Integrated hydrological risk analysis for hydropower projects

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ABSTRACT: The production of electricity from hydropower is exclusively determined by the availability of water. Upstream water use such as irrigation and drinking water supply, downstream constraints and climate change are just some of the factors that can pose a risk to the hydropower producer. The relationships between these factors can in many river basins be very complex, introducing large uncertainties to future revenues. Tools to analyze the wider understanding of the hydrological risks in river basins with multiple and geographically distributed water uses have to a limited extent been applied in the long-term planning of hydropower projects. The use of such tools will reduce the financial risk of a project, as well as providing a basis for a dialogue between stakeholders. We have reviewed a set of different tools/approaches to assess the hydrological risks of hydropower projects, which include; i) hydrological models with functions to run scenarios with climate change and different allocation and priorities between sectors, ii) integration of model simulation and expert judgement using Bayesian network methodology and iii) other risk assessment approaches, including the decision-tree framework, as proposed by the World Bank.

RÉSUMÉ : La production d'énergie hydro-électrique est largement dépendante de la disponibilité des ressources en eau. Les prélèvements d'eau en amont pour l'irrigation ou l'approvisionnement en eau potable notamment, les contraintes diverses en aval, ainsi que le changement climatique sont autant de facteurs qui présentent un risque pour la production hydro-électrique. Les interdépendances entre ces différents facteurs peuvent s'avérer relativement complexes dans un grand nombre de bassins versants et engendrer une importante incertitude sur les revenus issus de l'exploitation des centrales. Les outils et méthodes permettant l'analyse du risque hydrologique dans les basins versants à usage multiple ont jusqu'ici peu été appliqué pour la planification des projets hydro-électriques. L'utilisation de tels outils dans la phase initiale du projet permettrait de réduire le risque financier de ces projets, ainsi que d'établir une discussion entre les différents acteurs et usagers de la ressource en eau. Nous avons étudié différents outils et approches permettant l'évaluation du risque hydrologique des projets hydro-électriques qui sont: i) les modèles hydrologiques ayant une composante pour la planification et gestion des eaux, ii) un système d'aide à la décision basé sur le modèle de réseau bayésien et iii) les méthodes d'évaluation des risques tels que le Decision-Tree proposé par la Banque Mondiale.

This is the accepted version of a paper published in Sustainable and Safe Dams Around the World: Proceedings of the ICOLD 2019 Symposium, (ICOLD 2019)

1 INTRODUCTION

1.1 *Characteristics of hydropower projects*

Hydropower production is exclusively determined by the availability of water. Water as the raw material for the production and cannot be substituted nor be imported from far distances. The availability of the water might also show a large variation throughout the year, and also vary from year to year. As such, a comprehensive assessment of the local and regional hydrology is prerequisite in planning of hydropower projects to understand the financial risks, as well as for designing all technical components.

Hydropower is a mature and robust technology that can provide base-load electricity, as well as a variety of electricity services, often to a low cost compared to other technologies. It is, however, financially challenging to develop hydropower projects as the up-front costs (CAPEX) are high. The operating costs (OPEX) are normally very low. The period from the planning of a project starts to a license agreement is awarded can take several years. reaching the stage of awarding and obtaining a permission for construction (license agreement) is extensive. When the permission is given, the construction can start which also can take years. The period from early planning to the plant is set in operation can in some cases sum up to 10 years, which is the time before the investments start generating revenues. When all these factors added, it is clear that hydropower will need several years to reach break-even from the point where the investment decision is made, and projects need to be planned with a long-time horizon. Hydropower is usually a technology with a very long life, sometimes more that 80 years, which potentially makes old hydropower projects very economically beneficial, as they can be run with very low operating costs. If sustainably operated and maintained, a hydropower project can have a high technical performance even after several decades in operation.

The traditional way of assessing the availability of water for hydropower production has been to measure or model the historical runoff at the site the hydropower project is planned. If monitoring data is available, the hydropower developer is in a very fortunate situation, but often only meteorological data is available. By use of hydrological models ('rainfall-runoff models), meteorological input can be transformed into timeseries of runoff and the planning of the size of the reservoir, turbines, etc. can start. The traditional approach has been to assume that the historical availability and variation of water will be reproduced in the future. This assumption is no longer valid as climate change will affect both expected total water availability and its intra-annual temporal distribution. In many regions of the world, several other aspects related to the use and availability of the water might affect how much can be used for hydropower production, such as changes in irrigation withdrawal, water releases for environmental purposes and changes in priority of water use between sectors. All these factors, and more, might pose a risk to the hydropower developer, and should be assessed systematically and quantitatively before an investment decision is taken.

