

Life-Cycle Cost and Life-Cycle Assessment of a Monumental Fiber-Reinforced Polymer Reinforced Concrete Structure

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Abstract: The objective of this study was to investigate the economic and environmental appeal of the world's largest glass fiber-reinforced polymer (GFRP) RC flood mitigation channel, which was built in Jazan (Saudi Arabia). The Jazan flood mitigation channel (JFMC) is a 21.3-km-long channel completed recently in the southwest area of Saudi Arabia on the outskirts of the new Jazan Economic City (JEC), which is an advanced industrial zone and encompasses an important network of high-end facilities. A deterministic approach is applied to a comparative life-cycle cost (LCC) analysis, and sensitivity analyses are used to predict the impact of uncertain factors, such as discount rate and maintenance periods, on the LCC analysis of JFMC. Additionally, the environmental credentials of the GFRP-RC channel are investigated through a life-cycle assessment (LCA) analysis. The LCA analysis is performed from cradle to gate and from cradle to grave, specifically from product stage (or resource extraction) to end of life (EoL). The JFMC is designed for a 100-year service life, and the LCC and LCA analysis performed are in compliance with the international standards ISO 15686-5, ISO 14040:2006, and ISO 14044:2006. The obtained economic and environmental results are compared to the results obtained from an epoxy-coated steel (ECS)-RC channel alternative that was originally designed. The results show the significant life-cycle benefits of the preferred GFRP-RC alternative from both an economic and environmental perspective, advancing the body of knowledge available for LCC and LCA of flood control and mitigation concrete channels reinforced with FRP materials. DOI: [10.1061/\(ASCE\)CO.1943-7862.0002339](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002339). © 2022 American Society of Civil Engineers.

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Introduction

There exist two types of design approach that can be used to prevent or mitigate reinforcement corrosion in RC structures: proactive or reactive approaches (Al-Mahaidi and Kalfat 2018). The latter approaches include generally costly repair activities, such as patch repairs or crack injections (De Belie and De Muynck 2008; Raupach 2006), whereas proactive approaches are preventive measures that are effective at avoiding pricey unplanned downtime from unexpected failures (Bertolini et al. 2013). Examples of effective preventive corrosion measures include the implementation of improved corrosion resistance reinforcement, such as epoxy-coated steel (ECS), stainless steel, or fiber-reinforced polymer (FRP)

rebars. With regard to FRP rebars, there are several types of FRP structural materials that depend on the types of fibers and resins they utilize. The two most common types of fiber systems currently used in concrete construction are glass-FRP (GFRP) and carbon-FRP (CFRP), known for their elastic, high-strength, reduced-weight, and durability features (Bakis et al. 2002). FRP reinforcement (prestressed and not) has positive economic and environmental implications (Cadenazzi et al. 2019, 2021).

Salan et al. (2021) describe the design characteristics and importance of the recently constructed 21.3-km-long Jazan flood mitigation channel (JFMC), located on the outskirts of Jazan Economic City (Saudi Arabia). This mitigation channel is of particular importance because of the implementation of about ten million linear meters of GFRP rebars, making it the world's largest GFRP structure ever built to date.

The purpose of this paper is to present life-cycle cost (LCC) and life-cycle assessment (LCA) analyses to show the long-term economic and environmental features of this monumental flood mitigation channel. In doing so, the paper aims to advance the limited body of knowledge currently available on LCC and LCA of control and flood mitigation channels. For example, Ali et al. (2004) carried out a LCC analysis of a natural channel compared to a concrete channel, showing that the favorability of the concrete channel was weakened by higher maintenance costs. In this regard, the GFRP-RC channel under investigation in this paper not only represents a more durable and resilient option, but also requires significantly reduced maintenance over time, addressing the main long-term costing concerns raised by Ali et al. (2004) with respect to concrete channel designs. As for LCA analysis, very few studies

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are currently available. Perhaps the most significant research on this matter was carried out by Brudler et al. (2016), who linked the current climate change scenarios to increased pluvial flooding events, which would require large construction operations for retrofitting of cities and, therefore, more environmental pollution. Brudler et al. (2016) remarked on the increased need for environmental assessment analyses of stormwater management systems. In this connection, Brudler et al. (2016) carried out a comparative LCA analysis of a stormwater management system case study in Copenhagen, Denmark, by comparing the results of a preferred green aboveground stormwater management system with those of a subsurface traditional alternative. To this end, the GFRP-RC channel under investigation in this paper also lowers environmental impacts due to climate change scenarios discussed by Brudler et al. (2016), making it a viable and environmentally appealing option.

Channel Design

The JFMC is designed to prevent flooding events in the living and working areas of the new Jazan Economic City (JEC). The purpose of the JFMC is to intercept the floodwaters originated from the eastern boundary of the JEC and divert them to the Red Sea, located on the western shore of the JEC (Fig. 1). The JFMC is designed as a RC-lined trapezoidal channel (for hydraulic performance and real estate reasons) with a side slope of 1:2, for a 1-in-100-years return period flood event (Salan et al. 2021). The JFMC's cross-sectional area increases incrementally from the upstream end to the outfall, as per Table 1 and Fig. 1, whereas its 2-m depth is constant over the entire length of the channel. Fig. 2 shows a typical cross section of the JFMC. The channel was designed using Euro codes and pre-EN revisions of the British Standards [BS 8002 (BSI 1994); BS 8110 (BSI 1997); BS 8007 (BSI 1987)] as well as other design standards

