Assessment of Adaptation Solutions to Floods with PCSWMM and a Multicriteria Analysis for a Very Small Watershed

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1 Introduction

In southern Quebec, the spring freshet generates flooding water levels in a large number of rivers [1, 2], affecting around 80% of riparian municipalities [3]. In summer and fall, heavy rainfall caused by convective or tropical storms can also cause their share of inconvenience [4], in particular over small rural watersheds. These pluvial flooding are also expected to be impacted by climate change through an intensification of extreme rainfall events [5]. Small cities located in very small ungauged watersheds are particularly ill-equipped to handle this situation.

Therefore, the main objective of this study is to develop and test a methodology to be used by municipalities located in very small ungauged watersheds in order to assess flood adaptation scenarios while considering climate change. A case study was conducted in the Municipality of Saint-Isidore (hereafter Saint-Isidore) located in Quebec, Canada (Fig. 1) at the head of the Saint-Régis River watershed. The aim is to apply the developed methodology to classify various potential adaptation

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S. Walbridge et al. (eds.), *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*, Lecture Notes in Civil Engineering 250,
https://doi.org/10.1007/978-981-19-1065-4_26

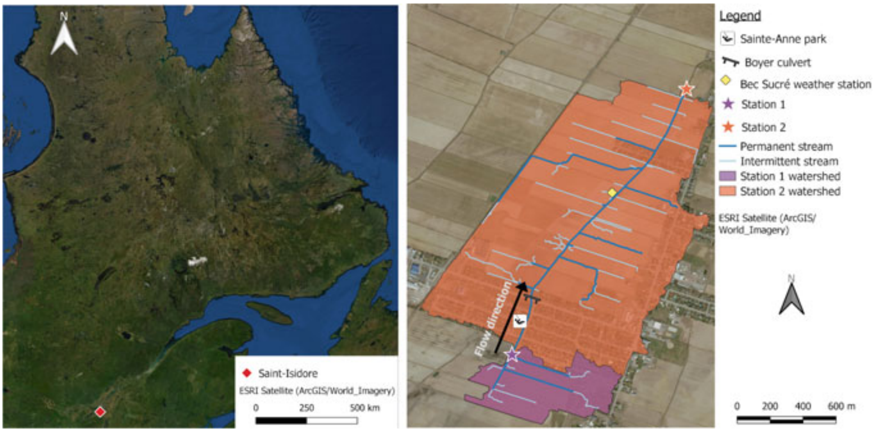


Fig. 1 Localization of the study site

solutions against flooding of fluvial origin caused mainly by the high water level of the river following summer intense rainfall. This initiative has been spearheaded by the watershed organization of the OBV SCABRIC (Châteauguay River conservation and development society), aiming to better understand flooding and the solutions that can be put forward while integrating the aspect of climate change as well as decision support for analysis.

2 Study Site

The majority of the municipality's watershed is made up of agricultural lands (75%), with the remaining being occupied by residential areas (25%) [6]. Several agricultural plots oriented perpendicular to the stream are drained using tile drainage directly into the Saint-Régis River to evacuate water from fields more efficiently to improve crop productivity. A large portion of the Saint-Isidore sewer network is pseudo-separative, meaning that foundation drains and roof gutters are connected directly to the sanitary sewer rather than the storm sewer. The storm sewer network collects runoff water through sumps and channels it directly into the Saint-Régis River.

The Boyer culvert serves as the outlet of the Saint-Régis River in the municipality's residential area (see Fig. 1). During intense summer convective storms, the network upstream of the culvert can become completely overloaded, causing local flooding in the city's area near the stream. These flood events are amplified with the water level remaining high near Sainte-Anne Park due to the culvert's raised elevation preventing proper drainage following rainfall events, also creating a safety issue for children.

3 Methodology

This section covers the three main steps to the proposed methodology to evaluate and compare various potential adaptation solutions against flooding: (1) the data collection, (2) the modelling component (hydrological, hydraulic and climate change) and (3) the decision support component (multi-criteria analysis).