Floods and the possible catastrophic consequences of dam failure is clearly a dramatic hydrological risk. This paper focuses, however, on the hydrological risks related to potential changes in the inflow to the power plant and the power production due to a set of direct and indirect factors. We neither discusses risks posed to the power producer due to aspects of water quality. Such risk factors can for instance be high sediment concentrations causing wear on the machinery, reduced efficiencies and higher maintenance costs, and water qualities leading to undesired growth of plants in the reservoirs potential clogging intakes.

1.2 *Global statistics on dams and reservoirs*

The majority of dams and reservoirs world-wide are used for other purposes than hydropower. The ICOLD database (ICOLD, 2018) holds information about more than 59 000 large dams and reservoirs and their statistics show that only 20% of the single purpose and 16% of the multi-purpose reservoirs are used for hydropower. Irrigation is by far the dominant use among both single and multi-purpose reservoirs. Statistics derived from the 2014-version of the database (ICOLD, 2015) show that around 10% of both single and multi-purpose dams and reservoirs in Asia (except China) and Africa are used for hydropower production (Figure 1).

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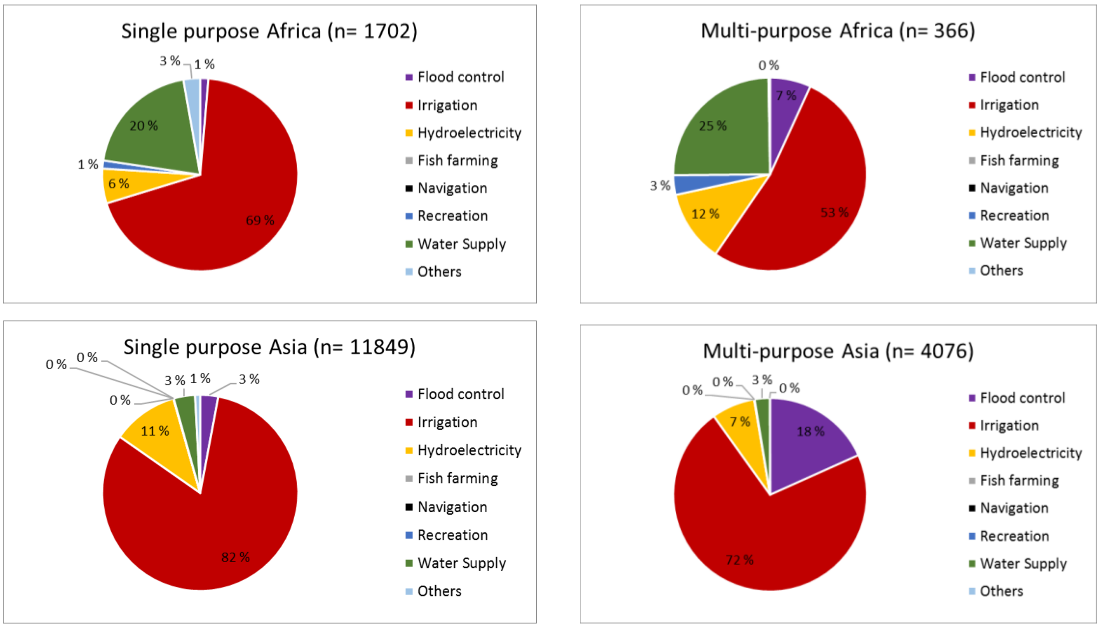

Figure 1. Pie charts showing the distribution of functions among single and multi-purpose dams and reservoirs in Africa (upper left and right, respectively), and in Asia, except China (lower left and right, respectively). Source: ICOLD (2015).

The statistics show that several dams and reservoirs are used for a different purpose that the production of electricity and indicate that there is a potential of retrofitting existing water infrastructure for the production of hydropower.

1.3 *The aim of this paper*

The aim of this paper is to identify the direct and indirect sources of hydrological risks and opportunities posed to hydropower developers related to the future availability of water for hydropower production. Further on, discuss the magnitude of the risks and how they might affect a hydropower project, and present some methodological approaches that can be applied to assess the hydrological risks. This paper;

- aims at increasing awareness about the potential large hydrological risks in hydropower projects related to future water availabilities
- contributes to identifying specific risks factors, potentially reducing the water available for hydropower production
- presents a set of analytical tools to systematically assess the hydrological risks of hydropower projects in a quantitative manner.

2 HYDROLOGICAL RISK FACTORS DIRECTLY AFFECTING WATER AVAILABILITY

Hydrological risk analysis in the context of hydropower planning traditionally refer to an assessment of the annual and inter-annual variations in the availability of water. As the availability of water is also affected by several other factors, such as climate change, water withdrawals for human consumption and ecological needs, the future variation in water availability might be very different from the past. Also changes in water policy, such as altered priority of water use and re-allocation of water might directly or indirectly affect the water available for power production, or change the periodicity of when water is available. This will pose a hydrological risk, in a wide sense, to the hydropower producer. The risk in this context might, however, also have positive connotations ('opportunities'), as there can also be positive relations between different water use.

