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Selection of sustainable projects for floodplain restoration and urban wastewater management at the lower Chubut River valley (Argentina)

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Abstract

Urban growth causes environmental degradation of extended areas at the coastal floodplain of the Chubut River (Argentina). We developed procedures to identify environmentally sustainable engineering projects for floodplain restoration and urban wastewater management. We addressed specific questions about considering basic hydrological knowledge, stakeholders' interests and social acceptance, and evaluated scoring methods that would be consistent, non-redundant and robust to various weighting criteria. Our procedures followed the following steps: (1) identification of sustainability paradigms adapted to local contexts; (2) development of hydrological modeling and collection of expert and stakeholders' judgment in order to formulate a wide palette of feasible project alternatives; (3) development of a set of indicators of environmental sustainability to evaluate the project alternatives and test of their self-consistency; (4) evaluation of the proposed projects by means of a hierarchical multivariate analysis, estimation of the indicator weights through multivariate analyses of the un-weighted judgment scores, and reduction of the redundancy incurred during project evaluation. Finally, we identified a small set of highly ranked project alternatives to achieve floodplain restoration and sustainable urban wastewater management in the area and tested the obtained ranks for sensitivity and robustness to eventual bias in the estimation of environmental scores. We discuss the methodological developments presented in this study and their eventual application to similar landscape and urban planning scenarios.

Keywords: Urbanized floodplain; Multiple criteria assessment; Sewerage pollution; Environmental impact assessment; Urban planning

1. Introduction

In this study, we formulate and develop techniques to inspect several scenarios of alternative projects for urban wastewater management and floodplain restoration at the lower Chubut River (Argentina). To this aim, we inspect the suitability of expert and stakeholders' criteria to develop scores of their ecological sustainability. Specific questions addressed were how to devise designing procedures that would consider basic hydrological knowledge, stakeholders' interests and social acceptance, and scoring procedures that would be consistent, non-redundant and robust to various weighting criteria. We also seek to improve understanding in the evaluation of sustainability of urban–floodplain systems through multiple criteria decision analysis (MCDA) models and present procedures for MCDA model construction and testing through multivariate statistical analysis.

1.1. Urban growth and environmental sustainability

Urbanization poses vexing challenges to the ecological sustainability and restoration of stream ecosystems (Walton et al., 2007). Urban wastewater treatment systems and disposal can contribute to stream and floodplain degradation (Balkema et al., 2002). Thresholds of urbanization effects differ among urban regions (Yoder et al., 1999; Coles et al., 2004). This partially justifies that in many cases where habitat restoration is needed, projects are not based on higher-level planning but depend on local decisions, e.g. flood defense work (Holmes and Nielsen, 1998; VAW, 1993). Due attention is not always given to the underlying ecological processes that form rivers and their floodplains and many projects have not been self-sustaining and

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required continued management input, for example, mimicking geomorphic processes with excavating works. It has been argued (Clarke et al., 2003) that river restoration will only be sustainable if it is undertaken within a process-driven and strategic framework with inputs from a wide range of specialists.

Recent approaches to floodplain restoration emphasize the potential of low impact drainage (LID) devices (Elliott and Trowsdale, 2007). LID devices include wetlands, ponds, swales, rainwater tanks, bio-retention devices, vegetated filter strips, and filter strips. LID approaches also include non-structural measures such as alternative layouts of roads and buildings to minimize imperviousness and to maximize the use of pervious soils and vegetation, contaminant source reduction, and programs of education to modify activities. LID particularly emphasizes on-site small-scale control of storm water sources (CIRIA, 2000).

The selection of sustainable engineering projects for floodplain restoration and urban wastewater management can be conceived as a MCDA (Belton and Stewart, 2002). A typical working flow in a MCDA of this type includes: (a) the formulation of various alternative projects; (b) the identification of evaluation criteria and quantitative indicators thereof; (c) the construction of project scores, e.g. a value function (Tillman et al., 1997; Gupta et al., 2003); (d) the design of adequate tests to evaluate the uncertainty, consistency, redundancy, sensitivity and robustness of the decision process.

The uncertainty in MCDA depends on the quality of the data available to the decision team. Consistency refers to the proper ordination of the evaluation criteria and can be rigorously defined through matrix algebra methods (Saaty, 2005). Redundancy refers to the evaluation of a same project trait through conceptually overlapping criteria, and eventually causes bias in project scoring. Sensitivity and robustness refers to the variation in project scoring caused by variation of the qualifying criteria and are related to the risk involved in adopting a given evaluation result.

Principal component analyses (PCA) can be used during the testing phase of the MCDA of environmental projects (Basson and Petrie, 2007). PCA is a multivariate data analysis technique that can be used to determine the underlying structure of multivariate data. This is done by describing the variation of the multivariate data in terms of a set of uncorrelated variables or principal components (PCs), each of which is a particular linear combination of the original variables. PCA is usually applied to summarize multivariate data within known levels of information loss, a characteristic of PCA that prompts its use in decision model testing.

In the MCDAs involved in selecting sustainable environmental projects, life cycle assessment (LCA) has gained recognition as a tool that can provide environmental performance information to support decisions in both the private and public sectors (Bare et al., 1999). LCA applied to an engineering project is a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of the project throughout its life cycle (Tibor and Feldman, 1996).

1.2. Study plan

We describe the study area (Section 2.1) and present summarily results of a water balance model of the Chubut River coastal floodplain (Section 2.2). We then describe a LCA-based technique to design several project alternatives for floodplain restoration and urban wastewater management (Section 2.3). In Section 2.4 we present a set of paradigms and indicators of environmental sustainability of project alternatives and PCA-based definitions of score weights, sensitivity and robustness of project evaluation. We report results of the water balance model in Section 3.1 and their application to the selection of alternatives, along with other indicators, as well as the results of sensitivity and robustness tests of the various scorings obtained, in Section 3.2. We discuss methodological developments in this study in Section 4 and summarize the main conclusions in Section 5.

2. Methods

2.1. Area description

The area between −43.23S/−65.28W and −43.28S/−65.06 W (Fig. 1) is the most densely populated at the lower Chubut River basin in Argentina, including Trelew city (population: 170,000) and the Chubut state capital Rawson (population: 25,000) as well as nearby agricultural land located by the river on the lower banks of the valley. Flooding risk is created by the lagoon system at the NE of Trelew city (lagoons 2–5) that discharge waters to the E–SE in direction to Rawson city.

Most of the landscape corresponds to old alluvial plains of fluvial-maritime origin with gentle slopes to the east and soils rich in clay fractions and low permeability. These are arranged in a complex system of flatlands–lowlands partially separated by coastal cord dunes, ravines and embankments that turn into semi-permanent lagoon systems depending on the intensity of seasonal precipitations. As in other similar flatland hydrological systems (Serra, 2003), the local hydrological basins are poorly defined, and runoff flow routing largely depends on the intensity of storms.

