Equity in water resources planning: a path forward for decision-support modelers

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# Introduction

Socially-engaged water resources management is paramount to ensuring access to basic water services while avoiding environmental degradation [[1,2]](https://paperpile.com/c/KlpQNa/TzntO+Piv1Q). Many communities across the globe face threats of droughts, flooding, food insecurity, and lack of drinking water access [[2]](https://paperpile.com/c/KlpQNa/Piv1Q). The burden of these challenges is not shared equally across population groups, with those most vulnerable receiving both reduced access and increased environmental consequences . For instance, in the United States, access to water is challenged by issues such as affordability [[3]](https://paperpile.com/c/KlpQNa/NVai), the drying of groundwater wells in rural and agricultural communities [[4]](https://paperpile.com/c/KlpQNa/2T8x), flooding, and contamination in poor and marginalized communities [[5,6]](https://paperpile.com/c/KlpQNa/ilRUs+ZhQb). These disparities arise both from historical disinvestments in marginalized communities and environmental racism, such as the targeted siting of hazardous waste and wastewater treatment facilities in poor and minoritized communities [[7]](https://paperpile.com/c/KlpQNa/3qEV). Climate change threatens to exacerbate these inequities.

As water resources engineers, we have an ethical responsibility to address these inequities in the communities that we serve; as stated by ASCE: “civil engineers shall protect the safety, health, and welfare of the public” [[8,9]](https://paperpile.com/c/KlpQNa/o5Bj+k9Jg). We argue that this includes an imperative to address the impacts that decision-support modelers and models have on marginalized communities. Indeed, many in the international water community have sought to declare water as a human right. However, traditional quantitative approaches to this issue have been criticized as oversimplifying a complex socio-technical problem [[10–12]](https://paperpile.com/c/KlpQNa/qkZNA+THPdG+EnnJ8). Pragmatically, the provision of water services requires costly infrastructure, maintenance, and technical expertise, and many water providers are woefully underfunded. Nonetheless, the concept of water as a human right presents an opportunity for water resources managers to develop goals and metrics centered on equitable water resources provision, working collaboratively with the most vulnerable communities [[12]](https://paperpile.com/c/KlpQNa/EnnJ8).

What does achieving water equity mean? Here, we draw on existing definitions of water equity that are focused on achieving fairness in water systems [[13,14]](https://paperpile.com/c/KlpQNa/OPEdJ+AlmB). The concept of equity has long been dominated by the concept of *equality*, where end-users are all treated as homogenous in their access to infrastructure systems [[13]](https://paperpile.com/c/KlpQNa/OPEdJ). However, this has resulted in *inequitable* service distribution, and the perpetuation of existing infrastructure injustices. For example, historical red-lining and poor housing quality have resulted in minimal access to quality water services in low-income and disadvantaged communities [[15]](https://paperpile.com/c/KlpQNa/d055). Clearly, there is an important distinction between equity and equality in engineering decision-making. To this point, we as engineers are pivotal decision-makers in implementing equitable, rather than simply equal, water practices through planning, design, and modeling.

The challenge to broaden the thought process to include principles of equity does not have to be shouldered by practitioners alone. Similar to other challenges in the field (e.g., responding to climate change), academia and researchers can champion these efforts. Other sectors in the civil engineering discipline have adapted equity frameworks, for instance transportation engineers have developed several racial equity toolkits that inform their models [[16–19]](https://paperpile.com/c/KlpQNa/7MJzO+1N8hl+EhBVm+RSMDq). In the air quality and energy sectors, similar efforts have been made by both practitioners and researchers alike [[20–22]](https://paperpile.com/c/KlpQNa/P3FGL+Ahn7Y+AQah1).

Therefore, the goal of this piece is to offer some key practical steps forward for researchers in the water resource systems decision-support modeling community. Key focus areas include (1) reimagining decision support processes to include tenants of procedural equity; (2) rethinking how equity is represented in models and the metrics used to evaluate equity; (3) discussing multiple modeling methods that address water systems as socio-technical systems with an emphasis on equity; (4) presenting examples that apply equity principles locally and globally; and (5) practical recommendations for researchers in water resources decision support modeling. While addressing equity in water infrastructure systems is multi-faceted, we find that useful decision-support models serve communities directly. The recommendations from this paper can serve as a first step in adapting existing modeling practices to be more equitable so that all communities benefit and prosper from water infrastructure systems.

