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A Sustainability-Based Monitoring and Decision Support Framework for Local Climate Adaptation via Water Retention Measures

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ABSTRACT

This paper presents a practical framework for the design and evaluation of local, nature-based water retention measures for small and medium-sized municipalities. The framework consists of two components: first, a site-selection score operationalises social, economic, and environmental–geographical sustainability pillars using transparent binary criteria aggregated through a multiplicative rule; and second, a lean monitoring design defines key hydrological, ecological and socio-economic indicators including the use of control sites. The framework is demonstrated on municipal climate-adaptation pilot interventions in Hungary, illustrating how the multiplicative aggregation highlights weak sustainability dimensions that may be concealed by additive indices. A three-dimensional visual representation supports communication of trade-offs to non-expert stakeholders. Overall, the framework improves measurability, comparability, and replicability of local climate adaptation and is suitable for municipalities with limited technical capacity.

KEYWORDS

Climate adaptation, Water retention, Water security, Integrated monitoring, Sustainability, Spatial planning

INTRODUCTION

Climate change is intensifying hydrological extremes globally, causing prolonged droughts and more frequent floods [1]. These impacts are particularly challenging for small and medium-sized municipalities, which often lack the financial, technical, and human resources to design, implement, and evaluate effective adaptation measures [2]. Recent climate projections for Hungary indicate a 3–5 °C warming, increased drought frequency, and irregular precipitation, raising flood and inland water risks. Lowlands are highly drought-sensitive, threatening food supply and small farms, while inadequate land use and river regulation heighten flood risk. Elevated groundwater along the Tisza often coincides with heavy rainfall, causing prolonged inland waterlogging, and the western and northern uplands are prone to flash floods.

Integrated water management is increasingly recognized as essential for balancing social, economic, and ecological objectives under growing climatic and hydrological pressures [3]. Sustainable urban water transitions depend on the simultaneous advancement of technological, institutional and social innovations, while [4] highlight the role of resilience-based planning frameworks in addressing deep uncertainties in water-related risks. Complementing these perspectives, [5] show that embedding ecosystem services into water-governance decisions strengthens both equity and ecological performance. At the global scale, [6] reveal accelerating groundwater depletion, underscoring the urgency of integrated and sustainability-oriented water-use strategies. In response to these trends, nature-based solutions have emerged as a cornerstone of contemporary adaptation policy: the [7] offers a systemic framework for enhancing ecological connectivity and hydrological regulation; [8] demonstrate that landscape-scale ecosystem restoration enhances resilience to drought and hydrometeorological extremes; and [9] show that natural retention measures can mitigate the severity of climate-driven flood and drought impacts. Together, these findings reinforce the need for planning approaches that integrate ecological processes, participatory governance and long-term resilience in water management systems.

Nature-based water retention measures (NWRMs) have emerged as cost-effective, multifunctional solutions that address both water scarcity and excess while generating ecological and social co-benefits [10] proves that nature-based solutions can simultaneously deliver hydrological regulation, biodiversity gains, and community-level benefits when implemented across landscapes. However, the long-term effectiveness of NWRMs depends on monitoring systems capable of tracking hydrological, ecological, and socio-economic outcomes over time [11]. Further argue that insufficient monitoring and evaluation frameworks hinder the integration of nature-based approaches into mainstream water management and reduce opportunities for evidence-based policy learning.

Recent international frameworks have significantly advanced the conceptualisation and evaluation of NbS/NWRM. The European Commission [12] defines nature-based solutions as resource-efficient, cost-effective interventions that provide environmental, social, and economic benefits while enhancing biodiversity. The EEA's 2023 briefing underscores the lack of standardized monitoring approaches as a barrier to scaling successful NbS across Europe[13]. Tools such as the DG R&I NbS impact evaluation handbook consolidate insights from 17 Horizon 2020 projects, offering comprehensive KPIs across 12 focus areas [14].

On the climate policy front, IPCC AR6 WGII [15] stresses the need for integrating ecological and socio-economic indicators in NbS performance evaluation, while the UNFCCC guidelines provide structured protocols for NbS implementation, incorporating vulnerability and adaptation metrics [16].

To ensure quality and replicability, the IUCN Global Standard for NbS [17] establishes eight core criteria and 28 indicators for assessing interventions across sustainability dimensions. Practical guidance continues to evolve: IISD (2024) offers a practitioner-facing checklist to design sustainable, inclusive NbS with robust monitoring components [18].

