaten raw, for at least ten months before the date of the beginning of the harvest;
- soil on which there is a danger of leaching sludge into surface waters;

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[113] https://narodne-novine.nn.hr/clanci/sluzbeni/2008_04_38_1307.html

[114] https://narodne-novine.nn.hr/clanci/sluzbeni/2019_07_71_1507.html

[115] "Land use interacts with changes in catchment hydrology to generate chronic nitrate pollution in karst waters and strong seasonality in excess nitrate export": https://www.sciencedirect.com/science/article/pii/S0048969719340392

[116] http://www.propisi.hr/print.php?id=7936

- soil with a pH value lower than 5;
- soil saturated with water, covered with snow and on frozen agricultural land;
- in the coastal and water protection area.

What action is needed?

- Cross-sectoral discussion on the Regional level;
- Elaboration of municipal sludge strategy document or feasibility study based on national strategies but taking into account local conditions;
- Elaboration of Guidelines for sewage sludge use.

6.7.2 Other final disposals

If the Municipality of Kastelir will not be able to use biosolids in agriculture, other options are very limited by the legislation, permitting processes, existing infrastructure for sludge management, and karst terrain. Potential other uses of biosolids are presented below:

- For now, the material cannot be incinerated because there is no incineration plant in Istria County or in whole Croatia that would accept dewatered sludge;
- Material cannot be burned in a cement plant because it does not meet 90 % of dry matter and the calorific value is probably too low[117];
- It could be deposited in the sealed basin;
- It could be deposited on the landfill, which is still in practice, but otherwise forbidden by the law;
- It could be used for landfill covering (part of landfill sanitation);
- It could be used for the revitalization of quarries or other degraded areas.
- It could be used for sanitation of erosion;
- It could be used for greening of highway embankments;
- It could be used in the construction industry (adding it/mixing with construction material);
- Additional composting of biosolids from RBs does not make sense because sludge has already been stabilized and mineralized. Stable biosolids generate little heat and consume little nitrogen and oxygen. Composting is also intensive technology (use of mechanical equipment, turning, addition of chemicals, monitoring, labor demanding, etc. and would create additional costs for manipulating biosolids, making them less competitive on the market. Extra activities related to the composting wouldn’t provide aggregate value to the final product;
- It could be mixed with soil and used as fertilizer for floriculture;
- It could be used as fertilizer for industrial plantations (e.g., hemp);
- It can be mixed with lime for better stabilization and applied on land;
- It could be used on green areas and parks;
- It could be used in recreational areas (e.g., football stadium).

When using biosolids for a recultivation layer (landfill covering, revitalization, and sanitation works), they can be mixed with soil. Their ratio depends on the sediment-water content and geomechanical characteristics of the mixture.

Permitting biosolids use may impose additional limitations and restrictions, especially in the karst region.

What action is needed:

- Cross-sectoral collaboration on the Regional level;

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[117] Calorofic value of biosolids from RB in Kastelir is not known.

- Environmental and economic assessment of feasible options;
- Establishment of pilot cases;
- Monitoring.

6.8 Lessons learned

Lessons learned from project RB Kastelir:

- RBs next to the constructed wetland for wastewater treatment can prolong the lifetime of the WWTP. Poor maintenance of primary treatment (irregular or no sludge collection from sedimentation tank) is one of the most common reasons for the clogging of a porous medium of constructed wetland, which results in poor treatment efficiency. Installation of RBs next to the constructed wetland can prevent poor maintenance because sludge pumping on RBs is usually simpler and cheaper solution in terms of O&M costs compared to sludge collection and transport to central WWTP;
    - RB technology can be designed as modular. Implementation can be planned in a series of phases, according to need. In Kastelir, three reed beds were designed, but so far, only one was constructed. The number of beds needed for sludge treatment is influenced by the WWTP capacity, loading rates, length of feeding/resting period, final resting period, operation, and maintenance activities. It is easier to control operation and efficiency (e.g., even sludge distribution) of the system containing more beds than one large. Also, in case of a problem, more beds enable the continuation of the operation and, at the same time, parallel sanitation of the specific issue on one bed.
- RB technology can be transferred and adapted to different climate conditions. Our pilot case is a first-ever constructed RB system in Croatia and adapted to the Mediterranean climate. Most of the adaptation is related to the operation, which also impacts design. The key aspects that require adjustment to climate are:
    - The RBs in Mediterranean Region can have bigger loading (kg TSS) per m^2. This means that RBs systems can be smaller compared to systems in Northern regions;
    - The warmer climate impacts the needed length of the resting period. The process of mineralization is faster (more extended vegetation period and more biological activity);
    - There is a risk of plants drying during warmer months. Thus, it is necessary to predict measures within the system to regulate the water level.
- RBs work well under seasonal loading variations and are thus appropriate solution for touristic areas;
- The WWTP Kaštelir (CW+RB) has a footprint of 19.600 m^2, incl. access roads, facility building, parking lot, etc. The net area of RB is 240 m^2. The alternative to NBS (constructed wetland + RB) would be a conventional technology based on activated sludge processes such as sequential batch reactor (SBR) technology with mechanical dewatering, which would require around 70 % less space (cc. 4.600 m^2)[118]. Along the Mediterranean coastline, RBs implementation is limited by the availability and high prices of land. Nevertheless, this case showed that RBs could be implemented in inland regions of coastline where land is cheaper or owned by the Municipality. RBs and other NBS can be integrated into urban and rural communities considering ecological functionality and their aesthetic value. The stakeholders should not only perceive RBs as land-intensive technology, but as a solution with high conservation value – integrating RBs in high scenic value areas. Engineers and architects should emphasize the importance of protection and the creation of areas of high (ecological) value. RBs as NBS support this process and its multiple benefits;WWTP Kastelir is an example of integrated wastewater management: collection, wastewater and sludge treatment, disposal, and reuse potential of wastewater and sludge reuse.