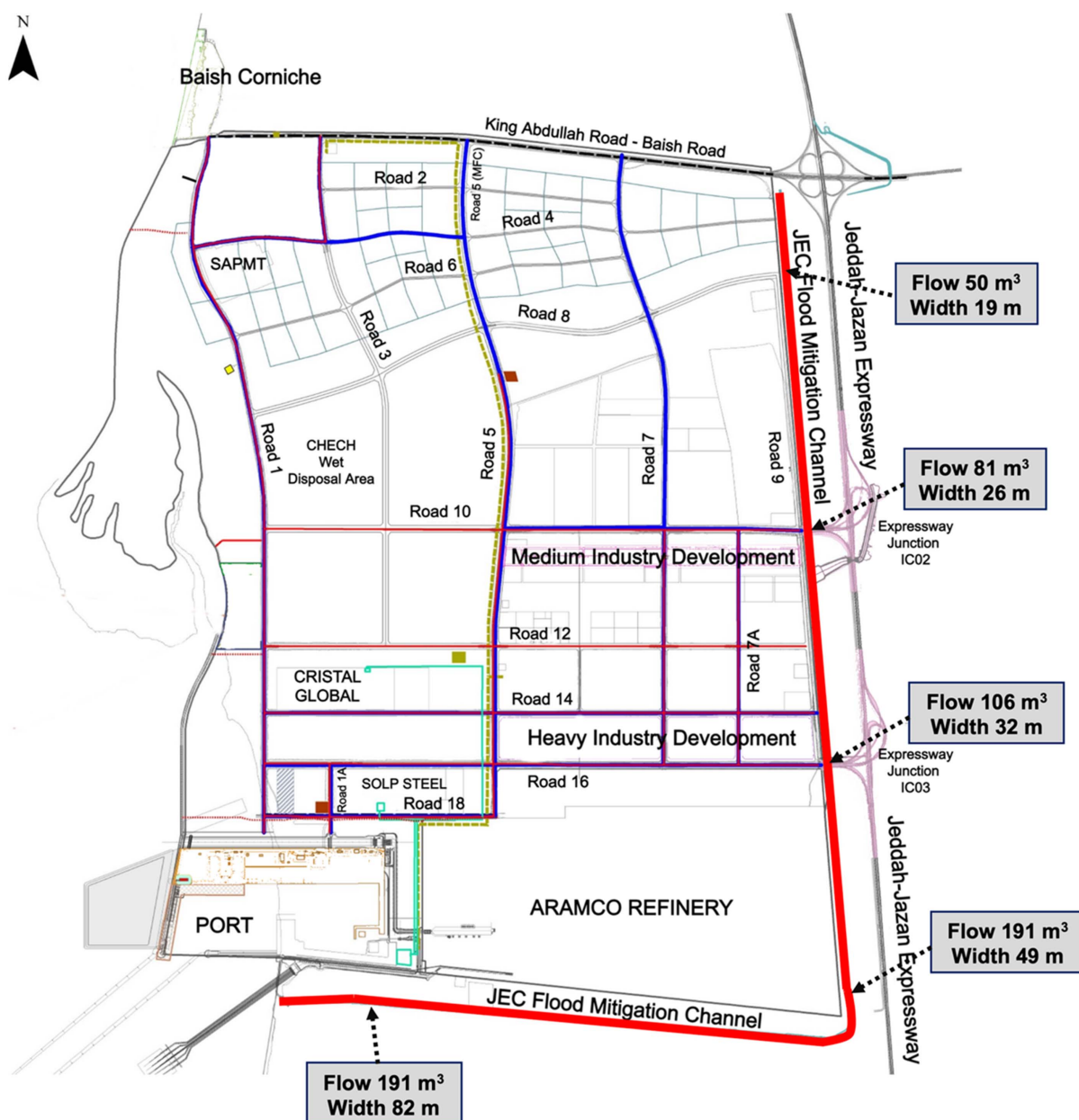


Fig. 1. Alignment, accumulating design flows, and required width for JFMC.

Table 1. Geometry of channel

Channel segment	Design flow (m ³ /s)	Length (m)	Channel geometry/side slope	Bed width (m)	Top width (m)	Design depth (m)	Design freeboard (m)	Minimum depth (m)	Design velocity (m/s)
JEC_FLD0	16	1,200	Trapezoidal/1:2	4	12	1.55	0.45	2	1.49
JEC_FLD1	50	2,200	Trapezoidal/1:2	11	19	1.55	0.45	2	2.37
JEC_FLD2	81	2,960	Trapezoidal/1:2	18	26	1.55	0.45	2	2.52
JEC_FLD3	106	4,850	Trapezoidal/1:2	24	32	1.55	0.45	2	2.66
JEC_FLD4	191	9,960	Trapezoidal/1:2	41	49	1.55	0.45	2	2.82
JEC_FLD5	191	300	Trapezoidal/1:2	74	82	1.10	0.90	2	2.31

Source: Data from Salan et al. (2021).

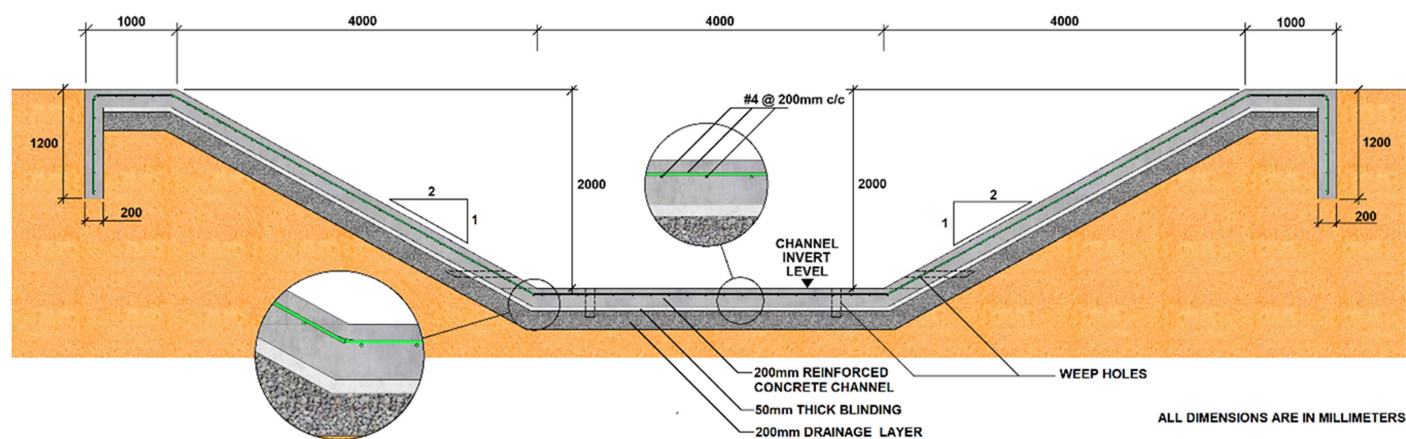


Fig. 2. GFRP bar RC channel. (Data from [Salan et al. 2021](#).)

