

Saving Venice: Engineering and ecology in the Venice lagoon

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Abstract

This paper describes some of the challenges of sustainability, and shows how they are manifested in coastal environments. It reviews the problems facing Venice and its lagoon, as a particularly interesting and complex example, and describes the technological, environmental, and scientific actions taken to address the problems of sustainability. Specifically, the actions and interdisciplinary research supporting management of the Venice lagoon environment are discussed, with a particular focus on the sediment. Conclusions are drawn regarding the integration of science, technology, and the environment, including the interactions of industry, the international scientific community, and governments.
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1. Introduction

1.1. The challenge of sustainability

The impact of human industrial development on natural ecosystems is increasingly evident around the world in many forms. Species are becoming extinct as a result of human encroachment on habitats. Fossil fuel consumption has increased greenhouse gas emissions resulting in rising sea levels, increasing atmospheric temperatures, and melting glaciers. Once-prosperous commercial fisheries have collapsed following the introduction of industrial fishing ships and refrigeration. Industrialized countries impact the natural environment at rates far in excess of long-term sustainability, and developing countries have yet to meet the basic needs of many of their inhabitants. Clearly, we need to find pathways to the future that allow environmental sustainability as well as economic and social prosperity.

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1.2. Sustainability in coastal ecosystems

The challenges of sustainability are not limited to any particular geographic area or to any social or economic group. However, coastal ecosystems represent one of the clearest interfaces between human societies and the environment. Whether in an ancient city like Venice, Italy, or relatively new city like San Diego, California, we are now witnessing the results of human activities that were undertaken during a period of time when nature was presumed to be limitless, resilient, and available for human exploitation. We have only recently begun to acknowledge that our planet is a finite, closed system whose resources must be nurtured and recycled. This, in turn, has made us realize that successful environmental management strategies must recognize the complex interdependence of human and non-human components of the natural system and strive for long-term sustainability. Whereas, once it was considered acceptable to dump toxic waste into the ocean, assuming the contaminants would be sufficiently diluted to be rendered harmless, now such practices are considered illegal and immoral.

By employing a broad range of expertise from the natural and social sciences, engineering, and the humanities, we have the potential to develop science-based, integrated, decision-support tools that enable us to describe and anticipate interconnections and impacts among the various aspects of a particular ecosystem. The global community of knowledge also enables us to draw on local, indigenous expertise and knowledge and combine it with lessons from other communities whose experiences might be applicable. This allows decision makers to apply the standards and values of their constituents while building on a knowledge base that is, in principle, global.

The historic city of Venice, Italy, and its lagoon, represent a fascinating and complex window into the challenges of sustainability: meeting today's needs without compromising the ability of future generations to meet their own needs [1]. The problem: the frequency of flooding in Venice is increasing. Managing the Venice lagoon in a way that protects the city from the floods while permitting a functional lagoon ecosystem to thrive is an excellent example of the dramatic interactions of nature, science, and technology made even more challenging by the historical and political context in which the problems and solutions are unfolding. With more than 50 different national governments in the last century of Italian politics, and with sometimes different political parties in power in Venice and in Rome, mounting a complex program to address the threats to Venice and its surrounding areas is a major political and organizational challenge as well as a difficult science and engineering problem.

2. About lagoons

Lagoons are inland bodies of water nourished by both fresh and saltwater inputs. Lagoons are always coastal and estuarine, located at the confine between freshwater and marine ecosystems. Because of this, lagoons are important structures from an ecological standpoint, sustaining a diversity of species. Lagoons are typically shallow, rich in nutrients, and associated with high productivity. They host abundant fauna and flora that are sometimes of socioeconomic importance, either on a permanent or temporary basis, even if the organism only takes advantage of shelter areas of the lagoon for reproduction purposes [2,3].

The environment in a lagoon is heterogeneous. There is, for example, a land-to-sea salinity gradient and variability of the bottom-floor profile following sediment transport and accretion by wind and/or tide-driven water circulation. Diversity in the geomorphology of a lagoon bottom provides diversity in habitats and niches, and these in turn support greater biodiversity. Thus, a lagoon's ecology depends on a delicate dynamic balance between multiple factors, including water circulation and input, sediment transport, geochemistry of sediment particles, and the life history, biology, and ecology of endemic species [2,4].

