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Opinion

Science Informed Policies for Managing Water

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Abstract: Water resource management policies impact how water supplies are protected, collected, stored, treated, distributed, and allocated among multiple users and purposes. Water resource policies influence the decisions made regarding the siting, design, and operation of infrastructure needed to achieve the underlying goals of these policies. Water management policies vary by region depending on particular hydrologic, economic, environmental, and social conditions, but in all cases they will have multiple impacts affecting these conditions. Science can provide estimates of various economic, ecologic, environmental, and even social impacts of alternative policies, impacts that determine how effective any particular policy may be. These impact estimates can be used to compare and evaluate alternative policies in the search for identifying the best ones to implement. Among all scientists providing inputs to policy making processes are analysts who develop and apply models that provide these estimated impacts and, possibly, their probabilities of occurrence. However, just producing them is not a guarantee that they will be considered by policy makers. This paper reviews various aspects of the science-policy interface and factors that can influence what information policy makers need from scientists. This paper suggests some ways scientists and analysts can contribute to and inform those making water management policy decisions. Brief descriptions of some water management policy making examples illustrate some successes and failures of science informing and influencing policy.

Keywords: science; policy making; systems models; communication; case studies; water management

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1. Introduction

The natural, economic, and social environment we live in today is changing at accelerating rates. Anthropologists are calling this "the Great Acceleration" [1]. The impacts due to changing climate are among them. They are becoming increasingly obvious even to nonbelievers [2]. In response to increasing public concern, more of our political leaders are proposing ways to reduce this increasing rate of change and its current and future adverse consequences [3]. Evidence of these consequences is especially clear to water managers who must cope with more extreme and frequent droughts and floods and water quality issues [4].

Besides the impacts of climate change, changes in new technologies are affecting almost every aspect of our lives. The science and technology that gave us the internet has changed when, how much, and how often, we communicate with each other, and access information, and even disinformation. For example, both the water and wastewater industries are undergoing a process of digital transformation in their production processes due to meters and sensors that can be read remotely and provide real time data. This significantly increases the timely detection of possible leaks in buildings and distribution networks or malfunctions in treatment plant operations. Similar sensor and data processing systems are providing real-time predictions of field conditions aiding agriculture and food processing operations. Data from global satellites, coupled with machine learning algorithms, are providing improved flood risk information and predictions to communities that are vulnerable to flooding. These examples could continue [5], but along with this technology brings cybersecurity issues that can disrupt such systems [6].

More dams are being built to meet the increasing needs for water security, to prevent floods, and to produce hydropower, among other purposes, but they also often bring with them unwanted environmental, ecosystem, and social problems [7,8].

Public policy makers are expected to deliver solutions to these problems—solutions that work, are acceptable, and sustainable. Sound scientific evidence can inform those responsible for establishing regulations and policies that address these management challenges. Acting on that evidence can only increase the likelihood that the resulting policy decisions will meet their objectives [9].

Scientists are, however, not always ready to provide this needed information when policy makers want it. Scientists prefer to first inform and convince themselves as they work toward developing new knowledge and new technology needed to better address various issues. Much of this potentially useful science takes place in institutions where science is performed for science's sake: aimed at better understanding aspects of our planet, how they function, and why. Society needs this, and eventually we all will benefit from new knowledge and technology. Performing science for science's sake tends to lead scientists to talk to themselves as they cope to keep up with all the changes in their own disciplines, let alone others [10]. Scientists can become entrenched in silos (ivory towers), challenged by their own problems, and very often isolated from, and not communicating with, the rest of society. All this, together with the explosion of data, including fake data, has sometimes resulted in a distrust of science, scientists, and their contributions. Hence, while there is a need to continue to support and encourage science for science's sake, there is also need to pay attention to how science can best inform those involved in creating policies that impact our individual and collective welfare, however measured. [11–16].

The focus of this paper is on the links between scientists and policy makers impacting the management of water. Informing policy makers is not the only reason that motivates scientists, but it is indeed an increasingly important one. This is evidenced by the growing interest and attention in professional scientific and engineering societies, such as the American Geophysical Union (AGU), the European Geosciences Union (EGU), the American Society of Civil Engineers (ASCE), the American Water Resources Association (AWRA), and the International Water Association (IWA), given to "science for policy" topics at their conferences and publications [17,18]. Producing science relevant for policy requires more than just presenting papers and writing journal articles, however. Collaboration between scientists and policy makers is key, and trust, good communication, and the ability to learn and adapt to each other's needs largely determine the extent scientists and their sciences are able to influence policy. Clearly, both scientists and policy makers can do without each other's inputs, but almost certainly both the benefits derived from science and the effectiveness of policies chosen by policy makers will be the poorer for it.

2. System Complexity and Interconnectedness

In today's highly interconnected societies and economies, policy makers addressing one issue must consider the impacts of their decisions not only on the issue being addressed but also if and how those decisions may impact other aspects of society over time [19]. We are all living in a multicomponent environment, hence taking a systems approach to managing it makes sense [20]. A systems approach focuses on the performance of the system as a whole, not of each component separately. How one component of a system is designed and managed may impact the performance of one or more other components of that system or even of other systems. These possibilities are worth being identified and evaluated, ideally before policy decisions are made. Better to prevent major problems or crises than to deal with their consequences in spite of the fact that politicians, and indeed all of us, probably get more credit and fame from solving crises than from preventing them [21].

The complexity and interconnectedness of our water resource systems, the purposes they serve, and the multiple demands they meet presents a major challenge to water managers. We depend on scientists to generate the knowledge needed to more effectively address these management issues and on management policies that are based on this knowledge. However, to create such policies, policy makers themselves need to be informed of the science. Science informing policy the subject of this essay.

