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COMPARATIVE PRELIMINARY EVALUATION OF TWO IN-STREAM WATER TREATMENT TECHNOLOGIES FOR THE AGRICULTURAL REUSE OF DRAINAGE WATER IN THE NILE DELTA

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Abstract. In the Nile Delta, a complex network of canals collects drainage water from surface-irrigated fields, but also municipal wastewater. The goal of this work was to assess the technical, environmental and financial feasibility of the upgrade of a drainage canal (DC) into either an in-stream constructed wetland (ICW) or a canalized facultative lagoon (CFL), in order to produce a water re-usable in agriculture according to the Egyptian law. The model-based design of the proposed technologies was derived from field experimental data for the ICW and laboratory data for the CFL. Both technologies, integrated by a sedimentation pond and a disinfection canal, led to the attainment of the water quality standards imposed by Egyptian Law 92/2013 for the reuse of drainage water. The life cycle assessment indicated that the upgrade of an existing DC to either an ICW or a CFL results in an extremely small environmental burden, ≤ 0.3% of that of a traditional activated sludge process. The cost/benefit analysis (CBA) was based on the assumptions that (i) farmers currently irrigate a non-food crop (cotton) with the low-quality drainage water present in the DC, and (ii) thanks to the upgrade to a ICW or CFL, farmers will irrigate a food crop characterized by a higher market price (rice). The CBA indicated that the DC upgrade to an ICW represents an attractive investment, as it leads to a financial rate of return > 10% over a wide range of cotton market prices. Conversely, the upgrade to a CFL is less attractive due to high investment costs. In conclusion, the upgrade of DCs to ICWs appears a promising option for the treatment of drainage canal water in the Nile Delta, thanks to the high pollutant removal performances, low cost and negligible environmental burden.

Keywords: drainage and municipal wastewater, constructed wetlands, facultative lagoons, life cycle assessment, cost benefit analysis.

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KEYPOINTS

- Evaluation of the technical, environmental and financial feasibility of the upgrade of an Egyptian drainage canal into an in-stream constructed wetland (ICW) or a canalized facultative lagoon (CFL) in order to turn drainage canal water into water re-usable in agriculture according to Egyptian law.
- Both technologies, integrated by a sedimentation pond and a disinfection canal, led to the attainment of the water quality standards imposed by Egyptian Law 92/2013 for the reuse of drainage water.
- The upgrade of a drainage canal to an ICW or CFL presents a negligible environmental impact (≤0.3% of the average impact of an activated sludge process) and leads to a marked improvement in water quality (90-99% decrease in BOD, 71-94% decrease in total nitrogen, 2.6-4.3 Log reduction in fecal coliforms).
- The cost benefit analysis indicated that the upgrade of a drainage canal to an ICW represents an attractive investment, leading to a financial rate of return > 10% over most market conditions examined. Conversely, the upgrade to a CFL is less attractive due to the high investment costs.

INTRODUCTION

In the Nile Delta region in Egypt, agriculture represents a crucial economic activity, and all the agricultural surface is irrigated with freshwater ultimately provided by the Nile river through a complex network of canals. Surface irrigation is widely applied, and the excess irrigation water, contaminated with fertilizers and pesticides, is collected by means of an intricate network of drainage water canals. However, several villages in Egypt are still suffering from low sanitation coverage and poor sanitary technology. Therefore, small drainage canals are often used to dispose untreated municipal wastewater (MWW) and industrial wastewater. The contaminated drainage canal water (DCW) is typically discharged in main drains, which eventually discharge in the Mediterranean sea (Frascari et al. 2018). The treatment of drainage canal water potentially represents an important option for the Nile Delta, with the double purpose to produce water that can be reused for irrigation or for aquaculture and to reduce the pollutant load discharged in the Mediterranean. Thus, simple, low-tech, low-energy water treatment technologies are needed to treat drainage water up to irrigation-quality water.

Two technologies are in line with these requirements: constructed wetlands (CWs) and facultative lagoons (FLs). CWs are characterized by a low investment and operational cost, and they are suitable for the treatment of several wastewater types. The use of CWs is a growing practice to mitigate the impacts of point and non-point source pollution. Wetlands promote physical, chemical and biological processes that attenuate pollution leading to an improved water quality (Bass 2000; Gorgoglione and Torretta 2018; Almuktar et al. 2018; Martinez-Guerra et al. 2015). Decreased velocities promote deposition of suspended solids in the wetland. Dense vegetation in wetlands can improve physical filtering of sediment, trash, and organic materials. Vegetation also shades shallow and slower moving waters to help reduce algae growth (Mitsch and Gosselink 2000).

In the specific context of the Nile Delta, the presence of a high number of canals carrying a mixture of drainage water and untreated MWW suggests the opportunity to convert the existing canals into in-stream constructed wetlands (ICWs). In general, an ICW consists of a primary sedimentation pond, a constructed wetland section, a disinfection section and a gated weir that governs the hydraulic retention time (Rashed and Abdel-Rashid 2008). The upgrade of an existing drainage canal to an ICW does not determine any additional occupation of land. This makes the proposed upgrade particularly attractive, as in the Nile Delta all the land not occupied by residential or industrial activities is dedicated to agriculture.

Facultative lagoons are increasingly applied for MWW and agricultural water treatment, particularly in remote and/or rural communities, as they can offer completely natural water treatment processes. In addition they are simpler to operate and they require less energy than aerated lagoons (US EPA 2002; Ho et al. 2017; Ewing et al. 2014; Liu et al. 2010). Facultative lagoons are usually 1.2 to 2.4 m deep and they are not mechanically mixed or aerated. The water layer near the surface contains dissolved oxygen due to atmospheric reaeration, a condition that supports aerobic organisms contributing to COD removal and ammonium oxidation to nitrate. The bottom, anoxic layer of the lagoon includes sludge deposits and supports facultative and anaerobic organisms contributing to nitrate reduction to nitrogen and partially to COD removal. In cold climates, fermentation reaction rates are significantly reduced during the winter and early spring, reducing drastically the effluent quality. Therefore, facultative lagoons systems perform better in warm climates, where effective removal of pathogens and coliforms can also be achieved. Most existing facultative lagoons are large, single-cell systems with the inlet located near the centre of the cell. This configuration can result in short-circuiting and ineffective use of the design volume of the system, as well as in difficulties to control ammonia levels in the effluent, due to limitations in the activity of ammonium-oxidizing bacteria in the aerobic layer. Recently, canals receiving partially treated and untreated municipal effluents resulted in interesting water treatment performances (Mancini 2008). Therefore, canalised facultative lagoons (CFLs) can attain simultaneous COD removal, nitrification and denitrification, provided that the canal depth and turbulence allow the establishment of (i) an upper, aerobic layer in which high oxygen concentrations maintained through dissolution from air allow aerobic bacteria to perform BOD oxidation and ammonia nitrification; (ii) a bottom, dark anoxic layer receiving nitrates from the upper one; and (iii) an adequate mass transfer of nitrate and BOD between the upper and lower layer (Mancini 2008). In the specific context of the Nile Delta, for the above-illustrated reasons, the upgrade of existing drainage canals into CFLs represents a potentially promising solution.

The main goal of this work was to assess the technical, environmental and financial feasibility of the upgrade of a typical drainage canal into either an ICW or a CFL. More specifically, the drainage canal upgrade was evaluated in terms of (i) the capacity of the proposed technologies to produce a treated effluent compliant with the limits imposed by the Egyptian law for the agricultural reuse of drainage water, (ii) the environmental impact and (iii) the attractiveness of the required investment for a farmer or a farmers' association, making reference to the specificities of the Egyptian context.