# Fostering Equitable Decision Support Processes

Decision support tools are typically built around models of real-world water resources systems. These systems are made up of complex interactions between human and natural processes. As such, and despite advances in hydrology and other natural sciences, they remain imperfectly represented in models. When water resources models are defined, even if not explicitly acknowledged, it is done through specific system framings (e.g., what is internal or external to the system, what is an objective or simply a variable, what is uncertain or treated as determined). This is often done within a perpetually evolving learning process with the goal of increasingly improving the model and our understanding of the system. Model-based decision support processes are also, by extension, built on the basis of decisions made by humans on how to model the system and quantify performance [[23]](https://paperpile.com/c/KlpQNa/mytu), decisions that are inherently value-laden and have implications for social equity [[24]](https://paperpile.com/c/KlpQNa/SB4L). Recognizing this fact has traditionally been less popular with natural scientists and engineers, but is becoming more prevalent among practitioners, who understand the inherent ambiguity of the modeling process and view models as useful heuristics for communication, tradeoff negotiation and assessment [[25]](https://paperpile.com/c/KlpQNa/lJoO).

This viewpoint places model-based decision support within a broader context of establishing confidence in a decision support process by ensuring the credibility, salience, and legitimacy of the process in the eyes of multiple stakeholders [[26,27]](https://paperpile.com/c/KlpQNa/H98d+XajK). Salience captures the relevance of the produced information for stakeholder decisions, credibility refers to the technical adequacy of the information, and legitimacy refers to the fairness of the process used to create it. Authors argue that these qualities can be established when knowledge is co-produced through the active participation of multiple and diverse views on an issue, exposing and contrasting alternative framings and preferences [[28]](https://paperpile.com/c/KlpQNa/9xCI). In this context, models and decision support tools serve as boundary objects–focal points around which divergent views can be exchanged to reach a common understanding. Such approaches embrace the plurality of value systems, agencies, and perspectives present between scientists and modelers, public and government bodies, and stakeholders, so that, through the exchange of information and shared learning, knowledge salient to every party can emerge [[29]](https://paperpile.com/c/KlpQNa/5XBa).

Participatory processes are in fact a [core tenant of Environmental Justice](http://www.ejnet.org/ej/principles.pdf), which “demands the right to participate as equal partners at every level of decision making, including needs assessment, planning, implementation, enforcement and evaluation”. We argue that the crux of this principle is indeed the *equal* involvement of participants and not their mere inclusion in a process. Critiques on co-production processes have argued that they often fail to consider the power dynamics and politics inherent in interactions among such diverse groups of people, where large economic interests, government bodies, or perceived experts end up having disproportionate sway over the process and its outcomes (Fig. 1). Inherent power imbalances end up shaping “whose knowledge is being co-produced—for which outcomes, to the benefit of whom, and who decides” [[30]](https://paperpile.com/c/KlpQNa/MaBS), creating at the same time a tension between research that aims at addressing inequity but that is also accountable to those that hold the most power. As a result, participatory processes that simply “bring everyone to the table” without addressing this fundamental imbalance might create the impression of a depoliticised, fair process, when in fact they act to further entrench the framings and policies of the establishment [[31]](https://paperpile.com/c/KlpQNa/HEuT). This relates to the distinction between equality and equity: equality in the deliberation process (“everyone is invited”) is not the same as equity in the deliberation process (“everyone is invited *and their needs and circumstances are considered in the process*”). As such, equal process participation cannot guarantee that the actualized outcomes will in fact address any of the inequities in water provision. We therefore argue that distributional equity is directly connected to equity in the decision-support processes themselves, which embrace stakeholder needs in their framing, metric selection, model development, and methods used.