From a methodological standpoint, [19] critically examine the application of MCDA in NBS planning and highlight underrepresentation of economic and technical criteria as well as limited stakeholder weighting. Meanwhile, [20] bring forward practitioner insights on indicator-based monitoring in urban and peri-urban NbS, emphasizing social metrics and feasibility.

Despite the growing body of conceptual and policy-oriented frameworks, there remains a gap in operational, locally adaptable evaluation tools that integrate hydrological, ecological and socio-economic performance indicators within small and medium-sized municipalities. By integrating these insights, our study aims to bridge theoretical frameworks and practical application, delivering a replicable tool that aligns with current international standards in NbS evaluation. By operationalizing international NbS standards within a locally adaptable, indicator-based evaluation framework, this study contributes to bridging the persistent gap between high-level policy ambitions and implementable, evidence-based water management practice at the municipal scale.

MATERIALS AND METHODS

This paper develops and demonstrates a decision-support and monitoring framework for local nature-based water retention measures. The primary objective is methodological: to provide a transparent and replicable approach, rather than to quantitatively evaluate individual sites. Accordingly, the framework is demonstrated through municipal pilot interventions, while quantitative impact assessment of individual sites is outside the scope of this study.

The analysis draws on the Hungarian LIFE-MICACC project (2017–2021), which implemented a series of small-scale NWRMs across rural municipalities to enhance local climate-adaptation capacity.

However, the integrated monitoring approach was not implemented, making it difficult to quantify long-term impacts or guide replication. To address this gap, a decision-support framework is proposed to provide a simple guide for introducing any type of climate-adaptation-oriented water retention measure in the future.

The LIFE16 CCA/HU/000115 "LIFE-MICACC" project [21]—led by the Hungarian Ministry of Interior in partnership with WWF Hungary—aimed to improve the climate resilience of the most vulnerable municipalities by integrating ecosystem-based water management and natural water-retention measures [22] into local spatial planning. Five pilot settlements (Bátya, Püspökszilágy, Ruzsa, Rákócziújfalu and Tiszatarján) represent both lowland and hilly conditions typical of Central and Eastern Europe, and implemented small-scale interventions to enhance local water retention and reduce flood and drought risks [23].

The project works on five intervention sample areas are located in Hungarian settlements where the water risks and settlement vulnerability typical of small settlements in Central and Eastern Europe are increasingly experienced as a phenomenon intensified by climate change. The project aims to address these situations by integrating natural water retention solutions into the local water management system among which there are solutions for plains and hills, as well as those that use both natural watercourses and rainwater.

Hungary is experiencing increasing climate variability, with alternating periods of excessive rainfall and prolonged droughts [24]. The LIFE project was designed to address these challenges by implementing ecosystem-based water management strategies that promote local and regional climate adaptation. The interventions sought to improve water retention capacities and reduce water-related risks at the municipal level.

Despite these efforts, the effectiveness of the interventions was limited by the absence of systematic environmental monitoring and lack of data-driven decision-making tools [14]. This paper examines the critical gaps in monitoring and decision support mechanisms, highlighting the importance of developing comprehensive models to support future climate adaptation projects.

It is necessary to recognize that decisions on the use of local water resources are not made by water management organizations alone, but together with all stakeholders through concrete measures that include the development of legal and institutional frameworks to ensure the implementation of sustainable water resource management and climate adaptation [25].

Water is an important factor at both the local and global levels. Major changes in water resources are a primary impact of climate change that is recognized and felt by local communities, farmers, businesses, residents and local governments [15].

Traditional water knowledge offers long-standing insight into local hydrological patterns and plays an important role in shaping socially accepted water-management practices. [26] shows that integrating traditional hydrological understanding into planning improves community engagement and strengthens acceptance of water-related interventions. [27] demonstrate that indigenous knowledge systems contribute to the sustainable management of water resources in rural communities by complementing formal institutional processes. [28] illustrate that traditional practices in semi-arid regions help maintain water availability through locally adapted land- and water-use strategies. Similar principles appear in the Hungarian context, where floodplain-based water retention along the Tisza builds on ecological memory and community-level landscape knowledge [29].

The framework combines:

1. a site-selection scoring system based on Brundtland's sustainability pillars—social, economic, and environmental/geographical—operationalized through a multiplicative binary-criteria model; and
2. a lean monitoring design specifying key indicators for small municipalities.