The upgrade of a typical tertiary drainage canal to either an ICW or a CFL was thus assessed in terms of Life Cycle Assessment (LCA) and Cost Benefit Analysis (CBA). This approach required a preliminary model-based design of both technologies. To this goal, two different approaches were applied for the ICW and for the CFL. For the first technology, on the basis of the encouraging results obtained by the National Water Research Council of Egypt in previous pilot-scale tests of DCW treatment by means of constructed wetlands (Rashed 2016; Rashed and Gammal 2018), an actual tertiary drainage canal – the Edfina DC in the Western Nile Delta – was upgraded to an ICW and the resulting water treatment performances were monitored for 18 months. The model-based design of the ICW used for the LCA and CBA was thus performed on the basis of the results obtained in the experimental full-scale ICW. Conversely for the CFL, given (i) the lack of previous field experiences in Egypt or in similar contexts and (ii) the higher excavation and building costs associated to the upgrade of an existing tertiary DC to a CFL, the model-based design used for the LCA and CBA was performed on the basis of the results obtained in a laboratory-scale pilot plant. To this goal, two stirred tank reactors (STRs) were set up and operated in batch mode, with a variable flow rate of mutual exchange between them, in order to simulate the biodegradation phenomena occurring in an actual CFL in the upper aerobic layer and in the lower anoxic layer. The results obtained in these two batch reactors were used to predict the profiles of pollutants concentration versus space along the actual CFL – represented as a continuous plug-flow reactor (PFR) – according to the equivalence between the time evolution of concentrations and reaction rates in a batch reactor and the variation of the same parameters with retention time in a PFR (Levenspiel 1999).

This work presents two main novelties. In the first place, even though CWs and facultative lagoons are well-known water treatment technologies, in this work for the first time these technologies were adapted to the Egyptian context, and more specifically an existing drainage canal was upgraded to an in-stream CW or facultative lagoon. In particular, even though a limited number of previous articles refers to the concept of "in-stream constructed wetland" (Stone et al. 2003; Bass 2000; Kasak et al. 2018), in none of these articles the CW was obtained within an existing canal, and therefore the CW was always characterized by an additional occupation of land. Conversely, both the ICW and the CFL object of this work do not require any additional land occupation, a crucial advantage in a highly cultivated context such as the Nile Delta. In the second place, the integration of technical performances, LCA and CBA in order to select the most promising water treatment technology among a range of proposed technologies represents an innovative approach in the literature.

This work contributes to the achievement in Egypt of sustainable development goal (SDG) 6 "Ensure availability and sustainable management of water and sanitation for all", with specific emphasis on targets 6.3 "Improve water quality by reducing pollution, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse" and 6.6 "Protect and restore water-related ecosystems".

MATERIALS AND METHODS

Analytical methods

The analyses of chemical oxygen demand (COD), total suspended solids (TSS), total N, NO_3^- and NH_4^+ were performed according to the following ISO standards: COD, ISO 15705:2002; TSS, ISO 11923:1997; total N, ISO 11905:1997; NO_3^-, ISO 7890 1-2:1986; NH_4^+, ISO 7150-1:1984. For all these analyses, Hach-Lange cuvette tests were used. The analysis of biochemical oxygen demand BOD (5 days, 20°C), Fecal Coliforms (FC) and Total Coliforms (TC) were performed according to the methods described by the American Public Health Association (APHA 2000).

Description of the Edfina Drainage Canal (DC) and drainage canal water characterization

Edfina village and drainage canal (DC) are located in West of the Nile River Delta (31° 17’ 45.14’’ N and 30° 30’ 18.9’’2 E). The drain, that receives daily 300 m^3 of raw sewage, serves 200 hectares of croplands. Further details on the Edfina DC are reported in Table S1 in the Supplemental Data. TSS, BOD, COD, total N and FC were monitored in the Edfina DC for 18 months to investigate the natural pollutant depuration along the drain. Six sampling locations were placed along the DC.

Laboratory tests for the model-based design of a canalised facultative lagoon

An average sample of DCW was used to produce an enriched microbial consortium to be used in the aerobic/anaerobic nitrification/denitrification tests aimed at simulating a canalised facultative lagoon. The procedure for the growth of the aerobic and facultative fractions of the bacterial community sampled from the DC is illustrated in Tables S2 and S3 in the Supplemental Data.

In order to gain insight on the performances in COD reduction and nitrification/denitrification attainable in a CFL using the microbial consortium enriched from drainage canal water, a laboratory-scale pilot plant comprising 2 bioreactors, one mimicking the aerobic and one the anoxic layer of an actual CFL, was designed and assembled. Two jacketed glass stirred tank reactors (STR) were used (Sartorius, Germany). The two STRs were hydraulically connected to each other and water was recirculated with a controlled exchange volumetric flow rate f (L/h) by means of a peristaltic pump, in order to simulate the exchange between the aerobic and anoxic layers of an actual CFL (Figure 1e). Further details on the layout and operational conditions of this plant are reported in Table S4 in the Supplemental Data.

LCA and CBA of the upgrade of an existing canal to an ICW or CFL

The core idea of this work consists in valorizing the presence of numerous drainage canals in the Nile Delta by upgrading them into an ICW or CFL, so as to (i) develop an effective water treatment technology without any additional land occupation, and (ii) minimizing environmental impact and cost relative to the implementation of the proposed technologies. Thus, the main goal of the LCA and CBA was to compare the upgrade of an existing canal to an ICW to the upgrade of the same canal to a CFL in terms of environmental impact and costs/benefits. For this reason, both the LCA and CBA were not referred to the construction of an ICW or CFL from scratch, but rather to the conversion of an existing DC to an ICW or CFL. The LCA was performed according to the ISO 14040 standard (ISO 2006). The LCA inventory was based on the design of a full-scale (350 m^3/d) CFL or ICW. A 30 year lifetime was considered. All values were referred to 1 m^3 of drainage canal water (functional unit). The software SimaPro 8.4.0 and the database Ecoinvent 3.3 were utilized (PRé Consultants 2017; Wernet et al. 2016). The LCA method ILCD 2011 Midpoint+ V1.10/EC-JRC Global, equal weighting, a widely recognized and harmonized method at European level, was applied (European Commission 2011).

The CBA of the upgrade of an existing drainage canal to an ICW or to a CFL was performed according to the European Union guidelines for the appraisal of investment products (European Commission 2014). The starting assumption of the CBA was that a successful implementation of the proposed technologies for DCW treatment requires a positive financial perspective for the farmer. The goal of the CBA was thus to assess the financial sustainability of the DC modification by comparing the Financial Rate of Return (FRR) of the investment relative to the upgrade of an existing canal to an ICW or CFL with a reasonable value of the Weighted-Average Cost of Capital (WACC) for the Egyptian context. The WACC represents the rate that a company is expected to pay on average to all its creditors and owners, to finance its assets. On the basis of specific studies relative to the Egyptian context, the minimum WACC required to generate a positive business case for the farmers was set to 10% (Dailami and Dinh, 1991. World Bank, 1998). The Financial Net Present Value (FNPV) of both options was calculated as well. The FNPV represents the sum of all the costs and benefits for each period of an investment, actualized to the present value on the basis of the selected discount rate. A positive FNPV means that the overall benefits of a project are larger than the overall costs. The CBA was referred to a 30-year period. The CBA was based on the assumptions that (i) farmers currently irrigate a non-food crop (namely cotton) with the low quality drainage water present in the DC, and (ii) thanks to the upgrade to a ICW or CFL, farmers will use the resulting higher-quality water - after dilution 1:1 with fresh Nile water - to irrigate a higher-value food crop that can be consumed after thermal treatment (rice). More details on the CBA methodology are reported in Table S5 in the Supplemental Data.