3.1 Data Collection

To build a hydrological and hydraulic model over an ungauged watershed, data collection is the first step that must be accomplished. With respect to this case study, two water-level stations (Stations 1 and 2; Fig. 1) composed of a pressure sensor were installed early September 2019 allowing the water level to be deduced by using an additional barometric pressure sensor. Unfortunately, following the flood preventive de-icing of the Saint-Régis River, Station 2 sensor was torn apart on March 13, 2020.

A land survey activity made it possible to generate cross sections and the longitudinal profile of the Saint-Régis River and to obtain the position and rim elevations of the storm manholes and culverts. In order to properly represent the storm sewer system, the invert elevation of the majority of the accessible storm manholes was measured and completed using as-built plans or by interpolation if needed.

The delimitation of the watershed is required to determine the surface area which is drained towards the water-level stations. To this end, a digital terrain model (DTM) produced using a LiDAR survey in 2017 with an altimetric and planimetric precision of ± 15 cm was used. The ArcGIS software was used to process the DTM and to make it hydrologically logical. During these manipulations, the culverts (invisible to the DTM) are artificially burned in the DTM allowing a complete and realistic layout of the hydrographic network. Stations 1 and 2 drainage areas were found to be 0.26 km^2 and 2.08 km^2, respectively. The delineation of the watershed then makes it possible to define the search for additional information to supply data to the hydrological and hydraulic model, such as the site pedology and detailed land use.

3.2 Hydrological and Hydraulic Modelling

The purpose of this study's hydrological and hydraulic modelling is to better understand all the processes generating runoff and its path over the territory leading to flooding problems for which a solution is to be identified. Considering the rural and urban component of the territory under study, the hydraulic model must be able to simulate both the flow processes for the rural drainage network (tile drainage, ditches and the Saint-Régis river channel) as well as the storm sewer network. In addition, since the land use of the study site is diversified and the flooding issues are located in different places in the watershed, semi-distributed modelling (whose parameters vary depending on the territory) is necessary. Finally, the watershed being of a very small area (~2 km^2), the hydrological and hydraulic processes must be resolved at a sub-daily time step to avoid missing peak flows.

The hydrological and hydraulic modelling tool used to take these different characteristics into account is the PCSWMM software developed by Computational Hydraulic Int. (CHI) incorporating directly into its calculation engine the latest version of the Storm Water Management Model (SWMM) developed by the United States Environmental Protection Agency (EPA). The following subsections present the steps to be taken in order to build and calibrate the model.

3.2.1 Building of the Model and Calibration

The PCSWMM model was built using the data collected at Sect. 3.1. The storm sewer network and the Saint-Régis River channel and banks were modelled using the surveyed data and the as-built plans. The rural drainage ditches were also modelled and extracted from the DTM in ArcGIS. The Green-Ampt infiltration scheme was selected and its parameters were adjusted according to the study site known pedology. Groundwater flow was added to the model and also parametrized according to the site's pedology. All rugosity values (Manning coefficient), impervious percentages, depths of depression storage, infiltration scheme parameters were initially adjusted based on typical values [7, 8].

The calibration of the PCSWMM model is conducted by further adjusting parameters such as the rugosity from the sub-watersheds impervious and pervious areas and the Saint-Régis River channel and banks. The sub-watersheds' conceptual lengths and widths and impervious percentages were also modified to improve the hydrograph timing. The calibration and validation results will be discussed in Sect. 4.1.

