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Uncertainty in climate change impacts on water resources

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ABSTRACT

The uncertainty concepts play a prominent role in global environmental change research, including climate change science and climate change impact science, with hydrology and water resources research in particular. One is uncertain, to varying degrees, about virtually everything in the future as well as about much of the past and the present state. The present paper reviews applications of the uncertainty notion to results of change detection, process understanding and modeling of systems, and – foremost – projections of future climate change impacts on water resources. We present a framework of assessing and reducing uncertainty and propose measures that could improve uncertainty communication, e.g. relying on ensembles and multi-model probabilistic approaches rather than projecting ranges of values. We distinguish two possible management strategies if uncertainty is irreducible – the precautionary principle and the adaptive management.

1. Introduction

The common-sense meaning of the term “uncertainty” denotes lack of certainty about something, ranging from small doubts and minor imprecisions to a complete lack of definite knowledge. The broad term “uncertainty” has many various interpretations and may mean different things to different people.

Uncertainty framing raised broad recognition, in relation to the “known knowns” (the things we know we know), “unknown knowns” (unknown but knowable) and “known unknowns” (expected or foreseeable conditions). The most puzzling notion is that of “unknown unknowns”, referring to things we don't know we don't know. They can be virtually unthinkable and may result from unforeseeable conditions that have never occurred, hence cannot be anticipated based on past experience or investigation.

The term “uncertainty” is used in different contexts in natural and social and management sciences. In natural sciences, it is, primarily, an attribute of the research process, going back to the Platonic view of reality that is out there as such, however, human beings can never fully grasp it. Here, uncertainty is related to the inaccurateness of humanly devised models and research tools to describe and represent the reality (Smithson, 1989). In social sciences, the primary focus is on uncertainty impact on human decision-making (e.g. Lipshitz and Strauss, 1997).

Uncertainty can be generally categorized as either epistemic or aleatory (Beven, 2016). The former is a consequence of a lack of knowledge, arising due to human ignorance and indolence. It can be reduced by gathering more data or by refining models. The latter is related to the intrinsic randomness of a phenomenon, hence there is no possibility of reducing it.

In taxonomy of uncertainties proposed by Beven (2016), epistemic uncertainty is subdivided into uncertainty related to system dynamics, forcing and response data, as well as disinformation. In addition, he recognized semantic/linguistic and ontological uncertainties. The former concept refers to uncertainty about the meaning of terms and the latter is associated with different belief systems.

Benestad et al. (2016) reviewed the concept of “agnotology”, being a counterpart to epistemology. It addresses the question “why we don’t know what we don’t know?”. With respect to climate change, ignorance can be a result of absence of knowledge and understanding or of the “inconvenient truth” syndrome (Kundzewicz and Matczak, 2012).

In last decades, uncertainty has played a prominent role in global environmental change research, including climate change science and climate change impact science. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2014) defines uncertainty as a lack of complete information, as well as incomplete knowledge or disagreement on what is known and knowable.

This paper examines the notions of uncertainty in climate change impact assessment on water resources, important in assessing the range of potential outcomes that can be related to observation data, to process understanding and modelling as well as – foremost – to projections for

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the future. Uncertainty assessment and opportunities for its reduction as well as implication for management are also discussed.

2. Process understanding and modelling

The Earth climate system, the principal natural driver of water resources, is very complex. There are external climate drivers, such as the solar radiation, the Earth's orbit, volcanic eruptions, collisions of celestial bodies with the Planet, properties of the atmosphere (therein atmospheric concentrations of greenhouse gases, GHGs) and land surface. Moreover, there are internal feedbacks in the system, diminishing or amplifying the effects and generating high variability. Climatic oscillations in the Ocean-Atmosphere system (such as El Niño Southern Oscillations, North Atlantic Oscillation, Arctic Oscillation, Atlantic Multidecadal Oscillation, Pacific Decadal Oscillation, etc.) are of importance for water resources. Advanced climate models intend to mimic essential physical mechanisms and internal feedbacks. However, the model-based reconstruction of past climate is still far from being satisfactorily accurate (Trenberth, 2010). Unknowns about climate change dynamics are true unknowns, so that improvement of understanding of climate dynamics as well as feedback loops and interconnections is needed (Kundzewicz and Stakhiv, 2010). Some authors bring attention that uncertainty is an attribute of research on complex systems that are not fully understood and there is a certain degree of unpredictability involved in the interactions of the system components (Funtowicz and Ravetz, 1990). Dynamic systems featuring deterministic chaos are a case in point (Lorenz, 1995).

There is a fine aphorism that all models are wrong but some are useful (Box and Draper, 1987). Indeed, there are uncertainties everywhere in modelling and acknowledging them is important. Uncertainties in the climate impact on water resources result from natural complexity and variability of systems and processes, and from deficiencies in our knowledge and models.