Sediment in lagoons is often highly contaminated because extensive human settlement is typically sited on lagoons; lagoons are also the end reservoir of contaminants transported by rivers [5]. Contaminants, whether chemicals like metals and hydrocarbons, or pathogenic microbes and viruses, thus end up in sediment where they are trapped and accumulate over time. However, they can be released and made available to the local ecosystem in response to changes in surrounding physical and chemical conditions [5,6]. These changes can be natural and inherent in the ecosystem, or induced by anthropogenic activity. In any case, because contaminants rendered available can be toxic to the local fauna and flora, it is essential to understand and

monitor lagoons in order to identify areas with distinct or variable physical and chemical conditions. This might require eventual control of sediment transport across the distinct areas of lagoons or away from variable conditions in order to better manage potentially hazardous situations.

Research that combines ecology and management of sediment in a dynamic system requires a multidisciplinary approach that integrates biological complexity (or lack thereof) of the ecosystem with local variability of physical and chemical parameters [7–9]. Even though ecosystems represent an optimal integration of physical, chemical, and biological parameters, addressing only one of those parameters does not allow extrapolation and understanding of the whole ecosystem that is ruled by an unrevealed, delicate, complex, and dynamic balance of interactions among parameters. Thus, today, integrative and realistic assessment of an ecosystem requires a multidisciplinary and interconnected effort [7–9].

3. Venice and its lagoon

Since its foundation, the Venetian Republic considered Venice and its lagoon as a single entity, and Venice as the center of a wide and productive commercial and residential system that should be carefully preserved in all its components. Over the past century this complex and dynamic environment has been heavily altered by intense anthropogenic interventions. At present in the lagoon there are varied and often contrasting activities being carried out. Local, regional, national, and international organizations have taken an interest and developed programs to “save Venice.” Thus, the lagoon is a highly complex issue, and the Venice problem is emblematic of our times, representing not just environmental complexity but also legislative, scientific, and institutional intricacy.

Sea-level rise, subsidence, erosion, pollution, fishery activity, and wave motion have all contributed to the general crisis of the Venice lagoon system. The ecosystem characteristics have undergone progressive impoverishment and deterioration, with a reduction of the surface area of the salt marshes, deepening of the lagoon beds, and worsening of the water and sediment quality [10].

The city of Venice has literally been sinking over the last centuries, with a drop of approximately 23 cm in just the last 100 years. This is primarily the combined result of natural subsidence, accelerated by groundwater pumping for industrial use, and sea-level rise resulting from climate changes. The frequency of flooding has increased dramatically, with St. Mark’s Square flooding more than 50 times per year in the 1990s. The problems are clearly evident on a daily basis, as can be attested by anyone who tries to traverse the Piazza San Marco when it is flooded, or anyone living in a building whose lower floor is being eroded by increasing wave action.

Further compounding the environmental problem is the increasing erosion of the lagoon, which is becoming deeper and flatter with the disappearance of salt marshes and mud flats. Sediment mass balance is a loss of one million cubic meters per year for the lagoon [11], most likely due to increased erosion but also to the fact that natural sediment input and replenishment is limited as main rivers were diverted away from the lagoon in the 16th century. Morphological restoration measures have been developed to protect eroding salt marshes, replant reclaimed areas in the lagoon, raise the level of the lagoon bed to reduce wave dynamics, and consolidate the bed by planting eelgrass. The programs include dredging lagoon channels and reusing the resulting sediment to reconstruct mudflats and salt marshes.

Sediment can be contaminated at different levels, and assessing sediment quality is a complex issue. Although recent studies have shown that bioavailability and toxicity of sediment pollutants are not always directly correlated to absolute concentrations, most of the sediment in the lagoon has been evaluated as potentially hazardous based on total chemical content. A comprehensive study is needed in order to assess geochemical and biological processes that could vary from one area to another in the lagoon and affect bioavailability and potential toxicity of the contaminants to higher organisms. However, understanding the effects of pollutants alone will not explain ecosystem health in the lagoon, so in parallel with the role of contaminants, the role of habitat loss (or restoration) on ecosystem dynamics and biodiversity must be evaluated (see Fig. 1).