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[118] WWTP Šentvid Pri stični (1.950 PE): https://www.jkpg.si/cistilne-naprave

- Utility operators and municipal officials established a collaborative environment to address municipal wastewater challenges. However, successful collaboration with farmers is not yet established. Even though WWTP Kastelir enables farmers to buy reclaimed wastewater, nobody buys or uses it.

7 BUSINESS MODEL

7.1 Description of business model

Sludge treatment technology in Kastelir enables the possibility to generate revenue from biosolids. It also offers incentives for business development and cost recovery.

Service and financial flows

Sanitation services in Kastelir are provided by the local government (Municipality of Kastelir-Labinci) and operated by the public utility Martinela Ltd. Any business of biosolids' use can start at the initiative of the municipality of Kastelir-Labinci. The options are the following (Figure 29):

- **to sell the biosolids**
    - to business entity, which re-sell them further to end-users (farmers)
    - to end-users (farmers)
- **to give biosolids free of charge**
    - to end-users (farmers)
- **to subsidize biosolids use**
    - to end-users (farmers)

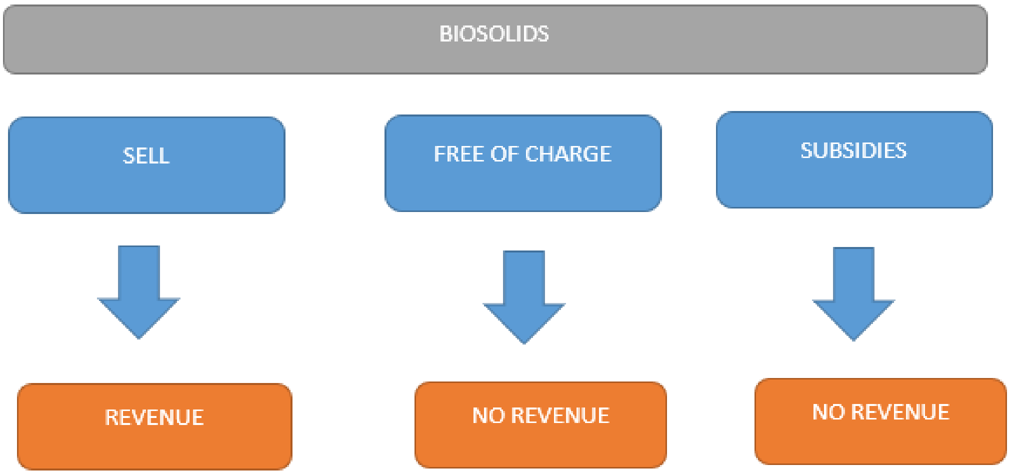

Figure 29: BM basis

Utility operators and municipal officials established a collaborative environment to address municipal wastewater challenges. However, successful collaboration with farmers is not yet established. Even though WWTP Kastelir enables farmers to buy purified water, nobody buys or uses it.

7.2 Competitive analysis

Competitors

Biosolids compete with animal manure and mineral fertilizers. Fertilizer prices in Croatia are:

- 140[119] €/ton for animal manure (sold by farmers);
- 337[120] €/ton for mineral fertilizer (sold in stores).

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[119] https://www.njuskalo.hr/zastita-gnojidba-navodnjavanje/stajsko-gnojivo-staro-2-godine-oglas-14915996 in https://lokalni.vecernji.hr/zupanije/zbog-smanjenja-broja-farmi-krava-stajski-gnoj-trazen-kao-suho-zlato-2964

[120] From 211 to 462 €//ton. Source: https://www.eistra.info/telefon/porec/agrokastelir-doo-domvrt/1025_13_0_0_0

7.3 Cost and revenues projections

7.3.1 BM 1: Contractual partnership (municipality/operator – business entity)

A business entity (e.g., private company) signs a contractual agreement with the Municipality of Kastelir-Labinci to collect biosolids at the WWTP site and transport them to the (approved) storage site from where distribution or sale of biosolids products is permitted. Provider of biosolids charges business entity collection fee for biosolids in €/ton. Business can be profitable with revenue earned from the biosolids selling to end-customers.

