Uncertainties in Water Engineering Design and Management: The Shortcomings of Technology and the Centrality of the Human Being

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Abstract: - The design of hydraulic structures and the management of public waters require knowledge of very specific technical methodologies, which current and future needs may require to change. The challenges of climate change and the scarcity of water resources in many areas of the world seem to impose clear directions. However, in this paper, the Author tries to show, through case studies, how these indications do not allow an objective development of new design paradigms. On the contrary, there are large margins of uncertainty that must be filled by human practical knowledge, guided by an *esprit de finesse* that can only be cultivated by experience, combined with an ethical sense that must be shared by the population.

Key-Words: - Water management, design drivers, uncertainties in engineering, involvement of society, limits of technology, importance of intangibles.

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1 Introduction

Water is a fundamental and irreplaceable resource that plays a crucial role in sustaining life and maintaining the health of our planet, both in the present and in the future. Since the resource is increasingly scarce and therefore more precious, it is necessary to optimize management choices, according to future challenges, as follows.

First of all, population growth: with the world's population continually increasing, the demand for water is also rising, [1], [2]. Then, the well-known problems given by climate change, which is altering precipitation patterns, leading to more frequent and severe droughts or floods in certain regions, [3]. As demand surpasses the available supply, competition for water resources can lead to conflicts, both at local and international levels. Finally, water pollution threatens the quality of available water. Contaminated water sources pose risks to both human health [4], [5], [6] and ecosystems [7]. Sustainable water harvesting, storage, and distribution systems are needed to meet new challenges, [8].

The involvement of civil society in decisions regarding water management is essential alongside the advancement of technological capabilities, [9]. Communities often possess valuable local knowledge about water resources, usage patterns, and environmental conditions. Engaging the stakeholders fosters a sense of ownership and allows for a more inclusive decision-making process, [10]. Moreover, water management decisions are more likely to be successful if they are accepted and supported by the local population, [11].

The paper examines some of the parameters which are considered compelling, to see if there are quantitative evaluations capable of demonstrating a fresh approach to designing water structures. Climate change, economic considerations, and the multidisciplinary approach, which involves integrating economic and environmental considerations, are discussed.

It is shown that scientific insights can only help the human decision-maker to clarify the happenstances of the real world, but there are no scientific drivers that justify a choice. Some possible solutions can be excluded by the scientific evidence, but the final decision is in the human's hands.

This is the reason why it is believed that the final choice of the decision maker, based on the *esprit de finesse* and experience of the operator, must be formed on the basis of a strong environmental awareness; and for the same reason the resident population is to be involved, considering that a mutual exchange will allow a harmonious growth of society.

2 Rainfalls and Climate Change

2.1 General Remarks

The study of climatic variations is based on the analysis of the interactions between the different compartments of the biosphere: atmosphere, oceans, dry land and cryosphere, [12], [13]. Mathematical modelling is required to evaluate which variables are responsible for climate change and to make projections of the future behavior of the biosphere.

Among all the presently available models, the most used are the GCMs (General Circulation Models). The first climate model dates back to 1956 [14]; following this work, several other groups began working to create GCMs, [15], [16].

In this scientific context, IPCC was created by the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) to analyze scientific, technical, and socio-economic information relevant to understanding the risks of human-induced climate change. Since its inception, the IPCC has produced a series of Assessment Reports, Special Reports, and Technical Papers to summarize the state of the art regarding understanding the causes of climate change, their potential impacts, and options for response strategies. In 1992 the first emission scenarios (IS92) were released with the aim of being implemented in global circulation models. Since 1992, considerable progress has been made in the study of greenhouse gas emissions and climate change.

Trends related to climate parameters are also presented in the European Climate Risk Assessment (EUCRA), by Climate Data Store, Climate Adapt, and others.

2.2 Case Studies using GCM

Many Authors applied the above briefly described procedure to forecast rainfalls in the years to come. It is clearly impossible to report all the works carried out through the years, but in the following an idea of the state of the art through some simple examples will be presented.

In China, GCM has been applied to two very different catchments [17]: the former being arid (Tarim River Basin, TRB in the following) and the latter being humid (Yangtze River Basin, YRB in the following). The Authors selected 20 high-resolution GCMs to explore how future temperature and precipitation change in the two catchments. They used the historical data in the baseline period (1961~2005) to evaluate the simulation ability and the future data to project the future climate in both the near future (2045~2065) and the long-term future (2081~2100). As has been found by other Authors in [18], [19], [20], [21], they also faced the need to correct the bias. They found, in terms of precipitation, the annual observation (simulation) equal to 100.45 mm (354.86 mm) in the TRB, and 1092.73 mm (1311.89 mm) in the YRB. They acknowledged that the GCM data perform better in the simulations of temperature than precipitation, and this is also in accordance with other Authors [22], [23].