The area collects runoff from an extended group of hydrological units spanning about 300 km^2, particularly during the winter rainy season (April–June). Due to additional discharges of urban wastewater (sewerage + runoff), extended parts of the area evolved into semi-permanent lagoons during recent decades. During periods of high water recharge, inter-connections of the lagoon systems occur, and extended land areas would remain under water during considerable periods. Urban runoff has increased steadily during recent years consequently with the expansion of the nearby Trelew city and the decrease in soil permeability due to urbanization (Bertoni, 2006). There is also evidence (Stampone et al., 1995) that the lagoon system receives underground water flows. Additionally, due to structural decay at locations along the urban sewerage collecting net, runoff waters eventually find their way to the sewage pumping facilities and to the lagoon system (Serra, 2005) where sewage flows from nearby Trelew city are also discharged.

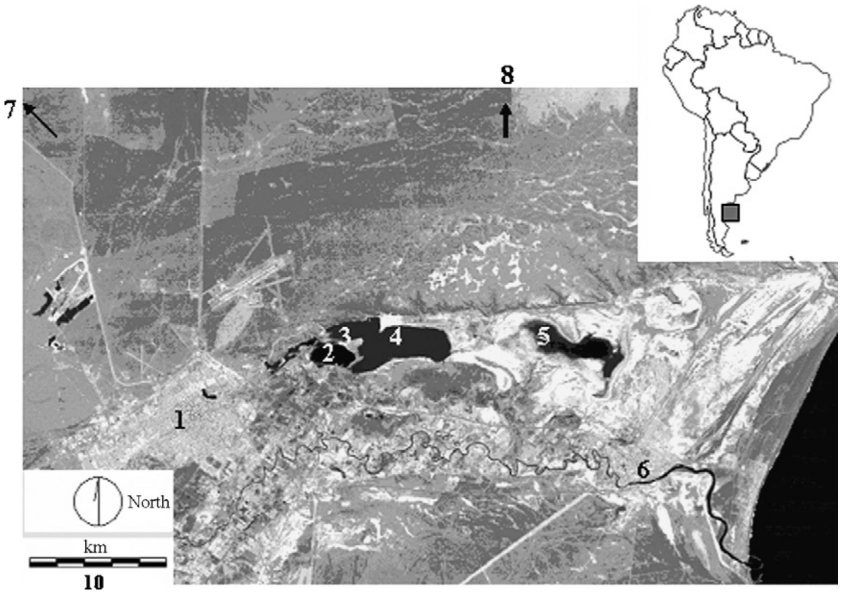


Fig. 1. Upper right inset: location of the lower Chubut River basin in the South American continent. Main inset: a composite image (Landsat 5, Bands 3–5, September 2005) of the study area obtained after the seasonal high flood period. 1: Trelew city; 2–5: main semi-permanent lagoons; 6: Rawson city. Outside image's area: 7: Devil's lagoon; 8: Simpson's lowland.

During early urban development in the region, the alluvial plains were effective in retaining the incoming water flows, and evaporation from the inundated areas sufficed to prevent flooding outside the most depressed areas. Natural attenuation (NA) was also effective in reducing pollution caused by sewage discharges. In recent years, flooding episodes have become increasingly frequent and required interventions in the form of small dams and routing devices, which proved to be insufficient to contain waters during unusually rainy years. These triggered the need to find sustainable ways of managing the hydrological systems that would consider further urban expansions and consequent modifications of the regional water balance.

2.2. Water balance: model development and validation

We formulated a water balance model of the area occupied by lagoons 2–5 in order to estimate the maximum elevation of their water surfaces, the volumetric content and feasible ways of water flow among them. The expression:

$$\frac{\mathrm{d}S_h}{\mathrm{d}t} = I_t - O_t \tag{1}$$

where S is the water storage below a defined lagoon control surface at height h and I_t, O_t, the inflow–outflow fluxes (Chow et al., 1994) was numerically solved by assuming $\mathrm{d}t = \Delta t = 1$ month. Storage changes were evaluated as

$$S_{h,t} = S_{h,t-1} + f_1(PA) + f_2(PR(A_{\mathrm{c},h} - A_h)) + f_3(U_\mathrm{r}) + f_4(W) - f_5(C) - f_6(I) - f_7(E) \tag{2}$$

where S_h is the storage (m^3) at height h and time t (months); P the precipitation flow; R the precipitation/runoff coefficient (0.11–0.23); $A_{\mathrm{c},h}$ the potential maximum area collecting runoff towards the lagoon system; A_h the lagoon area at height h; U_r the urban runoff flow discharged to lagoons through urban main drain; this is estimated on the basis of average inflows to lagoons in excess of daily urban water consumption rates; W the sewerage inflow to lagoon; C the consumptive use (irrigation); I the infiltration through lagoon base estimated as in Horton's equation (see Beven, 2004) corrected with field infiltrometer data and inverse simulation modeling; E the evaporative flow, as estimated from tank data; f_i is the coefficients for dimensional equivalence.

We considered precipitation (P) anomalies due to potential global change during 2003–2028 in the context of IPCC (2001, 2007) possible climate change scenarios A2 and B2 as available from URL: http://ipcc-wg1.ucar.edu. These represent rather extreme cases among those regarded as feasible considering expected trends in the world economy. The A2 scenario results in atmospheric $[\mathrm{CO}_2] \approx 800$ ppmv at the end of this century as compared to $[\mathrm{CO}_2] \approx 594$ ppmv as predicted by B2 scenario (Schlesinger and Malyshev, 2001). In order to predict anomalies in the precipitation regime corresponding to these scenarios we used the AOGC models HadCM3 (Hadley Centre for Climate Prediction and Research, Berkshire, UK; Gordon et al., 2000; Pope et al., 2000), CCSR/NIES (Center for Climate System Research, National Institute for Environmental Studies, Tokyo, Japan; Emori et al., 1999), and CSIRO Mk2 (Australia's Commonwealth Scientific and Industrial Research Organisation, Mordialloc, Australia; Gordon and O'Farrell, 1997; Hirst et al., 2000). All three models, participated in a recent coupled model intercomparison project (CMIP2) (Covey et al., 2003) and the HadCM3 model partly supported the predictions in IPCC (2007). We expressed the outputs of runs of each model at A2–B2 scenarios as relative precipitation (P) deviates with respect to predicted baseline values. We found that adopting the uncertainty range generated by application of these various scenario–model combinations led to a less conservative flood risk estimate than adopting the P series corresponding to the most humid hydrological year (1998) recorded at the area during the period 1914–2003, which was alternatively selected for this study.

We simulated inter-lagoon flows in a cascade-storage tank paradigm (Croley, 2002) based on the differences in hydraulic head among lagoon surfaces and their corresponding volumetric differences as estimated from height–volume functions characteristic of each lagoon.