RESULTS AND DISCUSSION

Natural attenuation in the drainage canal (DC) and legal limits for the reuse of treated water for irrigation

In order to assess the natural biological depuration occurring in the DC before its upgrade to an ICW or CFL, a water sampling campaign was carried out in 6 locations along the DC (Figure 1a). The results, summarized in the upper part of Table 1, show that natural attenuation occurred in the DC, with BOD, COD and TSS removals in the 80-90% range, and a 2.2 Log reduction of fecal coliforms. The profiles of concentrations vs residence time obtained from the data reported in Table 1 were satisfactorily interpolated with a first order model: $c_t = c_{IN} \cdot e^{-k\,t}$, where *t* indicates the retention time corresponding to each sampling point, at the average flow rate of 350 m^3/d. The resulting first-order constants are reported in the last column of Table 1. This natural depuration was not sufficient to meet the water quality standards imposed by art. 51 of the Egyptian law 92/2013 (Table 1), which applies to drainage water that can be reused to irrigate crops after 1:1 dilution with high quality Nile water. The standards defined by art. 51 represent the minimum target to be achieved in DCW treatment. The ISO 16075 limits for the agricultural reuse of treated wastewater are shown in Table 1 as well.

Design and operation of the in-stream constructed wetland (ICW)

As first step in the ICW design, a 350 m^3/d volumetric flow rate was selected, 14% higher than the actual one, to cope with expected future population growth. The potential effect of the irrigation events on the treated flow rate was neglected in the ICW and CFL design, according to the rationale illustrated in Table S6 in the Supplemental Data.

As first stage of the treatment train, a sedimentation pond was excavated at the beginning of the Edfina DC, in correspondence of the sewage discharge. This pond is 2 m wide, 1.5 m deep and 200 m long, leading to a total volume of 600 m^3 and a mean residence time of 1.7 d. The sediment is dredged once a year.

As a second stage of the treatment, after the sedimentation pond, 4 in-series free water surface constructed wetlands were designed and constructed. In the first 3 cells, reeds (*phragmites australis*) were planted at the drain bottom and sides. In the last cell floating duckweeds and water hyacinth were combined. This aquaculture composition was selected to cope with hyacinth death during cold winters, since duckweeds are cold tolerant. The CW was designed on the basis of a first order model. In particular, HRT_i - the *HRT* required for each pollutant *i* taken into consideration – was calculated as: $HRT_i = ln(c_{i,IN}/c_{i,OUT}) \cdot (1/k_i)$. The design *HRT* was calculated as the maximum of the HRT_i relative to the single pollutants. First-order constants k_i assessed from a previous wetland project relative to the treatment of drainage canal water in the Lake Manzala region, Egypt were utilized (Rashed and Abdel-Rashid, 2008). The wetland area resulted equal to 1800 m^2, with an 800 m length, a mean 0.6 m depth and a width of 2.25 m. Each cell was 200 m long, 2.25 m wide, 0.5 m deep, resulting in a mean residence time of 0.64 d. Thus, the total residence time in the ICW was 2.6 d. Submerged precast plan concrete weirs were placed along the canal between treatment cells to enhance aeration, and to uniformly redistribute the outlet water from the previous cell to the inlet of the following cell. A steel screen was placed after the hyacinth cell to avoid plants dispersion into the following open-water disinfection canal (Figure S1 in the Supplemental Data).

To complete the treatment train, the remaining 1200 m of the DC length were dedicated to a shallow, plant-free canal (2.25 m wide, 0.75 m deep, with a mean residence time of 2.6 days) in which sun radiation and air-water interaction determine pathogens disinfection and tertiary removal of TSS and BOD remaining after the previous two stages. Schemes of the whole ICW treatment train are shown in Figure 1b and in Figure S1 in the Supplemental Data.

The monitoring of the ICW performances started 6 months after the ICW start-up, when a sufficient plant growth and a stable bacterial biofilm had been achieved. The monitoring continued for 18 months. The mean results of this monitoring campaign are shown in Table 1, in section "Existing ICW". The ICW led to an increase in removal from 89 to 97% for TSS, from 81 to 91% for BOD, from 82 to 92% for COD, and from Log 2.2 to Log 3.8 for fecal coliforms. The average FC level at the ICW outlet (990 MPN/100 mL) is in line with the limit of 1000 MPN/100 mL imposed by the ISO 16075 standard for the irrigation of cereals (cat. B, Table 1). In addition, this average FC level corresponds – according to the average TC/FC ratio in Egyptian DCW resulting from over 100 analysis – to about 2600 MPN/100 mL, a value well below the 5000 MPN/100 mL limit prescribed by art. 51 of the Egyptian law 92/2013 for TC. The profiles of concentrations vs residence time obtained from the data reported in Table 1 were satisfactorily interpolated with a first order model: $c_t = c_{IN} \cdot e^{-kt}$, where t indicates the retention time corresponding to each sampling point, at the average flow rate of 350 m^3/d. The resulting first-order constants, as well as the surface loading rates and the surface removal rates are reported in Table 1. The constant for TC was assumed to be equal to that for FC. Both the TN 1st order constant (0.58 d^{-1}) and surface removal rate (1.6 g/d/m^2) are in good agreement with the corresponding ranges reported in the literature for subsurface wetlands (0.5-0.9 d^{-1} and 0.2-1.2 g/d/m^2, respectively) (Tuncsiper et al. 2006; Garfì et al. 2012; Vymazala and Kröpfelováb 2015). Conversely, the in-stream ICW technology allowed the attainment of a rather high BOD surface removal rate (47 g/d/m^2) in comparison to the typical literature values (3-10 g/d/m^2) (Garfì et al. 2012; Gorgoglione and Torretta 2018).

Despite these satisfactory performances, as shown in Table 1 the ICW was not capable to reach the limits imposed by art. 51 of Law 92/2013 for BOD and COD. This determined the need to re-design the ICW, increasing the length of the constructed wetland section and reducing the length of the disinfection canal. The actual constructed wetland residence time – and therefore length – required to attain the limits of art. 51 of Law 92/2013 for BOD (30 mg/L) and COD (50 mg/L) was assessed on the basis of the 1st order constants obtained in the experimental ICW (Table 1). The average concentrations measured after the sedimentation pond were used as inlet concentrations for the designed CW. The art. 51 limits were used as target values at the ICW outlet ($c_{i,out}$), and the required mean residence time was calculated for each parameter as follows: $HRT_i = ln\left(c_{i,IN}/c_{i,OUT}\right) \cdot (1/k_i)$. The resulting values are: BOD = 4.5 d, COD = 3.8 d, TN = 1.7 d, FC and TC = 3.4 d. The highest value (4.5 d) was taken as design value. The resulting CW length was equal to 1400 m. The additional 600 m CW with respect to the existing one were articulated into 3 additional 200-m cells. Conversely, the length of the disinfection canal was reduced from 1200 to 600 m, as the limit for TC imposed by art. 51 of Law 92/2013 is expected to be reached at the end of the CW section. The predicted concentrations of the main pollutants at the outlet of the upgraded ICW are reported in Table 1, in section "upgraded ICW design". A scheme of the upgraded ICW treatment train is shown in Figure 1c. The main dimensions of the different sections of the designed upgraded ICW (length, depth, surface) as well as the corresponding HRTs are reported in Table S7 in the Supplemental Data. The amounts of soil to be excavated and of cement, sand, metals, limestones and plants needed to upgrade an existing typical DC to an ICW are reported in Table S8 in the Supplemental Data. Table S8 includes also the evaluation of the amount of plant biomass to be cut and disposed annually, as well as the variation in the amount of sludge to be dredged and disposed annually in comparison with the DC. The data reported in Table S8 represent the inventory for the LCA and CBA relative to the upgrade of a DC to an ICW.