3.2.2 Potential Adaptation Solutions

Various potential adaptation solutions were identified together with Saint-Isidore that could potentially be implemented. These are presented in Fig. 2 and can be summarized as follows:

- *Lowering of Boyer culvert (C)*: this culvert is currently raised above the river bed, creating an accumulation of water upstream within the residential area. Lowering of the culvert would allow for a proper drainage, providing more storage capacity during subsequent rainfall events.
- *Reprofiling of the Saint-Régis River (DR and UR)*: the river bed would be reprofiled using an average slope from its source to the outlet (Station 2) to remove the non-uniform accumulation of deposits, providing more conveyance. Downstream (LR)

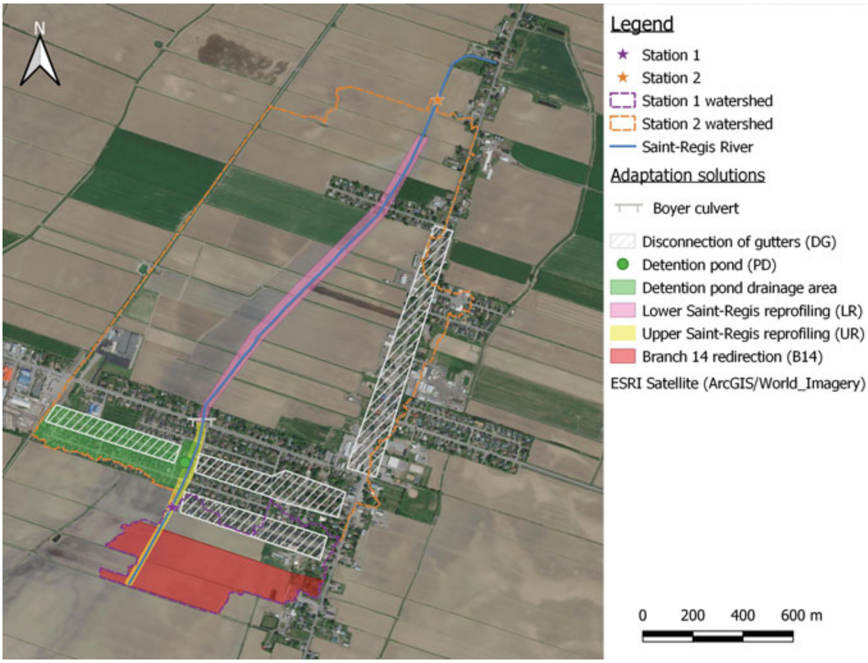


Fig. 2 Localization of potential adaptation solutions within the territory of Saint-Isidore

and upstream (UR) reprofiling from the residential area (near the Boyer culvert) are considered as two distinct measures.

- *Detention pond (DP)*: construction of a dry detention pond in the Sainte-Anne Park, storing runoff volumes from approximately an 8000 m^2 drainage area and gradually releasing it in the river. The storm sewer network from the targeted areas would be redirected towards the detention pond.
- *Branch 14 redirection (B14)*: historically, a small portion of the Station 1 watershed was diverted towards the municipality. The Branch 14 could be restored to its previous configuration, but would likely require environmental administrative procedures to do so.
- *Disconnection of gutters (DG)*: even though a portion of the municipality's sewer network is pseudo-separative, multiple gutters were found to be connected to the storm sewer network. These gutters would be disconnected from the network and redirected towards permeable surfaces or in rain barrels.

The calibrated PCSWMM model is used to evaluate individual adaptation solutions and combinations of those thereof. A 3-h Chicago synthetic storm with a 25-year return period was selected as the design event under which all scenarios are evaluated and compared. This storm was generated using the intensity-duration-frequency (IDF) curves from Environment and Climate Change Canada's Ste-Clothilde weather station closest to the study site. In order to take the impact of climate change into account, an 18% correction factor was applied to the storm intensities following the Quebec Ministry of Sustainable Development, Environment and Fight Against Climate Change recommendations [9].

3.3 Multi-criteria Analysis for Decision Support

The comparative analysis of the various adaptation solutions is based on socioeconomic, technical and environmental criteria, which can be determined using a multi-criteria analysis. This analysis makes it possible to rank the measures and requires the identification as well as the weighting of the criteria considered. The choice of criteria and their units is based on the literature as well as the specificities of the proposed technical solutions. The attribution of the value to each adaptation solution for each selected criterion is based on the results of the modelling component and on knowledge from the literature or expert judgments. The decision support process is based on the PROMETHEE method [10] for which the method as well as the methodological approach are explained by [11]. The study's selection of criteria is shown in Table 1 and are divided into three categories according to the fulfillment of three conditions: (1) the list of criteria relevant to the study must be exhaustive, (2) consistency in the role of a criterion at its local level and when it is immersed in its category, and (3) the non-redundancy of the criteria [12].