We obtained data (1994–2005) about daily sewerage discharges, domestic water demand, and water surface height at lagoons from the Trelew city authority, and meteorological and tank evaporation data (tank factor: 0.7) from INTA (National Institute for Agricultural Technology) meteorological station, Trelew. We further estimated runoff values by comparison with similar gauged hydrologic units in the study area, monitored at storms during 1992 and 1998 (Serra, 2006). We estimated the potential maximum runoff collecting area A_c through mapping of the flooded area following a 160-year recurrent storm (23 cm) that occurred 22 April 1998 to 25 April 1998 (Chachero, 2006). Mapping of the flooded area was performed on image WRS = 227/090F obtained by the TM10 sensor (LANDSAT 5) at 25 April 1998. S values were estimated from height–volume functions obtained by analysis of a Digital Elevation Model (x–y resolution: 90 m) supplied by the National Aeronautics and Space Administration (NASA, USA) validated with a local field topographic survey.

2.3. Compilation and design of project alternatives to flood prevention and urban wastewater management

An expert team at the UNPSJB compiled previous studies, ideas, projects and past initiatives about flood prevention and urban wastewater management in the area and formulated additional project alternatives along ecological engineering concepts. A preliminary survey of previous local studies and stakeholders' interests about feasible courses of sustainable action identified several alternatives varying in their emphasis depending on the particular dimension of the floodplain scenario that would be addressed. These included flood prevention, social costs, wastewater management, re-use alternatives for wastewater, and floodplain restoration.

Technological scenarios were classified according to possible combinations of feasible alternatives of sewerage net conditioning, sewerage routing treatment and excess flow disposal (Table 1). With respect to conditions at the urban sewerage net collection systems of Trelew city, three possible alternatives were considered:

- *As in present status* (2006): this group of alternatives (#1, #8) considers maintaining the present status of the collecting systems at Trelew. This is characterized by severe damage at places in the sewerage system, resulting in extended mixing of urban rain runoff and domestic waters; public education programs and/or micro-measurement aiming to minimize water use are scarcely developed.
- *Improved situation I*: this group of alternatives (#2, #5, #10, #14, #17, #20, #23) considers public works to be done on major sewerage collectors and structures for urban runoff control to achieve a reduction of up to 10% of total sewerage flow.
- *Improved situation II*: this group (#3, #6, #12, #15, #18, #21, #26) considers improvement actions taken at level I supplemented with additional works to achieve a reduction of 26% of sewerage flow (3.5% of urban runoff). Public water use would be reduced by 10% through investment in micro-measurement of water demand and educational programs.

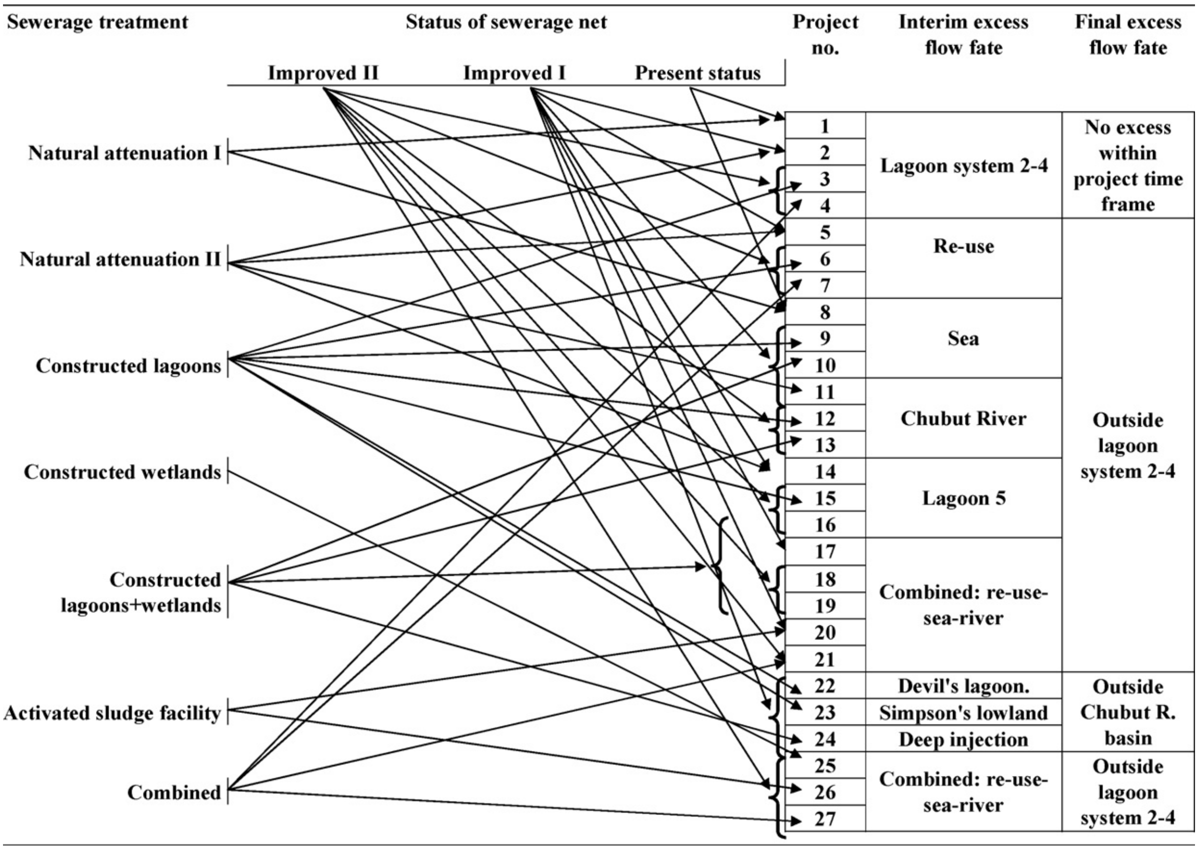
Alternatives for sewerage + runoff flow routing and treatment systems included separate channel systems to divert urban runoff waters and two levels of intensification of NA (Friedler et al., 2003) processes. At NA I (#1, #8), part of the lagoon system would receive sewerage flows that would decay to environmental acceptable standards of biological oxygen demand (BOD) and total suspended solids (TSS) as measured at a point defined within the existing hydrological system. At NA II (#2, #5, #11, #14) this would be combined with engineering practices for proper routing of sewerage flows and flood prevention. A third group of treatment alternatives (#3, #6, #9, #12, #15, #22, #23) considered constructed lagoons (Saenz, 1985), with engineering improvements (non-permeable lagoon bottom, controlled flow-residence time) to achieve BOD and TSS standards while making optimal use of space. Constructed wetlands (Belmont et al., 2004) were also considered as unique treatment system (#25) and in combination with lagoons (#10, #13, #16–#19, #24) in order to reduce N and P water loads to conform local discharge standards.