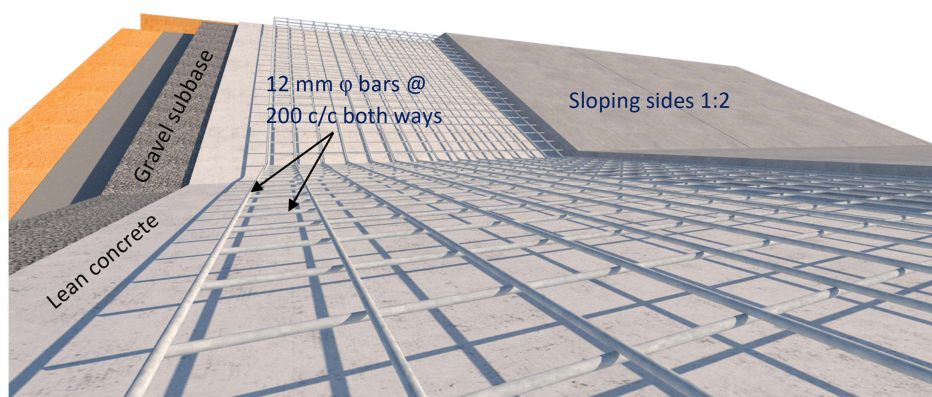


Fig. 3. Schematic view of the reinforcing details and layers of the channel.

and guides (CIRIA C683 2007; Balkham et al. 2010). More specific details on the JFMC design parameters are provided by Salan et al. (2021). The originally designed JFMC was an epoxy-coated steel (ECS)-RC structure, using 370 kg/m³ sulfate resisting Type V portland cement with 7% silica fume. However, in January 2018, Saudi Aramco, which is entrusted with designing and building the strategic infrastructure in JEC, made a strategic decision to use only nonmetallic GFRP rebars as reinforcement to increase the service life and reduce its maintenance. In doing so, the crack width was limited to 0.7 mm as per ACI 440 (ACI 2015), instead of limiting the crack width to 0.3 mm, imposed by the original steel design alternative (Salan et al. 2021). This positively affected not only the construction costs but also the maintenance and future repair costs

because the GFRP-RC design required less reinforcement for a typical $30 \times 30 \times 0.2$ -m slab panel. Fig. 3 shows schematically the channel slab reinforced with one layer of 12-mm-diameter GFRP bars at 200 mm center-to-center (c/c) in both longitudinal and transverse directions. For ECS bars the stricter limit on crack width decreased the spacing to 150 mm c/c.

The construction of JFMC was carried out by a single contractor, Al-Yamama Company for Trading and Contracting (AYC) (Dammam, Saudi Arabia). Fig. 4(a) shows concrete placing activities for a typical 30×30 -m panel of the base slab, where an 8-person crew worked to tie the GFRP bars into a grid and construct the formwork for the base slab and side slab, and consequently, a 10-person crew worked on placing concrete. Fig. 4(b) shows the

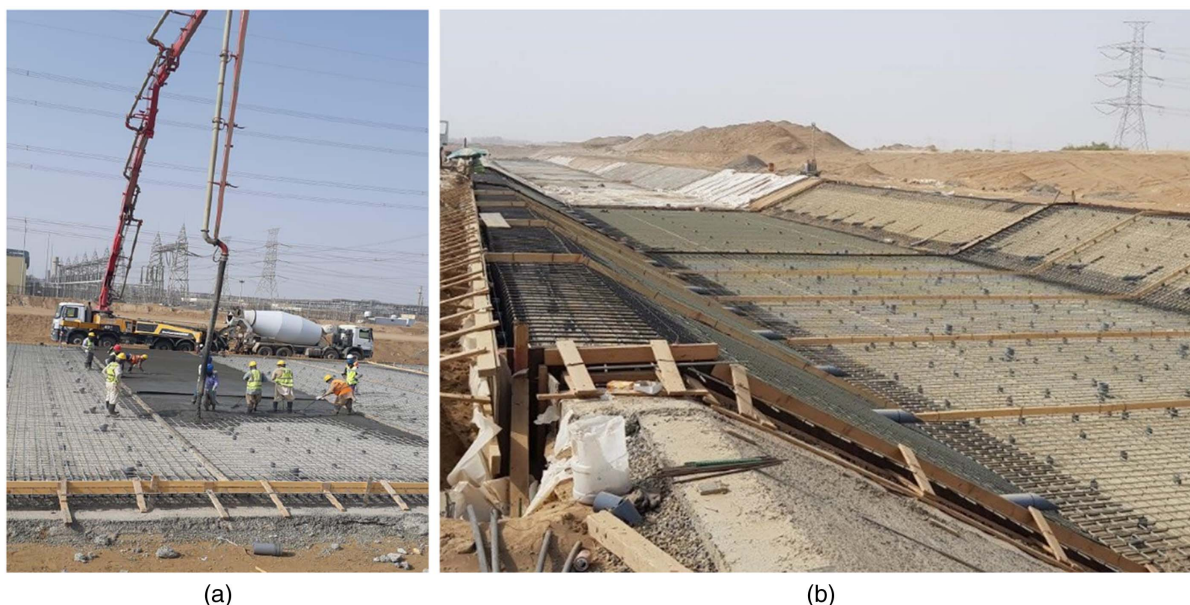


Fig. 4. (a) Placement of a typical $30 \times 30 \times 0.2$ -m concrete slab panel; and (b) concreting progress of work over 21.3-km-long JFMC.

progress of work for a sequence of typical panels, where on the front the GFRP bar mesh is clearly ready for the application of concrete.

Life-Cycle Model

Design Alternatives and Service Life Selection

The first segment of the JFMC, 11.2 km in length, runs from the upstream northern end southward parallel to the coastline of the Red Sea, cutting off the flood water from the east. The channel then takes a right angle turn toward the west and traverses for a length of 10.3 km to dump the flood water into the Red Sea. The route of the channel is characterized by uneven ground, which is composed of sand dunes and flats as well as salty marshes at the channel outfall in the Red Sea. Flood water traversing across the plains and sabkha soil regions from the east transports chlorides and sulfates into the RC channel, together with the salt-laden dune sand from frequent sandstorms in the area. In addition, the maximum chloride ion concentration contained in the soil at some locations along the channel was 1.6%, whereas the sulfate ion concentration contained in the soil in the area surrounding the alignment of the channel at the downstream end was 0.5%.

These durability aspects were critical during the design of the RC channel, and therefore the design team initially decided to reinforce the concrete channel lining with ECS rebars in lieu of the traditional carbon steel rebars. In this way, the originally designed channel was planned for an extended service life of 50 years (BSI 2005), as opposed to the 35 years' service life of a traditional carbon steel RC solution (as per Saudi Aramco specifications).

