On climate change, hydrological extremes and water security in a globalized world

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Summary

There is growing empirical evidence that the length of the return periods of extreme hydrological events, such as floods and droughts, is decreasing, i.e. the frequency, or the probability of extreme events, is increasing yielding more frequent disasters at both ends of the hydrological spectrum. Furthermore, it is observed that the 100-year flood occurs nowadays every 20 years or so in many parts of the world. Together with the ever-increasing world population these drivers cause a decreased water security. Also, the question of what caused the change in the hydrological cycle that seems to accelerate or intensify is being asked? Some argue that it is basically due to the large planetary cycles, such as the Milanković-Bacsák cycle, while others attribute it to the increasing green house concentration ever since the industrial revolution. However, the acceleration of the hydrological cycle has been observed quite recently at a decadal time scale, which is by orders of magnitude much smaller when compared to geological time scales of the MB-cycle. The hypothesis that is being tested, and has already yielded quite important affirmative answers, is that the intensification of the hydrological cycle is due to anthropogenic changes observable since the industrial revolution. On the one hand, new design methodologies and standards are needed to properly take into account the non-stationarity of hydrological processes as the current design methodologies, such as the concept of T-year design floods, developed under the hypothesis of stationary hydrological processes, is not valid anymore. On the other hand, these global drivers might lead to some serious reductions in water security if not to water conflicts. Both mitigation and adaptation measures are equally needed. It is argued that the re-examination of some of the structural measures, such as the need for more water storage, is necessary at all scales.

Keywords: water security, conflict potential, climate change, accelerating hydrological cycle, water disaster

Klímaváltozás, hidrológiai szélsőségek és vízbiztonság a (egy) globalizált világban

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Összefoglalás

A cikk a vízbiztonság szempontjából áttekinti a vízgazdálkodás jelenlegi főbb globális kihívásait és a lehetséges megoldások körvonalait, ideértve az ENSZ Fenntartható Fejlesztési Céljait (SDG). A globális népességdinamikai előrejelzések és a várható klímaváltozás tükrében a jelenlegi vízgazdálkodási gyakorlat nem tartható fenn a XXI. században, ami a vízbiztonság csökkenését, illetve súlyos konfliktusok kialakulását eredményezheti. Ezért paradigmaváltás szükséges. A víz a XXI. század egyik legnagyobb, ha nem *a* legnagyobb kihívása lesz. A XX. századi népességrobbanás következtében – amikor is egy évszázad alatt a Föld népessége 2 milliárdról 6 milliárdra háromszorozódott, miközben a vízkivételek globálisan meghatszorozódtak – az egy főre jutó éves vízkészlet 1975 óta drámain lecsökkent: 12 000 m^3/fő/évről a mostani 5000 m^3/fő/év vízmennyiségre. A vízkészletek csökkenésére azonban nem lehet olyan lineáris előrejelzést adni, mely szerint a következő 35 éven belül az emberiség „kifut" vízkészletéből, hiszen a hidrológiai ciklus állandóan megújítja a vízkészleteket, ám kétségtelen, hogy további csökkenés várható. Ma a Föld

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édesvízkészlete épp annyi, mint a holocén klímaoptimum idején volt. Ugyanakkor a felhasználók száma háromszoros exponencialitással növekedett, bár már felismerhetően egy logisztikai görbe felé tart, és a száz év múlva várható 12 milliárdos népesség eléri azt az aszimptotát, ami a fenntarthatóság határa. Azt meghaladva (humán és ökológiai) rendszereink irreverzibilis állapotba kerülnek, és gyorsuló sebességgel az összeesés felé tartanak. A vízkészletek egy főre jutó csökkenése elsősorban a fejlődő országokban jelentősen növelheti a vízkészletekkel kapcsolatos konfliktuspotenciált, mivel a klímaváltozás primer módon a víz által manifesztálódik. A szélsőségek előfordulási valószínűsége várhatóan tovább növekszik, azaz több árvíz várható, ám ugyanakkor az aszályosság mértéke térben és időben is növekedni fog. A távérzékelés és a számítási korlátok voltaképpeni megszűnése azonban új lehetőségeket nyitott a numerikus hidrológiai modellezésben a lokálistól a globális szintig a Big Data algoritmusok, a mesterséges intelligencia és a blokklánc-technológiák alkalmazásával. A digitális technológiák teljesen új lehetőségeket teremtenek. Globális változás és adaptáció szükséges a vízgazdálkodás minden szintjén, az integrált vízgazdálkodástól kezdve az intézményes felépítésen át az oktatásig és kutatásig. A megállapítás egyaránt érvényes a fejlődő és az iparosodott országokra. Különösen érvényes ez Magyarországot illetően, ahol az elmúlt évtizedek a dezintegrált vízgazdálkodási intézmények sajnálatos példáját mutatták.