Alternatives places for final disposal of eventual excess water flows were considered in various combinations with the above-mentioned cases. A group of alternatives (#1–#4) considered containing all excess flows within the components of the lagoon system 2–4, with final disposal based on natural or forced evaporation. Another group (#5–#21) considered alternatives outside the area of lagoons 2–4, either through temporary storage and seasonal irrigation use, disposing to the coastal sea, to the Chubut River main stream, to lagoon 5 or combinations thereof. A group of alternatives raised by some stakeholder groups implying disposal of excess flows outside the lagoon system and even outside the Chubut River basin were also considered (#22–#27).

2.4. Selection of a set of indicators of environmental sustainability of alternative projects

A list of indicators to evaluate the environmental sustainability of alternatives for flood prevention was constructed based on ecosystems management (Grumbine, 1994), life cycle-based criteria of environmental quality (IKP-PE, 2005), technical feasibility, local social acceptance and expert advice as obtained from previous studies in the area and ad hoc required, mainstream expert opinion on the state of the system. Main sustainability criteria adopted and their conceptual justification were as follows:

Table 1
Structural characteristics of proposed projects at the lower Chubut River basin



Project no.	Interim excess flow fate	Final excess flow fate
1	Lagoon system 2-4	No excess within project time frame
2		
3		
4		
5	Re-use	Outside lagoon system 2-4
6		
7		
8	Sea	
9		
10		
11	Chubut River	
12		
13		
14	Lagoon 5	
15		
16		
17	Combined: re-use-sea-river	
18		
19		
20		
21		
22	Devil's lagoon.	Outside Chubut R. basin
23	Simpson's lowland	
24	Deep injection	
25	Combined: re-use-sea-river	Outside lagoon system 2-4
26		
27		

- *Preservation of the floodplain habitat and natural runoff routing*. The halomorphic floodplain at the lower Chubut River results from present geomorphology and past action of glaciary processes. As other floodplains (Naiman et al., 1995; Malanson, 1995; Ward et al., 1999), the area constitutes a local biodiversity hotspot (Lizurume et al., 1995; Blanco and Canevari, 1996) as well as a potential space for community amenity and education. Flooding of the area is to a certain extent a natural process resulting from the seasonal balance of rainfall and evaporation demand. The preservation of near-natural river flows is a key element in restoring floodplains and the establishment and persistence of riparian habitats and species rely on a complex, dynamic hydrological regime. This regime includes intra- and inter-annual flood variations in timing, duration, magnitude and shape of the hydrograph (Brookes and Shields, 1996; Pedroli et al., 2002). High scored projects for floodplain restoration should address an adequate mix of traditional engineering works and LID alternatives.
- *Minimization of material, energy expenditure, and waste disposal and maximization of pollution control at the sources*. This is a numerous group of evaluation criteria and refers to project engineering details and technical specifications. High-scored projects for floodplain restoration should be among those that would minimize the amount of polluted sewerage flows, soil movements, materials used, and energy expenditure both during the engineering works as well as during the operative phase of the project. These criteria imply a life cycle approach to evaluating alternative projects for flood prevention. The time boundaries of the life cycle analysis were conventionally set from present time up to the end of the project cycle (25 years).
- *Conformity with state-of-the-art, voluntary international norms of good practices in environmental management*. These imply that high-scored projects should be amenable to efficient monitoring (Carroll and Meffe, 1997) and measuring (i.e. continuing evaluation) according to accepted statistical sampling theory (Christensen et al., 1996). Results should be suitable to generate documentation for external project auditing (including control by the local population), continuing improvement, and pollution prevention. This implies that the engineering solution should respect to the possible extent the views and requirements of the involved populations both at Trelew, Rawson and the rural area. It is recognized that public acceptance might depend on proper information. Also, identifying public wishes might require specific techniques to avoid circumstantial political scenarios, considering the life cycle defined for the project.

Projects involving final disposal of wastewaters under the sea surface, through deep ground injection or discharge to desert areas outside the Chubut basin would obtain low scores under these criteria.

- *Project operation should be amenable to quantitative modeling, research, adaptive management and environmental* *education*. The structure of the project should allow efficient quantitative modeling, continuing research and adaptive management (Hale and Adams, 2006). This characteristic is tied to technological advance in floodplain restoration (e.g. a project that would consider underground injection of excess water would not be highly ranked under this item considering the current state of the art and attainable precision in underground water modeling). Continuing research would also serve the purpose of environmental education.

The above-mentioned criteria were presented to a panel of experts that included municipal architects and engineers, technical staff at the local university with expertise in the local hydrology, supervisors of the sewerage-collecting system and municipal authorities at Trelew and Rawson. The panel reviewed the concepts and reworked them into several groups of sustainability indicators. Emphasis was on measurable indicators even if presently available data would only support semi-quantitative assessment of their value-intensity during the project life cycle. Social acceptance was tested through an extensive grid of interviews with citizens living near the area under flooding risk, public hearings with the local population and meetings with the local municipal councils. Table 2 describes the set of indicators finally adopted. All indicators were defined in terms of positive environmental impacts ("the larger the better", Zhou et al., 2006) and assigned a rank through a scale: 0, absence of the attribute in the considered alternative; 1, low expression; 2, mid-term expression; 3, high expression or attribute value.

2.5. Scoring of alternative projects

In a preliminary scoring process, each alternative project was independently evaluated for each of the sustainability indicators and a matrix **A** was constructed such that:

$$\mathbf{A}=\begin{bmatrix} w_1\times s_{1,1}, & w_2\times s_{1,2}, & w_3\times s_{1,3}, & \dots & w_j\times s_{1,j}\\ w_1\times s_{2,1}, & w_2\times s_{2,2}, & w_3\times s_{2,3}, & \dots & w_j\times s_{2,j}\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ w_1\times s_{i,1}, & w_2\times s_{i,2}, & w_3\times s_{i,3}, & \dots & w_j\times \mathbf{s}_{i,j} \end{bmatrix} \tag{3}$$

where $0\le \mathbf{s}_{i,j}\le 4$ are j un-weighted scores corresponding to i alternative projects evaluated according to j indicators of sustainability, and $0\le w_j\le 1$ is a vector of corresponding indicator weights. Each alternative project was characterized by a value function $0\le y\le 1$:

$$y_i=\Sigma j\, w_j\times \mathbf{s}_{i,j} \tag{4}$$

where $s_{i,j}$ is a normalized s_j score. Non-weighted value functions ($w_j=1$, $\forall\, j$) were also computed for comparative purposes. According to Saaty (1980) **A** is consistent provided:

$$w_{ij}=w_{ji}^{-1}\quad \text{and}\quad w_{ij}=w_{ik}\times w_{kj} \tag{5}$$

for all i, j, k. Consistency of **A** was achieved through estimation of the normalized eigenvector corresponding to the maximum eigenvalue of **A** (Deturck, 1987; Xu and Wei, 1999). Next, the matrix $\mathbf{B}_{(q\times q)}$ of binary comparisons among alternatives (weight ratios) was defined:

$$\mathbf{B}=\begin{bmatrix} w_1/w_1, & w_1/w_2, & w_1/w_3, & \dots & w_1/w_j\\ w_2/w_1, & w_2/w_2, & w_2/w_3, & \dots & w_2/w_j\\ \vdots & \vdots & \vdots & \vdots & \vdots\\ w_j/w_1, & w_j/w_2, & w_j/w_3, & \dots & w_j/w_j \end{bmatrix} \tag{6}$$