To deal with these conditions and identify solutions, the Venice Water Authority, through its concessionary, the Consorzio Venezia Nuova (CVN), has promoted a coordinated system of activities aimed at the physical and environmental safeguarding of Venice and the lagoon. This system is described in the “General Plan of

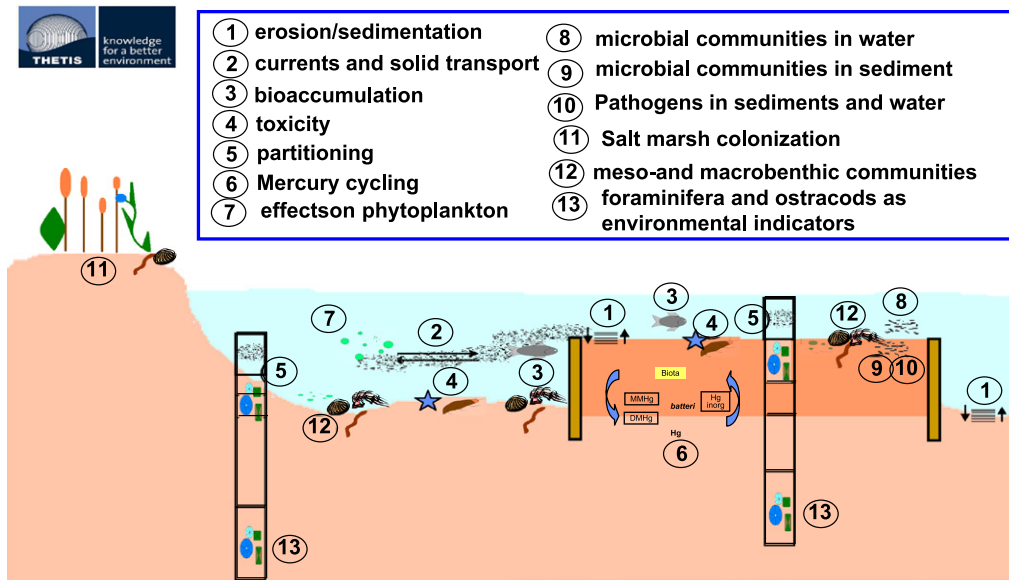


Fig. 1. Schematic representation of topics addressed by the SIOSED project while monitoring re-use of sediment in salt marshes and sub-tidal banks.

Intervention,” which links the defense of Venice with its prestigious historical buildings and the lagoon ecosystem, from high tides to environmental problems, according to distinct but reciprocal and systemic actions:

- defense from high waters,
- defense from sea storms,
- morphological restoration of the lagoon,
- arrest and reversal of deterioration processes in the lagoon basin.

The activities already completed or currently underway represent the most important program of defense, recovery, and management of the environment ever undertaken by the Italian government.

Potential solutions are complex and variable. Many measures have been proposed, debated, and some adopted, including an end to groundwater pumping, reinforcement of buildings, creation of artificial salt marshes, restoration of some of the morphology of the lagoon floor, and reconstruction and raising of the lagoon banks.

Most notable is the development of the Modulo Sperimentale Elettromeccanico (Experimental Electromechanical Module) (MoSE) project, which involves the construction of 78 mobile and articulated barriers at the three lagoon inlets (see < www.salve.it >). The barriers will lie on the sea floor during normal sea and weather condition, thus allowing natural exchanges between the lagoon environment and the Adriatic Sea. The barriers will be raised to an upright position during high seas and/or when weather conditions could lead to sea levels that might possibly flood the city of Venice. For as long as needed, the barriers will block the influx of excess seawater into the lagoon, while navigation passage in and out of the lagoon will still be possible through locks. In addition, as a defense from sea storms, a well-defined program of interventions, which includes building new beaches and rebuilding coastal dunes, has been developed to reinforce the littoral together with the consolidation of outer breakwaters. This work is almost completed.

The interventions in the lagoon are authorized under ordinary and special legislation, with the responsibility distributed as follows: Italian State (measures to physically safeguard the lagoon and restore hydro-geological balance), the Veneto Region (abatement of water pollution), and Venice and Chioggia local authorities (urban restoration and maintenance, and measures to promote and encourage socioeconomic development).