In Pakistan, an arid area has been analyzed [24] using gauge-based gridded precipitation data obtained from the Global Precipitation Climatology Centre to re-construct historical droughts and to downscale future precipitation projected by seven general circulation models under four Representative Concentration Pathways scenarios; support vector machine was used for downscaling and quantile mapping was used for GCM bias correction. Increased risk of droughts has been projected in many regions due to the increased variability of precipitation. Analysis of projected precipitation carried out in the paper showed an increase in precipitation, which does not confirm the reduction of droughts for all severities and return periods. On the opposite, droughts were found more severe with low return periods covering larger areas.

In Iran, GCM has been applied to assess future changes to precipitation patterns for the Isfahan-Borkhar plain [25], a semi-arid area. In that area, precipitation decreased and there is the need to forecast future rainfalls in order to design the appropriate water management. The chosen period to predict the effects of climate change on precipitation in the future included the 25-year period 2020–2044. Five general circulation models were applied (MIROC5, MIROC-ESM, MIROC-ESM-CHEM, MRI-CGCM3, and NorESM1-M), implemented using three emission scenarios: RCP2.6, RCP4.5, and RCP8.5. Finally, the GCM models were downscaled using the LARS-WG model. A comparison of the models showed that, in general, the MIROC5 model with a weighted average of 0.33 is the best model for precipitation prediction. However, considering only the selected best model, the expected changes in precipitation for the different months of the year still show a strong variability.

2.3 Case Studies using Real Data

As uncertainties are quite high, some Authors preferred working with recorded data, acknowledging that past rainfall variations might be able to anticipate the expected rainfall changes over different time scales.

In Portugal [26], long-term rainfall trends, their temporal variability, and uncertainty have been analyzed. The study was based on monthly, seasonal, and annual rainfall series spanning a period of 106 years, between October 1913 and September 2019, at 532 rain gauges evenly distributed over the Country. To understand the rainfall behavior over time, an initial sub-period with 55 years and a final sub-period with 51 years have been used. The trends identification and the assessment of their magnitude were derived using the nonparametric Mann-Kendall (MK) test coupled with Sen's slope estimator method. The results showed that after the initial sub-period with prevailing increasing rainfall, the trends were almost exclusively decreasing. The study also shows that approximately from the late 1960s on, the rainy season pattern has changed, with the last months prior to the dry season showing a sustained decrease of their relative contributions to the annual rainfalls. The Authors acknowledge the difficulties in making precise predictions, but the expectation is that precipitations will decrease and therefore the need to implement strategies to face reduced freshwater availability in sub-tropical latitudes.

In Zambia [27], research has started because farmers were migrating from the southern part of the Country, citing climate change as the reason why they couldn't farm as they used to. The Authors used data from Moorings Station in southern Zambia from February 1922 to June 2010, which means eighty-nine years of daily rainfall data. June to September is usually completely dry (a rainy day was defined as one with more than 0.85 mm of rain), so the analyses were for the eight months from October to May. The Authors found no evidence of climate change; the number of rain days per month has also been examined, finding oscillations but not a definite trend. The Authors also highlight the need to be cautious when reporting the results from a single station. Results are particularly significant because these long-time series are not very frequent. However, no evidence of climate change rainfall variations has been found, but the Authors stated that rainfall is extremely variable from year to year; therefore technicians have to solve the problem that the cropping systems have to be able to cope with this variability.

In Bangladesh [28] climate change variability has been assessed on the base of historical data of temperature and rainfall recorded at 34 meteorological stations located in seven regions for the period of 1976-2008. Analyses have been carried out for four periods, as follows: pre-monsoon (March-May), Monsoon (June-September), post-Monsoon (October-November) and winter (December-February). Trends have been observed: among the 34 stations, 16 stations showed increasing trend, while 18 showed decreasing trends in total rainfall in the winter season. For the monsoon season, 31 stations showed a rising trend; 30 stations showed an increasing trend of total rainfall for post-monsoon and 20 stations for pre-monsoon. However, what has to be highlighted is the Authors acknowledge the observed trends are not statistically significant in most cases. The reason is probably to be ascribed to the short length of the series coupled with the relative slowness of the changes.

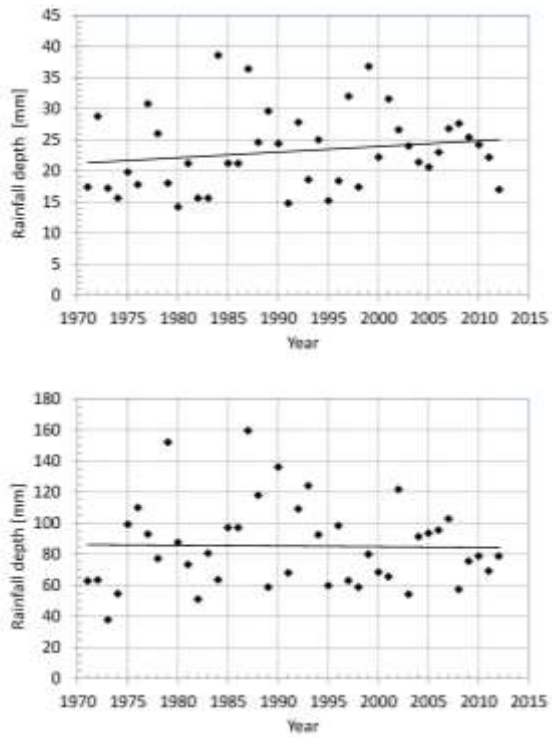

Fig. 1: Rainfall depths for 41 years of historical series at Milano's raingauge: 20 minutes (above) and 1440 minutes (below) durations, [29]