Relative weights w_m/w_n ($0\le m,n\le j, m\ne n$) were estimated from corresponding averages of the load coefficients of the first 5th, 2nd, and 1st PC(s) of the binary correlation matrix ($i\times i$) of un-weighted **A** rows ($w_j=1$, $\forall\, j$). The procedure described in Eqs. (3)–(5) was followed and projects were assigned a rank r according to their decreasing value function.

Redundancy R_e was quantified as

$$R_e=\frac{m}{t} \tag{7}$$

where m is the number of significant ($P\le 0.01$, two-tail test) binary correlation coefficients between paired un-weighted **A** rows, and:

$$t=\frac{i\times i-i}{2} \tag{8}$$

the number of correlation coefficients in the correlation matrix, excluding the diagonal elements.

Sensitivity S was defined as

$$S=\frac{\sum_{i=1,\dots,r}(100y_i-100\hat{y}_i)^2}{p} \tag{9}$$

where y_i ($i\le r$) is the value function score (see Eq. (4)) of a project among those within the higher r value ranks, attained with a given weight vector w_j estimated with a PCA reduction of total variance $(1-p)$; $\hat{y}_i$ is the un-weighted value function corresponding to the same project when $\hat{w}_j=1, \forall\, j$ and p is the fraction of variance of the correlation matrix of **A** rows explained through PC extraction. Similarly, robustness R_0 was defined as

$$R_0=\frac{1}{S} \tag{10}$$

3. Results

3.1. Water balances

Fig. 2 shows the changes of water surface height observed at lagoon 3 during the period 1993–2005 as recorded at monthly intervals as well as the reported urban sewerage discharge volumes into the lagoon system during the same period. Modeling results indicated that the balance of cold-season precipitation and summer evaporation cycles accounted for the observed intra-annual cycles of variation in lagoon height. A steady increase of both the minimum and maximum height values within intra-annual cycles is also observed. The corresponding increase in annual average flooded surface correlates with increasing sewerage flows from Trelew city during the same period ($y=471.1\,\mathrm{e}^{1\mathrm{E}-07x}$; $R^2=0.99$; y: flooded area (ha); x:

Table 2
Environmental indicators to evaluate the sustainability of floodplain restoration and urban wastewater management projects

	Indicator (+)	Meaning
1	Indicators related to production-emission of sewerage flows	
1.1	Sewerage flow (quantity)	Effective separation of urban wastewater-precipitation-runoff. Control of unauthorized inflows, micro-monitoring of water use, public education program to reduce water use
1.2	Sewerage flow (quality)	Control of industrial-commercial unauthorized inflows (oil-greases, chemical loads)
1.3	Technical-instrumental capacity to measure sewerage outflow variables	Operative feasibility to monitor-measure relevant qualitative-quantitative parameters of sewerage outflows
2	Indicators related to transport, dispersal and treatment of sewerage flows	
2.1	Processing time to attaining target BOD	Sewerage outflow treatment effective through improved exposure to anaerobic-aerobic conditions during treatment process
2.2	Lower BOD at time of final disposal	Treatment process efficient in attaining low loads of non-persistent organic matter
2.3	Land surface occupied by sewage treatment	Treatment process efficient in terms of area of land surface occupied by treatment facilities
2.4	Added value of products derived from water re-use	Sewerage collection, treatment and transport costs partly recovered through production of products with market value: forage, groceries, fruit trees, lumber)
2.5	Excess flow discharged to landscape compartment (river, soil, sea)	Treatment process generates and allows water consumptive use through plant biomass production, efficient evaporation, etc.
2.6	Chemical quality (low content of N, P, heavy metals) of excess flow	Treatment process improves chemical quality in terms other than BOD
2.7	Feasibility of monitoring excess flow discharges to river, soil, sea	The project allows continuous monitoring of excess flow discharges from the lagoon system
2.8	Water re-use produces positive environmental impacts	Spaces generated by water re-use are suitable for amenity, insect-bird biodiversity, flowering plants suitable for feeding of bees, etc.
2.9	Re-location of lagoons respect valuable water resources	The location of untreated sewerage facilities is sufficiently far from underground water sources or neighbor lagoon systems
2.10	Energy consumption	The project minimizes energy consumption at pumping and sewerage treatment
2.11	Feasibility of mathematical modeling and functional analysis	The project implies proven technologies with analogous dimensional characteristics, from which quantitative-functional knowledge is available
3	Indicators related to the final disposal of solid waste generated during sewage treatment (salts, mud, heavy metals)	
3.1	Drainage of soluble salts from lagoon water	The project allows adequate drainage rate of soluble saline waste to water compartments with adequate dilution capacity
3.2	Load of sedimentary solids to lagoon systems	The project provides for separation of sedimentary solid wastes, thus reducing the embankment processes at the lagoon system
3.3	Sedimentary solids	The project defines procedures to remove sedimentary solids at lagoon system
3.4	Final disposal of sedimentary solids	The project defines environmentally sustainable alternatives-facilities for final disposal of sedimentary solids
3.5	Feasibility of tracing the environmental fate of pollutants from urban runoff	The project includes procedures-facilities to account for the fate of organic and inorganic pollutants eventually reaching the lagoon system
4	Conformity of the project with international environmental management standards	
4.1	Feasibility of continuing improvement in project efficiency	The structure of the project (modular, progressive) allows considering continuing improvement of urban and land runoff control
4.2	Feasible environmental auditing and documentation	The structure of the project makes feasible environmental auditing and procedural documentation on flows, pollutant concentrations, hydrometric data, etc.

urban sewerage flow (m^3/year)).The water balance model further predicts that under the present average annual precipitation regime the water surface height at lagoons 3–4 would attain levels between 5.0 and 6.2 m implying a corresponding flooding surface of 450–520 ha. Occasional high precipitation events would produce flooding downstream to lagoon 5, in the vicinity of Rawson city. The flooded surface would increase at a rate of 8 ha/year resulting from predicted increasing sewerage flows from Trelew city into the lagoon system. In case of extreme (160-year recurrent) precipitation events, intense flooding would occur towards the east occupying up to 750–770 ha, corresponding to an excess flow of 3.2 Hm^3/year. This would imply reverse flooding into urban runoff collecting systems and water intrusion into populated areas.