There is a growing understanding about the close relation between water and energy, sometimes entitled the water-energy nexus (Gleick, 1994; IEA, 2012; Olsson, 2012; World Energy

Council, 2015). Water is a highly needed resource in the development of energy resources and access to energy is prerequisite in the provision of water services. According to IEA (2012), the global freshwater withdrawals for energy production in 2010 were estimated to 583 billion cubic metres (bcm), which is approximately 15% of the world's total water withdrawals (around 4000 bcm). Of that, close to 10 % of the water withdrawn was consumed (66 bcm) and not returned to its source. Projections for the future indicate a rapid increase in both withdrawal and consumption (IEA, 2012). Several international organizations and initiatives are raised to call for an approach that integrates management and governance across the water and energy sectors. There is also a water-environment nexus where hydropower reservoir operation can worsen and mitigate climate change impacts on habitat quality of wetlands and non-consumptive recreational uses.

This section of the paper reviews a set of factors that can affect the future availability of water for hydropower production, discuss how they interact and to what extent the risks can be analyzed, quantified and ultimately reduced.

2.1 *Irrigation*

Agriculture is the sector with the largest water withdrawals, accounting for approximately 70% of the global water withdrawals (FAO, 2018). The statistics provided by ICOLD (ICOLD, 2018) show that irrigation is also the most common purpose among single purpose reservoirs, and also the most common use among multi-purpose reservoirs. Generally, irrigation leads to decreased streamflow and increased evapotranspiration and several publications have shown the effect of irrigation on the water resources. Haddeland et al. (2006) found that the streamflow in Colorado and Mekong river basins decreased by 37% and 2.3%, respectively, in the analyzed period. Bakken et al. (2016a) found large flow reductions in Kizilirmak river basin due to irrigation withdrawals, in particular in the middle and lower parts. The results from Devoll river basin in Albania showed a different picture as only limited effects could be seen due to irrigation, which to a large extent was explained by the collapse in the agricultural sector in the early 1990's (Bakken et al., 2016a). Leng et al. (2015) found that irrigation had a larger effect on low-flow than on high-flow of streams.

Irrigation withdrawals upstream the hydropower plant will directly reduce the streamflow and hence reduce the water for power production. As some of the water withdrawn for irrigation might return to the river via base flows, there is not a simple 1:1 relationship between irrigation withdrawals and hydropower losses. Irrigation withdrawals downstream of the power plant are usually not a direct threat to the hydropower production, as the power production and agriculture will mutually benefit of the regulated flow provided by the upstream reservoir. One exception is if downstream irrigation gives minimum flow restrictions on the hydropower producer in order to secure the availability of downstream irrigation, which is known for instances from Devoll in Albania (Bakken et al., 2016a). Anyhow, irrigation is most likely a large risk factor in many river basins, particularly where the hydropower projects are located in the downstream parts of the river basin, where all upstream activities will affect the availability of water.

As the water use in the agricultural sector can be inefficient, e.g. if the water is simply flown into the farmland, or if the irrigation canals are in poor conditions, there are opportunities to reduce the water consumption and secure the water available for hydropower production. This will require both technical, economical and institutional means, but development of a market for water-trading between the hydropower sector and farmers is a mechanism that should be explored for the potential benefits to both sectors (Barton & Bergland, 2010). This can both de-risk investments and increase the revenue of hydropower projects.

2.2 *Drinking water supply*

Supply of drinking water is a basic human need and a growing population, increasing welfare and degrading supply network with large water losses all point in the direction that the volumes needed to meet these demands will increase. Drinking water supply often has a high priority in water scarce basins with competition over water resources, but at the same time often represents relatively small volumes compared to the water needs in the agricultural sector. The production of clean water for domestic consumption is a frequently used example of the close relation between water and energy (water-energy nexus) as the purification of and distribution of water requires substantial volumes of energy (Olsson, 2012).

Criteria for dimensioning the domestic water needs are typically in the range of 150-250 l/person/day in developed countries. This number integrates a variety of activities and distribution losses beyond personal use. Gleick (1996) defined the basic human needs for water to 50 l/capita/day (equivalent to 18.3 m^3/capita/year), a number which is supposed to be independent from climate, technology and culture and based on fundamental health considerations. The basic water requirements were developed based on four basic domestic needs, i.e. drinking water for survival (5 liters), water for sanitation services (20 liters), bathing (15 liters) and the water needed for food preparation (10 liters). Gleick (1996) does not include water needed for agriculture, industry or other sectors. In the other end, the Falkenmark indicator (Falkenmark et al., 1989) is an integrative number including the water needs for domestic purpose, industry and in agricultural production, where 1000 m^3/capita/year is the threshold value between water stress and water scarcity (equivalent to 2750 l/capita/day). The indicator classifies the total available freshwater resources to the population of a region (nation) according the severity of the water-scarcity. These numbers presented above can be used as a basis to assess to what extent the supply of drinking water might pose a risk for the hydropower developer.