Laboratory tests aimed at designing the canalised facultative lagoon

To start up the aerobic and the anoxic STRs, a bacterial community was sampled from the Edfina DCW, enriched according to the procedure described in the Materials and Methods and inoculated in both bioreactors. The plant was started-up with the two bioreactors disconnected from each other. Several runs were conducted in fed-batch mode to grow the microbial community. The organic mixture reported in Table S3 in the Supplemental Data and ammonium sulphate were periodically supplied to replenish the consumed COD and NH_4-N in the aerobic STR, whereas the same organic mixture and potassium nitrate were periodically added in the anaerobic STR. The initial denitrification rate was characterized by a four-fold decrease when the COD concentration fell below a threshold value between 200 and 350 mg/L, whereas nitrification proceeded rapidly and independently of the COD level (Figure S2 in the Supplemental Data).

The two STRs were then hydraulically connected and a first set of fed-batch tests was run with a $V_{aerobic}/V_{anaerobic}$ ratio equal to 0.5 ($V_{aerobic} = 1\ L$, $V_{anaerobic} = 2\ L$). This choice was made on the basis of the observation that in the actual DC, with a total depth of 1.15 m and a $V_{aerobic}/V_{anaerobic}$ ratio in the 6-10 range (anoxic layer height of only 10-15 cm), the TN removal, equal to 50%, is not satisfactory. In addition, preliminary tests showed that denitrification represented the rate-limiting step of the overall N removal process. Therefore, the first set of tests was operated in a condition characterized by a significantly higher volume and HRT dedicated to anoxic denitrification. In the actual DC this condition can be obtained by significantly increasing the total depth up to about 3 m, so as to configure a 2 m anaerobic layer below a 1 m aerobic one, thus attaining $V_{aerobic}/V_{anaerobic} = 0.5$. This condition is therefore characterized by a significant excavation cost. In addition, in order to maintain the same wall slope of the existing DCs, this conditions requires a considerable increase in canal width, with a consequent significant additional space occupation. Several tests were conducted by varying the exchange flow rate *f* between the two STRs in the 0.13-0.5 L/h range. The flow rate exchanged between the 2 STRs corresponds, in the actual CFL, to the mass transfer occurring between the upper aerobic layer and the lower anaerobic layer as a result of turbulence. Such mass transfer is a crucial aspect of the facultative lagoon technology, as it feeds to the anaerobic layer the nitrate produced by the upper aerobic layer; on the other hand, an excessive mass transfer will increase O_2 transport towards the bottom of the canal, thus reducing the depth of the anaerobic layer. In the actual canal, the entity of such mass transfer can be dosed by adding baffles aimed at enhancing turbulence.

Each test was run in fed-batch mode with addition, only in the aerobic STR, of the organic substrates mixture (Table S3) and of ammonium sulphate. As an example, the concentration profiles and the total masses of COD, N-NH_3, N-NO_3 and N obtained in the two STRs with $V_{aerobic}/V_{anaerobic} = 0.5$ under the best performing configuration ($f = 0.17$ L/h) are shown in the Supplemental Data in Figures S3 and S4, respectively, whereas the specific depletion rates are reported in the upper part of Table S8. In agreement with the typical behavior of a municipal wastewater activated sludge process, the COD depletion rate resulted significantly higher than the total N rate, indicating that N removal represents the key process in the determination of the required retention time.

A second set of tests was conducted increasing the aerobic bioreactor volume to 2 L and decreasing the volume of the anaerobic bioreactor to 1 L, so as to increase the $V_{aerobic}/V_{anaerobic}$ ratio from 0.5 to 2. These additional tests were aimed at verifying if an acceptable N depletion rate could be attained in a more realistic situation characterized by a limited depth of the anaerobic layer and therefore a limited increase of the canal depth. Indeed, assuming that the first meter of the canal depth is aerobic (Mancini 2008), the condition $V_{aerobic}/V_{anaerobic} = 2$ can be attained with a canal depth equal to about 1.5 m, corresponding to an increase in canal depth of just 35 cm, and consequently a limited increase in canal width. The volumetric exchange flow rate *f* was varied in the range 0.13-0.50 L/h. The operating conditions and the main results of these tests are shown in the Supplemental Data in Table S9. The total COD and N specific rates were of the same order of those of the first set of experiments ($V_{aerobic}/V_{anaerobic} = 0.5$), indicating that a CFL with an anaerobic bottom layer equal to half of the upper aerobic layer is capable to lead to acceptable COD and N removal rates.

To identify an optimal configuration, the total N specific rates were tentatively correlated with the residence time in the anaerobic bioreactor, calculated as the ratio between the volume of the anaerobic bioreactor and the volumetric exchange flow rate. This key parameter combines both variables that can be changed in the two-STR test: volume ratio and exchange flow rate *f*. The plot of the specific rate of total nitrogen depletion versus this key parameter ($V_{anaerobic}/f$) is shown in Figure S5. The two sets of data were coherent, and the maximum TN rate observed for a 12 h residence time in the anaerobic STR.

These results show that the two-bioreactor plant used in this work is capable to reproduce the interaction between the upper aerobic layer and the lower anaerobic layer of an actual CFL. The experimental setup allowed to study qualitatively and quantitatively the effect of the two features that can be varied in the actual system: the intensity of turbulence in the canal and the canal depth, that in turn determines the depth of the anaerobic underlying layer. In conclusion, the depth of the actual canal can be varied over a wide range while maintaining an acceptable COD and nitrogen removal performance, provided that a well-tuned mixing between the two layers can be provided.

Design of the in-stream Canalized Facultative Lagoon

Even if an analysis of the fluid-dynamic behavior of the Edfina drainage canal would be necessary to perform a complete model-based optimization of the canalized facultative lagoon design, a preliminary design can be derived from the experimental work conducted with the 2-STR system.

For the purpose of removing suspended solids to an acceptable level, the first section of the CFL was dedicated to a sedimentation basin equal to that realized in the first portion of the ICW (length 200 m, depth 1.5 m, width 2 m).

The second section of the CFL was dedicated to the actual canalized lagoon, the heart of the CFL technology. The first step in the design of the canalized lagoon was to assess the mean residence time required for the removal of COD, N and pathogens. To this goal, a simplified first-order kinetic analysis was conducted, integrating the experimental data obtained in the 2-STR tests with those provided by the monitoring of the former DC (which can be seen as a canalized lagoon with a 1.15 m depth). The analysis led to estimate the following values of the first-order constants: $k_{BOD,CFL\ design} = 0.38\ d^{-1}$, $k_{COD,CFL\ design} = 0.41\ d^{-1}$, $k_{TN,CFL\ design} = 0.072\ d^{-1}$, $k_{TC,CFL\ design} = k_{FC,CFL\ design} = 1.38\ d^{-1}$ (Table 1). The assumptions and the procedure that led to estimate these values is described in detail in Table S10 in the Supplemental Data. The values measured after the sedimentation pond were used as inlet concentrations. The above-reported first-order constants are in good agreement with those reported in the literature for facultative lagoons and ponds, which are in the 0.04-0.30 d^{-1} range for BOD and 0.01-0.04 d^{-1} range for TN (Long et al. 2017; Saqqar and Pescod 1996). The residence time HRT_i required to attain for each pollutant i the threshold concentrations imposed by art. 51 of Law 92/2013, calculated as $HRT_i = ln(c_{i,IN}/c_{i,OUT}) \cdot (1/k_i)$, resulted equal to 6.1 d for BOD, 5.6 d for COD and 13.3 d for TN. In conclusion, a residence time of 13.3 d was assumed for the design of the canalized lagoon section. While the *HRT* recommended for BOD removal (6.1 d) is in good agreement with those typically reported in the literature (4-5 d; Long et al. 2017), the rather high *HRT* selected in this work for the CFL is due to the need to achieve a marked TN removal.