In the PROMETHEE methods, the adaptation solutions $A = (a_1, a_2, \ldots, a_n)$ are noted for each criterion $C = (c_1, c_2, \ldots, c_n)$. Then, the difference $d_c(a_i,a_j)$ is computed for all pairwise comparison of adaptation solutions according to each criterion c: $d_c(a_i, a_j) = c_c(a_i) - c_c(a_j)$. Afterwards, these differences are translated in a preference degree P ranging from 0 to 1 based on a preference function. A score of 1 indicating a strong preference for an adaptation solution against another for one criterion comparison, and a score of 0 means no preference. In this study, two preference functions are employed:

$$\text{Linear } P(a_i, a_j) = \begin{cases} 0 & \text{if} \left| d_c(a_i, a_j) \right| \le q \\ \frac{\left| d_c(a_i, a_j) - q \right|}{p - q} & \text{if } q < \left| d_c(a_i, a_j) \right| \le p \\ 1 & \text{if} \left| d_c(a_i, a_j) \right| > p \end{cases} \tag{1}$$

$$\text{Usual } P(a_i, a_j) = \begin{cases} 0 \text{ if } d_c(a_i, a_j) \le 0 \\ 1 \text{ if } d_c(a_i, a_j) > 0 \end{cases} \tag{2}$$

Then, these preference degrees are paired with the weight's criterion given by the authorities. Due to COVID-19, synthetic weights were defined instead until public consultation can be conducted.

$$\pi(a_i, a_j) = \sum_{c=1}^{n} P_c(a_i, a_j) w_c \quad \text{and} \quad \pi(a_j, a_i) = \sum_{c=1}^{n} P_c(a_j, a_i) w_c \tag{3}$$

Table 1 Description and units of the selected criteria

Context	Criteria	Description of the criterion	Units
Socioeconomic	Administrative complexity	Solution requires the mobilization of resources from the municipality to achieve the solution	$
	Cost of investment	Cost required to design and build the solution	$/year
	Operation and maintenance cost	Cost required for the operation of the solution and its routine maintenance	$/year
	Repair cost	Cost to be expected to bring the solution up to standard	1–5
Technical	Ease of implementation	Ease with which a solution can be implemented	1–5
	Ease of maintenance	Simplicity with which it is possible to keep the solution running smoothly	1–5
	Adaptable	Ease of upgrading the solution	1–5
	Water flow	Diminish or maintain the water flow at the watershed's outlet	m^3s^{-1}
	Water level	Peak water height at Sainte-Anne park	m^3s^{-1}
	Proven solution	Solution commonly used occasionally, or in development	1–5
Environment	Water quality	The solution minimize the contribution of contaminants to waterways	1–5
	Faunic habitat quality	The solution optimize or improve the quality of habitats for aquatic and terrestrial fauna	1–5
	Erosion potential	The solution reduces sediment inputs downstream	1–5
	Infiltration potential	The solution promotes the recharge of the water table	1–5

Thus, the leaving (positive) flow (Φ^+) and the entering (negative) flow (Φ^-) are deducted. The former means how this adaptation solution outranks all the other adaptation solutions according to one criterion, in contrast to the entering flow, which means how the adaptation solution is outranked by all the other adaptation solutions.

$$\Phi^+(a_i) = \frac{1}{n-1}\sum_{x \in A} \pi(a_i, x) \quad \text{and} \quad \Phi^-(a_i) = \frac{1}{n-1}\sum_{x \in A} \pi(x, a_i) \tag{4}$$

where n is the number of adaptation solutions considered in the analysis. The net flow (Φ) is the difference of the leaving flow (Φ^+) and the entering flow (Φ^-). The flow score is computed as the difference between the positive flow and the negative flow: $\Phi(a_i) = \Phi^+(a_i) - \Phi^-(a_i)$.