3. Characterizing Water Policy Issues

Some water management policy issues are relatively simple to analyze and address. The scientific data are relatively certain, the behavior of the system in response to various policies is relatively well understood, and given the policy objectives, the choice of the best policy is relatively obvious. But this is not typical for many water management issues. Such cases are often characterized by uncertain facts, disputed or conflicting values, high stakes, and tight time pressures. Such situations are labeled as "wicked." Wicked policy problems are complex, meaning they are difficult to analyze and understand, they are interconnected with other systems, impacted by other issues, multidisciplinary in nature with many cultural and social aspects, and have conflicting objectives or goals among known stakeholders both of which are changing over time [22]. As a consequence, they are not "solvable" in a technical sense. They have no one best solution. Moreover, there are no criteria that enable one to prove that all feasible and reasonable policies addressing a wicked problem have been identified or considered. This makes the policy making process challenging at best.

While classical scientific approaches cannot solve problems that have no solution, this does not negate the value of scientific evidence that is relevant to those issues and problems. Policy makers can still benefit from considering the analytical scientific evidence pertaining to policies that may favor or constrain them from achieving particular objectives or goals. At the same time, policy makers have to reconcile conflicting values and objectives and also ensure that any chosen course of action is politically acceptable, which hopefully means acceptable to a majority of the public. Good policy solutions are those that reconcile all these considerations [23,24]. Scientists can help address the technical or analytical part, but the rest falls to the policy makers.

Example 1. *The current conflict in the Nile River Basin between Egypt and Ethiopia over the filling of Ethiopia's newly built Grand Ethiopian Renaissance Dam (Figure 1) is perhaps one of the best examples of an international "wicked" water management problem. So far, after a considerable number of modeling studies by just about every academic, consulting firm, NGO, and agency or research institution that models water, including modeling studies to check up on the results of other modeling studies, no acceptable solution is apparent in spite of negotiations that continue to take place at the highest government, and even international, levels. Egypt does not want any increased risk of not having the water it considers it is entitled to, and Ethiopia wants to fill the dam so as to produce hydropower to help meet the considerable demand for energy in their country and surrounding region. Water stored in a dam or that evaporates from the dam is not then available downstream and that scientific fact for Egypt is unacceptable. All water allocation issues can turn into wicked ones that have no solutions when there is an unwillingness to compromise or think outside the box in order to enlarge the options for achieving an acceptable water management policy [25].*

Figure 1. Grand Ethiopian Renaissance Dam on the Blue Nile.

Few would disagree that the public policy world of today can be volatile, uncertain, complex, and ambiguous. Solutions proposed to address problems or opportunities in this environment, are often strongly contested. As a consequence, many policies developed to address problems fail because of unforeseen side effects or difficulties in coordination and monitoring [26]. Sustainable development issues related to water and the natural environment are among those that policy makers must address. The challenge for scientists is therefore to generate meaningful (and useful) policy options that can adapt to future surprises and conditions that are today unknowable, while satisfying today's goals and needs [27].

In science, the process of solving a problem involves understanding the nature of that problem. Scientific questions, especially those tackled by individual research projects, are typically narrow in scope. Science has a collective responsibility to collect, verify, and synthesize research results, in pursuit of more and more coherent and complete knowledge, say for "what can be done about *X*." However, the scientific method cannot answer political or normative questions like "what should be done about *X*." Therefore, the process of interpreting science involves bridging the gap between producing scientific evidence relevant to what can be done and deciding what policies should be selected based in part on this evidence [28,29].

To add to the challenges of policy making, science itself can not necessarily provide clear-cut options for addressing wicked policy issues or problems. However, systems analysis methods can often help provide scientific evidence useful to policy makers as they select policies for addressing those issues or managing those problems. Reductionist approaches are useful for focusing on the parts of a system, i.e., parts of the economy, the environment, and society. When it comes to understanding the complex dynamics resulting from the interaction of these parts, it is useful for both scientists and policy makers to shift their attention from the parts or components of the system to the interactions among them. Systems analysis methods allow taking a plurality of social values, perspectives, and interests into account in a coherent and transparent manner [20].

4. Scientists Informing Policy

The work of many scientists in academic or research institutions is largely driven by curiosity, rational analysis, and educated subjective judgements. They have ideas, they write proposals to obtain the funding needed to pursue those ideas, perform the needed research, and if successful, publish it. Scientists working in a policy making environment, or for policy making institutions, have similar interests and standards but have some additional drivers and incentives as well. Those working in the policy making environment, e.g., in The Institute of Water and Hydropower Research (IWHR) within The Ministry of Water Resources (MWR) in China, or in the Army Corps of Engineers (USACE), the Bureau of Reclamation (USBR), or the Environmental Protection Agency (USEPA), to mention a few US federal agencies dealing with water, are mainly influenced by their agency's policy agenda, its mission and authority, with perhaps some room for exploratory research. These agencies employ scientists who perform science, and recommend or make policy decisions as well [30]. Science topics in these agencies are typically determined by existing or proposed regulatory requirements or by the needs to have estimates of social, ecological, economic, and environmental impacts of proposed infrastructure design and operating decisions. Research "questions" needing answers from scientists serving in or for these agencies are often posed by legislators and regulators or policy makers who wish to know the immediate and longer term impacts of possible decisions they might make.

Similar conditions apply for consulting firms such as the Danish Hydraulics Institute (DHI) and Deltares in The Netherlands that support (i.e., inform) policy making institutions. The National Research Council of the US National Academies and think-tanks such as RAND Corporation in the US and Europe, while not government agencies, are almost solely devoted to performing science that informs public policy issues, including those related to water management. The International Water Management Institute (IWMI) in

Sri Lanka, the International Institute for Applied Systems Analysis (IIASA) in Austria, and many other international agencies such as those of the United Nations FAO, UNESCO, WHO, WMO, and the World Bank (IBRD) provide a similar service by producing scientific knowledge useful for addressing regional and global water, among other, policy issues.

Water management policies are rarely dictated by science alone. In addition to considering scientific evidence, policy makers also consider values, political relationships and concerns, and a need to build majority coalitions. Policy makers must consider and work with the values, preferences, and opinions of many including the public, other policy makers and scientists, and the regulatory/legal community. While scientific evidence is useful and relevant for developing policy solutions, science alone is not sufficient to replace politics just as politics is not needed to perform science. Yet scientists and their scientific inputs to policy can be more effective if scientists become aware of these other factors that policy makers consider, including the desires and concerns of the public. These factors may affect the usefulness of any science-based evidence or advice being offered as well as the how and how much of it is being offered.