To combat the harsh and highly corrosion-prone environment at the site, a concrete mix incorporating silica fume and sulfate-resisting cement was proposed. A concrete mix design with 370 kg/m^3 sulfate-resisting Type V portland cement with 7% silica fume replacing the cement was proposed. According to Bamforth (2007), the crack width in the channel lining was limited to 0.3 mm. This was based on placing temperature values of 32°C and 60°C for peak hydration, without any allowance for solar gain in temperature during the hydration. The values of seasonal temperature changes

(maximum and minimum average temperature in Jazan city) were determined. For a specified compressive strength of 28 MPa, the concrete required a 75-mm clear cover. As Saudi Aramco envisioned the utilization of nonmetallic reinforcement for this specific application, the world's largest GFRP-RC structure is now expected to provide a low-maintenance service life of 100 years.

In this paper the two design alternatives are compared: the original ECS-RC solution with a service life of 50 years and the as-built GFRP-RC solution with an intended service life of 100 years. However, for an effective comparison, the functional unit of both LCC and LCA analysis is the 50-year service life of the ECS-RC alternative. Hence, this comparative analysis does not account for the remaining depreciated value and associated cash flow after 50 years for the GFRP-RC alternative, making the analysis more conservative for the noncorrosive solution.

Maintenance Schedule

The maintenance and repair schedule of both designs was developed using the software Life-365 (Silica Fume Association 2017). A maximum chloride ion concentration value of 1.6% was used for the analysis, and the predicted repair actions of the ECS-RC alternative were given by the sum of the corrosion initiation and corrosion propagation periods (Ehlen et al. 2009). With regard to the ECS-RC alternative, the model considers the maintenance activities shown in Table 2. The repair amount, as estimated via Life-365, was supposed to be on 10% of the total surface area of the project. However, both patching and replacement activities were assumed to be limited to the bottom slab of the trapezoidal flood mitigation channel only, and not the sloping sides. Therefore, authors calculated the bottom slab surface area to be 83% of the total channel

Table 2. Planned maintenance activities for ECS-RC flood canal design

Activity	Repair amount	Year
Patch	8.3% of total area	12, 22
Replace corroded steel	8.3% of total area	32, 42

area, which included the two side slopes, as shown Fig. 2 and detailed in Table 1.

With regard to FRP-RC designs, the scheduled maintenance operations consist of minor repairs to concrete that take place every 10 years. Similar to previous assumptions (Cadenazzi et al. 2019, 2020a, b), the patching activities for the FRP-RC design are estimated at 33% of the ECS-RC solution.

End of Life

The end of life (EoL) represents the end of the useful service life of the channel. At this phase, demolition activities, disposal, and recycling activities are considered in the analysis. Given the 50-year selection of the functional unit for both the LCC and LCA analyses, both the ECS-RC and GFRP-RC flood canal alternatives undergo demolition, material disposal, and recycling activities. For both alternatives, demolition and disposal activities were assumed to be equal, even though this was a conservative choice given the fact that GFRP-RC structures are easier to cut through and may lead to reduced costs and time. The recycling activities were assumed in the analysis for concrete and ECS rebars only. For these two materials, this paper considers a 10% wasting rate, given by material constraints, facilities, and transportation limitations or unexpected events and contingencies.

Life-Cycle Cost and Life-Cycle Assessment Methods

The LCC and LCA analyses were conducted in compliance with the international standards ISO [ISO 14040 (ISO 2006a); ISO 14044 (ISO 2006b); ISO 15686-5 (ISO 2017a); ISO 21930 (ISO 2017b)]. For LCC, the software used to assess maintenance and repair schedules of both alternatives was Life-365 version 2.1 (Silica Fume Association 2017). Additionally, MS Excel and MATLAB software programs were used to assess the long-term costs, including calculations of discount rate values, and sensitivity analyses. The software adopted for the LCA analysis was OpenLCA, GreenDelta GmbH 2021 (openLCA 1.10). The LCA analysis was performed from cradle to gate and from cradle to grave.

Functional Unit and Data Source

In compliance with ISO standards, the 50-year service life of the ECS-RC flood canal was taken as functional unit. The 50-year period of analysis was selected to be impartial over differences in alternatives' service lives.

The main data source for both LCC and LCA analyses were construction design plans and field data collected on site by the contractor during construction. The data source specifically referred only to the activities and corresponding cost elements that differed between alternatives. The analysis excluded cost elements that are the same between alternatives. Therefore, secondary data sources that have a minor impact on the results of the analyses were not included. Secondary data included excavation activities and utilities.

Discount Rate

The discount rate selected by the authors for the LCC analysis was 1%. The discount rate is a financial tool that reflects the value of money over time (Haghani and Yang 2016). For long-term investments, the discount rate is typically lower than that of short-term investments (Cadenazzi et al. 2019). Given the functional unit of 50 years, the authors assumed the value of the discount rate to be that of a long-term investment. Until 2018, Saudi Arabia had a

constant long-term discount rate value of 2%. In 2019 it increased to 3%. However, during the past 2 years, the long-term discount rate slipped to 1%. Saudi Arabia currently (as of 2021) has a long-term discount rate equal to 1% (<https://perma.cc/98Q2-RASX>), which agrees with the financial situation of the country post the COVID-19 pandemic.

Impact Assessment

The software Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI, version 2.1) was chosen, in compliance with ISO 21930 (ISO 2017b) standards, as the impact assessment method for the LCA analysis. TRACI is a midpoint-oriented life-cycle impact methodology that considers cause-effect chains of each impact category, prior to the endpoint (Bare et al. 2000). The TRACI methodology reflects recent developments and advancements consistent with EPA regulations in the United States. The impact categories used by the authors are the mandated ones: global warming potential, ozone depletion potential, eutrophication potential, acidification potential, and smog potential.

Life-Cycle Cost and Life-Cycle Assessment Analyses

Production Costs

For the GFRP reinforcement supply of the 10 million linear meters, three international vendors were approved based on their quality, technical capabilities, and localization plan. The localization of GFRP pultruders would be advantageous as it would result in reducing delivery time, reducing the material cost, and enhancing local industrial fabric in the Kingdom. The approved vendors were the following:

- Pultron, based in Dubai, which supplied 50% of the total GFRP bars required;
- Galen, based in Russia with a 25% quota; and
- Dextra, based in China with the remaining 25% quota.

At the time of writing (December 2021), Pultron Dubai shifted its entire production lines to Dammam (Saudi Arabia), and it is known as IKK Mateenbar. Dextra also has a factory in Dammam (Saudi Arabia), and its current production is in trial phase. The source of cement was Southern Cement Company in Jazan and Tahama near Makkah, as the plant in Jazan eventually closed due to the COVID-19 outbreak. Both coarse and fine aggregates were obtained locally from Jazan.

Transportation Costs

For Pultron, bars were provided by about 24 trips of a convoy of trailers. The convoy had three trailers, each 12 m long. This means that about 72 trucks brought 5 million meters of bars. Each truck brought GFRP bars roughly enough for four channel panels.