These results implied that project alternatives #1–#3 (Table 1) are not feasible within a projected time scenario of 25 years. All other remaining alternative projects (#4–#27) constitute feasible solutions to sustainable flood prevention at the area, and include provisions for disposing excess water flows outside the lagoon system or outside the Chubut River basin.

3.2. Scoring alternative projects

Table A1 (Appendix A) shows the un-weighted scores corresponding to all indicators of environmental sustainability (see Table 2) assigned to each project through expert judgment.

Table 3 shows the matrix of binary correlation coefficients among un-weighted scores in Table A1. The inspection of the

Table 3
Correlation matrix of indicator un-weighted (see Appendix A, Table A1) scores among alternative projects for floodplain restoration at the lower Chubut River basin (see also Table 1)

Indicator	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	3.1	3.2	3.3	3.4	3.5	4.1	4.2
1.1	1.00																				
1.2	**1.00**	1.00																			
1.3	**1.00**	**1.00**	1.00																		
2.1	0.48	0.48	0.48	1.00																	
2.2	0.34	0.34	0.34	**0.68**	1.00																
2.3	0.40	0.40	0.40	**0.69**	0.45	1.00															
2.4	−0.04	−0.04	−0.04	0.10	−0.11	−0.18	1.00														
2.5	0.41	0.41	0.41	0.17	0.09	0.08	0.17	1.00													
2.6	0.39	0.39	0.39	**0.69**	**0.69**	0.39	−0.05	0.24	1.00												
2.7	**0.54**	**0.54**	**0.54**	0.50	0.48	0.43	−0.16	0.15	0.33	1.00											
2.8	−0.24	−0.24	−0.24	0.06	0.04	−0.28	**0.79**	0.19	−0.09	−0.09	1.00										
2.9	0.38	0.38	0.38	0.33	0.19	0.35	−0.28	0.24	0.18	**0.70**	−0.32	1.00									
2.10	0.36	0.36	0.36	−0.27	−0.32	−0.02	−0.14	0.16	−0.28	0.23	−0.31	0.47	1.00								
2.11	**0.61**	**0.61**	**0.61**	0.31	0.08	0.45	−0.33	0.21	0.00	**0.69**	−0.38	**0.77**	0.43	1.00							
3.1	0.15	0.15	0.15	**0.67**	0.34	**0.55**	0.23	0.00	0.20	0.37	0.31	0.02	−0.29	0.16	1.00						
3.2	**0.82**	**0.82**	**0.82**	0.37	0.46	0.45	−0.07	0.34	0.42	**0.57**	−0.19	0.38	0.44	0.47	0.08	1.00					
3.3	0.20	0.20	0.20	**0.57**	0.33	**0.57**	−0.01	0.37	0.41	0.30	0.09	0.29	0.06	0.10	0.40	0.32	1.00				
3.4	0.20	0.20	0.20	0.28	0.04	0.21	0.00	0.36	0.20	0.20	0.17	0.10	−0.03	0.13	0.13	0.26	**0.63**	1.00			
3.5	**0.53**	**0.53**	**0.53**	**0.54**	**0.56**	0.48	−0.21	0.35	0.48	**0.90**	−0.14	**0.78**	0.21	**0.68**	0.23	**0.57**	0.43	0.29	1.00		
4.1	**0.58**	**0.58**	**0.58**	0.21	0.35	0.39	−0.34	0.24	0.40	**0.61**	−0.42	**0.60**	**0.56**	0.47	−0.10	**0.82**	0.38	0.29	**0.67**	1.00	
4.2	**0.61**	**0.61**	**0.61**	**0.70**	0.33	**0.63**	−0.06	0.40	0.38	**0.70**	−0.16	**0.75**	0.37	0.72	0.37	**0.55**	**0.62**	0.41	**0.77**	**0.56**	1.00

Values in bold correspond to significant coefficients ($P \leq 0.01$, two-tail test).

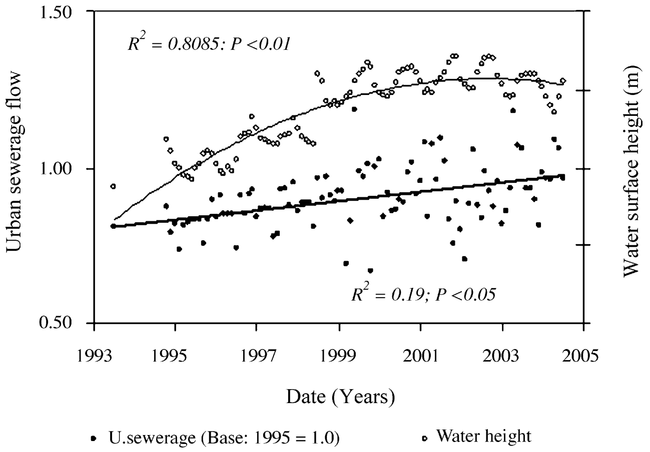


Fig. 2. Observed changes in daily sewerage flows from Trelew city discharged into the lagoon area and observed water surface height at lagoon 3 during the period 1993–2005.

matrix reveals a moderate degree of redundancy ($R_e = 0.26$). The summarization of these data through five PCs (accounting for 81.3% of the total variance of the correlation matrix), two PCs (57.1% of the variance) and one PC (41.9% of the variance) removes redundancy in gradual steps. Table 4 shows the value functions y (Eq. (4)) corresponding to project alternatives (only those projects corresponding to $r \leq 10$ shown) at various stages of redundancy removal. In all cases project #4 outscores the rest followed by projects #21 and #12. The relative ranking of this top sub-group of projects is independent from the degree of variance retained in the data set.

Several traits common to all three contribute to enhance their environmental value function. All of them consider improved collection treatment II which maximizes pollution control at the sources. Also, they result in low BOD residual waters and they also minimize excess flows either by forced evaporation (#4), redirecting the flows to their natural course at the Chubut River (#12) or in irrigation re-use (#21). Rank values show low sensitivity S (high robustness R_0) to variance reductions up to about 60% (two PCs) but S–R_0 vary by nearly one order of magnitude when only 42% of the score variance is employed in the estimation of the value function. This however does not modify the top three project ranks.

Alternative #4 includes discharges of excess water flows within the lagoon system area and final disposal through mechanically forced evaporation. Although this alternative outscored the rest in terms of its ecological qualities, forced evaporation was considered excessively expensive at a further

Table 4
Value function (y), sensitivity and robustness of scores of alternative projects for floodplain restoration at the lower Chubut River basin depending on the degree of redundancy resulting from PC summarization of the correlation matrix of the un-weighted scores (Table 3) (Only indicator-group weights shown for brevity).