Kulcsszavak: vízbiztonság, konfliktuspotenciál, klímaváltozás, gyorsuló hidrológiai körfolyamat, vízkatasztrófák

Introduction

As a result of the population explosion of the 20th century – when, in a single century, the Earth's population tripled from 2 billion to 6 billion while water abstraction has increased six fold worldwide – a gap has opened up that is impeding the sustainability of our human and environmental systems *(UNESCO 2018)* and may lead to decreased water security and to potentially serious conflicts. This emerging issue, however, has not been treated extensively prior to the mid nineties. The picture has become even darker by today when the world population exceeds 7.7 billion humans.

Water security as a new concept became the focus of extensive debates in the first decade of the 21st century.

After a lengthy process a consensus-based definition of the concept was elaborated by *UN-Water (2013)* that reads as follows: *"The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability."*

This definition goes far beyond the somewhat stricter notion of water security that primarily concentrated on water conflicts and their resolution. In that regard *Fraser–Hipel* (*1984*) provided the first comprehensive groundbreaking treatment on water conflict analysis and resolution. The utilization of transboundary water resources became an important subject worldwide in the seventies of the 20th century. Intergovernmental discussions started within the United Nations, which, after some twenty-seven years of negotiations, led to the *"Convention on the Law of the Non-navigational Uses of International Water Courses"*, shortly: New York Convention, adopted by the United Nations General Assembly *(United Nations 1997)*. It took yet another seventeen years until the Convention entered into force in 2014 as it had to be ratified by 36 UN Member States. A number of countries still fiercely oppose that convention and are not ready to ratify it The Convention. Although the convention is rather weak one needs to recognize the political sensitivities between upstream and downstream countries that were linked to issues of national sovereignty and hindered the process a great deal. It was not until the end of the 20th century when, within the framework of its International Hydrological Programme (IHP), that UNESCO took the lead and launched, not without major opposition by certain governments, the PCCP initiative (From Potential Conflicts to Cooperation Potential) within the framework of the UN World Water Assessment Programme (WWAP). A large number of methodological guidelines and case studies were published over the first fifteen years of PCCP that are available on the Internet (*UNESCO 2005*). Not surprisingly quite a large number of studies are concentrating on the difficult water situation in the Middle East *(Turkish Government 1996; Murakami 1995; Biswas et al. 1997; Strategic Foresight Group 2013; Megda et al. 2013)*. The *World Water Council (1997)* published a commission report on a water secure world. Earl and colleagues (*Earle–Jägerskog–Öjendal 2010)* and *Gonzáles (2007)* provide a global overview while *Hori (2000)* assesses the situation evolving in the Mekong Basin, another not easy area. The Red Cross issued a popularized volume on war and water *(ICRC, n.d.)* while *Ganoulis–Fried (2018)* examine the issue of transboundary water governance from conflicts to shared management. Due to the still unsettled dispute between Slovakia and Hungary concerning the Gabčikovo-Nagymaros dam conflict quite a number of publications are devoted to the utilization of the Danube River *(Jansky–Murakami–Pachova 2004; Sámsondi Kiss 2019)*. Under the auspices of the *Geneva Water Hub* an international global high-level panel on water and peace, led by former President of Slovenia, Danilo Turk, was set up, that published its report *(GWH 2017)* that covers a wide range of concrete recommendations with respect to water security in an international context.

The Drivers

There are two major drivers that impact significantly water security at all scales, from local to global. Those are the impacts of population change and of climate change. At the global scale the average annual water supply per capita has decreased dramatically since 1975: from a global average of approximately 15,500 m^3/person/year to an average of 5,000 m^3/person/year by today. It should be emphasized that this number is a global average for the current population of 7.7 billion, with a very wide range from 120,000 m^3/person/year in Canada to 11,700 m^3/person/year in Hungary and to 120 m^3/person/year in Jordan. Today, the Earth's freshwater supply is as much as it was during the Holocene Climate Optimum in the period between 5,000 and 9,000 years ago. 97.5% of all water is contained in the seas and oceans, while the remaining 2.5% is humankind's freshwater supply. About 60% of this is solid water, i.e. ice and snow found in the Arctic, Antarctica, glaciers, alpine snow cover and in the permafrost. 90% of the remaining freshwater is non-frozen groundwater. What is left is a total of approximately 42,000 km^3 of easily accessible surface water (*Shiklomanov–Rodda 2003*), 90% in lakes and reservoirs, and the remaining 10% in rivers and other watercourses. What is available, therefore, for immediate human use is a mere 0.007% of the total water on Earth.