For Dextra, bars were provided in about 25 shipments. The bars were brought in 12-m bulk containers. Each shipment consisted of 2 containers and approximately 50 to 60 containers were used to ship the 2.5 million meters of GFRP bars. The containers were brought to the site in flat-bed trailers. The route was China-Jeddah by ship and from Jeddah port to Jazan by trailers.

For Galen, bars were provided in about 26 shipments by trailers. Each time, shipment involved a convoy of 2 trailers, so that approximately 50 to 60 trailers were used to ship the 2.5 million meters of GFRP bars. The route was Russia to Dammam by ship and in some cases by air from Dammam port to Jazan by trailer.

Table 3. Construction cost dependent on reinforcement selection

Basic resource	Quantity	Unit	Unit cost (\$)	Cost	ECS Total cost (\$)	FRP Total cost (\$)
GFRP M13	10,000,000	m	0.87	8,700,000	—	—
ECS 12 mm	13,205,260	m	0.74	9,771,892	—	—
Spacers for ECS	952,323	unit	0.54	514,254	—	—
Spacers for GFRP	1,190,404	unit	0.54	642,818	—	—
Concrete C25 for GFRP	188,000	m ³	88.00	16,544,000	—	—
Concrete for ECS	188,000	m ³	97.00	18,236,000	—	—
Manpower for GFRP	109,503	man-hour	10.70	1,171,908	—	—
Manpower for ECS	328,510	man-hour	10.70	3,515,197	—	—
Tie wire for GFRP	10,810,000	joint	0.07	797,057	—	—
Tie wire for ECS	18,620,000	joint	0.07	1,372,915	—	—
Crane for ECS	1,044	unit-hour	534.23	557,733	—	—
					33,967,992	27,855,784

For the alternative ECS-RC design, because ECS manufacturers are not available in Jazan or a nearby area, the ECS bars would have been shipped to Jazan from Dammam. However, given the large amount of reinforcement required, for production and to meet the appropriate design requirements, the ECS bars were assumed to be shipped also from Jeddah. For this reason, 50% of the required ECS rebars were assumed to be shipped from Dammam and the remaining 50% from Jeddah using flat-bed trailers of 30-t capacity. Based on this, the total tonnage of steel required for the 188,000 m³ of concrete was approximately 11,500 t, resulting in around 400 trailer trips.

Construction Cost

Concreting operations started in March 2019 and were completed in November 2020. The excavation activities started prior to March 2019. Closures due to the COVID-19 pandemic affected the initial construction plan and the initial setting of workers' camps. The transformation from ECS to GFRP bars also delayed the construction schedule earlier.

Two concrete batch plants were used, each having a capacity of 120 m³/h. The batch plants worked on one or two shifts during the concreting operations. There were 16 concrete mixer trucks, each with a capacity of 8 to 10 m³, and 5 pumps for placing concrete (with 4 pumps that were working simultaneously). Each pump had 20 operators directing the booms to control concrete output, safely maintaining the machinery, and carefully pouring concrete.

A total of 800 laborers were employed at the project site. These included mason laborers, bar fixers, laborers, carpenters, surveyors, and supervisors. Additionally, there were 120 laborers at the batch plant and 400 employees working in the office for logistic support, quality control, office staff, purchase, and delivery activities.

As for equipment, there were two cranes for distributing the GFRP rebars at various locations, two boom trucks, and a number of excavators, bobcats, and other machinery.

The central site office was located at Stn 6 km (0 km being at the outfall point in the sea, as shown in Fig. 1), and the maximum lead distance was 14–16 km from the site office.

Table 3 shows the cost of construction activities that are dependent on the reinforcement selection and represent the construction cost baseline of the LCC and LCA analyses. Thus, activities that were required to complete the project but had the same cost for both alternatives (such as excavation activities) are not included in the analysis.

Maintenance Cost

Table 4 shows the costs associated with the maintenance operations of each alternative design. Cost estimations of maintenance as well as demolition and recycling (profits) are based on existing Florida Department of Transportation (FDOT) inventories and a historical repair cost database available to authors. It is important to note that this choice may have affected the results of the LCC analysis because there may be dissimilarities between Saudi Arabia and the United States. The local Saudi Arabia contractor kindly provided production and construction costs but could not provide specific future maintenance and EoL cost items.

End-of-Life Cost

Both ECS-RC and GFRP-RC alternatives were assumed to be demolished at the end of their service lives. Although noncorrosive, GFRP may experience some strength degradation under alkali exposure (Won et al. 2008; Rajput and Sharma 2017; Lu et al. 2020), resulting in an estimated 100-year service life. However, for an

Table 4. Maintenance costs (breakdown by year with discount rate assumed 1%)

Activity	Year	GFRP-RC flood channel (\$)	ECS-RC flood channel (\$)
Concrete patching	—	2,237,879	6,713,644
Reinforcement replacement	—	—	13,216,442
Demolition	—	33,838,358	33,838,358
Recycling	—	8,143,698	10,047,632
—	12	1,986,004	5,958,018
—	22	1,797,904	5,393,716
—	32	1,627,619	9,612,372
—	42	1,473,462	8,701,955
—	50	20,575,036	41,382,790
—	51	−4,902,658 (profit)	−6,048,862 (profit)

impartial comparison, the GFRP-RC construction was assumed to be demolished at 50 years, similar to the ECS-RC counterpart. The recycling at EoL was considered in the analysis for the ECS rebars and concrete only. ECS rebars and concrete recycling activities were priced by weight and at an efficiency rate of 90%. Pricing of recycling activities was based on US available data and were \$0.18/kg for steel and \$0.02/kg for concrete. On the other end, GFRP rebars were not assumed to be recycled given the lack of cost data and experience with recycling GFRP bars. This provided a conservative estimation of the savings resulting at EoL for the GFRP-RC solution (Correia et al. 2011).

Results and Discussion

The cost of the GFRP-RC Jazan flood canal was \$28,297,149. This cost comprises production, transportation, and construction costs and is only specific to costs dependent on the selection of reinforcement. On the other hand, the cost of the ECS-RC Jazan flood canal was \$34,221,096. Therefore, the initial ECS-RC design cost was about 21% more expensive than the GFRP-RC counterpart. This major difference arises from the fact that for grade supported slabs with steel bars, the crack width must be limited to 0.3 mm, whereas for GFRP bars the crack width can be 0.7 mm, as per ACI 440. Therefore, the JFMC needed #4 steel bars at 150 mm c/c and #4 GFRP bars at 200 mm c/c. For a typical slab panel, the overall cost of the designed ECS-RC canal is higher, even though the raw material cost of GFRP bars is higher (\$0.87/m for GFRP bars versus \$0.74/m for ECS bars in Saudi Arabia). These unit costs include production, transportation, and additional customs and value-added taxes for the GFRP bars (which caused an increment in unit cost of about 17% over the original GFRP unit price of \$0.74/m).