Similar results have been carried out also by analyzing the rainfall in Milano [29], in the North of Italy, in the years 1971-2012. The annual maxima of rainfall depths have been extracted for 20 durations, ranging from 5 to 1440 minutes (24 hours). For all durations, a least square linear function of the rainfall depths *Vs* time was fitted. As can be seen (Figure 1) a gradient is notable for shorter durations, while large durations show no trend. This seems to be in agreement with the common idea that climate change increases the frequency of extreme events, of shorter duration and higher mean rainfall intensities, while the average values remain constant. However, to verify the existence of a monotonic trend in the series of annual maxima of rainfall depths the Kendall Tau test was performed for all the 20 durations: the observed trends are not statistically significant for all 20 durations.

2.4 Dealing with Uncertainties

Exploring uncertainties and providing reliable information is a major challenge in climate change research [30], in which results are qualitatively clear, but quantitatively uncertain.

According to the periodical reports of the Intergovernmental Panel on Climate Change [31], [32], [33], the increasing sea surface temperature and the consequent intensification of the hydrological cycle [34] has a significant effect on the rainfall, which is expected to increase globally [35]. Nevertheless, at regional and local scales, decreasing trends in rainfall are also expected [31], [36].

This pattern is in line with the general climate change predictions and the documented evidence; however, while temperatures, sea levels, and other well-known phenomena associated with climate change may be predicted with sufficient precision, current studies on climate change are unable to provide a precise, quantifiable picture of what we can anticipate in the future about rainfalls. It is therefore impossible to impose a change in design.

3 Water Management

The intrinsic variability of rainfall requires a holistic, transdisciplinary approach to the design of hydraulic works. A cost-benefit balance is implicitly made when a hydraulic structure is designed for a certain return period. However, it is inappropriate to design a single structure assuming it will work independently from the others. When it is possible to create a network of mutually linked devices, then the crisis can be solved or at least mitigated by the system. Non-structural measures must be designed together with more traditional structural measures, [37].

3.1 General Guidelines-First Considerations

When different scenarios have to be considered, it is necessary to define which criteria and parameters need to be evaluated. The first step is to define what “optimum” means. Creating a scenario involves crafting strategies to produce a project structure. To accomplish this, a variety of measures can be taken into account when formulating a plan, in order to enhance water availability, control demand, and the effectiveness of water usage.

The first category of actions that can be performed is the use of unconventional waters, water reuse, and the construction of river expansions and dams, [38]. In some cases, treatment and desalination can be evaluated. The second category focuses on actions aimed at enhancing irrigation and industrial use [39], [40], [41] as well as raising awareness among users to minimize water loss. Reduction of water losses in the network and change in agricultural practice are included in the third category. The methods employed by the Authorities to achieve these enhancements tend to be primarily financial.

The parameters that can be used to select “the best” scenario are numerous [42] and often a multi-criteria analysis is necessary, [43], [44]. To compare the various scenarios, scores must be assigned to each parameter. Although it should be carried out with the most objective possible criteria, the attribution of these scores is often dependent on a very subjective evaluation. A similar evaluation is when the parameters are left uneven, in order to find a Pareto frontier in such a way that it is the decision maker who has the final word on the choice to be made.

3.2 Economic Evaluations – Case Studies

An apparently objective option is leaving the decision to the market, by basing it on costs and revenues. In this case, the political decision-maker estimates the worth of an environmental change based on society’s willingness to pay, which is a consequence of this criterion. The idea is well-established, but these assessments must take into account the concern for the environment among citizens or decision-makers, and, consequently, must take into account the historical and cultural context.

Analyses of a project always include financial assessments. Estimating the economic worth of water is recognized as crucial for allocating scarce water in a rational manner, [45].

3.2.1 Portugal

The Ribeiras do Algarve case study in Portugal, with a total area of 3837 km^2, was analyzed, [46]. When the research was carried out, the economic revenues due to tourism were very important, as the Algarve is the most popular tourist destination in mainland Portugal, and the total population usually increased on average by 200 percent during the summer months. Water management in the area is difficult because of conflicting interests in water resource uses: tourism sector and agriculture (mainly in summer); moreover, the area suffers because of infrastructure deficiencies, poor groundwater quality, high values of secondary water supply network losses, and inadequate irrigation methods. The total water demand in the river basin was 64.4 percent in 2002, with irrigation sites and golf courses accounting for the next 34.4 percent. Golf courses were increasing in number, as they were considered a strategic product for tourism. Different scenarios have been built, related to the different development of the area, combined with hydrological options, supposing the dry period can increase.