4 Results and Discussion

This section presents the results obtained for the modelling components (hydrological, hydraulic and climate change), followed by the multi-criteria analysis for decision support. First, the calibration and validation of the PCSWMM model are presented. Then, the potential adaptation solutions are simulated in current and future climates to determine their strengths, weaknesses and possible synergies between them. Finally, the data obtained from PCSWMM modelling as well as other data from practice and expert judgments are fed into a multi-criteria analysis in order to obtain a ranking of the adaptation solutions.

4.1 PCSWMM Model Calibration

The objective of the PCSWMM model is to reproduce the water dynamics of the Saint-Isidore watershed. A few rainfall events were selected to calibrate and validate the PCSWMM model using the water level gauging (between September 12, 2019, and September 11, 2020). Consecutive rainfall events that took place between October 15, 2019, and November 3, 2019, were selected to calibrate the model, providing diversity in the intensity and duration of those events [13]. According to Moriasi et al. [14], several indicators can be used to jointly assess the performance of a hydrological model as satisfactory or not. The model is deemed acceptable when the following conditions are met: 1) the Nash-Sutcliffe coefficient (NSE) > 0.6, 2) the coefficient of determination (R^2) > 0.6 and 3) the percentage bias (P_{BIAS}) $\pm$ 15%.

Due to the limited number of events with enough rainfall to generate above average water levels, two sequences of two rainfall events (occurring in summer and in fall) were selected for the validation, whereas the remaining ones served for the calibration. Similar values were obtained for both calibration and validation events. The two validation events between October 25 and November 4 are presented in Fig. 3 and the performance indicators for both fall and summer event sequences are shown in Table 2.

Validation results shown in Table 2 indicate that satisfactory performance is obtained for all indicators at Station 2 during the fall event, and Station 1 for the summer events. For the fall events, Station 1 performance is poorer (as seen in Fig. 3) and is, in fact, systematically lower than Station 2 performance. This can possibly be explained by the presence of the Boyer culvert and the historical diversion (see Sect. 3.2.2) that may affect the runoff and routing processes in that particular area.

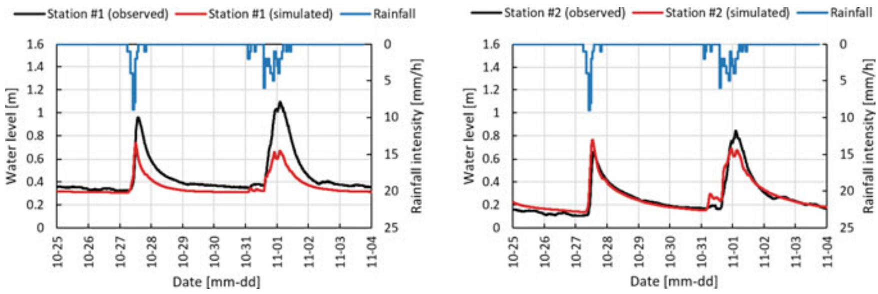


Fig. 3 Validation at Station 1 (left) and Station 2 (right) from October 25 to November 4, 2019

Table 2 Performance indicators for both validation events

Events dates	Station #	NSE	R^2	P_{BIAS} (%)
2019-10-25 to 2019-11-04	Station 1	0.46	0.90	19.0
	Station 2	0.90	0.90	−2.5
2020-08-02 to 2020-08-09	Station 1	0.75	0.91	10.0

Note that Station 2 data is not available beyond March 13, 2020, due to equipment damages and malfunctioning from that date on. Overall, the calibration was considered satisfactory to conduct the case study and evaluate the performance of the various adaptation solutions. However, a larger monitoring time would have provided more rainfall events for both calibration and validation periods, leading to more robust results for the analysis.