The second step in the sizing of the canalized lagoon was to design the transversal section. The design was performed on the basis of the following elements: (i) due to the presence of houses on the sides of the existing canal, the maximum acceptable canal width is equal to 3.8 m; (ii) it was decided to maintain the same side slope of the existing canal. Thus, the maximum water depth at the center of the canal resulted equal to 2.0 m. As the first meter of an open-air canal is generally aerobic (Mancini 2008), a 2.0 m water depth roughly corresponds to a $V_{aerobic}/V_{anaerobic}$ ratio equal to 1. This value falls within the range that gave satisfactory results in terms of COD and TN removal in the laboratory tests (0.5-2). On the basis of the 2-STR tests, a $V_{aerobic}/V_{anaerobic}$ ratio equal to 1 should allow the attainment of an acceptable rate of nitrogen removal by nitrification/denitrification with a relatively low level of exchange between the aerobic and anaerobic layers, that can reasonably be attained without any addition of baffles in the canalized lagoon. The canalized lagoon section was therefore designed as follows: (i) trapezoidal section with the same side slope as that of the existing canal; (ii) width at the water table 3.6 m; (iii) maximum water depth 2.0 m; (iv) no addition of baffles. The water section resulted equal to 4.5 m^2. Due the increase in canal depth up to 2 m, a re-enforcement of the side banks with limestones is necessary. With a 4.5 m^2 transversal section and a 350 m^3/d flow rate, the canal length corresponding to a 13.3-day HRT resulted equal to 1023 m.

Considering that the total canal length is fixed and equal to 2200 m, and that the initial 200-m section was dedicated to the sedimentation pond, the residual 977 m portion was dedicated to the disinfection treatment. On the basis of the disinfection performances observed in the former DC and in the existing ICW, a 977 m length of the disinfection canal after the 1023 m canalized lagoon was considered largely sufficient to guarantee the threshold concentration of total coliforms imposed by art. 51 of Law 92/2013 (5000 MPN/100mL). Further details on this evaluation are reported in Table S11 in the Supplemental Data.

In conclusion, the CFL treatment train was designed in order to meet all the legal limits imposed by art. 51 of Law 92/2013, while maintaining the same geometry of the DC, with a limited increase of the drainage canal depth to 2 m and a moderate increase in canal width. No baffles were included, as an excessive exchange between the upper aerobic and the lower anoxic layer of the CFL should be avoided. The disinfection canal was shortened and slightly enlarged in order to maintain the same HRT and water depth, and therefore the same efficiency, of the canal located downstream from the existing ICW. The predicted concentrations of the main pollutants at the outlet of the upgraded ICW are reported in Table 1, in section “CFL design”. A scheme of the designed CFL treatment train is shown in Figure 1d. The main dimensions of the different sections of the designed CFL (length, depth, surface) as well as the corresponding HRTs are reported in Table S7 in the Supplemental Data. The resulting CFL surface loading rates, reported in Table

1, are in good agreement with the values recommended in the literature relatively to facultative lagoons and ponds for both BOD (2-40 g/m^2/d, versus 27 g/m^2/d in this work) and TN (1.2-16 g/m^2/d, versus 3.3 g/m^2/d in this work) (Long et al. 2017; Karnchanawong and Sanjitt 1995).

The amounts of soil to be excavated and of cement, sand and limestones needed to upgrade an existing typical DC to a CFL are reported in Table S8 in the Supplemental Data. The data reported in Table S8 represent the inventory for the LCA and CBA relative to the upgrade of a DC to a CFL. The amount of sludge to be dredged and disposed annually in the CFL was assumed to be the same as in the DC. Given the very high scale-up factor applied from the laboratory STRs (3 L) to the designed canalized lagoon (4670 m^3), the limited number of experimental points and the fact that kinetic constants obtained in batch tests were used to design a canalized lagoon schematically represented as a plug flow reactor, the above-illustrated CFL dimensions and the estimated outlet concentrations represent preliminary values, to be used only for an approximate comparison between the CFL and the ICW in terms of LCA and CBA. Conversely, an accurate design of the CFL should be based on continuous flow tests operated in a pilot-scale canalized lagoon characterized by the same geometry of the full-scale one and by a less extreme scale-up factor.

Life cycle assessment of the upgrade of an existing drainage canal to an ICW or CFL

The LCA inventory relative to the upgrade of an existing drainage canal to a 350 m^3/d ICW or CFL is presented in Table S8 in the Supplemental Data. The results of the LCA, performed according to the ILCD 2011 Midpoint+ V1.10/ EC-JRC Global, equal weighting, are presented in Figure 2. In addition, a Monte Carlo uncertainty analysis was conducted for both upgrades for a 95% confidence interval. The upgrade of an existing canal to an ICW is characterized by a negative LCA score (-29 ± 4 μPt/m^3), indicating that the environmental impact of the construction works required to transform an existing canal into an ICW is offset by the lower environmental impact of the ICW maintenance and by the higher quality of the treated drainage canal water, leading to an overall environmental benefit in comparison with the existing drainage canal. Conversely, the upgrade to a CFL is characterized by an extremely small increase in environmental burden (8 ± 12 μPt/m^3). The minor difference in environmental burden between the two proposed technologies (37 μPt/m^3) is due to infrastructure (the CFL requires a higher amount of excavation and limestones, due to the higher water depth) and to the lower nitrogen concentrations attained by the ICW, which in turn determines a higher level of avoided eutrophication. However, it should be noticed that the 37 μPt/m^3 difference between the two LCA scores is equal to 1.5% of the typical environmental burden associated to an average wastewater treatment, equal to 2400 μPt/m^3 (PRé Consultants 2017; Wernet et al. 2016). On the basis of this observation and of the above-reported confidence intervals, the difference between the LCA score of the 2 proposed upgrades was considered as negligible. For both technologies, the environmental impact due to operation is almost negligible, as neither process requires electricity or chemicals. Two aspects that were not considered in this assessment are emissions to air and photosynthesis in the CW plants. The direct emissions to the air (CO_2, CH_4, N_2O) were not included as they were supposed to be the same as those of the original drainage canal. In the case of the ICW, plant photosynthesis actually determines a reduction of the CO_2 emissions, therefore the LCA of the upgrade of a DC to an ICW would result even better than the one presented in Figure S5 if photosynthesis was included. The LCA methodology applied in this work is comparable to that of similar papers that analyze different types of CWs (Pan et al. 2011; Fuchs et al. 2011; Corbella et al. 2017; Garfí et al. 2017; Mander et al. 2008). Nevertheless, this LCA refers to the upgrade from DC to CFL or ICW, and not the construction of a CFL or ICW from scratch, making direct results comparisons with literature not feasible.

In conclusion, this analysis indicates that the upgrade of an existing tertiary drainage canal to either of the two proposed technologies is an environmentally sound solution, characterized on the one hand by a negligible environmental impact in comparison to that of a standard wastewater treatment, and on the other hand by a significant improvement in terms of drainage canal water quality (90-99% decrease in BOD, 71-94% decrease in total N, 2.6-4.3 Log reduction in fecal coliforms).