The analysis was conducted from an economic perspective. Direct costs for the implementation of the measures have been calculated as well as revenues for water use. To maintain an aquifer (Querença-Silves aquifer), the environmental cost was equal to the construction plus operation and maintenance costs of a desalination plant, designed to ensure the same volume. To estimate surface water abstraction environmental costs, two options have been considered: (1) construction of a dam with an overall storage capacity of 48 hm^3; and (2) construction of two desalination plants. The environmental expenses associated with the pollution resulting from effluent discharges are estimated to be equal to the operating expenses of a secondary wastewater treatment plant.

Deficiencies in urban and irrigation supply in the Algarve region were the primary objective of the water management strategies. The main goal is achieved by combining different water management options with the described strategies.

3.2.2 Italy

A work based on costs has been carried out also in Italy [47], in order to evaluate the use of "unconventional" water resources, i.e. water of lower quality, to be used for activities and services that do not require drinking water. Two cases have been studied, only considering the economic aspects.

The first case is located in Rho, a town in northern Italy, residential and characterized by low-rise houses. Water pumped from wells already built to lower the aquifer to protect the underground parking lots from the risk of flooding is considered for the planned reuse; the presence of a geothermic plant is also considered. Water is currently discharged into the sewer, involving a reduction in the conveying capacity of the sewer, an increase in the risks of surface flooding during intense meteoric events, and in the frequency of activation of the combined sewer overflows. Moreover, the wastewater arriving at the treatment plant will undergo a greater dilution, leading to a decrease in the effectiveness of the treatment procedures and higher expenditures due to volumes arriving at the plant. The project aims to reuse these waters, redirecting them to an alternative system for conveying and distributing water that can meet the demands of non-potable water: irrigation, and sanitary use within schools. The proposed water system consists of a network of free-surface underground channels and conduits. The available flow rate is approximately 110 l/s, i.e. approximately 3.4 million m^3/year.

The quality of the available groundwater is compatible with the non-potable uses established by current regulations. The use of alternative sources of non-drinking water for sanitary and irrigation use will reduce the consumption of drinking water by about 139,000 m^3/year, which approximately corresponds to a saving of 139,000 euro/year. The indirect benefits related to the reduction of high-quality water use from deep aquifers are estimated as 10% of the current use value. The energy savings for pumping water from the deep aquifer are estimated at 7000 euro per year, and an additional 10% indirect environmental benefit is to be added. Reusing water from other pumping systems in the future could significantly boost these numbers. With a treatment price of 0.52 euro/m^3, the reuse of the groundwater supplied by the pumping system will result in savings of around 2 million euro/year.

Total costs (pipes, channel constructions, devices, …), excluding those in the buildings, are estimated at around 2.2 million euro, and maintenance costs around 160,000.00 euro/year.

The second case is located in Milano, close to the universities, where the pumping system from the underground station discharges continuously 52.8 l/s in the combined sewer system, about 1.6 million m^3/year. The proposed uses are the same as above. The required annual volume is estimated equal to 90,000 m^3. Construction costs are estimated at around 500,000.00 euro and operational and maintenance costs are equal to 50,000.00 euro/year (10% of the construction costs). By applying the same costs as in the case above, a small saving is obtained if only the non-use of drinking water is considered, while a significant saving is obtained when the water is diverted from the sewer and, therefore, from the purification treatment.

3.2.3 Cyprus

The exploitation of the Kiti aquifer in Cyprus for agricultural purposes has been studied, [48]. Competitive extraction of groundwater means that each farmer makes their extraction decision without considering its effect on the other farmers' expected pay-offs, trying to maximize their own. On the other hand, cooperative extraction implies a centralized control to optimize the existing resources.

Most of the water not used by the plant is lost due to deep percolation, while a much smaller percentage is lost due to evaporation or run-off, according to the model the Authors developed and applied. Overuse of the water implies its waste.

It is not the goal of this paper to go into the mathematical details of the simulation algorithm, but the findings confirm that competitive extraction results in serious depletion of an aquifer of small storage capacity and significant welfare losses in an aquifer of small storage capacity. The centralized, optimized management of the resource proves to be far more effective than its rival applications: economic revenues are tenfold higher and it avoids aquifer depletion.

3.3 Not Only Economic Evaluations, Case Studies

As briefly described above, in most cases economic criteria are the basic measures in evaluating alternative water resources development projects.

However, societal well-being is equally important. A project that can be said to be "socially committed" should guarantee equity in water resources allocation; it should be selected among those that guarantee more job opportunities; it should respect traditional and religious beliefs, reduce damages to historical sites, reduce people resettlement (see, for instance, the controversy that arose around the construction of the Belo Monte dam, in Brazil, [49]).

Each aspect can't be examined on its own, as the various phenomena are connected. It is to be noted, however, that different goals may be conflicting. It is possible to draw a Pareto frontier, but the trick is to pick the best option and to do that, the definition of what "best" means is needed.