Key actors:

- Biosolids provider: Municipality of Kastelir-Labinci or public utility MARTINELA Ltd.
- Biosolids buyer: Business entity
- End-user: Farmers

The operator excavates biosolids after the end of the first operating cycle. The business entity pays collection fees and arranges to collect biosolids at the WWTP site. Costs for excavation of biosolids are estimated at 4.896 € (sludge volume in m^3 x price of excavation in €/m^3). The cost of excavation is a little bit higher because public utility MARTINELA does not own the required machinery. Collection fee should at least cover excavation costs, everything above the cost recovery price (10,43 €/ton) is revenue for the provider of biosolids. The minimum cost recovery price is calculated from the produced volume of biosolids (m^3) divided by the excavation costs (€). The supplier could earn 4.488 € by collection fee of 20 €/ton. In the table below, cost and revenue projections for Contractual partnership (BM 1) are presented.

Table 44: Cost and revenues projections for contractual partnership (BM 1)

PROJECTIONS	**RB**
COSTS	
Excavation cost (€)	4.896
REVENUES FROM COLLECTION FEE	
Scenario 1 - collection fee (11 €/ton)	5.161
Scenario 2 - collection fee (20 €/ton)	9.384
Scenario 3 - collection fee (30 €/ton)	14.076
COST RECOVERY	
Cost recovery price (€/ton):	10,43

7.3.2 BM2 2: Local-public partnership (municipality-operator-farmer)

Plant operator, public utility MARTINELA Ltd, is contracted by the Municipality of Kastelir-Labinci to implement biosolids use in the Municipality. This might require the plant operator to enter the strategic partnership with community-based organizations to reach end-costumers. Community mobilization and campaigns can help to sell and use biosolids. This way, the biosolids can become the income source for the biosolids provider.

Key actors:

- Biosolids provider: Municipality of Kastelir-Labinci or public utility MARTINELA Ltd
- Biosolids buyers are also end-users: Farmers

The second business model, Local-public partnership (BM 2), predicts that the operator excavates and sells the harvested biosolids. Establishment costs, for on-site storage facilities for biosolids are not taken into account due to the small biosolids quantity and high demand in the area. Storage facility costs can be avoided if all biosolids are sold in advance and harvested up on the same day when the retrieval is carried out. The cost recovery price for the biosolids is 10,43 €/ton. The biosolids provider could earn 23.256 € by selling biosolids at market price of 60 €/ton.

The forecasting of a price for biosolids is difficult as there is no regional experience with biosolids reuse in terms of what price the farmers are willing to pay. It is reasonable to expect a reduced price which reflects beneficial reuse. The set market prices (Table 45) for biosolids demonstrate the potential revenues. The scenarios take into account the biosolids market prices that are much lower than animal and manure fertilizers in order to make alternative economically attractive. The value of biosolids is a key factor when attempting to develop a business model.

Table 45: Cost and revenues projections for local-public partnership (BM 2)

PROJECTIONS	**RB**
COSTS	
Excavation cost (€)	4.896
REVENUES FROM SELLING	
Scenario 1 - collection fee (40 €/ton)	18.768
Scenario 2 - collection fee (60 €/ton)	28.152
Scenario 3 - collection fee (80 €/ton)	37.536
COST RECOVERY	
Cost recovery price (€/ton):	10,43

7.3.3 BM 3: Subsidizing biosolids use

Biosolids use application requires incentives. A strategy with subsidies payable to consumers (e.g., farmers) for the use of biosolids could be one of the mechanisms to stimulate biosolids use among farmers. Reasonable subsidies could reduce O&M costs for the final disposal of biosolids. The model is dependent on government support.

Key actors:

- Subsidies provider: Municipality of Kastelir-Labinci
- Subsidy receivers: Farmers

In the analyzed business model subsidizing biosolids reuse (BM 3), we advocate that it is still cheaper to subsidize the use of biosolids than to transport excavated material to another site for final disposal. It is important to arrange the material's pick-up in parallel with the excavation process to avoid the establishment costs of an on-site storage of biosolids.

In the cost analysis chapter we used unit price of 17 €/ton for local biosolids use. Costs per ton increase as the distance increases. Here we used the assumption that final disposal costs for sludge in Kastelir are 14.076 € (30 €/ton), while excavation costs (4.896 €) and subsidizing the use of biosolids at 6 €/ton (2.815 €) would together amount to 7.711 € (Table 46). Cost savings from this source are 11.261 € every time RB is emptied. With this example we wanted to show that it is cheaper to subsidize local biosolids use than to dispose sludge regionally.