Our framework builds on these principles to improve measurability, comparability, and replicability of local climate adaptation, offering a practical tool for municipalities with limited capacity.
This dual approach ensures that decision-makers can both select sites with the highest potential benefits and track the effectiveness of implemented measures over time, even in resource-limited contexts.

The methodology presented in this study is based on well-established decision-making and sustainability assessment frameworks, including Multi-Criteria Decision Analysis (MCDA), sustainability indicators and indexes, GIS-based decision-making, and spatial modelling.

Furthermore, the framework employs a multiplicative formula ($P = S \times G \times E$) to calculate the final value, in contrast to the common practice of simply summing the factors, as seen in many sustainability indexes. This approach allows for consideration of interactions between factors, ensuring that if any factor is zero or very low, it significantly reduces the overall score. (For example, a project that is economically sustainable but socially unacceptable would receive a low score.)

Another key feature of this method is the spatial visualization of results in a three-dimensional cube, allowing for a clear representation of sustainability dimensions. Such visualization is rare in traditional MCDA or sustainability assessment methods.

Additionally, the method frequently employs a binary (yes/no, 1/0) decision logic for specific criteria (e.g., "Is local funding available?" Yes = 1, No = 0), simplifying the decision-making process and making it particularly useful for non-expert decision-makers.

This methodology is particularly beneficial for small and medium-sized municipalities, where decision-makers may not have extensive expertise in sustainability modeling. Thus, this approach combines existing techniques in a novel way, specifically designed to support local governments in making water retention decisions. 1 1. summarises the characteristics of the demonstration sites and the associated monitoring possibilities, serving as an input for the methodological framework rather than as a result of the quantitative evaluation. Figure 1. 1 shows the location of the water retention measures on the map of Hungary.

Table 1. Grouping and proposed monitoring of sample areas aiming nature-based water retention in Hungary

Settlement	**Type**	**Water retention method**	**Nature of water**	**Possibility of monitoring**	**Possible areas for development (environment, economy, society)**
Bátya	storage + habitat	lowland	precipitation	1,2,3	SOC, ECON
Püspökszilágy	flow slow down + storage	hilly	(periodic) river	2,3,5	ECON
Ruzsa	storage lake and canal	lowland	precipitation + treated wastewater	1,2,4,5	SOC, ECON
Rákócziújfalu	storage + habitat	lowland	inland water + precipitation	1,2,3	SOC
Tiszatarján	storage + habitat	lowland, floodplain	flood, inland water	1,2,3	SOC, ECON

1: groundwater, 2: moisture, dew, 3: water level, 4: water quality, 5: water yield. (Source: authors: Boglárka O.Lakatos, Zsolt Hetesi)

Figure 1. Water retention measures in Hungary by LIFE_MICACC project. Source: https://vizmegtartomegoldasok.bm.hu

The prominent classification of water retention projects is possible by the nature of the solution and the topography. There is only one hilly solution, which is an essential element of flow slowing, but at the same time, it hardly makes a real difference from a monitoring point of view. The various types of measurements found in the "monitoring" column of the table play an essential role in the specification of the measurement technique. In the case of such investments, it is not enough to get to the implementation stage alone. However, it is worthwhile to establish a multi-criteria ranking of possible sites before the investment starts and to set up an adequate monitoring system to check the desired results during implementation. Both are proposed in the Results chapter.

RESULTS AND DISCUSSION

The results presented in this section demonstrate the internal logic and applicability of the proposed decision-support and monitoring framework. Rather than providing a quantitative impact evaluation of individual interventions, the results focus on site prioritisation, sustainability-based comparison, and monitoring design in municipal climate-adaptation contexts.

Monitoring technical considerations

To evaluate small-scale water-retention interventions, five key parameters are considered: groundwater level; air and soil humidity; surface-water level and discharge; water quality; and vegetation response. Each requires a control site with similar soil and microclimatic conditions to separate the intervention signal from background variability.

These considerations are intended to illustrate monitoring design principles and measurement logic, rather than to support statistically inferential evaluation of intervention impacts.

- Groundwater – The new water body generates an excess hydraulic pressure that decays with distance. The control probe must be outside the influence radius yet in the same hydro-stratigraphic unit.

Excess head is observed when the trend-removed series of intervention (I) and control (C) match except for the added pressure of the retained water.