Cost-Benefit Analysis of the upgrade of an existing drainage canal to an ICW or CFL

The benchmark condition selected for the CBA was the use of the low-quality water available at the exit of a typical drainage canal to irrigate cotton, a widespread non-food crop in the Nile delta region. In addition it was assumed that, thanks to the upgrade of the DC to an ICW or CFL, farmers will use the resulting higher-quality water - after dilution 1:1 with fresh Nile water - to irrigate a higher-value food crop that can be consumed after thermal treatment, namely rice. A difficulty encountered in the CBA of ICW and CFL scenarios was the assumption of the cotton market price, as the cotton price in Egypt proved to be quite unstable in the recent years. To circumvent this issue, a parametric analysis was made in order to assess how the cotton price affects the FRR of the two proposed technologies and for which price the FRR equals the assumed WACC, equal to 10%. For rice, an average price of 0.28 $/kg was assumed corresponding to the mean market price in Egypt. In addition, in order to assess the effect of possible variations of the rice market price on the financial rate of return of the investment, the analysis was repeated with a 25% increase and a 25% decrease of the rice price. The CBA was repeated for both the ICW and CFL scenarios assuming varying cotton market prices starting from a minimum value corresponding to the current production cost (no net revenue). As shown in Figure 3, the ICW FRR is significantly higher than that of CFL for any cotton price. At the average rice price of 0.28 $/kg, the ICW results to be an attractive investment up to a cotton price of 0.619 $/kg, whereas the CFL FRR is always lower than the WACC, even at a low cotton market price corresponding to the production cost. The sensitivity analysis conducted with a ± 25% variation of the rice price indicated in the first place that, even if the rice price drops by 25%, the ICW still represents an attractive investment (FRR > 10%) up to a cotton market price equal to about twice the current cotton production cost. This analysis also indicated that, in case of a 25% increase of the rice price, the CFL becomes an attractive investment (FRR > 10%) over a wide range of cotton prices (0.1-0.35 $/kg). In conclusion, the ICW scenario proved to be an attractive solution over a wide range of cotton and rice market prices, whereas the CFL seems to be a financially sustainable in the Delta Nile context only if a moderate increase of the rice price occurs.

In order to gain more insight on the impact of the specific cost items on the total cost, a more detailed analysis was performed assuming the current rice price (0.28 $/kg) and a cotton market price equal to 0.358 $/kg, the mean value between the current production cost (0.097 $/kg) and 0.619 $/kg, i.e. the price that generates the last positive business case for the ICW (FRR = WACC = 10%, FNPV = 0). Under this assumption, as shown in Table S12 in the Supplemental Data, the total cost of DC upgrade to an ICW over a 30-year period resulted equal to 242 k$, of which 12% was given by the CAPEX and 88% by the OPEX. In the case of a CFL, the total cost equals 346 k$, of which 46% was represented by the CAPEX and 54% by the OPEX. Table S10 shows that the main difference in the economical performances of the ICW and CFL lies in the total cost, as the revenues are almost equal. Indeed, the CFL scenario presents an approximately 4 times higher CAPEX, due to the substantially higher amount of excavation and limestones required. The final result is that the ICW scenario has an FRR equal to 27%, largely higher than the assumed WACC, and a positive FNPV equal to 45 k$. Conversely the CFL scenario resulted in an FRR (4.7%) equal to about half of the assumed WACC, and a negative FNPV (-64 k$).

CONCLUSIONS

- Both the ICW and the CFL, if integrated by a sedimentation pond and a disinfection canal, result in satisfactory water treatment performances and allow the attainment of the water quality standards imposed by art. 51 of Egyptian Law 92/2013 for the reuse of drainage water, within the length of the typical existing tertiary DCs.
- The upgrade of an existing DC to an ICW resulted in an overall decrease of environmental burden, whereas the upgrade to a CFL resulted in an extremely low environmental impact, equal to 0.3% of that of a traditional activated sludge process.
- The CBA indicated that the DC upgrade to an ICW is expected to be an attractive investment in Egypt, as it leads to an FRR > 10% over a wide range of cotton and rice market prices. Conversely, the upgrade to a CFL presents a lower attractiveness due to the high investment cost, which in turn is to be ascribed to the higher canal depth required. Nevertheless, at the current market price, the upgrade to a CFL is characterized by an FRR in the 5%-9% range over a wide range of cotton market prices, which indicates that this technology could represent an attractive investment in other financial contexts.
- The ICW appears to be a very promising option for the treatment of DCW in the Nile Delta, thanks to its capacity to combine high pollutant removal performances with particularly low costs and environmental burdens.

SUPPLEMENTAL DATA

Table S1. Details relative to the Edfina drainage canal. **Table S2.** Experimental procedure applied for the growth of the aerobic and facultative fractions of the bacterial community sampled from the Edfina drainage canal. **Table S3.** Composition of COD source periodically supplied in the laboratory-scale tests conducted in the 2-STR plant simulating a canalized facultative lagoon. **Table S4.** Layout and operational conditions of the laboratory-scale pilot plant aimed at simulating the aerobic and anoxic layers of a canalized facultative lagoon. **Table S5.** Procedure and assumptions applied in the cost benefit analysis of the upgrade of an existing canal to an ICW or CFL. **Table S6.** Rationale for the selection of the input flow rate in the ICW and CFL design. **Table S7**. Main dimensions and retention times of the drainage canal (DC) and of the designed ICW and CFL. **Table S8**. Inventory relative to the upgrade of a 350 m^3/d drainage canal to an in-stream constructed wetland or to a canalized facultative lagoon. **Table S9**. Main results and performance obtained in the two-STR pilot tests simulating a canalized facultative lagoon. **Table S10.** Assumptions and procedure relative to the kinetic analysis aimed at designing the canalized facultative lagoon. **Table S11**. Elements for the assessment of the coliform removal performances of the disinfection canal placed after the canalized lagoon. **Table S12.** Relative contribution of the single CAPEX and OPEX elements to the total cost of upgrade of the DC to either an ICW or CFL. **Figure S1.** Schematic representation of the ICW treatment train implemented in the Edfina drainage canal. **Figure S2.** Laboratory-scale tests conducted in the 2-STR plant simulating a canalized facultative lagoon: denitrification rates obtained at different initial COD concentrations. **Figure S3**. Laboratory-scale tests conducted in the 2-STR plant simulating a canalized facultative lagoon: concentrations of NH_4-N, NO_3-N, total N and COD. **Figure S4.** Laboratory-scale tests conducted in the 2-STR plant simulating a canalized facultative lagoon: total masses of NH_4-N, NO_3-N, total N and COD in the entire 2-STR system. **Figure S5.** Laboratory-scale tests conducted in the 2-STR plant simulating a canalized facultative lagoon. Effect of hydraulic residence time in the anaerobic bioreactor on the specific rate of total nitrogen removal in the system.