Over the last century, the number of water users has increased threefold in an exponential manner. This is the primary reason for the drastic decline in water resources per capita.

The growth of water abstractions in the 20th century took a sharp increase. Today the total water use is not far from the 4,000 km^3/year proposed planetary limit *(Rockström et al. 2009)* that has been recently revised by *Gleeson et al. (2020)*. At the same time, the pace of growth is slowly moving towards logistic growth, that is, to the threshold of Earth's carrying capacity. Therefore, the concept of sustainability is not an oxymoron but the very key to humanity's survival. Developing countries, especially in Asia, account for 60% of humanity, but only 36% of the global water supply. That in itself could be a potential source of conflict, given that in hundred years time the Asian population will likely grow up to 7.2 billion, that is almost the same as the current world population. Yet, the Asian water resources will be the same. On top of this, the climate change and its effects are being further superimposed on the population growth induced change.

The global water crisis does not mean that water "is running out" for humanity, since the hydrological cycle is a continuously renewing cycle. The crisis essentially stems from the way the institutions manage water resources. What sort of legal framework do we establish and how effective is it; how do we operate our hydrometeorological observation systems; how to make publicly available measurement data about water as a public asset; how, if at all, does scientific research support government decisions: is there a national interdisciplinary water management institute for the development of innovative technologies, how are we training our professional workforce, are we establishing integrated water management or are we disintegrating our systems through selfish political aims and lobbying? These are some of the questions that need to be addressed with a high degree of urgency.

The effects of climate change on the hydrological cycle

The other significant driver is climate change. The primary effect of climate change on the hydrological cycle is likely to be the acceleration of the cycle *(Szöllősi-Nagy 2018a)*. This can have many serious consequences, namely that more extreme hydrological events will occur per unit time. The frequency and scale of floods will likely increase. The increase in water-related disasters was already evident in the 20th century. Nearly 80% of all natural disasters were water-related.

The condition of continuity must always remain valid – there is just as much freshwater on Earth today as during the Holocene Climate Optimum –, which can only happen if the duration and extent of droughts are also increasing. Of course, it should be emphasized that atmospheric and hydrological processes are characterized by a multitude of complex elements related to feedbacks, strong non-linearity, chaos and stochasticity. This is precisely the reason why many large-scale climate simulation models may lead to somewhat contradictory results, although there are no contradictions when it comes to identifying major trends.

With the temporal and spatial variations in rainfall patterns, groundwater reserves can also change significantly; so climatic changes and fluctuations can affect the entire hydrological cycle, therefore the safe access to water as well. Climate change is thus superimposed on anthropogenic effects – granted it is partly anthropological in nature as well – that is, it is expected to further exacerbate the uncertainty of hydrological events and thus the risk factors related to water management.

The nearly 30 percent increase in the global population to take place over the next 35 years, resulting in a population of more than 9 billion people, is expected to cause changes orders of magnitude greater than those expected from climate change during the same period in the hydrological cycle and water management. A consensus is emerging that about 80% of the change in hydrological variability is caused by population change and its related effects, while the rest is triggered by climate change. Water on the other hand is the primary medium for climate change, whether it is sea level rise due to thermal expansion or the land portion of the hydrological cycle, including the role of melting glaciers and permafrost.

Unfortunately, however, it is precisely the hydrological cycle – perhaps the most sensitive and least understood part of the climate system – that receives the least attention in current debates and research on climate change, including water security. The importance of solving this, literally, vital question central to humanity's survival, and the importance of adaptation via water management cannot be emphasized enough.

The future will not be like the past

Over the past several decades, there have been many signs that the hydrological cycle has changed fundamentally. One record of this, as mentioned earlier, is the increased likelihood in the occurrence of extremes. The existing classical hydrological statistical methods, i.e. assumptions of homogeneity, independence and identical distribution of the data – that is, the stationarity hypothesis – cannot explain the reason why 100-year floods, which occur statistically once in a hundred years but at any time, appear to be occurring almost once every twenty years lately. An example of this is the series of floods along the Danube over the past two decades.