2.3 *Upstream regulations*

In countries with small volumes of water withdrawn for irrigation (e.g. Norway) and limited evaporation, upstream regulation will normally be beneficial for downstream power producers with limited storage capacity, even if located many kms downstream of the reservoir. The construction of new upstream reservoirs and regulation capacity can provide additional regulation and as such enhance the utilization time (increased capacity factor) of the downstream power plants. In other cases, the construction of upstream regulation, even if used exclusively for hydropower production, can be a risk for downstream power production, as illustrated in (Bakken et al., 2016a), as more water is withdrawn for irrigation due to the provision of regulated flow. In addition, storage of water in reservoirs will normally increase the evaporation losses from the reservoir surfaces, which can be large (e.g. Strzepek et al., 2008). The effect of the upstream regulation can be illustrated by the tension caused by the construction of the Grand Renaissance Dam (GERD) on the Blue Nile in Ethiopia. The regulated flow provided by this reservoir will smoothen out the flow, increase the flow in the low-flow period and enable farmers to develop irrigated agricultural production, with the results that less water will hence enter Lake Aswan in southern Egypt.

Another aspect related to the construction of dams and reservoirs is the temporal effect of filling the reservoir. During filling, downstream areas will experience reduced runoff. The tension over the Nile water between Ethiopia and Egypt is also related to the period GERD is filled, which will have adverse effect on Lake Nasser, possibly leading to losses in hydropower production, reduced water for irrigation and maybe also affect the security of supply of drinking water to Egypt. For a hydropower developer in a basin where good sites for reservoir establishments are not yet exploited, such risk assessments should be made.

2.4 *Flood control*

Floods are causing large societal damages and big human losses. In Norway, the losses due to floods have been calculated to approximately 100 mill. Euro annually since 2011 (Multiconsult, 2018). It is also interesting that damages have increased dramatically the last decades, and the costs are now (2011-2016) estimated to be 4 times higher than in the period 1980-2010. There might be several reasons behind this trend, but one reason is (moderate) floods tend to happen more frequent than earlier. Several floods in Norway the last years have proven that reservoirs reduce the flood risks and damages, even though the reservoirs are primarily built for hydropower production. This was also clearly documented in a study of the regulated Orkla river basin in central Norway (Hansen, 2018). This is an additional societal benefit from reservoirs beyond power production, and the role of reservoirs during flood situation has gained increased attention in Norway.

In emergent situations, authorities (in Norway, maybe also other countries) can instruct the hydropower producers to operate their reservoirs in such a way that they reduce the downstream losses and damages to a minimum. We have also seen several cases where hydropower producers on their own initiatives have released water prior to predicted floods and saved large societal values. In this context we would underline the societal responsibility the hydropower producers have to avoid structural failure of their installations. What is perceived as a societal benefit can also be perceived as a societal responsibility, required by the right to operate a reservoir. Failure to fulfill this responsibility would result in cost to society of e.g. a dam failure, or amplification of the flooding peak through loss of maneuvering capability once the reservoir is full (Tolo et al., 2017). A more active use of reservoirs in reducing floods can introduce new limitations on the operation of the reservoirs, but also open new business opportunities. It should be investigated how a possible operation with respect to reducing flood damages will affect the power production during the planning of a new reservoir. It should be analyzed whether flood mitigation is in conflict with optimization of the power production, and to what extent future floods will affect the revenue of the power producer.

2.5 *Environmental flow releases*

Mandatory releases of water to bypass sections and river sections downstream hydropower outlets are becoming more common world-wide in new licenses for the purpose of sustaining ecological qualities in the regulated rivers. In old hydropower licenses environmental releases are less common, and the revision of hydropower licenses might introduce mandatory releases from a large number of power plants (NVE, 2013), such as in Norway. NVE (2013) calcutated the power losses in the Norwegian power system to be in the range 2.3-3.6 TWh/year if environmental flows are released in prioritized rivers without minimum flow equal to Q95 (a water flow value exceeded in 95% of the time). This compared to the total annual production being around 135 TWh/yr. Q95 corresponds to a value typically around 10% of the mean discharge, but this varies extensively between rivers and hydrological regions. Bakken et al. (2012) reviewed standards for release of minimum flows in selected European countries and found that flow values similar to Q95 are very common, and Q95 can be considered a typical flow value set aside for environmental reasons also outside Europe.