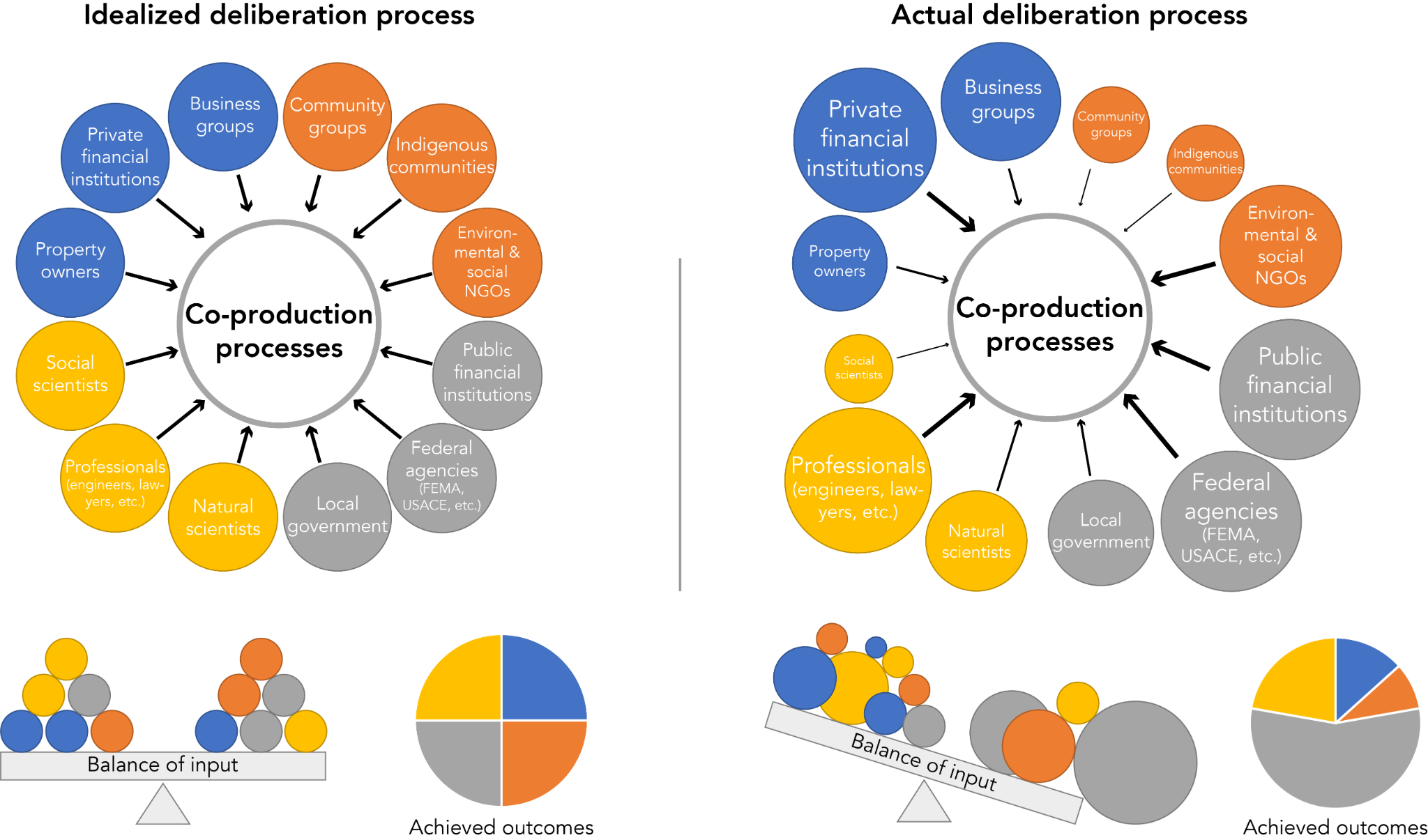


Fig. 1 - Idealized co-production processes (left) and actual processes where power imbalances and inequalities in participation shape the deliberation process to produce inequitable outcomes (right).

