Sustainability in Water Resources Management
Changes in Meaning and Perception

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Abstract:
The meaning of sustainability in the context of water resources management has changed through the time. Initially meeting water demand was the dominant concern. While later quality issues became more important followed by wider water reuse, today sustainability must include a whole range of aspects (e.g., energy, pollution, persistent chemicals), spatial and time scales. New approaches to define sustainability metrics are needed. A possible approach is to use fundamentally-based entropy and energy flows.

Keywords: water resources, water quality, water demand, physical sustainability, water reuse, entropy, energy

The Beginnings

Through the human history, the meaning of sustainability in the context of water resources management has been changing slowly but quite perceptibly. Originally, sustainability simply meant meeting human demands by natural supplies. For this reason, all human settlements arose in a proximity of sufficient water sources where even peak demands were smaller than the available "base" flow in a river or groundwater supply. As the demand for human consumption, agriculture, and later industry grew, the most easily reachable resources became insufficient. The solution was to find another source further out and bring water where it was needed, again to balance supply and demand. This pattern of water resources management persisted through the millennia. Some solutions could be as simple as digging a deeper well. More complex approaches included early irrigation schemes in the Fertile Crescent, Roman aqueducts, Versailles fountains and culminated with grand water transportation projects in California. When the quintessential great builder William Mulholland said at the opening of the LA Aqueduct, "*We are here consecrating this water supply and dedicating the Aqueduct to you and your children and your children's children-for all time*" he expressed the spirit of the time.

Of course, such water projects were never without challenges and constraints. For high peak demands, hydrologic limitations required either finding a bigger source or building sufficient storage. Technical problems were common. Ancient conduits limited the pressure under which water could be moved. Pump technology was often inadequate. The first attempt to bring water to new gardens for the enjoyment of Louis XIV led to the construction of the famous "*machine de Marly*", a formidable system of tanks, supply lines and two hundred pumps powered by paddlewheels. Unfortunately, the "machine" did not provide enough water and the ultimate water supply came from the river Eure some 70 km away. Big dams posed its own technical problems. Construction was always difficult and dam failures were quite numerous. In California alone, at least 460 people were killed in the past hundred fifty years due to 46 dam failures and world-wide casualties are much larger. Finally, economic and political problems were always present, boiled down to the essential question, “Who will pay for water and how much?” However, the underlying meaning of sustainability was still quite simple: *Supply should be at least equal to the demand.*

As water demand continued to grow and water sources became more polluted, the simple sustainability paradigm underwent a change. On one hand, recognition that many illnesses were water-borne pushed toward improved sanitation of urban centers. Pavements and sewers led to effective disposal of waste from the streets improving life conditions for many millions of people. These efforts, championed by great sanitarians of the 19th century in the developed world had a significant positive impact on public health, a contribution often forgotten today. In parallel with waste disposal, significant efforts were made to provide safe water cheaply and conveniently to the "general populace". While water supply to individual private households could be traced to the ancient Roman waterworks, it was much an exception and the privilege of the rich rather than the norm. Even as late as the mid-20th century numerous inhabitants of European metropolis had to be satisfied with a single tap per household (or sometimes with an even less convenient situation). These great strives, initially available in the most advanced and wealthy urban areas, gradually spread into other communities although at a very uneven rates.

Engineered Water Supply

Water treatment became initially a possibility and later the necessity. The continuing development of water purification technologies allowed for balancing the water sources of different quality and availability. Sometimes, it was possible to bring clean water over long distances and avoid an extensive treatment. As another option, local, less-clean water supplies could be used when enhanced by treatment using a variety of processes. Thus, the modified sustainability framework was to match water demand with available supplies in terms of both quantity **and** quality. As a single water supply system commonly provides water for different purposes (e.g., drinking, hygiene, irrigation, waste disposal), the quality of all supplied water was dictated by the most stringent requirements, most frequently those for potable water. While in the past, achieving drinking water quality was technically and economically less demanding than its distribution, increased drinking water quality expectations shifted the balance, at least in the developed world. In the US, a series of regulations significantly tightened drinking water standards forcing many utilities to used advanced and costly treatment processes despite the fact that people drink less than 1% of the total water supplied.