Depending on the configuration of the regulation, minimum flow releases can be considered 'lost power generation' if the released water is not turbined on its way to the receiving river section. If the water can run though the turbines in its way to the river, the power losses will be much smaller and the losses in revenue will be related to the fact that the releases might be in periods with less favorable power prices.

With the introduction of "environmental design" of regulated rivers (Forseth and Harby, 2014), win-win solutions can be identified, where more power can be produced and a higher environmental standard can be achieved (Bustos et al., 2017), in particular if the whole regulated system is investigated. The concept of environmental design is that water should be released according to the needs of the ecosystem. This asks for more dynamic water release schemes than typical constant values. Better solutions can more likely be found if a larger part of the regulation and potential upgrading/extension projects are included. This would require some flexibility in the legislation process, and from the power producer a willingness to look for better solutions beyond the specific power plant under consideration. With respect to environmental impacts from hydro-peaking operations, which is a special type of problem downstream hydropower plants operated with rapid and frequent changes in power production, Bakken et al. (2016b) developed an approach for assessing the environmental impacts from hydro-peaking operations. It was also proposed a set of guidelines in how hydro-peaking can be undertaken within acceptable levels of impacts.

We have also seen cases where reservoirs with cool water have been used to release water of low temperatures to secure the survival of specie less tolerant to higher water temperatures. This has happened a few times in salmon rivers in central Norway, including during the dry and warm Summer of 2018.

2.6 *Other water uses*

While irrigation, hydropower, flood control and water supply are the most prevalent uses, reservoirs can also be used for other purposes, such as recreation, navigation, fish farming, cooling of thermal power plants. Globally, almost 30 %, and 6 % of multi-purpose reservoirs registered in ICOLD database are used for recreation and navigation respectively (ICOLD, 2015). In the US, 76 % and 27 % of multi-purpose hydropower reservoirs are authorized for recreation and navigation respectively (Hadjerioua et al., 2015).

The impoundment of water in reservoirs allows for a variety of recreational uses such as fishing, swimming, sailing, water sports, hiking, camping and wildlife observations. Recreational activities play an important role for the people living close to the reservoir as well as they attract tourists. The economic benefits (direct and indirect) of recreational activities might overcome the hydropower benefits (Hadjerioua et al., 2015). Reservoirs play an important role in transportation of goods as they allow the transport of merchandises by boat instead of train or trucks. Navigation is hardly ever the main purpose of a reservoir (ICOLD, 2015), but reservoirs may play a central role for inland navigation as they may enhance and constraint navigation conditions. The release of water from the reservoir to the downstream river can help to maintain conditions for navigation during the whole year. However, dams themselves constitute barriers to navigation, and the passage from upstream to downstream and vice-versa is insured by ramps, lifts, or ship locks.

In some cases, or times of the year, the use of reservoirs for recreation or navigation may conflict with hydropower generation. EDF and the World Water Council developed the SHARE concept as a solution to the challenge of sharing water among water-users (Branche, 2015). The Villarest dam (128 mill. m^3, 770 ha) is located in the upstream part of the Loire river and is a good illustration of multi-purpose management of reservoirs. The reservoir was designed from the start as a multi-purpose infrastructure and is currently operated in coherence with the different uses of water. However, some of the water-use constraints like recreation were implemented later due to increasing recreational interests in the area. Recreational activities and the associated tourism play today an important economic role for the local communities. For this reason, a public consultation was carried out to define the need of water for this type of use. Today, the regulation of the reservoir, particularly the level of water and the rate of change in water level, are to a certain extent adapted to the water needs for recreation.

We have also seen examples (e.g. during the heat waves in France in 2003 and 2018) where the cool water in reservoirs have been used to secure the operation of nuclear power plants by the supply of water of sufficiently low water temperatures. It is, however, difficult to obtain scientific documentation of this type of emergent operation of the reservoirs.

2.7 *Climate change*

Climate change will introduce changes in precipitation, air temperatures, evapotranspiration and the periodicity and variability of these factors. Climate change might also lead to more extremes, and some regions will experience higher and more frequent floods and more intense and longer-lasting droughts. The changes in climate will, however, vary greatly between regions, as well as the effect on the water resources available for hydropower production and other use.

A large number of studies have investigated the effect of climate change on the hydropower resources. Hamududu and Killingtveit (2012) analyzed the effect on the global hydropower production and concluded that the production will stay more or less constant with climate change, but with regional differences. Van Vliet et al. (2016) also carried out a global study and predicted a slight reduction in global hydropower production, depending on emission scenario selected. The study by Haddeland et al. (2014) combined several anthropogenic influences on the water resources and indicated that the combined impacts of climate change, man-made reservoirs, water withdrawals, and water consumption are small on the long-term global terrestrial water balance, but found that the impacts of anthropogenic interventions are significant in several large river basins.