4.2 Evaluating the Different Adaptation Solutions

4.2.1 Baseline Scenario

As seen in Fig. 3 for Station 1, the restriction caused by the Boyer culvert is preventing the water level to decrease below approximately 0.4 m following any significant rainfall event. Indeed, the municipality has mentioned that this is a recurrent problem where the water level remains high for a long period of time, further contributing to potential flooding in the residential areas. Figure 4 shows the maximum water levels at a cross-section upstream of the Boyer culvert reached during the 3-h Chicago storm with a 25-year return period under present climate conditions for the six individual solutions described in Sect. 3.2. A 25 mm rainfall event was used in the model 3 days before the event to better demonstrate the problem of drainage in the residential area.

Results shown in Fig. 4 suggest that the lower Saint-Régis reprofiling and the lowering of the Boyer culvert are needed together (LR+C) to allow the upstream section to properly drain itself and lower the water level following significant rainfall

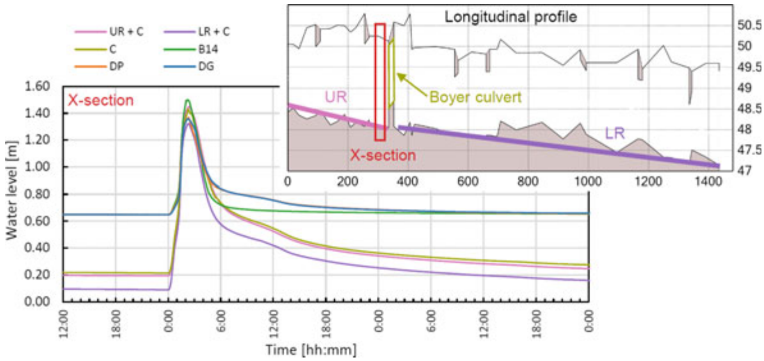


Fig. 4 Cross section (X-section) and longitudinal profile of maximum water levels for each adaptation solution alone for a 3-h 25-year return period Chicago synthetic storm following a 25 mm rainfall event

events (similar behaviours were obtained for more frequent events). This can be explained by the culvert's raised elevation with respect to the river bed as well as the important accumulation of sediments downstream of the culvert preventing its lowering alone from achieving the desired result. Thus, the combination of both lower Saint-Régis reprofiling and the lowering of the Boyer culvert (LR+C) are considered as the minimum solution and will serve as the baseline scenario hereafter.

4.2.2 Comparing All Solutions Together in Future Climate

Combining all individual adaptation solutions shown in Fig. 2 with the baseline scenario (LR+C), the PCSWMM simulations were run once again, and the results are shown in Fig. 5 in both the current and future climate conditions (i.e. with the 18% majoration factor). Furthermore, the maximum potential gain is shown with the black curve, combining all solutions together. All possible combinations of two or more measures were also tested for the multicriteria analysis, but are not shown in Fig. 5.

The results suggest that each individual solution provides improvement over the baseline scenario in both the current and future climate in terms of flow at the outlet of the Saint-Régis River segment studied. The only exception is the Branch 14 redirection (B14) which results in a lower total volume, but an increased peak flow. This could be explained due to the smaller storage area within the river bed in the residential area, leading to higher water levels and flows. The combination of the remaining solutions provided the best improvements in terms of peak flow reduction. While the detention pond (DP) and the disconnection of gutters (DG) both provide the largest gain in terms of peak flow reduction, the remaining options are intertwined together making it difficult to distinguish them. The multi-criteria analysis will allow to obtain a ranking of each individual and combination of adaptation solutions to determine the