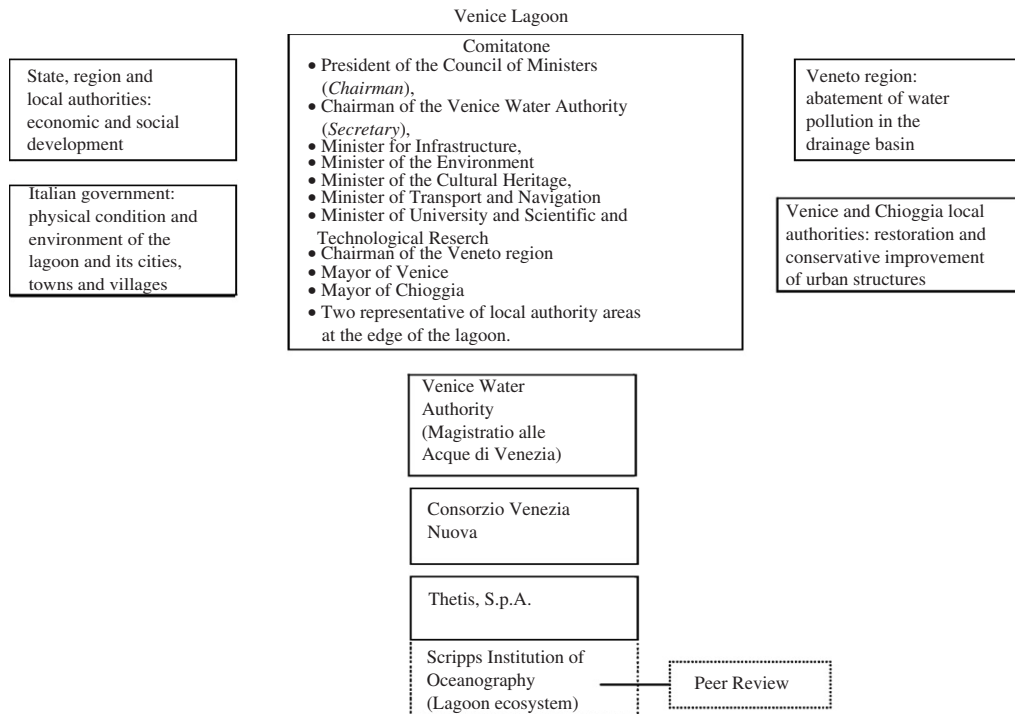


Fig. 2. Oversight structure of Venice and its lagoon environment.

The system of safeguarding measures is directed, coordinated, and controlled by a Committee (as per Art. 4 of Law No. 798/84) called *Comitatone*, chaired by the President of the Council of Ministers. It consists of representatives from local and national authorities and institutions: Ministry of Infrastructure; Ministry of the Environment and Land Defense; Ministry of the Cultural Heritage; Ministry of Education, Universities and Scientific Research; the Veneto Region; the local authorities of Venice, Chioggia and Treporti-Cavallino; and two of the local authorities in the lagoon boundary area. The Secretary of the Committee is the President of the Venice Water Authority. Fig. 2 shows a simplified diagram of the structure of the *Comitatone*.

4. International involvement

While the protection of Venice is an effort undertaken by Italy and implemented in large part by CVN (the consortium of Italian engineering companies mentioned earlier), international experts have also played important roles. From the US, engineering experts from the Massachusetts Institute of Technology (MIT) and scientists from Scripps Institution of Oceanography (SIO) have been involved at different times in various aspects of the endeavor to save Venice. This international effort is necessary in order to bring independent expertise and evaluation of the multiple steps taken toward resolving the complex problem of Venice and its lagoon. Recognition of the problem and its international significance were heightened by the involvement of UNESCO, which declared the Venice lagoon a World Heritage site in 1987.

As a complex ecosystem that supports a complex city-region, there is no single engineering solution that will solve all the problems. Nor is it possible to completely and comprehensively understand all the dynamics of the natural and social systems involved. Therefore continued research, monitoring, and adaptive management are required.

In 2004, CVN approached Scripps and asked it to provide scientific advice regarding the ecotoxicology of the sediments reuse in the lagoon. Scripps scientists have a history of involvement in Venice, including an analysis by the distinguished oceanographer, Walter Munk, who showed how the MoSE floodgates could be used to manage and preserve the circulation in the lagoon and to enhance the health of the ecosystem. Another

Scripps scientist, Yehuda Bock, used precise GPS measurements to monitor changes in the elevation of structures in the region due to subsidence.