This is quite embarrassing because we did not prepare for it. How can we interpret the relevant flood levels at all in this situation and provide engineering practitioners with useful design methods to ensure water security? How can we adapt our tools to non-stationary hydrological phenomena and not the other way around by artificially rendering the data homogeneous, as we have done for a long time as we considered the outliers as errors (physics of the early 20th century fell into this trap until it was realized that the theory was wrong, not the data...)

The future will not be like the past, that is, we have to give up the assumption of stationarity and look for another way to best adapt to the impacts of climate change. Our method appears to be flawed and in need of improvement; the reason is not the peculiar behavior of the hydrological cycle. We simply did not notice the change. We did not realize that the future did not resemble the past, and that the assumption of stationarity was no longer correct *(Milly et al. 2008)*. And yet, all over the world to this day, we still estimate extreme situations required for engineering design according to the assumption of stationarity as if nothing would change in the future and it will be the same as in the past. National standards are based on this hypothesis. Even if we deceive ourselves by generating hundreds of thousands of years of data using the Monte Carlo method – thus covering a long period of time, true – it is just that we generated a set of data whose statistical parameters are (or rather, should be) by definition the same as those of the recorded time series. If the statistical parameters of the generated sequences are not the same as those of the historical data, then we are basically simulating the Creator by creating something out of nothing.

Even in the best-case scenario, we just preserved the information content of the recorded time series, not created a new one. At the same time, we still stayed with the assumption of stationarity. This poses a significant risk, carrying with it the possibility of either over or under design. Thus, non-stationarity can have serious practical consequences that fundamentally bring into question even the design principles of our water management systems, which generations of engineers have relied upon. For example, the 100-year, or T-year, standard flood level is no longer applicable, since – apart from the charming anecdote published by *Szöllősi-Nagy (2017)* – a whole series of examples prove that floods that occur once every 100 years (could have) occurred much more frequently lately. This can lead to numerous claims litigation and disputes in connection with the operation and security of our engineering works.

What is the reason for the change? The inevitable global changes that define the boundary conditions of the local actions. In addition to the aforementioned effects of climate change, our existing water resources are under additional pressure from global demographic trends taking place, including migration and radical urbanization. The effects of these trends in this new antropocene are thus greater than the expected impacts of climate change. Even in the short term, i.e. within a few decades, the functioning of the hydrological cycle will likely be changed significantly. Therefore, the key issue is to adapt the design principles of our engineering works to the non-stationary world.

While climate change is a slow process – it took the passing of 200 years since the Industrial Revolution for a perceptible change in the hydrological cycle and for the non-stationary state resulting from the acceleration (intensification) of the water cycle to be detected – the direct impact of human activity on water security has been measurable for decades. The primary cause of the impacts, therefore, is indeed the demographic change. With the demographic dynamics of the 9.6 billion population projected for 2050 (growth, mobility, migration) and the consequent changes in secondary land and water use the functioning of the hydrological cycle will fundamentally change. About 80% of the consequences of climate change, which is caused by human activity, are water-related – occurring as its direct or indirect result. Sustainable water management is therefore a key issue for humanity's sustainability. As a result of population growth, water resources per capita will be drastically reduced by the middle of the century, which could obviously be an unsustainable and serious source of conflict, both internationally and domestically *(Wolf 2007)*.

Does a solution even exist for water security?

Yes, there is a solution. And it is merely up to us to set it.

Of course, it will not be easy to find the right solution, because we will need to change old paradigms. Furthermore, there is no silver-bullet solution, but a range of solutions within which we can only move about. It will not be easy to make the jump from the classical civil engineering paradigm of “straight-channel-construction-concrete-structure” to soft engineering, where ecosystem services in nature-friendly solutions provide functions that until now were thought to be accessible only by works of art.

Obviously, more water storage is needed to achieve the interlinked water, food and energy security. And more storage cannot be achieved without understanding the proper functioning of impoundments and dams, whether it be more intensive irrigation, water transfer, or the provision of an adequate level and amount of cooling water to power plants. The same is true for international river navigation – low waters over the past years on the Danube may have been exceptionally shallow, but they were not singular and we can expect more of them in the future.