Outside these well-recognized considerations around participatory processes, we as water resources decision-support modelers face unique challenges that we see as potential reasons limiting the uptake of equity principles in our work. First, the primary users of our models are often public utilities and local agencies that do not have a mandate nor the capacity to address the fundamental causes of inequity in their communities. This is also exacerbated by the fact that marginalized communities often lack sufficient funds, resources or the data to develop model-based analytical capabilities themselves. Second, a lack of formal training and experience in issues of social equity and justice in the civil engineering community might make us hesitant to include equity and justice considerations in our work. This is arguably also because, even without formal training, most modelers and engineers recognize that a shallow treatment of such complex issues is neither productive nor helpful in actually addressing them. Nevertheless, we should not use this as an excuse to ignore equity entirely. Learning from and collaborating with social scientists using developed theories and indicators for social equity can ensure both that the approach is grounded in a sound theoretical conceptualization of equity and that insights from these communities are directly utilized without “reinventing the wheel” of quantifying equity.

# Representing Equity in Models

## Problem Framing

In working with stakeholders to frame water resources planning and management problems, we often start with the goal of addressing an impact of concern such as poor water quality, lack of water supply to meet demands in times of drought, or damages caused by floods. To evaluate alternatives aimed at reducing these impacts, we need to develop quantitative performance metrics that will be used for the comparison and build a model that simulates performance of the designs on those metrics [[23]](https://paperpile.com/c/KlpQNa/mytu). Here we discuss how to develop these tools through an equity lens.

## Metrics

Designing performance metrics plays a critical role in shaping equitable model outcomes, as metrics directly inform how a management option is perceived by decision-makers. Water resources systems serve multiple purposes over long time horizons and there are innumerable ways to quantify performance across those dimensions. As such, metrics typically reduce that complexity by aggregating performance over time and space into a single number [[32]](https://paperpile.com/c/KlpQNa/UWgv). This presents two challenges to decision-support modelers in designing metrics: 1) in defining a quantitative measure of the outcome of interest, and 2) in aggregating that measure into a summary statistic to inform decision-making. Both steps have important implications for equity, and can be framed with this purpose specifically in mind.

With respect to quantifying the outcome of interest, consider the issue of water supply. Common metrics for quantifying performance on this objective are the frequency, duration or intensity of deficits with respect to demand. These different aspects of shortage might be differentially important for different users. For example, a farmer with significant capital growing perennial crops may be able to weather a single year of severe shortage by paying for additional groundwater supply, yet suffer from several consecutive years of drought, making drought duration a better metric of their vulnerability [Mall and Herman, 2019]. However, the vulnerability of a poorer farmer growing annual crops who doesn’t have the capital to weather a year of severe drought would be better captured by a drought severity metric. Neither of these measures considers the *quality* of that supply, though, which may be of equal or greater concern. As such, it is important to ensure we are first, measuring the right thing (e.g. quantity vs. quality), and second, measuring it in a way that captures the elements of concern (e.g. duration vs. intensity).

Another important question with respect to these performance indicators, is for whom are they calculated? Typically, they are aggregated over time and space, but that aggregation may not capture the impacts on the most vulnerable in their time of greatest vulnerability. The expected costs or benefits over time and space is arguably the most common objective used to evaluate water resources systems’ performance [38], but is one example of a metric that can mask these impacts. For example, while average flood damages of $10,000 may not be critical to a well-off individual, they could be crippling to another. Normalizing costs by income level may avert this issue, but computing the expected value still only captures the central tendency, ignoring impacts on the most vulnerable. **Satisficing** and **min-max** metrics would be better alternatives for ensuring the impacts on the most vulnerable are captured in metric aggregation. Satisficing metrics quantify the percent of stakeholders meeting an acceptable performance threshold [[33,34]](https://paperpile.com/c/KlpQNa/PcOW+Ze1J), while min-max metrics measure the performance of the most marginalized communities [[35]](https://paperpile.com/c/KlpQNa/jgih). Min-max metrics can be thought of as an application of Rawls’s difference principle [[36]](https://paperpile.com/c/KlpQNa/KSIY), which permits social and economic inequality only if the benefits of that inequality accrue to the least advantaged members of society, highlighting the important distinction between equality and equity. This principle is widely applied in multi-actor water resources systems, illustrating how water resources engineers are already operationalizing principles developed in social science and philosophy to include equity considerations when measuring performance outcomes [[24,37,38]](https://paperpile.com/c/KlpQNa/mLoa+Tl5i+SB4L).