Other publications have studied the effect within one or a few river basins or hydropower projects. Bakken et al. (2016a) found that water available for hydropower production in central Turkey will decrease quite dramatically due to a combination of climate change and irrigation withdrawals, while the results from Albania showed a much more moderate reduction. These findings confirm the study on changes in runoff generation from Milly et al. (2005), covering the same regions. Another example is the modelling study of Targus in Spain (Lobanova et al., 2017) that showed reduced water availabilities. The authors promote coupling of the human-hydrological systems in order to find a balanced allocation of the water resources in such water scarce regions. Anghileri et al. (2018) carried out a comparative assessment of the impact of climate change on Alpine hydropower and also found a reduction in water available for hydro-power production, which confirms findings from Ravazzani et al. (2015), but found that the revenue is still expected to increase due to higher future power prices. In other regions (e.g. in Norway) the hydropower production is today higher compared to the period where a large part of the were developed, i.e. in the 1950s-1970s. Climate change predictions point in the direction of increased runoff (Norsk klimaservicesenter, 2018). In order to reduce risks in hydropower projects due to climate change, Ray & Brown (2015) proposes a systematic approach for the assessment of risks (see Section 4.3).

3 FACTORS INDIRECTLY AFFECTING WATER AVILABILITY

3.1 *Changes in priority of water use/allocation*

The availability of water for hydropower production is in many river basins with complex relationships between water use challenging to determine, and the priorities over water might affect the power production. In some countries the rights to use water are juridically well-defined, while in other countries the allocation can simply be given from the location in the river basins, i.e. that the upstream users are served before the next, etc. In many regions, the historical rights are very strong, which can make changes in water allocation challenging. Historical rights can be associated with the farmers and their farmland along the rivers. The hydropower producers can also have strong rights. In Sweden, hydropower licenses have been issued as ever-lasting (Sweden) with limited possibilities to re-negotiate the terms. In Norway, state-owned hydro-power licenses are ever-lasting, while privately owned power plants will after a period be returned back to the state. Hydropower licenses in Norway (before 1960), typically have no mandatory releases of water for environmental purposes, while more recent licenses have designated environmental flows. In these cases, the releases of environmental flows have a higher priority than hydropower production. Hydropower licenses can also have restrictions related to the timing of the filling of reservoirs, adding additional complexity to the operation. As discussed in Section 2.5, the introduction of mandatory releases of environmental flows can in many cases directly affect the revenue of the hydropower project. In more complex river basins, other priorities can pose larger risks.

3.2 *Reservoir sedimentation*

Sediment inflow into reservoirs is a major challenge for the sustainability of dams and reservoirs as it reduces the storage capacity (Schleiss et al., 2016). Sediment transport continuity is interrupted by dams which act as a barrier in the hydrological system. The sediment yield describes the amount of sediments entering reservoirs and is a function of local parameters such as soil type, vegetation, catchment slope, precipitation, temperature. Sediments inflows entering reservoirs are trapped and accumulate in reservoirs reducing their lifetime. Trapping efficiency is defined as the ratio of incoming sediments which deposit in the reservoir to the total incoming sediment entering the reservoir and varies with reservoir and sediments characteristics. Trapping of sediment is thus site-specific depending among other on the geometry of the reservoir.
Sediment trapping in reservoirs can induce a significant loss of the storage capacity and reduce reservoir lifetime. In some cases, lifetime is reduced to less than 100 years (Morris & Fan, 1998). Sedimentation of reservoirs occurs generally at a shorter timescale than the degradation of the installation itself.

Globally, the net storage capacity (defined as the installed capacity minus the losses due to sedimentation) is currently declining after a peak in 2006 (Wisser et al., 2013) and the decline is even larger when assessed as storage capacity per capita, due to population growth. Wisser at al.

(2013) estimate that the net storage capacity per person has decreased by 21 % between the peak time in 1987 and 2010. The risk for sedimentation is unevenly distributed on earth and shows some regional differences. While some rivers basins located in India and China are the most vulnerable to sedimentation, other river basins have almost no sedimentation like in Northern Europe. Today, a large number of hydropower reservoirs are already filled with sediments and cannot be used longer to produce electricity questioning the sustainability of some hydropower projects. Climate change might amplify the sedimentation rates in river basins in regions in regions of higher total rainfalls and higher variability, which can be further increased by land use changes.