Rational and sustainable management of highly sensitive and highly vulnerable groundwater is extremely important. If we connect the various aquifers to 80-meter wells without any consideration to the hydrogeological conditions, measurements, or monitoring, then we are transferring the first completely polluted aquifer with non-point contaminants into the pristine downstream aquifers, depriving future generations of clean water. This is more than just a narrow lobbying policy decision that serves short-term interests. It is now an ethical as well as security issue. In the same way as all sustainable water management decisions are. Politicians today are slowly realizing that the 21st century will either be witness to a knowledge-based society, or there will not be a 21st century. One of the practical drivers of this realization is probably the fact that by the mid-1990s, the digital frontier had fallen, and we were entering the digital age in almost every sphere of life. At the mezzo scale almost everything is computable today – it is just a matter of computing time. And, of course, it is a question of knowledge. The same is true in water management as well. A host of well-functioning digital models *(Vörösmarty et al. 2018)* are available to the hydrologist, the hydraulic engineering practitioner, and the strategic water planner at various levels, from local to regional to global. An example of this on a local level is the control technology of wastewater treatment plants from sensors to controls, from remote process optimization of regional water supply systems with shared intelligence process control systems to the computation of biogeochemical fluxes of the global hydrological cycle – in a geographic information system (GIS) framework, combining elements of the atmospheric and terrestrial parts. These were previously not possible, partly due to computational limitations and partly due to the lack of adequate and sufficient data in quantity and quality. Regarding the latter, we have witnessed incredible progress in the last quarter century. Satellites and remote sensing techniques now transmit 1 Exabyte of hydrologically relevant data per day to Earth at terahertz speeds. That’s quite a big number: one billion gigabytes, or one followed by eighteen zeros. That is a lot of data every single day.

But how do we process this incredible amount of data in real-time and how do we connect the different levels of models that also serve as boundary conditions to one another in order to contribute to various facets of water security? Further, they contain a host of uncertainties, and thus Laplacean determinism fails. It does because the hydrological cycle is not a 3D water machine whose operation can be calculated using classical deterministic hydrodynamics tools and routine numerical methods. Randomness due to the heterogeneity of hydrological processes – and the matrix in which they occur – as well as the fractal nature of the scale transition precludes this path.

How can a lot of data nevertheless help operational water management? How can we identify from this enormous amount of daily data the pattern required to make a good decision? As data collection techniques evolve – be it the in-situ intelligent sensors or the data obtained by remote sensing – data processing methods capable of rapidly processing large data sets have evolved in step. Big Data and pattern recognition algorithms – applying the principle of recursive learning – filter patterns of various levels out of data filled with uncertainties at incredible speed. Learning algorithms are already within the realm of Artificial Intelligence (AI), and while it may seem distant, the possibility of establishing a discipline and practice of digital water management based on machine learning is close *(Szöllősi-Nagy 2018b)*. The use of AI will make it possible to connect the different levels of water management decisions impacting water security, from local to global. These varying levels of water management machines/models are expected to form a certain kind of IoT (Internet of Things) system, allowing local optimums to be part of a global optimum, while at the same time acting as boundary conditions to one another. We may also get answers to questions about how to scale our structures in a world where the condition of stationarity – upon which generations of engineers have grown up – is not true even at a first approximation.

One thing we should not forget: water management is not primarily a technical issue but a social one. And if it is social, then it is political and ethical for that matter. If water is a social issue, however, modeling the possible response mechanisms in society is inevitable in our decision models, which is probably at least by an order of magnitude greater in complexity than 2D/3D local hydraulic computation, because there is a greater order of uncertainty (and risk) in social responses. Whether this can be successfully solved by agent-based behavioral modeling *(Akhbari–Grigg 2013)* and integrated into modeling fluxes of environmental processes is the big challenge that AI and machine learning are expected to answer in the not too distant future. AI is expected to substantially transform the human condition as a whole and in detail, from design standards and procedures through the use of earthmoving equipment to river basin-level strategic planning. Anyone who does not realize this is intellectually beyond help, as they do not understand the 21st century.

Discussion

According to Wittgenstein "the world is all that is the case". This world, however, is sorely missing a new water management research institute in Hungary to support government policy decisions and innovation ever since the Budapest based Environmental Protection and Water Management Research Institute (VITUKI) was erroneously terminated. It is a *condition sine qua non* for secure water management in the country. What certainly is an issue that goes beyond science in the narrow sense is the disintegration of the Hungarian water institutions. This fragmentation of the system of water management is an obstacle to efficiency and makes the situation very difficult. Climate change, which primarily affects the hydrological cycle, poses new challenges for Hungarian hydrological and meteorological services. If we truly accept the integrative role of the hydrological cycle – and there is no other logical choice – splitting it anywhere is arbitrary, as it violates the principle of integrity. The hydrological cycle is also separated into atmospheric and terrestrial cycles. It is even more contrary to this principle to treat the quantity and quality of surface and groundwater separately at various institutional levels. And yet this is what we are currently doing.

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