- Air humidity – Independent control is essential since measured vapor depends on several factors:

$$q_{vapor} = q_{vapor}(t, n_1, \dots, n_i)$$

where ni are local environmental parameters. Control and intervention sites must share similar wind and insolation so that the difference reflects only the water body.

- Surface water & yield – For streams or canals,

$$\Phi = \Phi_0 \cdot f(t)$$

where Φ is discharge and f(t) captures the time-dependent component of retention. Upstream control flow allows estimation of the “water gap” attributable to the measure.

- Water quality – Follow EU Water Framework Directive criteria to maintain good ecological status.

- Vegetation – Changes in hydrophilic indicator species or satellite NDVI reveal ecosystem effects and micro-climatic feedbacks.

This concise scheme preserves comparability across sites and is feasible for resource-limited municipalities while retaining the key equations and reasoning for each measurement [34].

Scoring system results

The scoring framework was applied to the LIFE-MICACC pilot sites to prioritise interventions according to the three Brundtland pillars—Social (S), Economic (E), and Geographical/Environmental (G). The aim of the index was to define an indicator that provides quantified information on the sustainability-related performance of a given area based on three selected parameters. Among commonly used aggregation methods, both additive and multiplicative models were considered. In both cases, higher parameter values increase the overall score, and both frameworks allow weighting, either via coefficients in additive models or exponents in multiplicative formulations.

However, the multiplicative model has a key advantage: it strongly penalises situations in which any individual parameter approaches zero. In such cases, the product becomes small, implying that improvement across all three pillars is required for the objective function to increase. This behaviour aligns with the sustainability principle that weak performance in any single dimension (social, environmental, or economic) constrains overall sustainability.

In contrast, additive models allow high values in one parameter to compensate for low values in another, which may mask structural weaknesses in the system. These differences are illustrated in Figures 3a and 3b, which present selected level surfaces of the additive and multiplicative objective functions.

Sub-scores (0–4 per pillar) are multiplied to give the composite index P=S×G×E, yielding a single scalar measure of overall sustainability. 2. 2. demonstrates the scoring system as “Local Water-Retention Assessment Index”. Binary scoring reduces subjectivity, increases transparency, and minimizes discretionary weighting bias in small-scale municipal decision-making.

Table 2. Local Water-Retention Assessment Index (binary scoring 0/1)

Category / Criteria	Description	Score (0/1) and usage	Comment
Geography / Environment	Local exposure to climate events [8]	0= no 1= more than used to	Are climate extremes in the broader environment more common?
	Topography features (0 = no place for water retention, 1 = suitable landscape)	0= no place for water retention 1= yes	Landscape (hilly) suitability for water retention.
		0= bad 1=good	The general state of the water body is present.
	Watershed size, condition (quality and quantity according to WFD)[9]	0= 4-1, 4-2 1= provision, regulating, cultural, supporting	Ecosystem services that can be developed.
	Potential ecosystem services (0 = 4-1, 4-2; 1 = provision, regulating, cultural, supporting)	0=no 1= yes	The local vulnerability of an ecosystem is due to some local features.
Society	Local vulnerability by extreme climate events	0=no 1= yes	Existence of decision-making social will.
	Local decision-makers willingness, openness/need	0=no 1= yes	Existence of citizens will.
	Stakeholders (local) willingness	0=no 1= yes	Availability of financial support.
	Finance support/availability	0 = no 1= occurrence of more than 1 extreme climate event in 5 years	Frequent extreme events that can be reduced by intervention.

Economy	Probability of damage by climate event (occurrence of >1 extreme event in 5 years)	0=no 1= yes	They are increasing economic potential as a result of intervention.
	Potential economic opportunities in case of water retention	0= no 1= environment affected	Territorial overuse from any point of view.
	Overused ecosystem services (forestry, agriculture)	0= no 1= yes	Vulnerability reduction.
	Decreased effect of damage from climate events by water retention	0= no 1= more than used to	

Higher P indicates better suitability for water-retention interventions. Each pillar ranges from 0 to 4, so the three dimensions—Social (S), Geographical/Environmental (G) and Economic (E)—span a cube whose ideal point is (4, 4, 4) (Figure 2).
To make the concept easier to understand, Figure 2. 2. and Figure 3. a.) 3. a.b.) illustrates the visual demonstration using cubes.