Since water became an integrated component of not only daily lives but of whole societal fabric, reliability of its supply became also a factor to be considered along with hydrologic, technical and economic constraints. Progressively, sustainability was achieved through more advanced and complex technical solutions integrating water withdrawal, conveyance, treatment, and waste disposal. However, the basic principle of water supply remained unchanged. Water was withdrawn from the natural environment, used and returned to the environment with lower quality and at a location different from the withdrawal point. Thus, such scheme was only a part of a hydrologic cycle, essentially a **linear chain** within a **larger circular pattern**. Figure 1 show a schematic flow patterns within a generic urban area (Hermanowicz and Asano, 1999).

In this process, both quality and quantity of the returning water is often different from that of the water withdrawn from the environment. While natural self-purification processes in rivers and lakes provide some capacity to deal with pollutant, today that capacity is generally insufficient (except in areas with low population density or otherwise protected). When self-purification processes are not sufficient, they need to be augmented by engineering solutions or the quality of water in the system becomes degraded. Similarly to quality, water quantity below the point of withdrawal can be augmented by natural processes but in many parts of the world, the quantity of water is managed through storage and transfers. Such management solutions, while technical in nature, are subject to severe social (political, economic, institutional) pressures on regional, national and transnational levels.

Water Reclamation and Reuse

An important breakthrough in the evolution of sustainability for water resources was achieved when water reclamation and direct water reuse were introduced as options to satisfy the demand. Although immediate drivers behind water reuse may differ in each case, the overall goal is to close the hydrologic cycle on a much smaller, local scale. In this way, the used water (wastewater) becomes a valuable resources literally "at the doorstep of the community" (Hermanowicz and Asano, 1999) instead of being a waste to be disposed. In many cases, water reuse is practiced because other sources of water are not available due to political or economic constraints while further attempts to reduce consumption are not feasible. Water reclamation is also the most challenging option, technically and economically, since the source of water is of the lowest quality. Instead of relying on self-purification to reduce some pollution load, technical solutions are called for. Figure 2 presents water quality changes driven by water reuse. As a result, advanced treatment is commonly used, often beyond pure requirements stemming from the final water use, in order to alleviate any health concerns and make the water reuse option palatable in public opinion. Such treatment and separate distribution system for reclaimed water make water reuse also costly, hence limiting its wider applications.

From the sustainability point of view, the advent of water reuse coincided with changes in public perception of water resources. Sustainability has acquired a broader meaning. It no longer means simply matching the quantity and quality of supplies and demands for domestic, industrial or agricultural uses. Concerns for the aquatic environment led to establishing the so-called "environmental flows" with water shared among a broader range of stakeholders, thus further prompting for search of reliable resources that can be directly controlled by the user. Although indirect water reuse has always been a part of the hydrologic cycle as used water discharged to a river was, in part, a source for other users downstream. However, direct water reuse crossed important societal and psychological barriers as "natural" environment was eliminated from the water loop (or greatly diminished). These factors and the lack of natural self-purification processes make water reuse schemes to include highly technical solutions in form of advanced treatment, dual distribution systems and significant monitoring and control systems.

New Paradigm of Sustainability

From the perspective of sustainability, we need to go beyond quantity and quality. We need to assess water reuse, and indeed all water resources management systems, in terms of their broader environmental and social impacts in addition to previously considered technical and economic constraints. The following examples illustrate the challenges facing decision makers at different levels of water resources management. At the most technical and detailed level, choices must be made between different treatment processes and associated equipment. For instance, should we consider membrane filtration that achieves high degree of water purification more or less sustainable than the classic coagulation-flocculation process that uses less energy but produces quantities of chemical sludge requiring further processing and disposal? On a larger scale, it is legitimate and important to ask how we should balance energy-consuming treatment processes for localized water reclamation *versus* transporting water from a more distant but cleaner source. Such questions should be asked about whole systems and also about their various parts. How should we account for far-away environmental impacts of energy generation needed to drive irrigation pumps?