Instead of looking for the "best" solution, it might be enough to look for a "sustainable" solution, the definition of which can be traced in the document of the World Commission on Environment and Development [50]: "Sustainable development is economic development that meets the needs of the present without compromising the ability of future generations to meet their own needs". But, again, the challenge is to operationalize the concept of sustainability.

These analyses should be based on various criteria to evaluate different scenarios. Many methods have been developed to apply this analysis, which varies in terms of how the decision-makers preferences for criteria are measured and the way preference information is used to rank alternatives. With this procedure, policy-makers have the possibility to use these solutions or scenarios to seek "defendable" decisions that could reduce the degree of conflict in order to reach a certain degree of consensus.

3.3.1 Colombia

In water management decision-making, it is very rare for non-economic criteria to be treated separately from those with pure economic meaning, [51]. The Authors propose the use of four main non-economic criteria: operational time, infrastructure setup, operational risk, and socio-environmental considerations. The proposed methodology has been applied to a case study in the city of Santa Marta, Colombia, which had a water shortage and an urgent need to build new water supply infrastructure.

The four non-economic criteria are evaluated and properly combined to produce an indicator of non-economic evaluation, to be combined in turn with the indicator of the economic evaluation.

Operational time captures the importance of providing water as soon as possible; this criterion is especially important in developing countries, where the current infrastructure is often non-existent.

Infrastructure setup is related to the operational characteristics of different alternatives: whether the system is centralized or decentralized.

Operational risk has been defined by the Basel Committee as the risk of losses arising from problems from internal controls, systems, people, and external events, [52]. In this context, it is important to ensure adequate water supply from both surface and subsurface waters, and in many instances, redundant water sources are essential.

Social and environmental impacts in this context are mainly tied to the need to minimize the area of influence of the project in social and environmentally protected areas, such as national parks or cultural reserves. Reduced environmental impact of the construction process is also desirable.

The town of Santa Marta has more than 500,000 inhabitants and approximately 51,000 additional tourists during peak seasons; in an average season, the inhabitants require 2.21 m^3/s of water, while the water supply is approximately 1.55 m^3/s. However, by 2040 the population is expected to reach 980,000 permanent inhabitants and a floating tourist population of 133,000; further increases are expected in subsequent years.

For this case study, the judgments and preferences of eight experts in water management problems, particularly drinking water and basic sanitation issues in Colombia, were collected. The experts express their preferences using the scale proposed in [53] and their judgment has been proven to be consistent. Seven alternatives have been analyzed according to this methodology.

Costs have been evaluated on a planned time of 50 years and results are briefly reported in Figure 2 together with the non-economic global indicator. As can be seen, the cheapest alternative is the number 3, while the environmental best alternative (according to the parameters defined by the experts) is the number 7. In the same figure, a possible Pareto boundary has been added by the Author of this paper: as can be seen, while the selection of alternatives 6 or 5 is unjustified, alternatives 3 and 7 are very different, but they can be considered appropriate from the point of view of a decision maker.

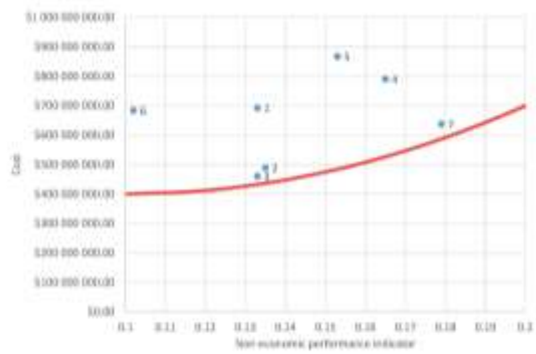

Fig. 2: Costs and non-economic performance indicator for the water supply rehabilitation and improvement in Santa Marta, Colombia. Data after [51]. Proposed Pareto boundary drawn by the Author.

3.3.2 Missouri

A work applying a similar methodology has been carried out [54] with the aim to evaluate the performances of five farming systems in Missouri, USA. Five economic and environmental criteria were included in the utility function, as follows:

i. increasing net return NR ($/ha);
ii. reducing economic risk RI ($/ha);
iii. improving drinking water quality DW (atrazine application rate, l/ha);
iv. enhancing aquatic ecosystems AE (soluble nitrogen concentration in surface runoff, ppm);
v. reducing soil erosion SE (tons/ha/year).

Economic criteria (i) and (ii) were selected because farmers must earn a reasonable income from farming in order to stay in business. Drinking water quality, aquatic ecosystems, and soil erosion criteria were selected because many non-farm groups and environmental agencies are concerned about the human and environmental health impacts of farming systems.