Table 46: Cost and funding projections for subsidizing biosolids use (BM 3)

PROJECTIONS	**RB**
COSTS	
Excavation cost (€)	4.896
Final disposal cost (€)	14.076
Total costs:	18.972
SUBSIDIES	
Scenario 1 - subsidizing use of biosolids (4 €/ton)	1.877
Scenario 2 - subsidizing use of biosolids (6 €/ton)	2.185
Scenario 3 - subsidizing use of biosolids (8 €/ton)	3.754

7.3.4 BM 4: Biosolids free of charge

Municipality of Kastelir-Labinci may decide to give biosolids free of charge in compliance with valid conditions, standards, regulations, and legislation. Biosolids give away would reduce O&M costs for the final disposal of biosolids.

Key actors:

- Biosolids provider: Municipality of Kastelir-Labinci or public utility MARTINELA Ltd
- Biosolids end-users: Farmers

Municipality of Kastelir-Labinci can give biosolids away to farmers, who can use it as a free-soil amendment instead of other commercial products. One of the most expensive components of fertilizer is phosphate, and biosolids are very high in phosphate. The excavation costs of biosolids are 4.896 € (Table 47). It is also necessary to organize the customers' collection on the same day as excavation is performed.

Table 47: Cost projections for giving biosolids free of charge (BM 3)

PROJECTIONS	**RB**
COSTS	
Excavation cost (€)	4.896
GIVE-AWAY	
Give away of biosolids	**0**

7.4 Assessment of feasibility

Development of BM for biosolids use in Kastelir comes with certain challenges:

- Small quantities (469 ton/operating cycle);
- Biosolids available only ten or so years;
- This has not been done yet in Croatia;
- Municipality has no experience with biosolids use;
- Farmers' lack of interest in biosolids use (only one farmer uses dried reeds from constructed wetland on agricultural land);
- Only WWTP Kastelir cannot provide enough biosolids to attract private sector investments. This kind of BM should be done on regional or state scale – collecting sludge from all WWTPs (feasible in Croatia, where RB application is increasing).

In Table 48, benefits and limiting factors of various business models for biosolids use are presented. Revenue created from biosolids based on the prevailing market price can help to maintain the treatment plant. In the long-term, the municipal target should be to reach full cost recovery of operational costs, whereby biosolids use can contribute to the achievement of this goal.

Table 48: Benefits and limiting factors of business models for biosolids use in Kastelir

	BM 1: Contractual partnership	**BM 2: Local-public partnership**	**BM 3: Subsidizing biosolids use**	**BM 4: Biosolids free of charge**
FINANCIAL IMPLICATIONS				
Creates revenue	Y-if sold above recovery price	Y	N	N
Reduces costs	Y	Y	N	N
Requires subsidy	N	N	Y	N
Cost recovery of use	Y	Y	N	N
REGULATORY AND MONITORING IMPLICATIONS				
Requires sludge analysis (paid by provider)	Y	Y	Y	Y
Requires soil analysis (paid by end-user)	Y-if applied on soil N-if mixed/added to material	Y	Y	Y
INSTITUTIONAL IMPLICATIONS				
Requires public sector involvement (producers)	Y	Y	Y	Y
Requires private sector involvement (consumers)	Y	Y	Y	Y
ENVIRONMENTAL AND HEALTH IMPLICATIONS				
Reduces indiscriminate disposal of sludge	Y	Y	Y	Y
Concerns of public health and environmental safety	Y	Y	Y	Y

7.5 Conclusions on business model

Business model conclusions for biosolids use based on pilot case in Kastelir:

- Local-public partnership is the most profitable BM and also the most feasible model to create revenue;
- Contractual partnership BM is the least feasible model due to small quantities of biosolids available every operating cycle;
- Biosolids free of charge or subsidizing biosolids use does not make revenue, but reduce costs for final disposal;
- Farmers from Kastelir are not yet considering wastewater or biosolids use as an option. Reclaimed wastewater has been available since 2016, but the perception has not changed since and continue to be the issue limiting the reuse of any kind of resources recovered from wastewater treatment around the region.The biosolids land application initiative would require a long-term effort of multiple levels and allocation of financial resources;

- Biosolids can compare in cost with commercial fertilizer under the assumption that Municipality bears the cost of biosolids production (OPEX and CAPEX of sludge treatment with RB technology);
- In order to safely apply biosolids to land, BM should be built around the health issues. The monitoring and supervision should support rules governing biosolids use;
- All presented business models can reduce O&M costs because biosolids land application is a cheaper option than other final disposal options;
- The process of establishment of BM in Municipality of Kastelir-Labinci would require the initiative, development and operational team, and involvement of various stakeholders.