Risk for sedimentation must be anticipated prior to the construction of the reservoir in order to estimate the potential loss of reservoir capacity and the viability of such projects. During the design phase an extensive analysis of sedimentation processes should be carried out, including estimation of sediment yields entering the reservoir, projections of future sedimentation load, calculation of sediment trapping rate in the reservoir and simulation of the rivers' sediment transport capacity. In rivers with modified land-use in the surrounding catchment, sediment delivery should also be calculated by measurements and modelling and be prevented with mitigation measures. Mitigation measures addressing the loss of reservoir capacity should also be anticipated and planned to the construction plan (Kondolf et al., 2014). These measures consist mainly in 1) routing sediments through and around the reservoirs, 2) removing sediments accumulated in reservoirs, and 3) minimizing the amount of sediment arriving to the river.

The retention of sediments in reservoirs has also ecological effects (Hauer et al., 2018). It modifies the dynamics of the sediments in the downstream rivers and impact the amount and distribution of sediments. This modifies strongly the habitat for fish population and is a threat to reproduction and survival.

3.3 *Political risks*

Political risks and the effect on the availability of water is to the authors' knowledge very little explored, but there are obviously clear relationships between policies and the water available for various purposes. As an example, a decision to change the agricultural policy in the direction of a higher degree of being self-sufficient in the production of food, or that the share of biofuel should be increased in transportation, will possibly lead to changes in land use and water needed for irrigation.

Another example will be how energy policies can directly affect the hydropower production via changes in subsidies and taxation. The green electricity certificates arrangement in Norway and Sweden is an example were the development of new renewable energy production is subsidies (by the consumers). In the case of increased biofuel production, this could be a threat to a specific hydropower developer, while the use of political instruments to the new hydropower developments could act as a both a threat and an opportunity, e.g. if the new developments provide better regulation.

Related to climate policies and the implementation of these can in the longer term be clearly give different effects of the hydrology, which will affect the hydropower potential. This can be seen on the differences in runoff coming out of the various emission scenarios (RCP2.6 – RCP8.5). In an early planning phase, it would be very useful to assess the risks related to changes in policies and how this would further affect the availability of the water resources, preferably is quantitative way. As the assessment of the political risks related to policy changes might be very uncertain, an estimation of the range of uncertainty would be useful for the hydropower developer. Such a systematic and integrated assessment of political risks could for instance be undertaken by expert consultation/judgements.

4 APPROACHES TO SYSTEMATICALLY ASSESS HYDROLOGICAL RISKS

4.1 *Hydrological models with scenario and water allocation functionality*

A large number of hydrological models are available for the purpose calculating the runoff. These models simulate runoff typically based on climatic input data and a description of the watershed, and available models can range from those sold by commercial vendors with user-friendly interfaces to tools developed exclusively for research purposes. Many of the hydrological models are mainly aimed at representing the natural processes within the watershed, but some also take into account the demand-side by describing the human water needs and the related infrastructure, sometimes named water allocation models.

The WEAP software (Water Evaluation and Planning Tool) is a tool developed by Stockholm Environment Institute (SEI) for the purpose of supporting integrated water resources planning and management (Yates et al., 2005). WEAP is configured for watersheds as the spatial unit and holds built-in algorithms for rainfall-runoff generation, including infiltration and evapotranspiration, as well as surface water/groundwater interactions. Water demands and human interventions to the hydrological cycle can be represented in the tool, such as drinking water supply, irrigation, crop water requirements and yields, hydropower production and multiple management objectives can be defined. The tool can also take into account ecological flow requirements and calculate several water quality parameters. WEAP can be coupled with LEAP (LEAP, 2018), the Long-range Energy Alternatives Planning System, which is a software tool for energy policy analysis and climate change mitigation assessment.

As WEAP is developed under the philosophy that all major process shall be represented, but without making the tool too complex. This makes the tool efficient and fast, and feasible to run several years of simulations. WEAP also includes functionality to run and analyze multiple scenario simulations.

WEAP can explicitly represent all water demands/requirements and hydrological risk elements described in Section 2 and 3 of this paper, maybe except for political risks, which needs to be translated into changes in water use or priorities. Nor can the tool calculate reservoir sediment directly, but a time variation in storage capacity can be given (e.g. decline in capacity). The tool is also useful in facilitating the dialogue between stakeholders.