The ranking of each farm has been computed adding each parameter accordingly weighted, which weights have been determined on the base of information obtained in a survey of 20 farmers in the catchment. Weights W are as follows:

$$W_{NR} = 0.339,$$
$$W_{SE} = 0.261,$$
$$W_{RI} = 0.165,$$
$$W_{DW} = 0.156,$$
$$W_{AE} = 0.079.$$

Table 1. Values for assessing the farming system in Missouri, after [54]

	NR	RI	DW	AE	SE	**PI value**
	($/ha)	($/ha)	(l/ha)	(ppm)	(t/ha/year)	**(-)**
FS1	328.53	27.92	4.68	12.69	4.48	**0.35**
FS2	241.39	20.44	3.74	4.66	6.94	**0.38**
FS3	218.95	19.68	1.75	7.81	5.15	**0.49**
FS4	296.38	24.25	1.75	8.33	4.93	**0.63**
FS5	201.82	23.18	4.91	5.7	1.9	**0.42**

Since W_{NR} is the largest weight, the average farmer in the catchment considers net return to be the most important criterion for selecting a farming system. These parameters took on the values indicated because they were suggested by farmers; if they had been suggested by environmentalists, it can be assumed that they would have been very different.

In Table 1 the values of the individual parameters together with those of the overall performance index are reported. Even when weights are chosen by farmers, who can be thought to be oriented towards greater profitability rather than towards the environment, the farm that obtains the highest score (number 4) is not the one that provides the highest income.

3.3.3 Iran

In [55] is studied the possibility of improving water use efficiencies in the Qazvin irrigation network, which is one of the oldest, largest, and most complex in Iran. It covers an area of 800 km^2; the network is fed by water from the Taleghan storage dam and its main canal and laterals have a cumulative length of 1100 km; flow rates in the main canal range from 3 to 30 m^3/s.

The Authors applied multi-attribute decision-making methodologies to select what can be thought the best option because of the great variety of solutions available today.

A number of intake structures and check structures have been studied and the used criteria have been grouped into the following categories: technical performance (installation, calibration, …); economic viability; societal adaptability; and ease of automation.

The proposed criteria are many and difficult to elaborate. The chosen decision framework combines the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) ranking method with the Entropy method for allocating optimal attribute weights. The evaluation has been carried out through the compilation of 25 questionnaires of which only 18 were used because they were the only ones completed. The pool of valid survey data came from 6 irrigation experts (e.g., engineers and researchers not directly working on the Qazvin network), 8 irrigation managers, and 4 operators. For each criterion, each expert assigned a score, which was averaged to obtain the score relating to the criterion itself.

In this case, the Authors used a so-called "objective" method to calculate the weights to assign to the different criteria, in order to avoid any presumed influence on the part of the operator. Obviously, the weight matrix is deduced from the scores assigned by the experts.

3.4 Remarks

In the analysis carried out for Algarve (Section 3.2.1), all values can be expressed economically; in other words, there are no "intangibles", or ethical values. This is only partially true, as the stakeholders stipulated that a solution can be considered satisfactory when the domestic demand falls within the range of 95-100% whereas the irrigation demand falls within the range of 80-100%. This implies that the value of water for human consumption is assumed to be greater than that used for irrigation. However, golf courses will receive more water if their revenues are higher than those from agriculture.

The Italian cases (Section 3.2.2) show that the design, in both presented instances, is financially advantageous. However, the greatest economic advantage lies in diverting water from the public sewer system, in order to avoid treatment costs. On the other hand, the economic advantages that are obtained from the use of unconventional resources are very limited and, by themselves, would not justify the aforementioned expenses. The construction of an alternative water supply system is, in the end, unjustified from a financial standpoint; only the diverting of wastewater from the sewer is advantageous. However, the political decision-maker felt it important to finance the entire project, also with the prospect of having a network that allows further connections in the future.

The case study in Cyprus (Section 3.2.3) demonstrates that, while it is undeniable that in the Western world the Darwinian theory of "competition" has been extensively developed and taken into account, the same cannot be said about its corresponding need for "cooperation", which distinguishes individuals and proves to be even more crucial in the pursuit of sustainable development.

To get a fuller picture of what the design will look like, more intricate settings are required. Section 3.3 discusses this, where the economic evaluation was associated with a non-economic evaluation. People's decisions, in some cases considered experts, define the relative importance of the selected parameters.

Section 3.3.1 presents a paradigmatic case, and in particular, Figure 2 can be analyzed from different points of view. The *x*-axis has values deduced from a heuristic analysis conducted by experts. The graph shows that the cheapest option is that of scenario 3, but the one that takes more of the environmental impact into account is number 7. The human decision-maker must decide whether to spend more to have a more environmentally sustainable solution or to save money in order to invest public funds with other objectives. The vertical axis should be more objective because it depends solely on the market, but a more subtle observation is in order. Actually, the market also depends on human society, as is well explained in the example in Section 3.2.1. This, in turn, can significantly influence the choices of the decision-maker.

The technique can put in order data that, when analyzed crudely, would be difficult to interpret, but the human being is actively involved in subjective weight determination because it is based on expert advice, [56]. The case study presented in Section 3.3.3 uses a so-called objective method, which has been developed [57] with the main goal of avoiding the involvement of preferences of decision maker on the criteria so that their weights are obtained from mathematical algorithms. Actually [57], [58], "different weighting methods produce a different set of criteria weights and final results of the multi-criteria decision-making methods are sensitive to criteria weights. Therefore, it is paramount to emphasize the selection of weighting method for solving a multi-criteria decision problem." Moreover, the selection of a method depends on the decision problem.