Policy making is a complex and not-infrequently random process that includes both scientific and normative dimensions. Scientists and policy makers tend to define and view problems differently: one as something to solve technically based on scientific data and methods, the other as a much more social process of negotiating solutions in an effort to find one that is both politically supported and technically feasible. Policy makers' norms and values typically determine what scientific evidence is desired and how they want it presented. For example, displaying Pareto frontiers identifying alternatives representing efficient tradeoffs among competing objectives may be interesting but not necessarily relevant to policy makers as might be other alternatives that are dominated (inefficient) but politically more acceptable based on values or reasons perhaps not even articulated [31]. Values and concerns of policymakers can be influenced by different types of evidence besides scientific data. This could include political and even religious ideologies, ethical principles, anecdotes and rumors, conspiracy theories, fake news and beliefs, disinformation, and so on. These factors can influence decision-making even more so than scientific data. There is no scientifically quantifiable right mix of all these inputs that would point to a "best" policy. As a result, there are no optimal policies, only ranges of feasible and infeasible ones. Of the feasible, some may be acceptable, others not. Different individuals will likely have different opinions. Debates that take place in an open democracy over what policies to implement or what decisions to make involve both scientific arguments and subjective judgements that cannot be combined and expressed as a benefit—cost optimization problem, as much as some of us might like [32,33], and as illustrated in Example 2.

Example 2. *A joint Canadian-US five-year 20-million-dollar study to identify improved operating policies for controlling the lake levels and river flows of the lower Great Lakes basin began over two decades ago. The study was undertaken for the International Joint Commission (IJC) that oversees the management and operation of the Great Lakes, among all boundary waters, between the two countries. The lakes and downstream river serve multiple purposes and users. These purposes include hydropower production, shipping, commercial fishing, recreational boating, shoreline protection, and ecosystem enhancement. Ecosystem enhancement is often in conflict with other goals, especially shoreline preservation. Floodplain ecosystems benefit from some variation in water levels and flows, whereas shoreline owners would prefer constant levels that cause less erosion. The higher and more constant the lake levels are, the better they are for the other purposes, as long as they are below flood stage. Furthermore, benefits derived from all the purposes but ecosystem enhancement can be expressed in monetary terms. But the main motivation for this study was to find operating policies that better protected, and in fact restored, wildlife habitat along the shores of the lakes and downstream river. Operating policies in force since the mid-1950s had not considered the welfare of wildlife, such as muskrats for example. At one point during this study the US co-chair of the IJC requested a benefit-cost analysis that included all the purposes served by the Lower Great Lakes system, including ecological habitat restoration. He specifically wanted to know the dollar value of* *a muskrat (as shown swimming in Figure 2), since the main conflict was between what shoreline owners wanted and what ecologists assumed muskrats and other wildlife wanted. Scientists were being asked to place a monetary value on an environmental benefit that they were not able to do. The study ended without having performed that benefit-cost analysis. The commissioner claimed later that not having that analysis was one of the reasons no decision on a revised operating policy was made until some nine years after the formal 20-million-dollar study ended [34].*

Figure 2. Muskrats could benefit from a new water control regimen. https://mymlsa.org/muskrats-in-the-lake-and-in-your-boat/ (accessed on 20 February 2021)

To bring science closer to meeting the particular needs of policy makers, scientists need to understand their information needs. They may not be able to meet them, as just illustrated in Example 2, but it helps to understand them. These needs can change depending on the particular issues being addressed. A way scientists can be better aware of what policy makers need, and when, and how to present it, is to work closely with them. This requires a transition from situations where scientists and policy makers are separated and in contact with each other only occasionally, to where they are working together more often in a more integrated environment. This transition is often difficult to achieve, but may be necessary if scientists are to become more successful in identifying and bringing politically feasible scientific evidence to the policy making process and in a timely manner. Collaboration and trust between scientists and policymakers, as well as others that impact the policy-making debates—experts, stakeholders, and the media—is at the core of successful exchanges of information among them [35].

Even though science may not be able to resolve all underlying value conflicts, it can help distinguish facts from values and thereby refocus policy making debates. This can be more easily achieved when scientists move from periodically advising to participating throughout the entire policy making process. It is up to both the scientists and policy makers to make that happen. While reasons for advocating for the input of scientific knowledge in a policy making process seem obvious to scientists, there are no guarantees that a scientifically-informed solution will inevitably be successful. Yet given the complexities of today's water management issues, it seems being informed by science is worth a try.

Policymaking is not, as often assumed, a sequential, stepwise, and deterministic process. Both the supply of, and demand for, scientific knowledge and evidence can occur in the policy making process at seemingly random times, depending in part on changing asymmetries of political power and conflicts of interest among policy makers representing different institutions and stakeholders. [36]. External events happen that influence policy makers' goals and constraints. With information and even deliberate disinformation overloads, it can become less clear what information is important and relevant, and when, and what, and who to trust. Close collaboration among scientists and policymakers helps build and maintain the trust necessary for successful science—policy interactions. It also helps scientists focus on what science evidence is relevant to achieve specific goals as opposed to what may not be. [37].