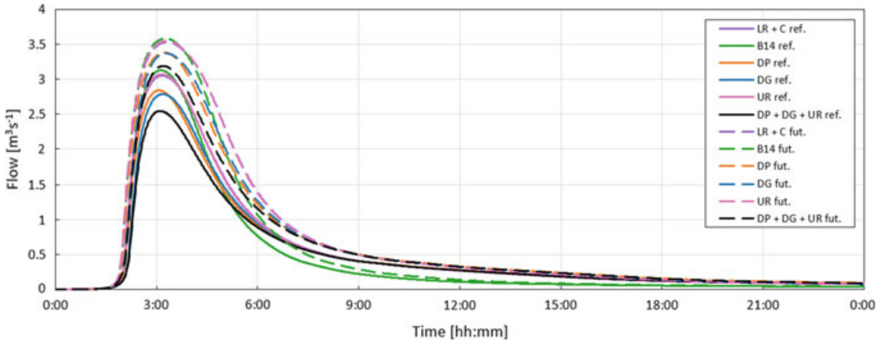


Fig. 5 Hydrographs of the flows at the outlet of the Saint-Régis River (Station 2), for the portion under study, for the baseline (LR+C), the four individual adaptation solutions combined with the LR+C baseline, and the best combination for peak flow reduction for a 3-h Chicago storm with a 25-year return period under the future climate

best scenario to be selected according to socioeconomic, technical and environmental factors.

4.2.3 Multi-criteria Analysis

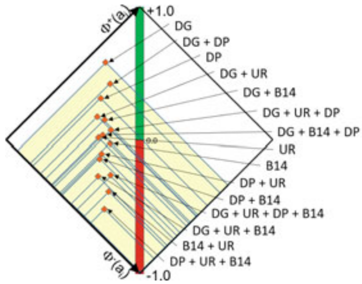
The analysis of the robustness of the multi-criteria analysis was carried out by constructing various scenarios with which a specific distribution of the weighting of the criteria is associated. The total weight of 100% is equally distributed among the three major categories of criteria (socioeconomic, technical and environmental) for the base scenario, while 75% is assigned to the major category for the other three scenarios. Table 3 presents the parameters as modeled in PROMETHEE, with q and p respectively defining the indifference and preference thresholds in the case of a linear function. Better performances are obtained for smaller values over all sub-criteria.

All 16 adaptation solutions combinations were included in the multicriteria analysis. To assess the performance of the solutions against each other and against the criteria, leaving, entering and net flows are computed, allowing to rank the solutions. Figure 6 presents the net (Φ), leaving (Φ^+) and entering (Φ^-) flows as well as the classification of the best five adaptation solutions obtained with PROMETHEE.

Results indicate that the disconnection of gutters (DG) is found in the first position for all scenarios, except for the environmental one where it is in second position. The base scenario shows that both DG and the detention pond (DP) share the first three ranks. With respect to the Branch 14 redirection (B14), it reaches second and third positions in the socioeconomic scenario, but only makes it at the fifth position at best for the other scenarios. It is possible that the cost for investment, operation and maintenance does not allow DP to rank among the best in the socioeconomic scenario. This analysis shows that the ranking is sensitive to the weights given to each scenario, ultimately depending on the preferences of decision-makers.

Table 3 The sub-criteria and their properties for the multicriteria analysis. The units of q and p are the same as their respective sub-criterion's units

	Sub-criteria	Weights (%)				Type	Function	q	p
		Base case	Socioeconomic	Technical	Environmental				
Socio-economic	Administrative complexity	8.33	18.75	3.13	3.13	Quantitative	Linear	n/a	n/a
	Cost of investment	8.33	18.75	3.13	3.13	Quantitative	Linear	82 867	199 472
	Operation and maintenance cost	8.33	18.75	3.13	3.13	Quantitative	Linear	1 980	4 124
	Repair cost	8.33	18.75	3.13	3.13	Quantitative	Linear	5 325	13 282
Technical	Ease of implementation	5.56	2.08	12.50	2.08	Qualitative	Usual	n/a	n/a
	Ease of maintenance	5.56	2.08	12.50	2.08	Qualitative	Usual	n/a	n/a
	Adaptable	5.56	2.08	12.50	2.08	Qualitative	Usual	n/a	n/a
	Water flow	5.56	2.08	12.50	2.08	Quantitative	Linear	0.09	0.14
	Water level	5.56	2.08	12.50	2.08	Quantitative	Linear	0.21	0.35
	Proven solution	5.56	2.08	12.50	2.08	Qualitative	Usual	n/a	n/a
Environm	Water quality	8.33	3.13	3.13	18.75	Qualitative	Usual	n/a	n/a
	Faunic habitat quality	8.33	3.13	3.13	18.75	Qualitative	Usual	n/a	n/a
	Erosion potential	8.33	3.13	3.13	18.75	Qualitative	Usual	n/a	n/a
	Infiltration potential	8.33	3.13	3.13	18.75	Qualitative	Usual	n/a	n/a
	Total	100	100	100	100				