Indicator group	Group weight (w)	Project	Value function (y)
a. Five Principal Components		A4	.060
		A21	.054
$p = 0.81$; $S = 0.026$; $R = 27.1$		A12	.050
		A15	.050
1. Production-Emission	.259	A20	.050
2. Transport, treatment	.244	A7	.049
3. Final sludge disposal	.232	A16	.048
4. Conformity w/international	.265	A19	.048
		A27	.048
b. Two Principal Components		A13	.047
$p = 0.57$; $S = 0.052$; $R = 19.03$		A4	.060
		A21	.054
1. Production-Emission	.271	A12	.050
2. Transport, treatment	.258	A20	.050
3. Final sludge disposal	.235	A7	.049
4. Conformity w/international	.226	A15	.049
		A19	.048
		A27	.048
		A13	.047
		A16	.047
c. One Principal Component		A4	.059
$p = 0.42$; $S = 0.214$; $R = 4.65$		A21	.053
		A12	.050
		A15	.049
1. Production-Emission	.298	A19	.049
2. Transport, treatment	.227	A20	.049
3. Final sludge disposal	.246	A27	.049
4. Conformity w/international	.229	A7	.048
		A16	.048
		A25	.048

Notes: p: fraction of accounted variance in PC reduction; w, y like in Eq. (4); S, R like in Eqs. (9) and (10), respectively.

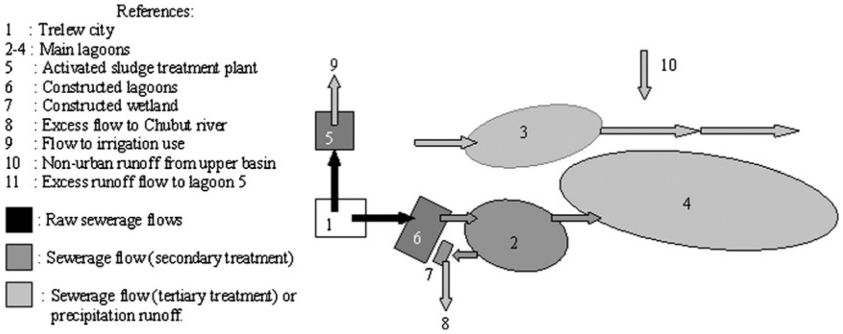


Fig. 3. Schematic view of project alternative # 21 combining conventional and LID engineering tools for flood prevention at the lower Chubut River basin (see also Fig. 1 for further geographic reference).

economic analysis, and accordingly, alternative #21 was selected as preferable by the stakeholders. Fig. 3 shows a schematic view of the flow system in project #21. Raw sewerage flows from Trelew city are collected at two existing pumping facilities. Those from the upper urban levels, with low saline content, are directed to an existing activated sludge treatment plant (5), and further sent to a reservoir for further irrigation use (9). Sewerage from the lower areas of the city with higher concentration of soluble salts will be treated at a constructed lagoon system (6) and stored exposed to further evaporation at lagoons 2 and 4. Eventual excess flows would be submitted to a tertiary treatment at a constructed wetland facility (7) and drained to the Chubut River. Non-urban runoff flows (10) as well as those from a nearby existing water treatment facility will be primarily collected at lagoon 3 and eventually allowed to drain downstream through a specifically dedicated channel (11).

4. Discussion

The analysis of floodplain restoration strategies at the lower Chubut River basin raises several types of considerations that can be of interest in similar environments. These refer to the significance of hydrological balances as primary indicators of sustainability, and the problems derived from multi-criteria scoring of sustainability of engineering projects. These latter include the need of appropriate techniques to check for indicator consistency, redundancy, sensitivity and robustness.

The analysis of the water balances indicates that the recent evolution of the lagoon system has been strongly modified by the increases in urban wastewater flows from Trelew city. It also predicts that the water surface height will continue to increase and overflows towards presently non-flooded areas should be expected. These findings were relevant in discarding project alternatives #1–#3, that were most favored by the local public opinion, and allowed concentrating efforts in finding alternative ways of action.

Several considerations must be taken in mind when evaluating sustainability through multiple indicators. Classical and recent approaches to MCDA in this respect (Leopold et al., 1971; Bojorquez-Tapia et al., 1998; Thompson, 1990; Antunes et al., 2001), rely on the use of aggregate indices, conveniently weighted according to previously established relevance criteria, including contextual elements of the analyzed situation. In all cases, mainstream expert opinion is the only available reference and the objectivity of the evaluation depends on the technical background, experience, and objectivity of the expert team and the pertinence of the set of indicators selected. Project alternatives always imply alternative uses of resources, environment, varying quality of health-safety prevention, and psycho/sociological consequences (Lindhom et al., 2007).

Due to these considerations, the expert team should develop criteria to test the internal consistency of the set of indicators used and the set of relative weights assigned to them, particularly when numerous indicators are proposed (Balkema et al., 2002). If the sustainability analysis follows objective and pragmatic criteria, then the selection of 10–20 indicators represents an acceptable compromise between time and accuracy (Lindhom and Nordeide, 2000). Internal consistency was in this study defined (see Eq. (5)) through the analytical hierarchical process (AHP) (Saaty, 1980). This allowed testing consistency among groups of indicators as well as within groups and contributed to organize and check the information supplied by the panel of evaluating experts.

Data reduction through PCA is used in this study to derive weights for the indicators. As different from ex ante imposing of weights by the expert panel, as is usual in most reported AHP (Farquhar and Keller, 1989; Forman and Peniwati, 1996), indicator weights in this study were derived from the load coefficients of the PCs of the matrix of un-weighted scores. Weights derived in this way reflected ex post the implicit importance assigned by the expert panel to the various indicators. Implicit importance can result from accumulation of redundant indicators about an environmental aspect judged to be relevant, or because the nature of the evaluated phenomenon is amenable to be related to many diverse indicators. The ex post evaluation of indicator weights implicit in expert judgment rather than ex ante definition (Li and Ma, 2007) seems preferable in capturing the value assigned by the experts to the various alternatives. Expert teams using MCDA produce redundant judgments. Redundancy in multi-criteria evaluation is a scarcely treated topic and refers to the construction of a value function y such that several of the component scores would be statistically correlated. This becomes evident through the occurrence of statistically significant coefficients in the project-scores correlation matrix (Table 3). Redundancy in multi-criteria evaluation cannot be suppressed, because indicators are arbitrary intellectual constructions that refer to our interpretation of the structure of natural processes or events. As an example, the quantity and the quality of sewerage flows in this study turned out to be highly correlated, because engineering actions to minimize the quantity (pipe lining, pipe reparation to prevent rain water inflow) would also result in improvement of their quality as inputs to a sewerage treatment facility. This same pair of indicators could behave as un-correlated metrics in other cases. Although absolute thresholds for accepting–rejecting redundancy in MCDA of ecological sustainability might be difficult to define, this study shows an example that could be used as a relative reference.