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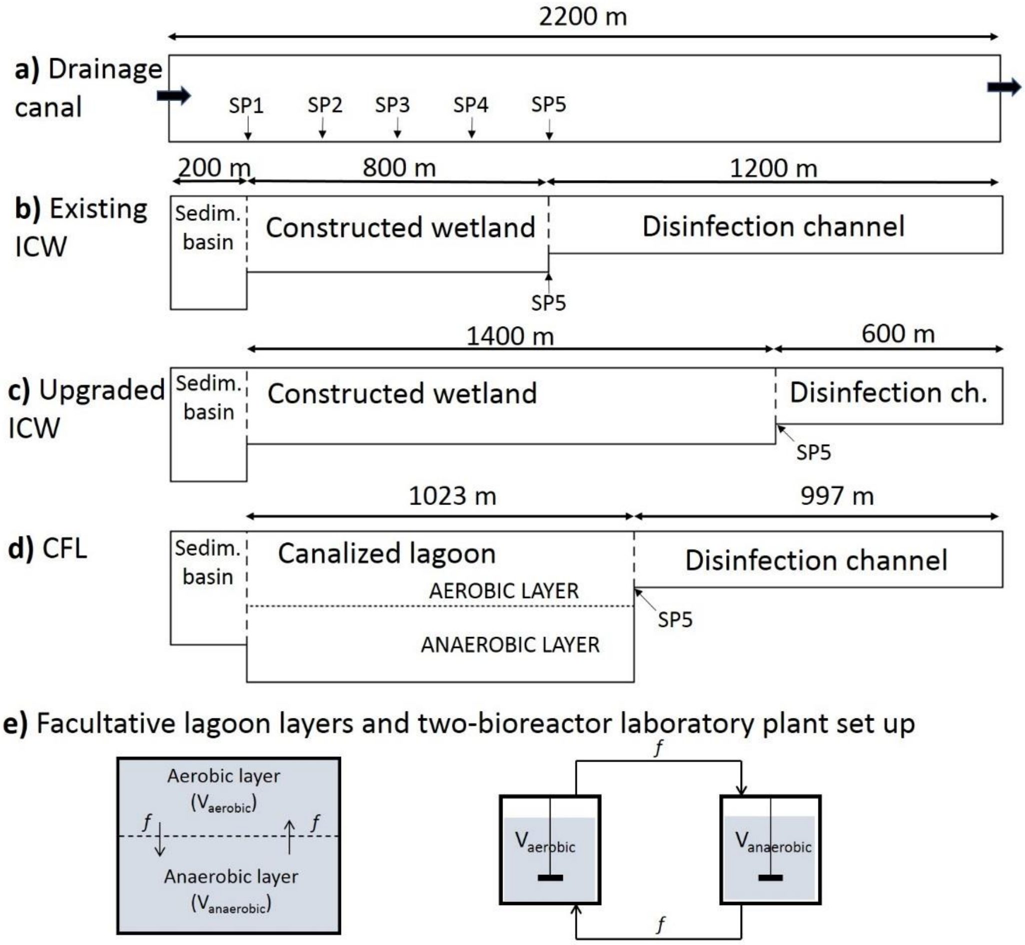

Figure 1. Schematic representation of the existing drainage canal (a), of the existing ICW (b), of the upgraded designed ICW (c) and of the designed CFL (d), with indication of the sampling points. The heights of the different sections of each treatment technology are reported in Table S6 in the Supplemental Data. Schematic representation of the facultative canalized lagoon layers and of the two-bioreactor laboratory plant set up for the simulation of a facultative canalized lagoon (e).

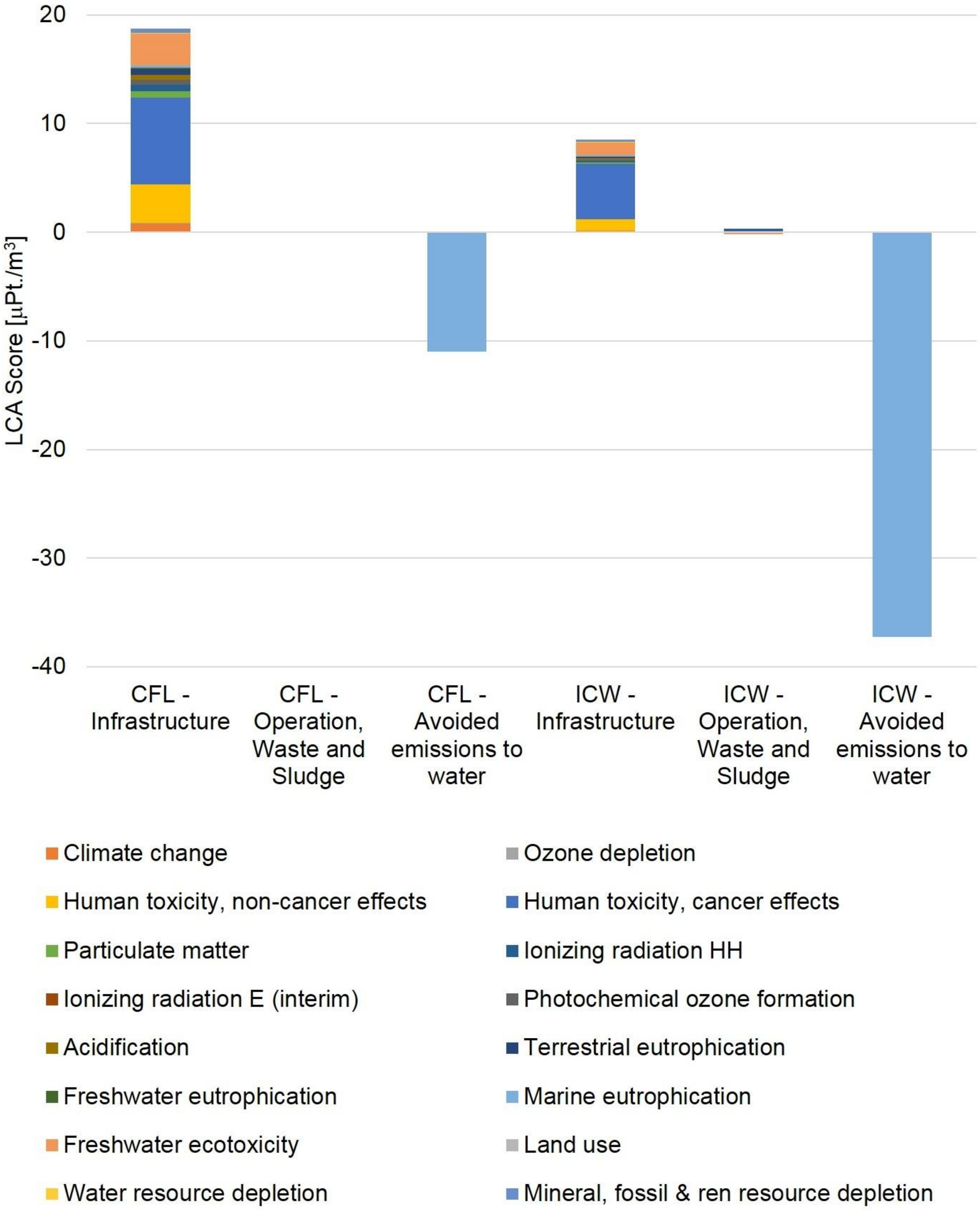

Figure 2. Environmental burden (+) and benefits (-) of the different life cycle stages of the upgrade of an existing tertiary drainage canal to an CFL or an ICW, according to the ILCD 2011 Midpoint+ method v1.10.