In thinking about the distinction between equality and equity, it is important to note that many metrics intended to quantify equity rely on measures of variability that may actually quantify equality at the expense of equity [[39]](https://paperpile.com/c/KlpQNa/K6ca). This can have unintended consequences if one chooses not to implement a planning option that increases variability in performance across individuals in the name of equity even though that option actually improves performance for the most vulnerable [[40]](https://paperpile.com/c/KlpQNa/MxHp). Metrics of relative variability, like the coefficient of variation and Gini index are two such examples that can suffer additional consequences when applied to quantities one wants to minimize, like water supply deficits or flood damages. In such cases, a management option that decreases deficits or damages for the worst-off individuals will decrease both the mean and standard deviation; but if it decreases the standard deviation faster than the mean, it will increase relative variability. This option would therefore perform worse on a relative variability metric, despite improving performance for the most vulnerable and perhaps even closing the gap between them and the least vulnerable.

## Models

Estimating the above metrics requires a model that captures our understanding of how the system functions so that changes in decision alternatives can be mapped to expected changes in outcomes of concern, as well as data to calibrate and validate that model. Unfortunately, sufficient knowledge and data are not always available, and this has implications for our ability to address equity in water management. With respect to the model itself, we have a fairly strong understanding of the physics of hydrology, but a much more nascent understanding of how human behavior and decision-making influence the impacts of engineering decisions on hydrologic systems [[41]](https://paperpile.com/c/KlpQNa/kV7w). As such, we can build predictive models of global inequity in access to water resources due to hydroclimatology, but struggle to model and address inequity due to human institutions that may result in inequity in even wealthy, water-abundant locations. This highlights the need for more interdisciplinary research between engineers and social scientists to fill this gap [[42]](https://paperpile.com/c/KlpQNa/5lOx).

With respect to model calibration and validation, while this is certainly important for advancing science, emphasis on this step of the modeling process can have unintended consequences for social justice, as insufficient data may prevent researchers from modeling systems in the Global South or from assessing household-level impacts on marginalized communities. Remotely sensed data and methods for decision-making under uncertainty can help overcome these challenges [[43–45]](https://paperpile.com/c/KlpQNa/McU7+umzG+LctC). More transformationally, reframing how we measure and value research impact by shifting from a focus on citations to a focus on real-world benefits could incentivize more research in data-scarce regions and on communities that could stand to benefit most from academic inquiry on improved water management.

## Modeling Methods

Given the challenges highlighted above with respect to ensuring equity in our models and metrics, it is important for decision-support tools to use modeling methods that 1) account for the influence of humans on water resources systems and their equity, and 2) consider multiple metrics to quantify equity, as some may have unintended consequences [[46–48]](https://paperpile.com/c/KlpQNa/BOvw+8aes+4MIF). To address #1, tools from **game theory** and **agent-based modeling** are useful for exploring multi-actor systems, potentially yielding insights into power dynamics which may reveal structural inequities [[49,50]](https://paperpile.com/c/KlpQNa/5VM1+qlgD). With respect to #2, we would be well-served to utilize the process of *constructive decision aiding*, through which decision support is treated as an iterative learning process for interactive exploration of modeling choices, including metrics [24,62]. No metric is a panacea, and as noted by [[51]](https://paperpile.com/c/KlpQNa/CqOr) and eloquently restated by Marilyn Strathern: “When a measure becomes a target, it ceases to be a good measure.” [[52]](https://paperpile.com/c/KlpQNa/G05T) Exploring *multiple* metrics, including rival framings of metrics for quantifying equity [[48,53–55]](https://paperpile.com/c/KlpQNa/4MIF+1Gfjj+KGF2M+e2vnu) can reveal and guard against these potential consequences, allowing decision-makers to weigh trade-offs across them.