To estimate the net present value (NPV) of all future costs, discount rate values are used to represent the effects of interest and inflation rates. As previously discussed, this paper considers a discount rate of 1% over the reference period of 50 years.

Life-Cycle Cost Analysis Results

Fig. 5 shows the progressive NPVs over the reference period for both flood canal design alternatives. The GFRP-RC design solution was revealed to be the most cost-effective solution, with a NPV over the 50-year period approximately 35% lower than that of the ECS-RC counterpart. Based on all life-cycle stage data and assumptions discussed in previous sections, the LCC of the GFRP-RC design was calculated as \$50,854,515, whereas the ECS-RC counterpart was estimated to be \$78,413,331. Despite the lower initial costs associated with the GFRP-RC design (due to its advantageous

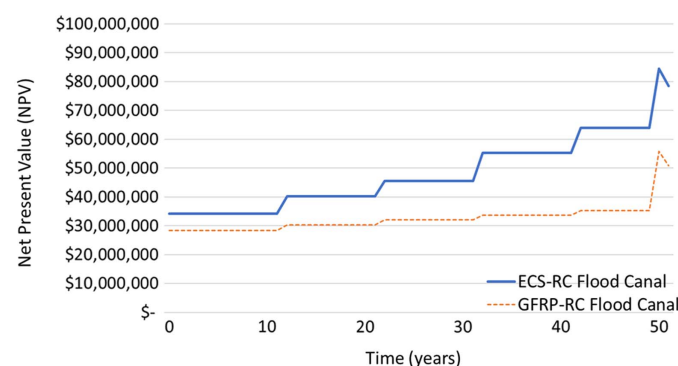


Fig. 5. LCC analysis results of design alternatives.

crack-width requirements), this latter revealed in particular significant long-term cost savings since GFRP resulted in longer service life and lower maintenance costs throughout the 50-year analysis period. Therefore, the GFRP-RC design turned out to be the optimal solution, with not only a lower initial investment (compared to the ECS-RC solution) but mostly a lower NPV in the long term.

Life-Cycle Cost Sensitivity Analysis

In this section, we provide illustrative examples to discuss the behavior of the NPV and the maintenance policy. Numerical examples are provided to conduct a sensitivity analysis and to present the practical utility of our results.

The NPV results are highly sensible to changes of discount rate values. The lower the discount rate, the greater the cost impacts of future repairs. For this reason, a sensitivity analysis was carried out on changes in discount rate values. Fig. 6 shows the variations in NPV values given changes of discount rate values on the order of 1% to 10%.

Additionally, a second sensitivity analysis is presented in Fig. 7, which includes four plots, where each plot is a three-way illustration of the NPV of the two design alternatives (ECS-RC and GFRP-RC design), and periodic maintenance duration (in years). Plots differ from each other due to varying discount rate values. This analysis takes into consideration four possible discount rates: 1%, 4%, 7%, and 10%. Further, the NPV under different maintenance policies where the timing of the periodic maintenance varies was computed, particularly by translating the first maintenance action between years 9 and 15. Subsequent maintenance actions took place consecutively every 10 years.

The first observation was the dominating NPV values of the ECS-RC alternative (colored dark gray bars) over the GFRP-RC design. This means that the GFRP-RC design always has economic advantages over the ECS-RC counterpart, as previously discussed. The second observation concerns the impacts of maintenance events on the NPV. It is likely that early maintenance events increase costs and, hence, the NPV. However, the cost savings (between the GFRP-RC design and the ECS-RC alternative, represented graphically by the difference of each pair of bars) resulting from delaying each maintenance action are similar at varying discount rates.

Plots in Fig. 7 also show the rather monotonic behavior of the NPV when the discount rate values are high, e.g., 7% and 10%. Roughly speaking, the NPV was a decreasing function of the discount rates, as expected. The NPV became more rewarding at higher values of discount rate. However, the changes in the values due to delaying the maintenance became less and less significant as

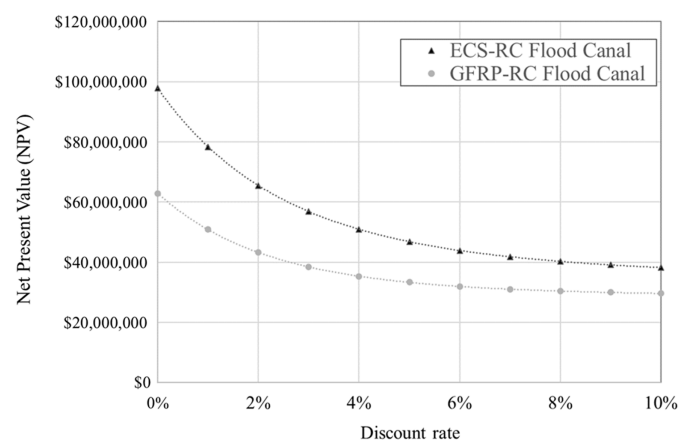


Fig. 6. Sensitivity analysis for discount rate values.