Discussions with Scripps began in April 2004 when a delegation of scientists was invited to attend a workshop organized by CVN on the subject of sediments and restoration in the Venice lagoon. After considerable discussion and negotiation, a contract was signed between Scripps and Thetis S.P.A. (the lead engineering company controlled by CVN) for a 33-month interdisciplinary study (known as SIOSED) involving the construction and monitoring of sub-tidal sediment banks in the lagoon (see Fig. 3). This project is currently underway, with first-year results presented at a workshop in mid-September 2006.

Maintaining lagoon shipping channels and reconstructing ecologically important lagoon-floor morphology involve relocating sediment within the lagoon. This must be done in compliance with Italian environmental regulations concerning possible toxins in the sediments. The institutions responsible for engineering and maintenance of the lagoon are interested in understanding the potential impact, if any, on the lagoon ecosystem from the movement of sediment under different conditions. The SIOSED project contributes to this understanding.

The project consisted of dredging about 1300 cm³ of sediment equally spread into six banks (30 × 10 × 0.7 m) in groups of three, in two distinct areas of the lagoon—one close to the channel source of dredged sediment, the other one further away in the shallows. The two recipient areas have distinct environmental characteristics, in particular the level of contaminants in the seafloor sediment. One is closer to land and the industrial area of Porto Marghera, the other is closer to the Malamocco inlet that opens to the Adriatic Sea.

Using a grab, the sediment was dredged 1 m deep and transplanted into the banks. The banks were contained by a wood-piling fence to protect against immediate erosion. The wood-piling area was also layered from the inside with fine mesh in order to retain and allow sedimentation of the smallest particles. The banks



Fig. 3. Satellite view of the Venice lagoon with indication of the three inlets connecting the lagoon to the Adriatic sea. Porto Marghera is the industrial center with important petro-chemical facilities. Squares are where the SIOSED project is being developed.

were built in a shallow-water area about 1.4 m deep. Soon after transplant, the height of the banks was about 1 m, exposing the top sediment to air for short periods of time at the occasional lowest-low tides. The wood piling was kept above sea level for enough time to allow the sediment banks to become compacted and stabilized, which took about 3 months. At that time, the height of the dredged sediment layer in the banks was about 70 cm, precluding the banks from atmospheric exposure at low tide. Then the wood piling and mesh were cut to the level of the sediment inside the banks in order to expose the banks to water flow while still providing an enclosure containing the sediment (see Fig. 4). The banks were then considered mature and at their final stage of engineering construction. Further transformation, evolution, and outcome of the banks were now up to nature.

A multidisciplinary team that included engineers and scientists from various fields closely monitored the construction, maturation, and evolution of the banks. In terms of academic research, the strategy consisted in measuring the bio-geochemical characteristics of the sediment at various stages in the banks' construction, from before dredging through the maturation process and exposure to the open environment. Bank behavior and possible impact on the surrounding environment through leaching, erosion, or change in local hydrodynamics were monitored for 18 months. Seawater and particulate samples, as well as 0.2 and 1.5-m-long sediment cores collected approximately every 6 weeks, represented the bulk of the work samples. They were analyzed for geochemistry, microbial community, fauna and flora content, metal concentration, polychlorinated biphenyls and polyaromatic hydrocarbons, and ecotoxicological profiles.

The data gathered by the scientists and engineers were used to address several questions, including:

Do dredging and translocation of sediment from the source in a channel “to-be-deepened” into shallow areas “with-the-profile-to-be-diversified” affect the intrinsic biogeochemical characteristics of the sediment?

Channels accumulate fine particles and organic material that can concentrate on various natural and anthropogenic contaminants. Such contaminants could leach from the sediment upon dredging, exposure to toxic condition, and translocation into shallows where water column hydrodynamics are greater. This research, therefore, quantifies such leaching, and determines whether it has a possible impact on the



Fig. 4. Experimental sediment banks in the Venice lagoon during maturation process when the wood pilings were above water, and after maturation when the wood pilings were cut at the level of the compacted sediment. Source: MAV-CVN, 2005.

surrounding environment. At this stage of the SIOSED project, preliminary results indicate that there are limited changes in the sediment characteristics once transplanted into sub-tidal banks. Possible leaching of material from the dredged sediment does not appear to represent an obvious and significant threat, based on the absence of evidence to the contrary, and contamination of the sediment from the surrounding environment also seems limited. Sub-tidal banks thus could be considered a possible strategy to reuse dredged sediment, which will be specifically addressed within the SIOSED project.