Although such questions become more important, we lack a framework for assessment of sustainability in its broader sense. Current definitions do not offer much help to an engineer, a planning official or a politician to deal even with purely technical questions and decisions. The most commonly accepted description was provided by the World Commission on Environment and Development (1987) in the so-called "Brundtland Report". The goal of sustainability is to "meet the needs of the present generation without compromising the ability of future generations to meet their own needs". Other descriptions are similarly phrased and often confuse sustainability with environmental protection and other lofty goals that, strictly speaking, are not required for sustainable operation. A much better metric is required for this purpose. An existing methodology of life-cycle analysis (LCA) suggests that a concept of **physical sustainability** could be developed as its extension. This description would be only a part of the total sustainability question but, if defined in a clear and workable way, it would be a positive contribution.

If sustainability is to be incorporated in common business and societal activities, it must have a reasonably simple and quantitative definition, somewhat akin to financial descriptors like price or cost. If such a description is developed for each activity, similarly to a dollar tag, it could then be used to compare alternatives. It could also be aggregated to evaluate more complicated systems such as an industry sector or a national economy. The ultimate goal of so-defined sustainability definition is not to pass a judgement on which activities are "better" or "worse" but rather to provide a framework for a meaningful comparison. Not every product that is less expensive is necessarily more desirable. Similarly, not every activity that is more "sustainable" is better whatever metric is applied. In both cases, the metric itself, whether financial or sustainability, cannot be substituted for judgement but can help reaching such a judgement.

All natural and engineered processes, including those applicable to water resources management, involve transport and transformation of matter and energy. These processes can be characterized in a rigorous way by energy fluxes and changes of associated entropy. Since the Earth's ecosystem is maintained by the flow of energy, it seems that by analogy the rate of entropy change combined with the energy flux may be a reasonable measure of sustainability. In general, changes of entropy resulting from transformation, concentration or dilution of individual constituents can be calculated using thermodynamics. Entropy of a system or its part can increase (e.g., as a result of dilution) or decrease (e.g., resulting from segregation of a mixed stream into its components). From the sustainability viewpoint, the processes that increase entropy or requires larger energetic fluxes are less sustainable. Although a complete reversal of entropy increases is not possible, lowering the rate of entropy increase is desirable. Thus, a suitable combination of entropy changes and energy may be a first step toward a good, practical definition of physical sustainability.

Entropy changes must be compared with the associated energy fluxes. Unlike entropy, the quantity of energy remains unchanged but its forms may (and do) undergo transformations. We propose to use in the sustainability assessment only this part of the total energy flux that changes form in association with the changes of entropy. For example, water flowing through a treatment plant contains (large) thermal energy. This energy would be not counted in our proposed analysis unless water temperature changes significantly. Similarly, only that portion of the potential energy of water pressure that is used to overcome headloss would be used in the assessment. The comparison of entropy changes with energy fluxes can be facilitated by a combined criterion Ω

$$\Omega = \Delta E + T \cdot \Delta S \qquad \textbf{(1)}$$

where ΔS is change of entropy, ΔE - associated energy flux, and T - absolute temperature. Processes that result in large positive entropy changes $\Delta S >> 0$ or use large amounts of energy $\Delta E >> 0$ are deemed less sustainable (perhaps unsustainable) and are characterized by $\Omega >> 0$. Highly positive values of ΔS indicate unsustainable processes as they "degrade" the quality of materials (e.g., by significant dilution or dispersion). Conversely, processes with smaller values of Ω (ideally $\Omega << 0$) are more sustainable.

While the proposed approach, is in our opinion, a promising first step toward a better definition of physical sustainability, more work is needed to demonstrate its usefulness. Current research in our group is oriented toward scale-up challenges and explicit incorporation of time dynamics.

References

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