The hypothesis that redundancy produces biased ranking of the evaluated projects can be tested through reduction of the correlation matrix of indicator scores to a minimum set of its PCs (Hartung and Elpelt, 1986). If the project ranking does not change with decreasing redundancy, then the MCDA can be interpreted as robust to indicator redundancy. This is the approach followed in this study, and the results obtained show that the group of top-ranked projects (#4, #21 and #12) remains invariant to data reduction.

Rankings of lower order ($r > 3$) however, do change with data reduction. This is usually irrelevant to the decision maker who is

Table A1
Scores (un-weighted) and y values (expert estimation) of sustainability indicators corresponding to 23 alternative projects of floodplain restoration

Project	Indicator																					*y* value
	1.1	1.2	1.3	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10	2.11	3.1	3.2	3.3	3.4	3.5	4.1	4.2	
4	3	3	3	2	2	2	0	3	3	3	0	3	3	3	0	3	3	3	3	3	3	**51**
5	2	2	2	1	1	1	2	1	1	1	1	1	3	1	0	2	0	0	0	1	1	**24**
6	3	3	3	2	2	0	2	2	2	2	1	2	2	2	0	2	0	0	1	1	2	**34**
7	3	3	3	2	2	2	1	2	2	2	1	2	2	2	0	3	2	2	1	2	2	**41**
8	1	1	1	1	1	1	0	1	1	1	0	1	1	1	0	0	0	0	0	0	1	**13**
9	2	2	2	2	3	2	0	0	2	3	0	3	2	2	0	2	2	0	2	2	2	**35**
10	2	2	2	2	3	2	0	1	3	3	0	3	2	2	1	3	1	0	2	3	2	**39**
11	2	2	2	1	2	1	0	1	1	2	0	1	2	1	0	2	1	1	1	2	1	**26**
12	3	3	3	2	2	2	0	1	2	3	0	1	2	2	2	3	2	2	1	2	2	**40**
13	3	3	3	2	3	2	0	2	3	3	0	2	2	2	0	3	1	1	2	3	2	**42**
14	2	2	2	1	2	1	0	1	1	2	1	1	2	2	0	2	0	0	1	1	1	**25**
15	3	3	3	2	3	2	0	1	2	2	0	1	3	2	1	3	1	0	1	2	2	**37**
16	3	3	3	2	3	2	0	2	3	3	0	2	2	2	0	3	1	0	2	2	2	**40**
17	2	2	2	1	2	1	1	2	1	2	1	1	1	2	0	2	0	0	1	1	1	**26**
18	3	3	3	2	2	3	2	1	2	2	0	1	2	2	1	3	1	0	1	2	2	**38**
19	3	3	3	2	3	2	1	2	3	3	0	2	2	2	0	3	1	0	2	2	2	**41**
20	2	2	2	3	3	3	2	2	2	3	2	2	1	2	3	2	3	2	2	1	3	**47**
21	3	3	3	2	3	2	2	3	2	3	2	2	2	2	2	3	2	1	2	2	2	**48**
22	2	2	2	2	3	1	2	1	3	2	2	0	0	0	1	2	1	1	1	1	1	**30**
23	2	2	2	2	3	1	2	1	3	2	2	0	0	0	1	2	1	1	1	1	1	**30**
24	2	2	2	2	3	2	0	2	3	0	0	0	0	0	0	2	2	1	0	1	1	**25**
25	3	3	3	2	3	2	0	1	2	3	0	2	1	3	0	3	0	2	2	2	2	**39**
26	3	3	3	3	3	3	0	1	3	3	0	2	0	3	3	2	1	0	2	1	2	**41**
27	3	3	3	2	3	2	0	2	2	3	0	2	2	2	1	3	1	0	2	2	2	**40**

Table A2
Main characteristics of highly ranked alternative projects of floodplain restoration at the Chubut River lower basin

Alternative	Main characteristics
#4	Urban wastewater collecting system incorporates significant improvements in sewage pipe lining and micro-measurement of water use. Treatment system combines existing sewage treatment (activated sludge) plant, constructed lagoons and wetlands. Low-salinity effluent from northern part of Trelew city treated in sewage plant and further used for irrigation projects at northern riverbank area. High-salinity sewage treated in constructed lagoons + wetlands at lagoon area. Excess of treated wastewater discharged to Chubut River. Although this alternative complies with most environmental criteria, stakeholders discarded it due to high economic costs and lack of local experience in several engineering aspects of forced evaporation systems
#21	Urban wastewater collecting system incorporates significant improvements in sewage pipe lining and micro-measurement of water use. Treatment system combines existing sewage treatment (activated sludge) plant, constructed lagoons and wetlands. Low-salinity effluent from northern part of Trelew city treated in sewage plant and further used for irrigation projects at northern riverbank area. High-salinity sewage treated in constructed lagoons + wetlands at lagoon area. Excess of treated wastewater discharged to Chubut River. This is a relatively low cost alternative using tested technology available in the region except for the wetland treatment component
#12	Urban wastewater collecting system incorporates significant improvements in sewage pipe lining and micro-measurement of water use. Low-salinity effluent from northern part of Trelew city is collected along with high salinity sewage and is treated in constructed lagoons at lagoon area. Excess of treated wastewater discharged to Chubut River. This is a relatively low cost alternative using tested technology available in the region. The quality of the excess effluent discharged to Chubut river might not comply with existing environmental legislation during eventual extremely wet periods at the end of project time-frame

interested in two to three top options. The occurrence of abrupt changes in sensitivity–robustness of the value function could be used in deciding about the convenient degree of data reduction to be adopted.

Although the results obtained in this study indicate that the obtained project ranking is relatively independent from weight variations among groups of indicators, exploring the results of weight changes is nevertheless viewed as a useful exercise. Expert teams conducting MCDA may host various technical or contextual perspectives whose prevalence in the teams' decisions might be related to reasons other than their intrinsic relevance to environmental sustainability. Exploring the resulting ranking under various relative weight assumptions would help to reduce eventual bias resulting from discrepancies about indicator weighing within the expert panel.

5. Conclusion

A combined system of hydrological modeling and expert judgment was applied to evaluate the sustainability of various engineering projects aimed to floodplain restoration and urban wastewater management at the lower Chubut River basin. The system allowed the identification of three feasible alternatives that satisfy tests of internal consistency of the expert panel and minimize redundant effects on the selection process. All the alternatives satisfy a set of previously defined sustainability paradigms and are robust to a wide range of variation in the relative importance assigned to evaluation criteria.

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Appendix A

See Tables A1 and A2.

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