Recent advances in decision support systems, high performance computing and human-computer interaction have created an opportunity to evaluate these competing metric framings [[56]](https://paperpile.com/c/KlpQNa/E7Z0). **Exploratory modeling**–which uses a structured set of computational experiments to systematically examine modeling assumptions [[57]](https://paperpile.com/c/KlpQNa/A79o)–leverages modern computing resources to enhance the robustness of inferences we make with models and greatly expand the scope of metric framings considered [[58]](https://paperpile.com/c/KlpQNa/aw2k). **Multi-objective optimization** (MO) is a powerful tool for discovering trade-offs between performance objectives, often representing the competing interests of system stakeholders [[59]](https://paperpile.com/c/KlpQNa/SKdb). MO provides decision makers with an explicit representation of system trade-offs across a set of planning alternatives from which stakeholders can choose which approach best balances their conflicting goals [[60]](https://paperpile.com/c/KlpQNa/rRsM). This *a posteriori* articulation of preference is well suited to addressing concerns of marginalized communities whose interests may be overlooked in single objective formulations. Insights from the above tools may be accessed via modern visual analytics [[61]](https://paperpile.com/c/KlpQNa/A0MM), a rapidly evolving field that enables stakeholders to explore system trade-offs and dynamically interact with modeling output.

# Examples

The modeling and process-based recommendations above can be implemented by both academic modelers and water managers in a range of settings, from river basin planning to urban water management, in both the developed and developing world. Here we discuss two contrasting examples demonstrating how these principles can be applied in research and practice.

## The human right to water in California

An estimated one million people in the state of California lack access to clean drinking water. To address this, California became the first US state to pass legislation in 2012 recognizing the human right to water, defined based on the three pillars of water quality, access, and affordability [[62]](https://paperpile.com/c/KlpQNa/T58cI). CA water agencies have used both equitable decision processes and representations of equity in models to achieve this goal. On the process-side, state water agencies have increased participation of state-identified disadvantaged communities in regional water resources planning processes [[63]](https://paperpile.com/c/KlpQNa/6kta0). Additionally, grant opportunities for water infrastructure development, maintenance, and drought responses dedicated to disadvantaged communities were funded [[64]](https://paperpile.com/c/KlpQNa/mmSzJ). These programs are an important step forward but still have limitations. For example, some disadvantaged communities have been limited in their participation due to time constraints or mistrust [[65]](https://paperpile.com/c/KlpQNa/03rdG). Despite technical assistance programs, many communities most in need of financial resources for drinking water infrastructure still lack the capacity to apply for state grant programs [[65]](https://paperpile.com/c/KlpQNa/03rdG). The state also developed metrics assessing the progress of all public water systems in achieving the human right to water for all [[66]](https://paperpile.com/c/KlpQNa/Acwqr). They worked with academic researchers to develop a set of indicators operationalizing the three pillars of access, quality, and affordability, and produced an initial state-wide analysis at the state-level [[67]](https://paperpile.com/c/KlpQNa/fDBMe). While this is an important step forward, the indicators used are limited by data available through public reporting requirements, highlighting the need for improved data collection to be implemented in tandem with modeling, process, and financial programs.

## Socially inclusive river basin development

In the last decade, Ethiopia has been experiencing rapid economic development. Despite the national electrical demand increasing by 70%, the country is striving for 100% electricity access by 2025 [[68]](https://paperpile.com/c/KlpQNa/Hlf6) through the exploitation of its exceptional renewable resource potential [[69]](https://paperpile.com/c/KlpQNa/xyPr). The Ethiopian Electric Power Corporation has thus embarked on an ambitious dam building program intended to exploit its abundant water reserves [[70]](https://paperpile.com/c/KlpQNa/fLvX) including the Grand Ethiopia Renaissance Dam on the Blue Nile, and Gibe III and Koysha dams on the Omo River. Hydropower dams produce a suite of benefits and risks that go beyond energy production, but the impacts of hydropower production on natural ecosystems and local subsistence needs are often overlooked during the dam design, threatening the livelihoods of vulnerable communities [[71,72]](https://paperpile.com/c/KlpQNa/m6bL+SxVU).