Are banks affecting local hydrodynamics? And conversely, is the local hydrodynamic shaping the banks?

Water circulation in the Venice lagoon, which has an average depth of 1 m, is intense, complex, and variable, and results from a combination of tidal fluxes, wind-driven currents, and shear from the sea floor. Mature banks represent a minor physical structure on the sea floor, and accordingly, currents do not appear to be changing dramatically in areas where banks were built. The reciprocal is true, at least during the summer months when banks showed little or no erosion. The banks will soon be exposed to winter weather, however, which is typically characterized by storms, strong waves, and surface currents, which will give a better indication of the banks' strength when confronted by physical stress.

Can organisms settle down and colonize banks?

The main observation, relevant to sediment management practices, is the fact that dredged sediment from the channel contained elevated concentrations of ammonia, which slowly diluted out into the water column during maturation of the banks. Thus, during the first few months of construction, the banks did not necessarily represent the best environment for settlement of new species. In other words, endemic species that had survived the dredging and transplant were present, but in low numbers. After the banks matured and the ammonia was diluted out of the first 10–15 cm of the top layer of sediment, the banks started showing a greater diversity of species and a greater abundance of organisms. These preliminary data suggest that dredged sediment from channels, reused in sub-tidal banks, could provide an appropriate substrate for new settlement of species, when time is allowed for the inherent concentrations of ammonia to dissolve.

The SIOSED project will continue until November 2007. A detailed analysis of the multiple approaches to the question of the effects of moving and reusing dredged sediment will be presented at a final workshop to be announced on the SIOSED website: <www.siosed.ucsd.edu>. We anticipate that the data will be of interest to policymakers, city planners, and environmental managers who deal with dredging and reusing marine sediment. While the research is specific to Venice, it will have applicability for any other coastal city in the world.

5. Conclusions

“Saving Venice” is a work in progress. The determination of what to save, who should be responsible, how urgently action is needed, the level of expenditure required, and who is responsible for providing the needed resources, are all societal questions, based on values, tradeoffs, and imperfect knowledge. Science and engineering are essential to inform these societal decisions, to help define the options, predict consequences, and provide scenarios based on different options. Science and engineering are also essential in identifying the uncertainties and evaluating the risks. But the decisions are not based solely on scientific analysis and engineering calculations.

The increasingly frequent flooding of Venice is not just a local or national problem. It has attracted the attention of academics, historians, artists, and the general public around the world. The Venice authorities have invited international researchers to work in partnership with local experts to integrate local knowledge with independent expertise. In the SIOSED project, the entire Scripps Institution is taking responsibility for the results. Because of the importance and the complexity of the project, Scripps built an independent external peer review into the contract so that the Director of Scripps can say with confidence that the science meets the scrutiny of the international scientific community. However, the SIOSED project although broad and interdisciplinary, and driven by a need for scientific knowledge to inform practical decisions that are being made, only addresses a small subset of all the questions that decision makers would like answered. It is the start of a continuous process of investigation, integration, evaluation, and more investigation.

It is impossible to halt life in Venice while the floodgates and their supporting infrastructure are being built, and as the lagoon is routinely dredged to maintain navigation routes. Continuous long-time monitoring of environmental conditions, ocean circulation, and human activities is essential. New research might offer a basis for changes in environmental regulations or in some aspect of the environmental engineering planned for the future.

Ultimately, when the MoSE project is complete and the floodgates are in operation, decisions will be made continuously about lagoon management. There will be operational scenarios to guide the day-to-day efforts, and contingency plans in the event of unusual conditions. If done well, the engineering and scientific work underway today will provide a foundation for enhanced understanding of the complex interconnections of the Venice lagoon ecosystem, including the human inhabitants. The more opportunities people have to access real-time information on water quality, circulation, sea level, and a forecast of changing conditions, the more trust and confidence they will have that their interests whether economic, cultural, or environmental are being appropriately incorporated into management strategies. The multiple actions taken in Venice over the years will eventually coalesce and provide a strong example of marriage between engineering, science, and socioeconomic interests. The historic city of Venice will have, once again, marked the world this time for its exemplary lead in sustainability, from which we all will learn.

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