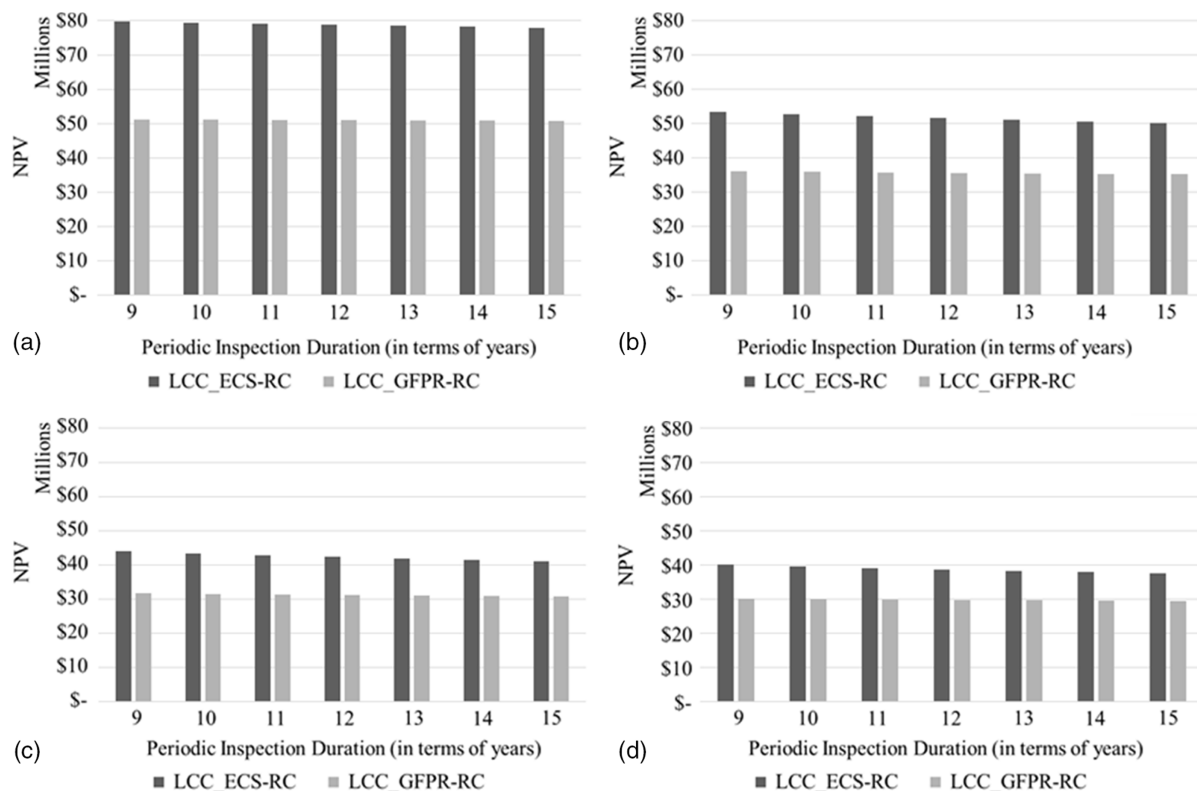


Fig. 7. NPV versus variations over periodic maintenance occurrences and variations of discount rate values. Discount rate values are set at (a) 1%; (b) 4%; (c) 7%; and (d) 10%.

the discount rate increased. This is visually represented in Figs. 7(a and b), where discount rate values change from 1% to 4%. There was a significant drop in the NPV. However, the drop was no longer noteworthy if discount rate values changed from 7% to 10%, as shown in Figs. 7(c and d). Although the difference in discount rates remained the same at 3% for both alternatives, there might be a threshold discount rate that can be identified at 5%. After this threshold was exceeded, the NPV became less sensitive to changes in the discount rate.

To understand the behavior of the threshold in detail, a further analysis was carried out. Eleven possible values of discount rate

(starting from 0% to 10%) were considered, with increments of 1%. This was done to further compute the percentage change in the NPV when the maintenance was delayed for a year. As a result, we generated percentage changes in the NPV of the ECS-RC design when maintenance duration was changed from (i) to ($i + 1$) years, $i = 9, 10, \dots, 14$. Similar logic is also applied to the GFPR-RC design.

Accordingly, Fig. 8 was generated, where Fig. 8(a) relates to ECS-RC design and Fig. 8(b) to the GFPR-RC design. There are six curves per design, and each curve, representing the percentage change in NPV, is a function of the discount rate. Evidently, in

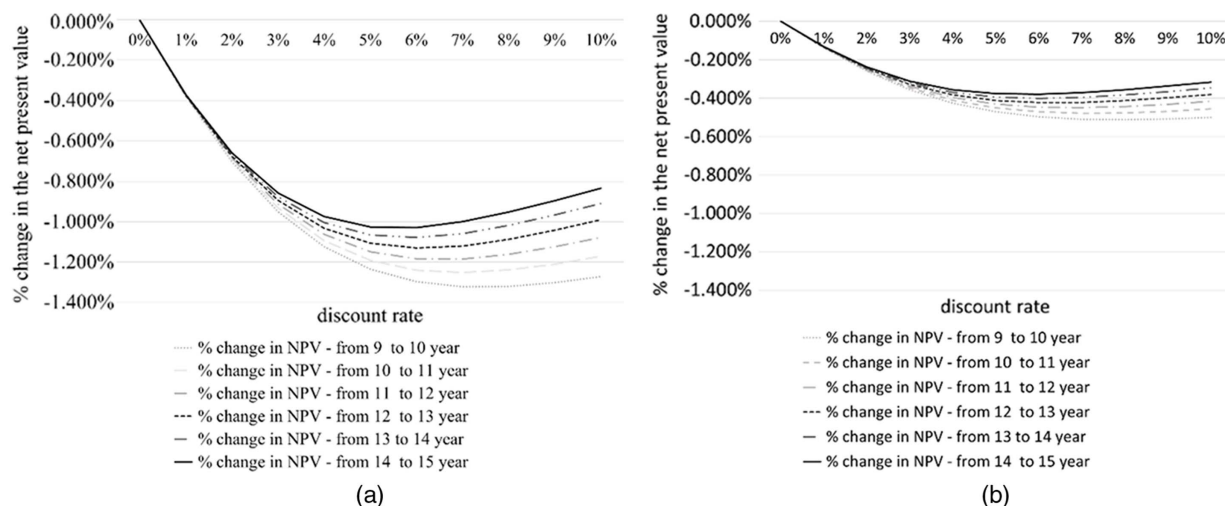


Fig. 8. Changes in NPV on y-axis across different discount rate values on x-axis: (a) ECS-RC alternative; and (b) GFPR-RC design.

Table 5. Environmental impacts of design alternatives (cradle-to-gate scenario)

Impact category	Unit of measure	GFRP-RC flood canal	ECS-RC flood canal
Acidification	kg SO ₂ eq	124,652	190,888
Eutrophication	kg N eq	70,598	176,164
Global warming	kg CO ₂ eq	36,873,346	54,986,557
Ozone depletion	kg CFC-11 eq	2.76	3.51
Smog	kg O ₃ eq	2,083,227	3,030,383

Note: Eq. = equivalent.

the ECS-RC design, the values are widely scattered compared to the GFRP-RC design. On the other hand, the GFRP-RC data are tightly clustered. This means that the ECS-RC design was more responsive to changes in the discount rate, and therefore the GFRP-RC design yielded to fewer risks associated with LCC implications.