4 The Myth of Science and the Centrality of the Human Being

As seen in the previous paragraphs, the current technique allows existing resources to be "optimized", which is especially important when they are in short supply. However, the definition of "optimum" is not trivial. The objective criterion for changing design methods is not provided by quantitative studies: it is impossible to discover unbiased methods for making decisions. The attempt to make the design choice automatic and "objective" always clashes with the requirement that a choice must be made by the decision maker: subjective, heuristic, based on experience and *esprit de finesse* of the human being. "Objectivity" seems like an unattainable myth.

4.1 Objectivity in Science and Technology

The concept of "objectivity" associated with positivism is now widely accepted as common sense. According to this idea, science and technology have no ethics and are neutral: this is a superficial position.

In [59] is noted that technology "does not exist in a vacuum; it develops in a social context, like all other human activities". The link between science and technology is influenced by the nature of social relations and between groups of scientists and technologists, as well as by the nature of social relations.

The ethical implications are strong. In [60] this topic is studied, with particular reference to hydrogeological risk, as decisions in this sector have consequences on people's lives. One epistemological answer to questions of model selection, as articulated by some philosophers of science, is that it makes no sense to reject a model until we arrive at a better one, especially because all models are imperfect in some respect. The ethical answer to questions of model selection, as articulated by some moral philosophers, is that, even if a better model is not available, scientists ought to reject some models. They reason that even the best model may not be good enough, especially if it could lead to undesirable public policy consequences.

In technological systems (and environmental engineering is among them), the systemic approach demonstrates how technology embraces individuals, who are not outside the system, but rather within it, [61]. The technological system can control the individual when advertising, propaganda, state administration, and everything in between are included. In [62] is added that technology is not under human control (technological autonomy), but it develops with its own logic. This Author also highlights that people (engineers, businessmen, and politicians) do not grasp the consequences of the technologies they develop or support. The social and political issues surrounding technology are often overlooked by technologists, and politicians are often unaware of how the technology works. The general user is unaware of both the technical and social aspects of the technology.

Conversely, social constructivism holds that people, especially social groups, play a crucial role in the development of technology, [63], [64]. Technological development is dependent on the choices made by social groups, which are not established in advance.

4.2 Choices

Making decisions when there are several options to consider is a major challenge, especially when there is less information available. The best designers of the past have achieved a balance between efficiency, economy, and elegance, [65]. Durability, constructability, upkeep, and other constraints could be included. Another term often used is quality, [66].

The problem has just shifted: how can quality be assessed? The problems encountered are complex and require experience and judgment to sift through multiple project ideas; therefore the project is more an art than a science, [67]. Design has to be completed by second-order thinking about perception, guided by stylistic practice and aesthetic feeling, [68].

A further issue that has not been explicitly mentioned is that hydraulic engineering, or more generally environmental engineering, places the product of design outside of the traditional paradigm of producing an object, which can be separated from its surrounding environment, [69]. In the "traditional" paradigm it is assumed that the behavior of what has been designed can be completely controlled, simply by controlling the behavior of its parts. Complex systems [70] pose challenges in relation to the applicability of the traditional design paradigm, both in terms of the socio-technological nature of the designed systems and the possibility of unforeseen outcomes.

If social elements are included in the system, then engineering systems must deal with socio-technological systems. The abandonment of Simon's "traditional paradigm" raises another issue: these systems include the behavior of human agents and social institutions and therefore they cannot be completely designed and controlled as if they were pure technological systems.

Finally, there is the problem of how to assign a value to the various parameters to be considered; this problem in some way involves ethics. It was emphasized that science or technology can indicate which are the consequences to be expected following some choices: but the latter must be made on the basis of ethical principles.

An anthropocentric approach leads to the idea that only man has intrinsic value. With this approach, despite the difficulty of evaluation, there is an ethical criterion that allows to guide the choices.

The focus should be on ecological collectives, not on individuals, according to some forms of environmental ethics [71], so that the moral sphere outside the human community is extended to include the biosphere. In this case, however, there are no ways to resolve conflicts between individuals and the earth.

It seems that we cannot deviate much from that "of all things the measure is Man" (Protagoras of Abdera), said to coincide with the birth of Western philosophical thinking.

4.3 Involving Society

The complexity of technological devices that are no longer fully comprehended by the end user makes it increasingly necessary to engage in greater awareness, returning to making man the subject holder of knowledge, who is competent to take action to enhance his living conditions. So far, it is acknowledged that "environmental ethics is, for the most part, not succeeding as an area of applied philosophy", [72].

The distance between political or economic decision-makers and society, at least when it comes to the most sensitive research topics, has decreased in recent decades, [73]. Public participation has received a new impetus within various socio-technical contexts.