Example 3. *Where the science informing process failed to have an impact on policy making occurred in Ghana a few years ago. The science was clear and convincing, but for the policy makers it was the wrong science. The African Development Bank funded a project involving the possible reoperation of the Akosombo Dam, also known as the Volta Dam. This hydroelectric dam on the Volta River in southeastern Ghana is operated by the Volta River Authority. Since the beginning of its operation in 1965, its regime of water discharges has degraded the downstream ecosystem of the river and its floodplains and adversely impacted those living downstream of the dam. Figure 3 illustrates one of the adverse impacts—the growth of water hyacinth weeds. The aim of the project was to find an alternative operating policy that would restore the downstream ecosystems while still meeting electrical energy demands. The institution overseeing the project was the power authority. It had the authority to alter the dam's operating policy, but producing power and generating electricity was their main mission and objective. Here come these foreign scientists and modelers on relatively short visits to work with the authority and to help them obtain the data and develop the necessary models needed for establishing a reoperation policy and estimating its impacts. While spending considerable time with many of the impacted stakeholders as well as with the staff of the power authority during those visits to Ghana, the authority made it clear during each visit that ecosystem restoration was not their mission or interest. It might not have made any difference, but not being able to work closely and continuously with all involved in the project surely contributed to the failure to gain the level of trust and understanding needed to enable a successful reservoir reoperation result [38].*

Figure 3. Aquatic weeds hamper users of the Volta River at Kpong downstream of the Volta Dam. Credit: Krobo Land.

5. Uncertainty and Complexity

Uncertainty and complexity is a key feature of our world today. This is reflected in the research being produced in the natural and social sciences and in our personal lives as well [39]. Uncertainty can be understood from a number of different perspectives: [40] suggests three:

- Technical (or conventional) uncertainty from the unavailability of data and, more generally, information and knowledge.
- System uncertainty from indetermination of the system component interrelationships and parameter values, since they are so complex, and consequently the model and its results are unreliable.
- Uncertainty from ignorance, which occurs when "we ignore what we do not know."

There are a variety of factors that can influence how effective scientists may be in informing policy decisions. They all add uncertainty and complexity to the science informing process. The following paragraphs discuss these factors and include some examples illustrating the extent they impacted policy making in particular situations involving water management.

The Great Lakes Example 2 highlights the fact that policy makers may want information that scientists cannot provide, except as opinions that may not be shared by other scientists. This limitation comes from complexity and uncertainties that scientists have to deal with, just as policy makers have to deal with the complexity of changing power structures and conflicts of interest among stakeholders, as well as among and within their own institutions or organizations. The following Flint Michigan Example 4 illustrates what may happen when the needed information is inadequate, unknown, or ignored.

Example 4. *Seven years ago, officials looking to save money switched to a new source of drinking water for Flint, Michigan, USA. Failure to treat the new water properly caused lead to leach out from aging pipes and contaminate the drinking water of thousands of homes, as shown in Figure 4. The economic and health impacts resulting from the high levels of lead, and the legal impacts resulting from the attempt to cover up the crisis and its damaging evidence at all levels of government, are still being felt today [41]. This still ongoing public health crisis highlights an example of environmental injustice and racism. Regretfully it is not the first of such cases in the US nor is it likely to be the last one. Ignoring science, even as it produces inconvenient truths, can be costly, but how much, to whom, and when seems to make a difference.*

Figure 4. Tap water in a Flint hospital on 16 October 2015 Credit: Flintwaterstudy.org (accessed on 20 February 2021).

Scientists are used to dealing with uncertainty especially when studying nature (including hydrology) and social-economic behavior, and accept it as part of the scientific process. Determining how best to manage water and its socio-economic impacts in large part involves determining how best to manage their uncertainties.

Policy makers generally seem less comfortable with scientific uncertainty and expect scientists to be “more certain” about their evidence and predictions than they expect from providers of other information. But given that scientific evidence is often itself uncertain, when communicating scientific evidence part of that evidence should include the sources and extents of possible uncertainties. These include not only the technical uncertainties but also the uncertainties just due to indetermination and ignorance [42].

Predictive certainty is typically desired by legal systems as well (see for instance the definition of “predictive knowledge” in [43]). Policy makers know that uncertainty in the predicted impacts of a proposed policy can increase its chances of failure. Nevertheless, policy makers almost always are having to deal with uncertainties in the information they have and in the information they wish they had but do not have, simply because it, like the future, is uncertain.

Policy makers have been accused of seeking “one-handed science advisors.” These are scientists who will not say “on the one hand it could be ‘A’, but on the other hand it could be ‘B.’” Nonetheless, today policy makers seem to be increasingly asking for information related to the uncertainty of scientific evidence or conclusions, perhaps hoping to use that information to justify their ignoring the science they do not want to hear, instead of properly using it to select among expected impacts of alternative decisions.

Given all these uncertainties, policy makers know implementing a new policy can involve risks. To a policy maker, the risks of failure can exceed the awards of success. When deciding among alternative policy options, policy makers are likely to be more interested in decisions that minimize the probability of a bad outcome, whereas scientists tend to work toward identifying decisions that maximize the probability of good outcomes. Stated another way, policy makers are often legally bound to minimize the probability of Type II errors—i.e., accepting an inferior alternative—even though that may increase the likelihood of Type I errors—i.e., rejecting the superior alternative. Scientists generally aim to maximize the probability of being right rather than minimize the probability of being wrong. The two objectives can lead to different decisions. Policy makers are sensitive to the possible legal and political consequences of any new policies they might implement should they turn out to make matters worse than the current situation [44,45].

5.1. Information Needs

Scientists are trained to strive to discover or create new knowledge that is true and can be verified by others. Policy makers, however, desire evidence from scientists that is good enough to allow an evaluation of alternative policies. It does not have to be new, nor does it have to be exhaustive. Good enough evidence rarely includes all available evidence. It is the evidence specifically relevant to, and in a form useable for, a particular policy decision at a particular place and time. It is likely to be evidence that comes from different research studies and not necessarily just the latest ones. Scientific evidence produced several years ago may be more relevant and useful for a particular policy than that produced last week. Scientific novelty is not necessarily a virtue when performing science to inform policy [46].

Example 5. *A wide variety of rainfall-runoff models are available for estimating the runoff from land areas such as shown in Figure 5. These range from the simplest empirical or data-driven models (such as regression equations, neural networks, machine learning, and the Rational method that simply equates runoff to a constant fraction of the average rainfall intensity over a given area), to conceptual approaches based on simplified equations of hydrological process in lumped or distributed form (such as NWSRFS, XINANJIANG, HBV, TOPMODEL, HSPF, and VIC) to the more complex models (such as VELMA, MIKE-SHE, TOPKAPI, G2G, and PIHM) that require detailed land surface and precipitation input data and have the potential of producing the most accurate runoff estimates. The particular water management policy issue being addressed, as well as the time and data available, may dictate which among this range of modeling approaches is the most appropriate. The best runoff estimates for informing a policy maker may come from the least accurate but most transparent model or the most complex and likely least transparent model, depending on the particular issue being addressed [47].*

Figure 5. Storm runoff. Image courtesy of the U.S. Geological Survey, Wisconsin Water Science Center.