The second remark has to do with the convexness of percentage change in the NPV under both design scenarios. This behavior again proves the existence of a threshold in the discount rate, around 6% for steel design, 4% for the GFRP design. After the threshold was exceeded under both design scenarios, the cost savings decreased and became less significant. For example, one can immediately recognize the major drop in the percentage change in the NPV when discount rate values were between 0% and 6% [Fig. 8(a)]. Once the discount rate assumed higher values, there were still cost savings because of the negativity of percentage change; however, the savings were less significant. Similar behavior was observed also for the GFRP-RC design [Fig. 8(b)]. However, the discount rate threshold for the GFRP-RC alternative was less than that of the ECS-RC design.

A final note must be made regarding the benefits of delaying the maintenance for 1 year. As shown in Fig. 8, each plot comprises six curves, where each curve displays a different scenario for

maintenance policy. For example, the first curve at the top of Fig. 8(a) reveals that a percentage change in NPV is shown when the maintenance initiation period is changed from 9 to 10 years. A similar statement can be made based on the bottom curve, where the maintenance duration is changed from 14 to 15 years. This means that cost savings are higher when maintenance actions are delayed, as seen in the previous sensitivity analysis (Fig. 7).

Life-Cycle Assessment Analysis

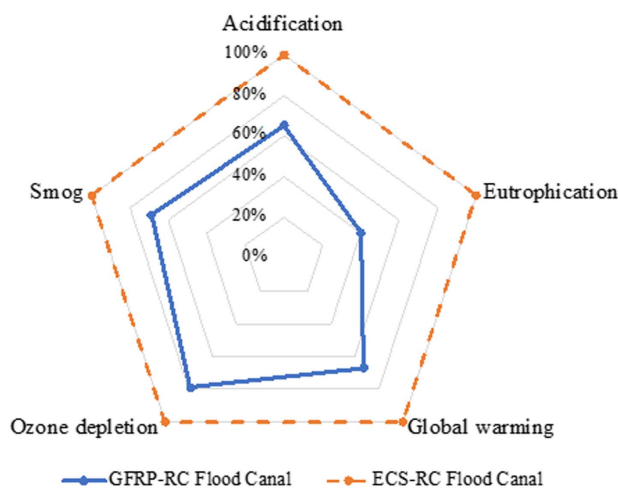
Table 5 lists the environmental impacts for the two flood canal design alternatives from cradle to gate. Though both alternatives showed similar results in terms of ozone depletion, the GFRP-RC design had much fewer impacts in terms of smog, acidification, eutrophication, and global warming. Fig. 9 shows a radar chart of the relative contribution of each category impact in percentage terms for both design alternatives. Percentages were estimated by referencing each category to the most impactful alternative, which is for each case the ECS-RC design.

Additionally, the LCA analysis further investigated the environmental benefits of the GFRP-RC design from a cradle-to-grave scenario. Table 6 lists the environmental impacts for the two design alternatives from cradle to grave. In this scenario, the environmental advantages of the GFRP-RC design are further accentuated. This is due mostly to the significant impacts made by the maintenance actions of the ECS-RC design alternative. Similar to the cradle-to-gate analysis, Fig. 10 shows the relative contribution of each category impact in percentage terms for both design alternatives in a cradle-to-grave scenario.

Conclusions

This paper analyzed the financial and environmental aspects of two design alternatives for the JFMC, located in Saudi Arabia. Upon conducting LCC and LCA analyses for both design alternatives, the authors drew the following conclusions:

- The GFRP-RC design showed significant economic benefits, especially over the 50-year reference period, when the cumulative NPV of the ECS-RC alternative was 54% higher than the selected GFRP-RC design. In particular, the net savings over the long-term analysis were equal to \$27,558,817, corresponding to an annual savings of \$551,176. The LCC analysis did not take into consideration the depreciated value of the GFRP-RC structure after 50 years. Therefore, the authors acknowledge that the

**Fig. 9.** Relative magnitude of environmental impacts of design alternatives (cradle-to-gate scenario).**Table 6.** Environmental impacts of design alternatives (cradle-to-grave scenario)

Impact category	Unit of measure	GFRP-RC flood canal	ECS-RC flood canal
Acidification	kg SO ₂ eq	201,909	400,755
Eutrophication	kg N eq	98,942	315,179
Global warming	kg CO ₂ eq	48,997,474	94,926,887
Ozone depletion	kg CFC-11 eq	6.67	12.99
Smog	kg O ₃ eq	3,669,780	6,370,155

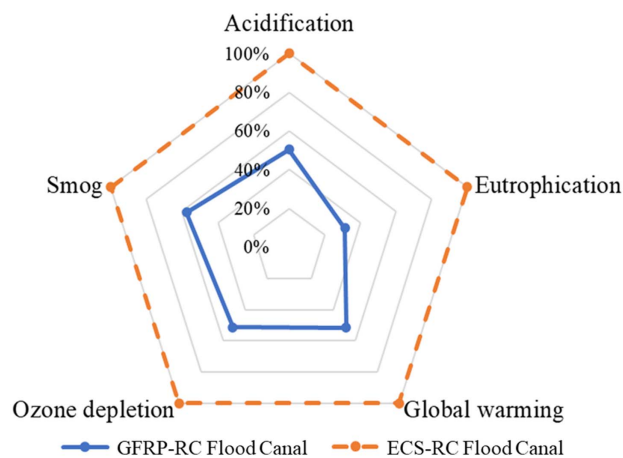


Fig. 10. Relative magnitude of environmental impacts of design alternatives (cradle-to-grave scenario).

LCC analysis might be conservative for the GFRP-RC solution, which was designed for a longer service life (of 100 years). Future research may be needed to address the LCC analysis results for an analysis period greater than 50 years.

- The environmental impacts of the GFRP-RC design were lower with respect to the ECS-RC alternative for both the cradle-to-gate and cradle-to-grave scenarios, in five out of five impact categories, namely global warming, ozone depletion, acidification, eutrophication, and smog. The higher number of reinforcing bars required and the higher environmental impacts at the production and construction phases of the ECS-RC alternative were both significant factors in determining its lower performance from an environmental standpoint.
- A sensitivity analysis was carried out on the values of discount rate. This paper considered a baseline value of the discount rate of 1.0%, to provide a current realistic estimation of the cost savings resulting from the use of GFRP reinforcement.
- Two further three-way sensitivity analyses were carried out with respect to maintenance events and discount rate values, both stressing the high dependence of NPV values (and respective cost savings) over delayed maintenance actions and lower values of the discount rate.

The preceding quantitative findings represent a profound advancement on the current body of knowledge for LCC and LCA studies of GFRP-RC flood mitigation channel structures. The LCC and LCA results of this study were based on the JFMC case study (in Saudi Arabia) but can be used as key tools to inform and support the decision-making process for similar projects.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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