Rank	Φ	Φ^+	Φ^-	Rank	Φ	Φ^+	Φ^-
Base case scenario:				**Technical scenario:**			
1: DG	0.62	0.68	0.06	1: DG	0.6	0.68	0.08
2: DG + DP	0.45	0.61	0.16	2: DG + DP	0.37	0.58	0.21
3: DP	0.34	0.52	0.18	3: DP	0.34	0.52	0.18
4: DG + UR	0.18	0.43	0.25	4: UR	0.21	0.45	0.24
5: DG + B14	0.17	0.45	0.28	5: DG + UR	0.19	0.44	0.25
Socioeconomic scenario:				**Environmental scenario:**			
1: DG	0.64	0.67	0.03	1: DG + DP	0.78	0.84	0.06
2: B14	0.30	0.49	0.19	2: DG	0.56	0.68	0.12
3: DG + B14	0.30	0.48	0.18	3: DG + UR + DP	0.51	0.69	0.18
4: UR	0.24	0.41	0.17	4: DP	0.46	0.62	0.16
5: DP	0.22	0.41	0.19	5: DG + B14 + DP	0.45	0.63	0.18

Fig. 6 Results from the multi-criteria analysis. The figure on the left is a visual representation of the base case scenario results, where the leaving flow (Φ^+) and entering (Φ^-) are added together to evaluate the net flow (Φ) corresponding to the red/green bar in the middle. A higher solution on the diamond is preferred. The flows and final ranks for all scenarios are shown in the table on the right

5 Conclusion

A case study was conducted during which the developed methodology was applied to serve as a benchmark for future studies involving very small, ungauged watersheds with the aim of helping small municipalities identify adaptation solutions to flooding. The proposed methodology includes three main steps: field data collection; hydrological and hydraulic modelling under present and future climate conditions; and multi-criteria analysis. Field data collection involved installing two water-level stations and recorded data over a one-year period were used to calibrate an event-based PCSWMM model. Then different possible adaptation scenarios were analysed and compared using the PROMETHEE method.

Overall, the results obtained from the hydraulic and hydrological simulations, as well as the multicriteria analysis indicate that a combination of adaptation solutions is likely the best option for Saint-Isidore. First, a minimal intervention consisting of downstream reprofiling (LR) and the lowering of the Boyer culvert (C) are necessary to provide proper drainage in the residential area following a significant rainfall event. In terms of resilience against climate change, the addition of gutter disconnection (DG), a dry detention pond (DP), and upstream reprofiling (UR) would lead to the largest peak flow reduction. However, while the DG scenario is an ideal solution based on the multi-criteria analysis conducted, the addition of the DP and/or UR solutions would ultimately rely on the decision-makers scenario selection (i.e. socioeconomic, technical and environmental) as well as their respective weighting. It should be noted that the multi-criteria analysis performed in this case study allows the mitigation measures to be further investigated in a design phase and could serve as a preliminary study.

We believe that this methodology could be applied to other cities located in very small ungauged watersheds to select optimal solutions to increase their resilience against climate change. The degree of complexity and tools required to conduct such an analysis will ultimately depend on the desired objectives as well as the municipality's capabilities and resources.

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