Policy making can become more difficult if provided with too much knowledge and information. Having a surplus of information does not automatically lead to a faster or broader consensus or greater clarity. Policy makers often lack the time necessary to digest all the information they get and thus expect simple, clear inputs. Scientists must often eliminate the details of their research that may interest and motivate them and spend more time on preparing summaries of what they believe should interest and influence policy makers.

Too often the media tends to misrepresent the scientific consensus and focus on dissenting pieces of information, for the sake of a "balanced approach" or by attracting attention to a conflict. Deliberate disinformation campaigns that produce false and carefully crafted messages can further confuse stakeholders and degrade the policy making process [48,49].

Example 6. *During the planning and construction of Libya's Great Man-made River, several engineers convinced the New York Times newspaper, that instead of being a water distribution system consisting of wells, pumps, and 4 m diameter pipes, Figure 6, for transporting water from aquifers under the Sahara Desert to agricultural and domestic demand sites, the project was really intended for transporting troops and tanks in trucks and trains to where they could invade Libya's neighboring countries without being seen by satellites. This "news"' was published on the front page of the New York Times, whose motto is "all the news that is fit to print," on 2 December 1997. Indeed, it supported the popular notion that Libya's government was not to be trusted [50].*

Figure 6. Transporting Pipes to become Part of the Great Man-made River in Libya. Credit: Wikipedia Commons.

5.2. Commuticating Science for Policy

Scientists working in a policy making environment should make it clear when speaking as scientists, and when, as citizens or policy advisers, giving educated opinions. Scientists contributing to policy making debates have convictions and values just like everyone else. However, there is a difference between presenting scientific results along with the assumptions and their uncertainties that those results are based on and offering advice based on those results and personal values [30]. Scientists cannot hide from the fact that they have opinions, but professional ethics requires that they make clear where their science ends and their normative opinions begin. Even the science itself may be biased toward particular stakeholder interests and based on uncertain assumptions, both of which should be made clear when presenting scientific evidence. Scientists can be advocates for the scientific evidence they produce, but opinions based on scientific studies are not always "the voice of science" just because they are expressed by scientists. Disrespecting this distinction can degrade the trust people have in scientific evidence and expertise.

Even when they clearly distinguish scientific evidence from opinions, scientists involved in informing policy operate in a grey zone between informing and persuading. Scientific research results are typically based on assumptions due to various uncertainties and perhaps even be biased in ways not recognized by the performing scientists. Scientists who present a range of relevant facts associated with different policy alternatives, adapting to what the policymakers want to know, but leaving the choice of solutions to them, can, and I believe should, offer opinions about the options if requested. If opinions are given, scientists should make it clear they speak as educated and informed persons based on their best attempts to seek and produce accurate scientific evidence. Scientists can opt to explain the weight of evidence for different policy goals and objectives, instead of giving general advice for action [51,52].

5.3. Time Constraints and Time Horizons

Just as policy makers are under time pressures that limit the amount of detailed scientific evidence they can consider as they debate policy options, scientists are often under time pressures to deliver their scientific evidence when policy makers can us it. A common cartoon image of a policy maker is someone facing urgent deadlines and demanding scientists submit all needed inputs yesterday.

For science to influence policy decisions, scientists must provide useful policy-relevant information before those decisions are made, or more accurately, before the debate on the impacts of alternative policies ends and attentions shift to other issues or crises. These windows of opportunity can end before all the needed scientific work is complete (let alone tested, validated, and peer reviewed). Debates over what to do about particular issues or problems are often crisis driven or dictated by court-mandated timelines. Thus, these windows of opportunities, within which scientists can usefully contribute, are finite and often quite short. This leads to decisions made based on incomplete information. Scientists working in or for policy making institutions and consulting firms are used to this. Those working in a more academic research environment may not have to meet such tight schedules but do have other challenges such as obtaining finding, recruiting and training graduate students, and getting the research done before those participating in it graduate or the funding grant ends.

As much as policy makers should consider long-term impacts of their decisions, especially if sustainability is among their objectives, they tend to favor short term goals given the limited time they have to gain the support they need to get re-elected. But decisions made to satisfy short-term objectives will have longer term impacts as well. In the words of Al Gore, [53] "the future whispers while the present shouts." Debates on many environmental and water management problems, climate change, and various social issues often show a bias toward solving the more current issues rather than the more uncertain future ones. The problems of biodiversity losses, sea level rise or acidification, the destruction of river deltas, and the potential of mass migration and destruction caused by extreme weather events might only be seen as serious political issues in the next decades.

Example 7. *Sana'a, the capital of Yemen, depends on an aquifer for its water. Years ago, a groundwater modeling study showed that this aquifer would be depleted in a decade or two due to excessive withdrawals. Most of the groundwater withdrawals were being used for growing qat, a green-leaved plant that has been chewed, Figure 7, for its stimulant effect for centuries. Asking Yemenis to restrict their chewing of qat in order to reduce the use of water would be similar to asking coffee drinkers to restrict their drinking of coffee. Finding a socially, as well as economically acceptable, solution to this water management problem proved to be difficult. When suggesting to policy makers that this issue be discussed in public, in hopes of alerting the public, and with their help identifying a suitable solution, the policy makers rejected the suggestion. "Why should we worry about this potential crisis? When it happens we may not even be alive."*

Figure 7. Yemeni men relax in the shade chewing qat, a mild drug used by most Yemenis. Photograph: Cris Bouroncle/AFP/Getty Images.