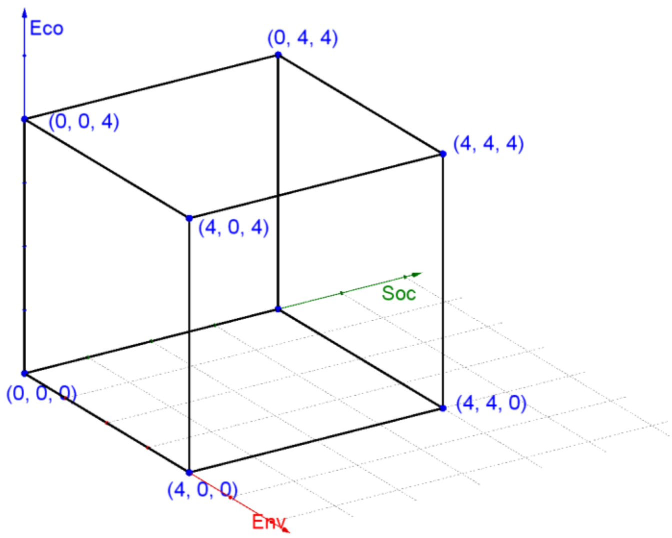

Figure 2. The ideal point is (4,4,4) Source: Edited by Zsolt Hetesi with GeoGebra

The composite sustainability index is calculated as P=S×G×E, which ensures that weakness in any pillar proportionally reduces the overall score.

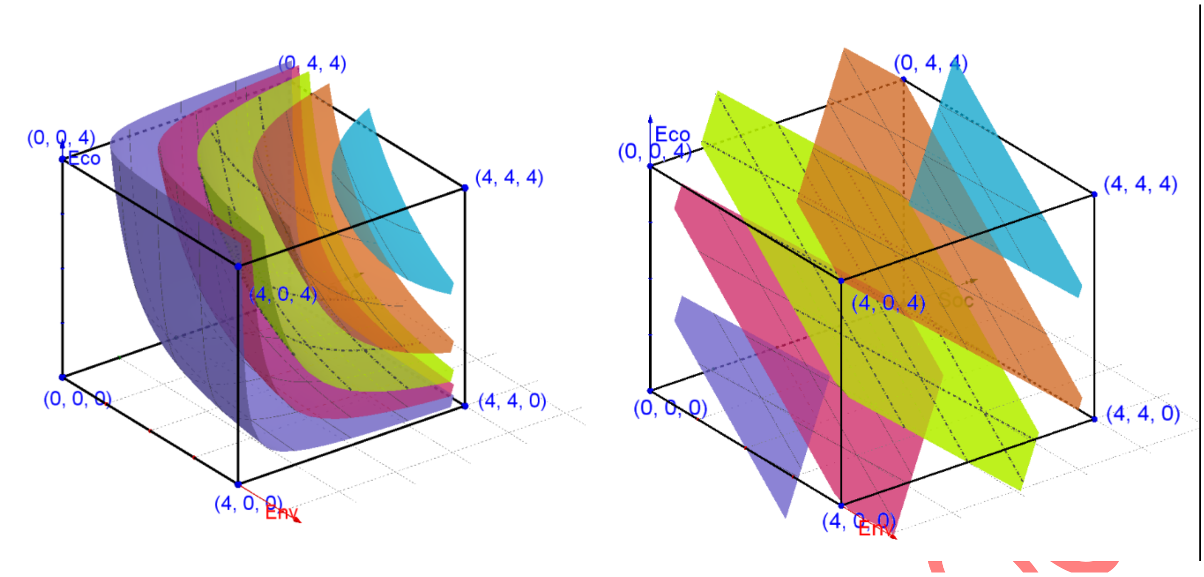

Figure 3. a.) Iso-surfaces of the multiplicative scoring function P=S×G×E within the evaluation cube (n=4). The axes represent Social (S), Geographical/Environmental (G), and Economic (E) scores ranging from 0 to 4. Curved iso-surfaces illustrate that low performance in any single pillar strongly constrains the composite score, reflecting the non-compensatory nature of the multiplicative

Figure 3. b.) Level surfaces of an additive scoring formulation within the same evaluation cube. The planar surfaces indicate that high values in one dimension can compensate for low values in another, highlighting the fundamentally different, compensatory behavior of additive aggregation compared to the multiplicative approach.

As an illustration, the full cell-by-cell evaluation of the LIFE-MICACC pilot site Püspökszilágy shows that all three pillars scored 4, giving the theoretical maximum composite value P=64. The complete detailed scoring is provided in Supplementary Table S1 for reference. By operationalizing sustainability theory into a transparent, low-complexity decision-support tool, this study contributes to bridging the gap between high-level climate adaptation strategies and implementable local action.