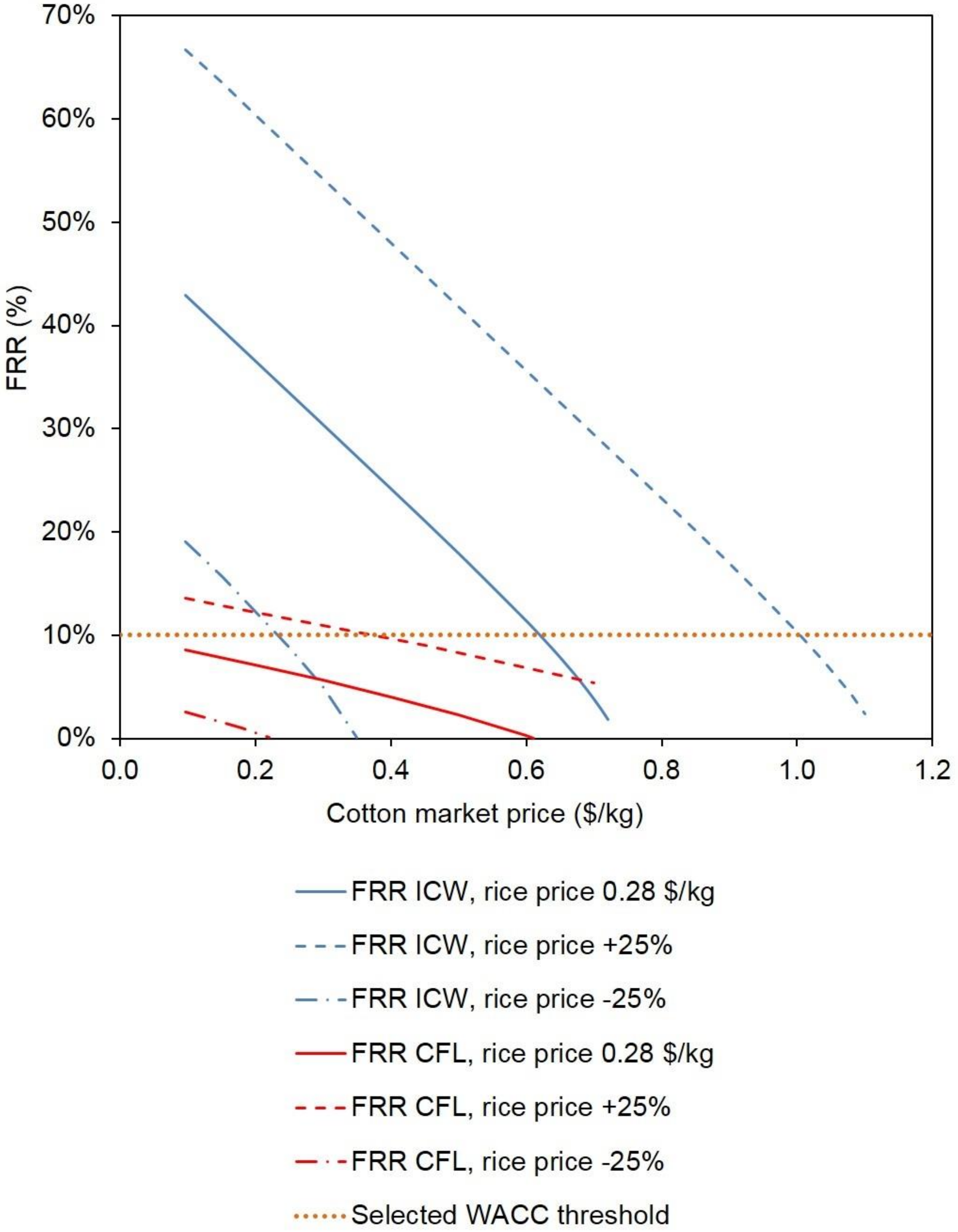

Figure 3. Cost Benefit Analysis of the upgrade of an existing DC to an ICW or CFL: financial rate of return (FRR) of the investment against cotton market price. Continuous lines refer to the current rice price in Egypt (0.28 $/kg), dashed lines refer to a 25% increase of the rice price whereas dot-dashed lines refer to a 25% decrease of the rice price. The CBA was performed under the assumption that the upgrade allows the farmer to replace the cultivation of cotton with that of rice, and that therefore the lack of revenues from cotton sale represents a cost for the farmer.

Table 1. Experimental performances of the DC and existing ICW, expected performances of the designed ICW and CFL, limits for the re-use of treated wastewater according to Egyptian Law 92/2013 and the ISO 16075 standard, surface loading rates and removal rates and first-order constants obtained by regression of the experimental data

		Inlet	SP1[a]	SP2[a]	SP3[a]	SP4[a]	SP5[a]	Outlet	Egyptian Law 92/2013 art. 51[b]	ISO 16075 Cat. A[c]	ISO 16075 Cat. B[c]	Surface loading rate (g/d/m²)[d]	Surface removal rate (g/d/m²)[d]	k_i[e] (1/d)
Distance from inlet (m)		0	200	400	600	800	1000-1600[f]	2200						
DC	TSS (mg/L)	1450	615	233	205	186	177	156	--	10	25			0.32
	BOD (mg/L)	475	365	195	152	127	100	92	30	10	20	20	14	0.38
	COD (mg/L)	838	563	263	205	182	157	152	50	--	--	31	21	0.41
	Total N (mg/L)	51						25	15	--	--	2.4	0.9	--
	FC (MPN/100mL)	$5.3\cdot10^{6}$	$4.2\cdot10^{6}$	$1.4\cdot10^{6}$	$1.9\cdot10^{5}$	$1.4\cdot10^{5}$	$4.0\cdot10^{4}$	$3.4\cdot10^{4}$	--	100	1000			1.38
	TC (MPN/100mL)								5000	--	--			1.38
Existing ICW	TSS (mg/L)	1279	480	120	93	61	44	32	--	10	25			0.80
	BOD (mg/L)	529	310	146	107	94	66	47	30	10	20	60	47	0.52
	COD (mg/L)	827	492	217	141	113	89	67	50	--	--	96	78	0.60
	Total N (mg/L)	51		39			31	6.5	15	--	--	7.6	1.6	0.58
	FC (MPN/100mL)	$5.7\cdot10^{6}$	$8.3\cdot10^{5}$	$3.8\cdot10^{5}$	$9.5\cdot10^{4}$	$2.8\cdot10^{4}$	7100	990	--	100	1000			1.78
	TC (MPN/100mL)							2600	5000	--	--			1.78
Upgraded ICW design	TSS (mg/L)	1279	480				13	10	--	10	25			0.80
	BOD (mg/L)	529	310				30	30	30	10	20	34	31	0.52
	COD (mg/L)	827	492				33	33	50	--	--	55	51	0.60
	Total N (mg/L)	51	51				2.9	2.9	15	--	--	4.3	4.0	0.58
	FC (MPN/100mL)	$5.7\cdot10^{6}$	$8.3\cdot10^{5}$				280	38	--	100	1000			1.78
	TC (MPN/100mL)	$2.2\cdot10^{6}$	$2.2\cdot10^{6}$				710	100	5000	--	--			1.78
CFL design	TSS (mg/L)	1279	480				> 25[g]	> 25[g]	--	10	25			[g]
	BOD (mg/L)	529	310				2	2	30	10	20	27	26	0.38
	COD (mg/L)	827	492				2	2	50	--	--	42	42	0.41
	Total N (mg/L)	51	51				15	15	15	--	--	3.3	2.1	0.072
	FC (MPN/100mL)	$5.7\cdot10^{6}$	$8.3\cdot10^{5}$				$1.4\cdot10^{4}$	1900	--	100	1000			1.38
	TC (MPN/100mL)	$2.2\cdot10^{6}$	$2.2\cdot10^{6}$				$3.6\cdot10^{4}$	5000	5000	--	--			1.38

[a] SP, sampling point along the canal or ICW. [b] Art. 51 of Law 92/2013: water suitable to irrigate food-crops to be consumed after cooking, after 1:1 dilution with fresh high quality water. [c] ISO 16075, Cat. A: water suitable to irrigate food-crops that are consumed raw. Cat. B: water suitable to irrigate food-crops that are consumed after cooking. [d] The surface load and removal rates refer to the surface of actual CW or facultative lagoon, excluding the surface of the sedimentation pond and disinfection canal, in order to allow a consistent comparison with the corresponding literature values. [e] First-order kinetic constants. [f] In the ICW and CFL, point 5 refers to the outlet of the constructed wetland section or canalized lagoon section. The distance of this point from the inlet is equal to 1000 m in the DC and in the existing ICW, 1600 m in the upgraded ICW, 1223 m in the CFL. [g] It was not possible to make a reliable assessment of the TSS outlet concentration in the CFL. On the basis of the TSS removal performances of the DC, it is reasonable to assume that the TSS outlet concentration will be > 25 mg/L.