Water management objectives can change over time. Objectives guiding future management policies will always be uncertain, and it is unreasonable to expect scientists to foresee them and to provide evidence on how they are impacted by satisfying current short-term objectives. Nevertheless, changes can happen, as illustrated by the following two examples. Science can help policy makers develop robust policies that can adapt in response to changing objectives over time.

Example 8. *Examples of the effects of ignoring the possible long-term consequences of short-term decisions are the drying of the Aral Sea in Southern Kazakhstan and Northern Uzbekistan, as shown in Figure 8, and of lakes and associated wetlands of Sevan in Armenia, Urmia and Gav Khuni in Iran, Chad in Northern Central Africa, Turkana in Kenya, and the Dead Sea in the Jordan Rift Valley, to name a few. In many cases, this depletion of water has resulted in large part from water abstractions to meet irrigation demands. In the short run, increasing crop production along with employment opportunities is beneficial. However, the long-term consequences, can range from environmental feedbacks affecting the health and even lives of people in and out of those basins [54,55]. The interesting question to ponder is whether or not policy makers that were promoting development knew these long-term impacts could occur, and if not, whether such scientific predictions would have changed their water management decisions. One cannot survive in the long-run if unable to do so in the short-run. Or, as they said in Yemen (Example 8): "Why should we worry about this potential crisis? When it happens we may not even be alive."*

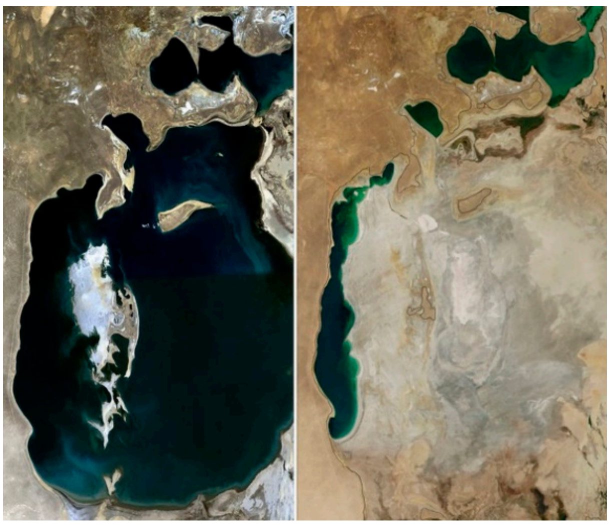

Figure 8. Aral Sea before and after diversions.

Example 9. *An example of having to adapt to unforeseen consequences involves the current project to restore the ecological health of the vast wetlands of the Everglades in the state of Florida, USA. Begun two decades ago, this project is arguably the most ambitious ecosystem recovery effort anywhere [56]. It is in some sense not in response to poor or incomplete past science but rather to past water management decisions that focused on development and did not consider the environment. The project is essentially a vast re-plumbing scheme aimed at replicating as nearly as possible the historical fresh water flows over the flat wetlands of the Everglades—often called the River of Grass (Figure 9)—that once made South Florida a biological wonderland. These flows were diverted when in the late 1940s the US Army Corps of Engineers initiated a massive flood control project aimed at protecting land for urban and agricultural development. Over a half-million acres were drained by a vast network of levees, canals, and pumping stations. While making Florida's eastern coast and midlands safer for development, it also destroyed much of the Everglades ecosystem including its wildlife. Now people care more about this unique ecosystem and environment in general than they did when the decision was made to "drain the swamp." Thus the current restoration project involves taking out much of that drainage and diversion infrastructure and restoring the overland flows to their original patterns to the extent possible. The goal is to maintain what remains of this unique environment and ecosystem. This unique ecosystem is a main reason why many people choose to visit (and spend their time and money in) Florida.*

Figure 9. View of wetlands of Everglades in South Florida. nps.gov (accessed on 20 February 2021).

5.4. Communication

Scientists, especially those engaged in informing policy, need to be good communicators. This involves making research results transparent by specifying the assumptions upon which the results are based and to address the uncertainties and alternatives openly, taking into account the different interests, goals, and perspectives of policy makers.

Part of being good communicators is recognizing that many terms scientists and policy makers use, such as the word "model," can mean different things to others. Just within different scientific disciplines this language barrier can exist, and to perform interdisciplinary research one of the first steps is to learn the language of those trained in the other disciplines. Scientists attempting to communicate effectively to other scientists and policy makers should be aware of this need to speak the language they understand.

What do policy makers expect from scientists? One might think they would like definitive advice on what to do, what policy to choose, what action to take, backed up by scientific evidence supporting that position. However, most know that science can by definition answer or address only analytical questions, not the normative ones. A push for decisive science not only overlooks uncertainty but lies beyond the competence of scientists to deliver under the label of "science."

Furthermore, scientists working for policy can discover an "inconvenient truth," i.e., results that that might make an otherwise popular policy undesirable and therefore complicate a policy response, or force a politically sensitive conclusion. Such a situation can cause two problems. One is the difficulty of communicating unexpected, disturbing results to the policymakers, thereby creating difficulties for them and possibly disrupting the relationship scientists have with them. The other is the dilemma of whether to publish such results, which can understandably be motivated by a sense of responsibility towards the public and the scientific community, as well as one's career as a scientist.

6. Science—Policy Interface

Informing, i.e., knowing what to present, and how and when, is learned through collaboration that generates a mutual understanding and trust between scientists and policy makers. Far less effective is the ad hoc scientific evidence delivered by parachute, either unsolicited, or in a rush when policymakers suddenly ask for the evidence scientists may or may not have. This especially applies when a level of trust has not been developed between the scientists and their client policy makers. Useful evidence comes from collaborative, continuous, long-term relationships with policy makers and their staff throughout a policy making process. This is one reason why there is a tendency for policy making agencies to select the same consulting firms to provide the scientific evidence desired over time. To be relevant to, and imbedded in, policy making, scientists must build up that level of trust and be aware of, if not engaged with, the world outside of science that impacts policy making. This is the world, the so called policy ecosystem, in which alternative policies and stakeholder values are considered, debated, and where choices are made. While scientific processes can provide a systematic way of gathering knowledge (again, possibly biased and uncertain) about this world and how it works, simple opinions and anecdotes coming from groups having different interests, perspectives, and power asymmetries are part of the policy ecosystem, and thus can influence final decisions [57,58].