Remarkable uncertainty of climatic input to hydrological models comes on top of the "traditional" uncertainty existing in hydrological models that can be related to portraying relations between variables, choice of model structure and parameterization as well as to parameter estimation. Much work has been done on hydrological uncertainty, see review by Nearing et al. (2016). Uncertainty can be involved in the input data (due to data scarcity, measurement errors, lack of representativeness of the measurement site, or problems in aggregating or disaggregating data in order to cover areas of concern). Uncertainty can be inherent in the variables and their distributions, but also in uncertain model error resulting from selection of the form of the probabilistic submodels, the probability distribution, and the physical models, including empirical equations. Uncertain errors are involved in measurements and observations, based on which the parameters are estimated, including errors involved in indirect observation, e.g., the determination of a quantity through a proxy.

It can be expected that, after successful calibration, the degree of uncertainty in a parameter estimate in a hydrological model would be lower than the uncertainty associated with the prior estimate before calibration, and uncertainty of outputs related to hydrological model would be reduced (Krysanova et al., 2017a,b). Reduction of uncertainty is a measure of relevance of a parameter. Uncertainty of parameter estimation is possibly inversely related to the information encapsulated in field observations.

3. Projections for the future

There are many sources of uncertainty in model-based projections for the future. For instance, there is uncertainty in knowledge of the external environment, uncertainty regarding future intentions driving choices, as well as uncertainty regarding the value judgments of consequences.

Technically speaking, uncertainty in projections of climate change impact on water resources is due to: (i) scenarios of future socio-economic development, (ii) GHG emission and sequestration scenarios, (iii) General Circulation Models, GCMs, (iv) Regional Climate Models, RCMs, or statistical downscaling methods, (v) choice of the bias correction method (if applied), (vi) input data for hydrological model(s), (vi) hydrological model(s) structure(s), and (viii) parameterization of hydrological model(s).

One can observe a forward-propagation (and likely increase) of uncertainty through a multi-stage process of developing projections of climate change impact on water resources and adaptation of the water sector to climate change. On the other hand, adding new information to the process (bringing in local observations, empirical knowledge, physics-based dependencies, statistical theory, etc.) constrains the range of possible outcomes. Every transfer function or modelling step bears uncertainty, as well as it may entail new information (i.e. Wilby and Dessai, 2010).

Uncertainties are introduced by the transfer functions: from GHG emissions and sequestration to atmospheric GHG concentration, further to climate change (global to regional to local), and then to impacts on water resources (and particularly on extreme hydrological events), as well as adaptation (Kundzewicz et al., 2017).

The uncertainty starts from the unknowns about the future society, as future development of socio-economic driving factors (population number, economic development/wealth and life style patterns, technology) is largely unknowable, and cannot be assigned objective probabilities. For this reason, it is suggested that a range of scenarios be applied in impact assessments rather than a single best-guess or average case. Differences in trajectories of atmospheric GHG concentrations (resulting from emission and sequestration) are a clear and important reason of discrepancy in water-related projections. There are two broadly applied approaches: one based on the IPCC Special Report on Emission Scenarios – SRES (Nakicenovic and Swart, 2000) and a more recent one, based on the concept of Representative Concentration Pathways (RCPs) (cf. Meinshausen, 2011). Some experts (Katz, 2002) propose that because all scenarios are not equally likely, one could try to envisage weighting each scenario by its likelihood.

There can be a large difference between results obtained by using different scenarios and different climate models, especially on local and regional scales. Intra-model uncertainty of projections (for the same model and different scenarios) can be lower than the inter-model uncertainty (for the same scenario and different models). Uncertainties in climate change projections clearly depend on the future time horizon of concern, usually increasing for a more remote horizon. In the near future (e.g. 2020s), climate model uncertainties may play a more important role than GHG emissions, because near-term climate is strongly conditioned by past emissions (committed warming), while for far future (e.g. 2090s), uncertainties due to the selection of future emission (and sequestration) scenarios may be more important. Sometimes, the picture is more complex (cf. Vetter et al., 2017).

Also differences in GCMs, RCMs and downscaling techniques are crucial. In older studies, only one GCM output was used, whereas ensembles of several climate models have been consequently used in recent studies. The selection of GCMs, as well as of a downscaling technique (empirical-statistical or dynamic) can explain a major portion of differences in reported projections (Vetter et al., 2017). Climate models do not satisfactorily simulate the present-day climate, showing large biases. Hence, a statistical bias correction is often carried out in order to render the model output closer to observation data in the reference period. The observations also are subject to errors, depending on the variable, location, and observational practices and changes over time (e.g. new instruments, relocation of instruments, or changes in the surroundings).

In high latitudes and parts of the tropics, climate models are consistent in projecting future precipitation increase, while in some subtropical and lower mid-latitude regions, they are consistent in projecting precipitation decrease and river flow may grossly follow the