Perhaps surprisingly, given the level of past and planned hydropower activity in the Omo River basin, a consolidated assessment of hydropower dams exploring how to equitably distribute their benefits and costs in the basin does not exist. In 1996, the Ethiopian government presented the Master Plan [[73]](https://paperpile.com/c/KlpQNa/1sn0) for developing the Omo Basin and exploiting its hydropower potential by constructing the Gibe cascade, which will also support the development of two large-scale irrigation districts covering about 180,000 ha [[74]](https://paperpile.com/c/KlpQNa/cpME). The potential negative impacts of these infrastructures on downstream riparian activities, including indigenous recession agriculture, ecosystem services in the Lower Omo, and fish yield in Lake Turkana (Kenya) were not considered [[75]](https://paperpile.com/c/KlpQNa/qPNU). An environmental and social impact assessment for Gibe III that considers the transboundary impacts was approved only three years after construction had begun [[76]](https://paperpile.com/c/KlpQNa/uQkf). Moreover, due to the lack of discharge data from Gibe III, it is unclear whether any of these mitigation measures have yet been adopted. These limitations in accounting for the dam impacts [[77,78]](https://paperpile.com/c/KlpQNa/s6hh+nqmR) made Gibe III the “most controversial dam in Africa” [[79]](https://paperpile.com/c/KlpQNa/2FZ2), and an unprecedented upsurge of national and international criticism erupted since the reservoir started to impound water in 2015 which gave voice to the downstream marginalized stakeholders.

Assessing the expected impacts of planned water infrastructures via participatory approaches that involve local stakeholders from different sectors and countries during the entire planning process enables the exploration of tradeoffs and the identification of acceptable compromise solutions (e.g. [[80]](https://paperpile.com/c/KlpQNa/oid6)). This practice therefore constitutes a crucial foundation for socially inclusive and equitable river basin development plans.

# Recommendations

Given the process- and model-based challenges and opportunities highlighted above as well as the lessons learned from some leading examples, we now make three key recommendations for next steps researchers in our field can take in advancing equity. We reiterate that there are many important actions outside the scope of this piece that researchers in any field can take to advance equity. These include advancing diversity and inclusion of underrepresented groups in research teams, which in addition to making scientific institutions more equitable has been demonstrated to lead to more dynamic and equity-focused research agendas, and incorporating equity in engineering education.

*Consider the audience your model serves*

Historically, water managers such as utilities have been the primary client of decision-support models. Working with managers is an essential component of improving equity as they make decisions about infrastructure investment, operations, and allocation that directly influence equity outcomes. However, working with the manager embeds their values into the research design, which may or may not be equitable. Participatory modeling can give marginalized communities a voice in the decision-support process and improve distributional equity through embedding the values of end users, in addition to managers, in the model design directly.

By centering the needs and concerns of marginalized communities in decision-support, models can transition from tools that support managers to tools that serve communities directly. Independent analysis from researchers highlighting the inequities embedded in our water resources systems can be a powerful force for change. Much like the role investigative journalism plays in raising awareness of environmental injustices, systems modeling can expose uncomfortable truths and drive change. Similarly, systems models can be used for public policy analysis. Because managers like utilities are often limited by financial and regulatory constraints, models assess the relative role that decisions at varying levels of governance can play in achieving equity outcomes. This can play a role in driving change at higher (e.g. federal) levels of governance beyond water managers themselves.

*Advance methodological gaps*

Given the ethical and pragmatic constraints that can arise in participatory research, not all research efforts focused on equity can or should take a co-design approach. Another important way to contribute is through methodological advances that allow systems models to better operationalize equity measures previously identified as important to marginalized communities. Some key opportunities include improving: the spatial resolution of models needed to measure impacts of decisions on specific marginalized communities, quantitative hydro-ecological relationships relating streamflow to ecosystem services, data collection needed to measure outcomes in marginalized communities. Researchers pursuing these advances should clearly state the methodological focus of their work, making clear the distinction between systems modeling research whose results do or do not reflect community-identified needs.

*Learn from social scientists*

A common barrier to engineers addressing equity in their research is the sense that as engineers, we do not have the expertise to conceptualize what equity means in water resources management. Fortunately, qualitative social scientists and philosophers who do have the appropriate expertise have written much on this subject that engineers can learn from. Indeed, humility about the limits of our knowledge is a strength, allowing us to focus on our areas of expertise 一 operationalizing conceptual definitions of equity in quantitative models 一 and using input from social scientists and communities themselves to drive conceptual advances. Although systems modeling requires quantitative inputs, the first steps in systems research are qualitative: conceptualizing the relationships between various inputs, system components, and outcomes. In this stage, we should draw on qualitative social science foundations in conceptualizing both the water system itself and what equity means in the context of that system. This can be achieved through collaboration or even reading widely in environmental justice and related literatures.

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