CONCLUSIONS

This paper proposes a monitoring procedure grounded in the biophysical and operational characteristics of the intervention sites, shaped by empirical insights from the LIFE-MICACC project and the overarching purposes of the water-retention interventions.

Additionally, for stakeholders to achieve climate-resilient settlements and sustainable water management, our research proposes a simple method to determine the best location to retain water. This method is based on the Brundtland Report [37] definition of sustainable development. The model can identify areas for improvement in environmental, economic, and social sustainability and identify complex opportunities for progress based on a simple decision-making process at all relevant levels of decision-making. The cube in the article can represent the three areas together; the relative independence of the three areas does not allow for other representations, e.g., in two dimensions. However, the cube can be placed in a Cartesian coordinate system with three coordinates. The proposed framework enables the identification of strengths and weaknesses across environmental, social and economic dimensions and supports transparent prioritisation of local water-retention interventions. By combining a simple multiplicative scoring approach with a lean monitoring design, the framework provides a practical decision-support tool for municipalities operating under limited technical and financial capacity.

Key findings

This paper suggests ways to approach more sustainable settlements without needing complex tools. It is often the case that local leaders have limited options for helping their communities through environmental initiatives. This method employs a straightforward 'yes' or 'no' approach to the elements that must be considered to achieve climate-resilient settlements. The proposed methodology supports the sustainability process in implementing water retention measures. The Local Water Retention Assessment Index advanced in this paper is flexible and applicable to any location or region. The cube-type visualization helps to see the results of developments, which show movement along a trajectory within the cube due to the decision-maker's interventions.

Limitations of the paper

Concerning the limitations of the model detailed here, it is limited in its ability to consider the geographic and hydrological variations at the global scale. Although it provides the steps required to build a monitoring network, it does not provide detailed technical content. Additionally, the paper's results are recommended for decision-makers without expertise in hydrology.

Implication for future results

The presented method can be refined with additional monitoring systems that work with climate change impacts. This could be an integrated drought monitoring system that works with a new drought concept, taking into account soil type and water retention [38]. It could be a new land evaluation system [39] that looks at the impact of soil physical properties on water retention and production potential. IoT solutions, such as water parameter monitoring systems, are also available to study water retention [40].

This paper reflects the lack of tools, knowledge, or actual place for local leaders to activate measures to adapt to climate change. However, climate adaptation cannot be regarded solely as a technical solution; as outlined in the introduction, the process must also be supported by local citizens. Thus, awareness-raising, stakeholder involvement, and a realistic target state are crucial parts of the process. The introduced method is a modest start to educating non-experts and has results simultaneously.

Conflict of interest statement

The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability statement

Publicly available data from the LIFE-MICACC project used as a case study in this article can be found at https://vizmegtartomegoldasok.bm.hu/en.

Author contributions

Conceptualization: Zs. H., B. L., and Zs. C. Writing: B. L. and Zs. H. Analysis and research: B. L., Zs. H., Zs. C., T. E. and D. Sz. Graphics and figures: Zs. H. and D. Sz.

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NOMENCLATURE

Symbols

P	Pillar	[dimensionless]
E	Economic aspect	[Rating (0–4)]
G	Geographical aspect	[Rating (1–10)]
S	Society aspect	[Rating (1–10)]
n	Environmental parameter	[various]
T	temperature	[°C]
f	function	
q	water vapor	[g/kg]

Greek letters

Φ	water discharge	[m^3/sec]

Abbreviations

ALADIN	Aire Limitée Adaptation Dynamique Développement International (Limited Area Dynamic Adaptation International Development)
ECON	ECONomy
GIS	Geographic Information System
LIFE	L'Instrument Financier pour l'Environnement
IRED	Indigenous Regenerative Ecosystem Design
MCDA	Multi-Criteria Decision Analysis
MICAC	Municipalities as Integrators and Coordinators in Adaptation to Climate Change
MSW	Making Space for Water
NBS	Nature Based Solution
NFM	Natural Flood Management
NWRM	Nature-based Water Retention Measures
RegCM	Regional Climate Model
SOC	SOCiety
RFR	Room for the River
WFD	Water Framework Directive
WNP	Working with Natural Processes
WWF	World Wide Fund for Nature

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