Yet policies chosen without sufficient supporting scientific evidence are more likely to fall short of being as successful as they could be. An excellent example of this is presented by [59–61] who observe that measures taken to increase the efficiency of water used for irrigation so that the savings could be beneficially used elsewhere had just the opposite impact. In this case one could argue the policy to increase irrigation efficiency in order to provide more water for other uses might have been informed by science, but the science was not sufficient. It was incomplete. It did not consider the whole system. While any policy may result in surprising outcomes, not foreseen when the policy was implemented, the scale and likelihood of adverse consequences stemming from a non- or incomplete evidence-informed decision can be another Flint (Example 4) or Aral Sea (Example 8).

7. Modeling Policy Issues

Modeling studies and their results can help focus policy making debates. However, this does not imply that the decision making processes are similar to modeling procedures. A decision making framework where first scientific data are collected, next policy objectives are defined, then alternative policies that meet these objectives are identified, analyzed and evaluated, perhaps using some multiple-objective models to identify the efficient tradeoffs among the multiple objective values, and finally a choice that maximizes some combination of social welfare (or minimizes political risk) indicators is made, rarely works in practice. For various reasons, this logical systematic modeling framework does not represent the reality of most policy making processes [62,63].

One reason why even well-informed policy making is different, and often more difficult, is the fact that policy problems not only have an analytical, scientific dimension but also a normative, value-based one. Policy makers need to find acceptable practical compromise solutions to problems or issues that meet the values held by all participants where there are no such obvious solutions. These so called "wicked" problems are hard to define, let alone solve, analytically using models. Thus, inevitably their resolution is temporary, tentative, and dependent on political judgements possibly informed by the results of models of those aspects of the problem that can be modeled. As the saying goes, performing the hard sciences is easy, performing the so-called soft sciences is hard [64].

This distinction between the scientific approach to discovery of knowledge and policy making does not make it impossible for scientists and policy makers to work together to better inform the policy making process. But it is not always easy. While policy decisions can certainly be made without being informed by scientists or their science, the added value of science informed policy suggests it is worth trying to make it work.

Example 10. *Successful examples of effective ongoing use of the systems approach to inform those managing water include the Mekong River Commission's Decision Support Framework (Mekong DSF), the Nile Basin Initiative's Decision Support System (NB DSS), and the flood forecasting model, FloRiAn, of the International Commission for the Protection of the Rhine (ICPR), the Corps' Water Management System (CWMS) used by the U.S. Army Corps of Engineers to support its regulation of river flows through reservoirs, locks, and other water control structures located throughout the USA. Other water allocation models are being used to inform managers of the Senegal and Zambezi Rivers in Africa and the Euphrates and Tigris Rivers and the Suez Canal (Figure 10) in the Middle East, the North-South water diversion project in China, and the designers and operators of the Great Man-made River systems in Libya. Another example of where the science informing process has succeeded in having an impact on policy making is in the operational management of Lake Como in Italy. Based on optimistic, standard, and pessimistic predictive probability distributions of future lake volumes derived from historical data, satellite imagery, and climatological forecasts, a decision support tool identifies the corresponding most appropriate daily releases from the lake. This decision supporting tool has been in successful use since its installation in 1997 [65–67].*

Figure 10. Computer-based decision support system for managing water. www.suez.com (accessed on 20 February 2021).

There are a variety of modeling approaches that can be useful tools for informing policy makers. Models used to inform policy are built and solved to provide information that can help policy makers develop insights on which they can base, at least in part, their policy decisions. The usefulness of such "policy modeling" is judged not by how accurately it reflects the real world, but by how well it is able to provide information that enables a policy maker to make knowledgeable choices among policy options—i.e., how well the modeling can help construct and defend arguments about the relative pros and cons of alternative policy options. A relatively crude model that can clearly demonstrate that alternative "A" performs better than alternative "B" under both favorable and unfavorable assumptions will probably lead to a better decision than a complex model that can perform only a detailed expected value estimation.

Policy models trade off rigor for relevance. In some cases, they are used for screening large numbers of alternative policy options, comparing the outcomes of the alternatives, and/or designing strategies considering a wide range of factors (e.g., technical, financial, or social), but not a lot of detail about each factor. The outcomes are generally intended for comparative analysis (i.e., relative rankings) of policy alternatives. Approximate results are often sufficient to map out the decision space—the ranges of values of the various input parameter values for which each of the various policy options would be preferred [68].

Example 11. *When in the 1970s the Clean Water Act (CWA) and its Amendments were passed in the USA, they required all point sources of wastewater to be treated using "best management practices" (that generally meant secondary treatment that removes about 80% of the carbonaceous biochemical oxygen demand (CBOD)) before being discharged into receiving surface water bodies. The CWA policy became an expensive national public works program [69]. Model studies showed that considerable money could be saved by adopting cost-effective policies, policies that met surface water quality standards at a minimum cost. In terms of infrastructure construction and operation costs, the CWA policy was expensive but politically it was cheap. To enforce the CWA policy required monitoring only the quality of wastewater treatment plant effluents (e.g. as shown in Figure 11), an easier task than monitoring the quality of wastewater influents and effluents and receiving surface water bodies. Modelers who could identify more cost-effective wastewater treatment policies for particular watersheds and river basins did not have to defend their models, along with their assumed model parameter values, in court. Every potential polluter was treated equally. Investigations into which polluter upstream contributed to a water quality standard violation downstream, and by how much, were not necessary. Politically, the CWA policy was a much easier and less costly policy to implement. So much for the education of those advocating cost-effectiveness.*

Figure 11. Polluted Water flowing from a drain pipe into a small stream. wikimedia.org/wikipedia/commons (accessed 20 February 2021). Public Domain.