The question to ask is whether or not this involvement has a positive impact. Public involvement in science leads to greater democracy, better accountability, and more effective policy decisions, according to advocates; but critics and skeptics argue that such involvement can significantly slow down decision-making, [74].

In favor [75], it is necessary to report that when people know they are responsible for finding a solution, they start asking for information, which in turn opens the way to the exchange of information and dialogue with a growth of knowledge and awareness. It is possible for the individual to acquire autonomy to carry out the actions and changes necessary for his personal and social growth and development, [76].

In [77] is argued that it is the economic elites who pursue economic growth at the expense of the environment, while people are more likely to accept limitations on such forms of economic expansion. The Author states that "there are no guarantees that people will make wise decisions, but they have an incentive to do so: they have to live with the consequences." This assumption is only partially true because it is still possible to export the costs of environmental choices to other Countries or impose them on other generations, [78]. This is already happening: but, perhaps, without society being aware of it. The transition from (metaphysical) beliefs to engineering has been able to lead to, for example, the design and creation of ecologically protected zones, [79].

It is a long path: public participation and commitment must be enriched with political theory and philosophy [80], in order to allow the necessary historical perspective on the deeper forces that shape scientific understanding. The future of environmental protection could result in financial restrictions, which could provoke opposition from part of the population; however, structural changes cannot occur without the participation and acceptance of the majority.

5 Concluding Remarks

Climate change, scarcity of resources, and the need to use energy for water treatment and pumping are some of the factors that impose a different conception of environmental engineering design and water management. However, as this paper has tried to show, none of the elements cited are capable of giving precise indications regarding a possible new design paradigm.

Several occasions have shown that global warming alters the pattern of rainfall, but we are unable to make certain predictions, for instance, regarding the evolution of the Depth-Duration-Frequency curves over the coming decades.

In order to arrive at an objective metric, reference is often made to the cheapest option, believing that this will allow for the inclusion of all the crucial elements of the design. There are at least two issues emerging from the reported case studies. The economic aspects are also influenced by human activity, as can be seen in the Portuguese case, where the influx of tourists can make it more financially feasible to allocate land and water to construct golf courses. The Italian case shows that the Public Authority may decide to take a course of action that may not be the most cost-effective but may have significant effects on the environment and society.

It seems that a good choice is the combination of economic and environmental parameters. The definition of environmental parameters is left entirely to the discretion of people, usually chosen from among the most experts in the sector. Even in this case, as can be seen in the paragraphs above, the definition of the optimal choice is ambiguous. These procedures can lead to the definition of a Pareto frontier, therefore to the exclusion of some scenarios, but leaving the final option to the decision maker.

In other words, the procedures used for design are heuristics and selected by a meta-heuristic, this latter being given by experience and common sense.

The best design depends on the value that is given to the different parameters that guide the design. This means that, even with the same technical abilities, the solution adopted at different times, as well as in different geographical locations and, consequently, in different cultural contexts, could be different. [81] is very clear and deserves to be quoted extensively: “Water is a technical subject, but that’s only part of what water is, and even the technology of water has values embedded in the technical choices. Moreover, the governance of water – the laws, policies, and institutions that set the context for technical water management – is anything but technical. Water governance is all about values.”

Environmental engineering design does not concern a single artifact, but it is a complex system, that also concerns the social and economic dynamics. These systems have issues that involve society. The complexity and fragmentation of knowledge that distinguishes our age make it difficult for society to fully comprehend the implications of certain choices.

The acceptance of new technologies that seem appealing and that also seem to simplify life is a consequence of this; on the other hand, there is a growing suspicion towards the authorities, both political and scientific. In the environmental field, the “NIMBY” syndrome is symptomatic.

The intertwining of science, technology, and metaphysics also implies a common sense that cannot be codified but already exists. Without an appropriate awareness on the part of society, reactions are not adequate to the complexity of the issue and create further problems. In an adequate and conscious way, a greater concordance between the different instances can help in the construction of the society that awaits us. On the contrary, being unaware of subconscious ethics may create a potentially disastrous basis for making decisions.

Most environmental goals cannot be reached without the involvement of society, and therefore this is an issue of paramount importance. But a person is not a computer and therefore the input of pure information does not necessarily imply a correct output. Training and adequate time are needed for people to learn how to behave. The extreme difficulty and breadth of each discipline make it impossible for a specialist to be competent in different disciplines.

A single modern Aristotle cannot provide for an arrangement of knowledge. The average person is incapable of comprehending the intricacies of technological advancements. Transdisciplinarity is the aim of understanding the complexity of the modern world with an encyclopedic approach that restores unity in diversity to human knowledge.

The technical nuances that each term has in each discipline need to be shared by the different specialists. Information needs to be provided clearly and understandably, knowing that information alone is not able to produce changes.

It is therefore necessary, in the Author’s opinion, for transdisciplinary study groups to be formed to find a common ethic that guides technical choices toward a shared use of resources.

Although the full achievement of the result in a short time is not foreseeable, no other possibilities seem to be available.

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