The responsible use of policy models requires some level of understanding of their limitations as well as their strengths. Along with presenting the outputs of their analyses, modelers should make clear the assumptions underlying the outputs, causes of potential error, and possible inconsistencies across different policy objectives. As useful as systems analysis models can be, they are still models, and all models depend on assumptions. The output of some types of optimization models can suggest the best policies to select given the assumptions, but they do not identify the best assumptions. Any model of a complex system is a simplification of that system and reflects only a subset of its possible representations. This implies that for any policy modelling exercise, there is a need to understand the information needs of all stakeholders. Knowing this may help determine the needed level of detail in models representing the real world system. Policy making processes are dynamic, and hence their information needs can change over time. Scientists developing and solving models need to be able to modify and adapt them as needed to meet those changing information needs. Models developed to inform policy makers can be viewed as learning tools to be used to facilitate the dialogue among policy makers, scientists and stakeholders. They can boost the effectiveness, consistency, and transparency of policy making processes.

Example 12. *In the mid 1970s, a study aimed at increasing Algeria's food security involved identifying the sites, design capacities, and operating policies of infrastructure needed to capture, store, and deliver water to irrigate parts of the Sahara Desert (Figure 12). The system performance measures the government wanted considered were instillation and operating costs as well as the amount and reliability of water delivered. The task was to identify alternatives that represented efficient tradeoffs among these conflicting objectives. Upon presenting some results for one region of the country, the government chose an inferior solution, one that cost more, was less reliable, and provided less water than many other possible solutions. When asked why that plan was chosen, the answer was that their chosen plan better satisfied other social objectives. The set of project objectives and their relative importance can change during a modeling, planning, and policy making process, especially as all involved learn more from the study and other sources about what is possible and hence what can be achieved.*

Figure 12. Installing 30 km pressure pipes for increasing Algeria's food security. https://www.amiblu.com/reference/30-km-pressure-pipes-for-irrigation-project-in-algeria/borgenproject.org, Creative Commons, Public Domain.

Example 13. *In the Mekong, as in many other rivers in this world, hydroelectric dam builders are busy practicing their trade to meet increasing demands for energy. In one recent study, the question being addressed was where to site, how to design, and operate a series of dams to produce hydroelectric power. Framing the question in this manner leads one to identify dam sites and capacities and operating policies needed to meet specified energy targets. Framing the question to be how to produce more energy leads to a broader range of options including the consideration of solar panels as illustrated in Figure 13. In the Lower Mekong, solar power was shown to be a much less expensive option than building and operating more dams, and less damaging to the ecosystems and biodiversity of the river. This information had an impact on a decision not to build a particular dam that would have had major adverse environmental and social consequences, but for how long that decision will apply, who knows [70,71].*

Figure 13. Saving the Mekong with Floating Solar Power. Photo: BayWa re rechargenews.com (accessed on 13 January 2021), Public Domain.

Modeling, as objective and value free as it tries to be, cannot insulate itself from value judgements and decisions. Values enter the modeling process even in the framing of research questions and objects of study, in decisions about what gets funded, in the selection of data to be collected, in the analytical methods to be used, and the scope of the analysis. Values also play a role in deciding what scientific evidence is deemed pertinent to be communicated and how it is to be presented. Just how effective scientific evidence is in informing policy makers depends on just how much trust exists between modelers and policy makers. Trust in science increases if scientists are engaged and open with the people they want to inform and influence.

8. Discussion

Establishing policies for managing water typically involves dealing with individuals who have conflicting views on which policy decisions to make. Thus, debates over how water should be managed take place in a politically driven policy making environment. In this environment, many different factors can influence policy makers and the decisions they make. Scientific data and recommendations based on those data are among them. Science and scientists have an important role in policy making, informing, and guiding decisions on a wide range of water management issues. While scientific evidence is not the only input affecting policy decisions, it is an important one. The challenge of scientists involved in policy making processes is in determining how best to create and present scientific evidence so as to maximize its usefulness to policy makers, especially when it is not always clear what they will need and when. Scientific evidence can influence the ways that policy makers frame issues, address problems, consider solutions, and develop and implement policies. Policies defining how water is to be managed will affect people. Their impacts can be economic, environmental, ecological, and social. Having predictions of these impacts before decisions are made helps policy makers make more informed decisions—decisions that are technically sound in that they work as expected and that are as economically, environmentally, ecologically, and socially acceptable as possible. The purpose of this paper has been to consider how scientists can effectively contribute to this policy making process as they provide scientific evidence relevant to the issues and decisions being debated.

There is little doubt that science can and should inform water management policies. Managing water supplies, demands, and qualities, is becoming increasingly critical and more complex. The rapid evolution of information and communication technologies, and advances in social media and communication platforms, have substantially improved the public's ability to access information and influence policy makers. All this has increased the pressure on scientists and policy analysis to provide answers and solutions to pressing water management problems while also opening them up to closer surveillance and criticism. What used to be "private" debates between different scientific viewpoints over areas of uncertainty now have the potential to become public disputes that can be exploited by different stakeholders to confirm or deny entrenched positions. In other words, science is increasingly visible and, in some cases, increasingly vulnerable in policy making processes. Yet policy making needs science. Policy makers must make decisions even with inadequate and possibly conflicting data and even when there are no perfect solutions to the problems they are trying to address. Having objective high-quality scientific evidence pertaining to these problems can only improve the outcome. Providing high-quality evidence into policy making processes, at the right times and in the right amount of detail, is challenging, but, along with transparency and public participation, are essential for effectively informing policy makers, the public, and improving policy decisions [72].

9. Conclusions

Scientists conducting research on water management problems with the intent of improving the practice of managing water must be able produce and present their scientific results in ways that meet the needs of those individuals and institutions actually managing water. The decisions water managers and policy makers make can be informed by scientists but are also made in response to a variety of other factors often under circumstances of asymmetries of political power and conflicts of interest. Scientists influencing policy should be aware of political environment these managers work in as they offer scientific advice.

Being aware of these factors and gaining the trust of managers can help scientists have a greater influence in the decision and policy making process.

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