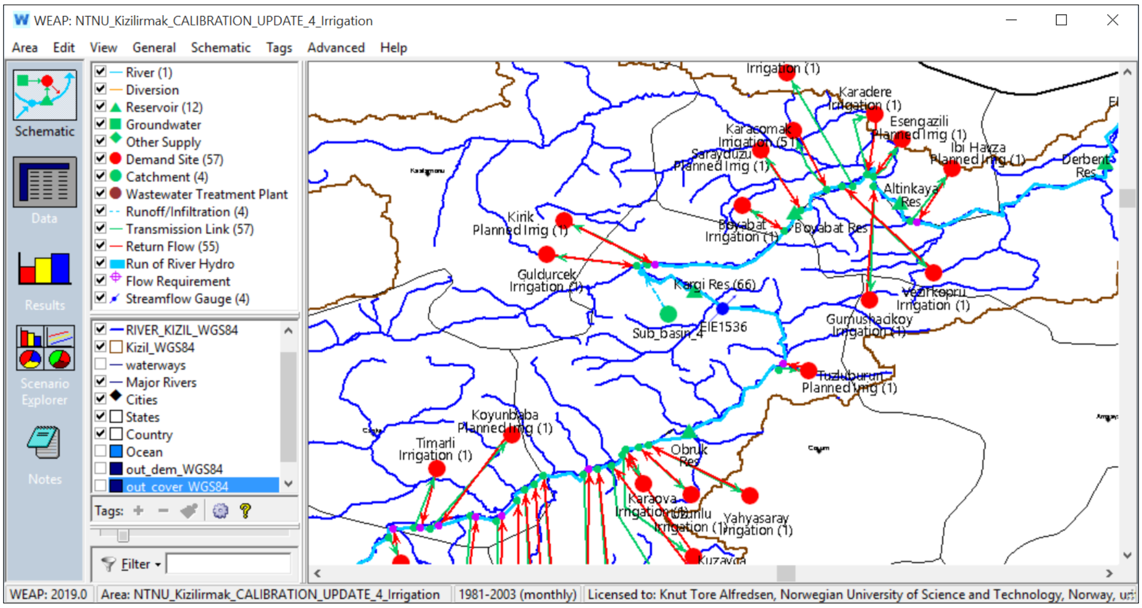

Figure 1. The figure shows a sceendump of WEAP as applied in Kizilirmak River Basin, Turkey.

4.2 *Bayesian network methodology*

Bayesian networks are a graphical representation of a joint probability distribution decomposed into a set of conditional probability distributions (Kjærulff & Madsen, 2013). They are a generic modeling tool used both for representing a correlation structure in a causal network and for decision analysis under uncertainty. The modeling approach is often called Bayesian belief networks, because a priori beliefs about causal relationships – often based on expert judgement using sparse data, are formalized and the updated and improved using Bayesian updating statistics. Bayesian belief networks (BBNs) are increasingly being used to document and improve expert judgement in ecological modeling, decision support in the provision and demand of ecosystem services, and environmental and resource management (Varis, 1997; Barton et al., 2012; Landuyt et al., 2013). BBNs are particularly useful for communicating risk and uncertainty and providing a framework for analyzing cause and effect relationships in natural systems. In a BBN conditional probabilities represent both temporal and spatial variation. Spatially explicit Bayesian networks can specify different conditional probabilities for discrete locations (Landuyt et al. 2013), while Dynamic Bayesian Networks can capture changes over time in causal relationships such as ecological threshold effects (Nicholson et al., 2011).

There has been limited awareness of Bayesian network models in the hydropower planning literature until quite recently, with earlier reference mainly to the prediction of downstream effects from dam releases (McCartney, 2007). Bayesian networks have been used in a number applications to renewable energy, but would seem not to have been applied to prediction of hydropower generation (Zomorodian et al., 2018). BBNs in hydropower has been used in failure probability diagnostics for production equipment (Borunda et al., 2016). One reason for lack of application of BBN to risk analysis of hydropower production is probably the availability of quantitative simulation models that can capture hourly variances in water availability based on high resolution meteorological and hydrograph data. Uncertainty of water availability is seemingly well described if the system boundaries are limited to hydrology. However, in an early example of Bayesian belief networks (BBNs) experts assessments of 24 key variables in the climate water system in Southern Finland were formalized in an explorative risk analysis (Kuikka & Varis, 1997). They found that the uncertainty in causalities between climate and hydrology were 'masked out' by uncertainty deriving from other sources.

Bayesian belief networks have more recently been used in assessing risk for impacts of hydropower, which are less well monitored, and where expert judgement and sparse observational data need integration into a formalized risk analysis approaches. For example, Tolo et al. (2017) used BBNs to assess the structural vulnerability of hydropower installations exposed to extreme climate events. Balbi et al. (2016) used BBNs to extend flood risk assessment to evaluate societal responses. They assess early warning of flood risk including modelling of people's mitigating actions in response to flood warnings.

Hydropower impacts on downstream aquatic habitats is another complex ecological system where qualitative expert judgement can be combined with quantitative model simulation. For example, BBNs have been used to formalize expert ecological knowledge of the effects of hydrological regimes on fish habitat (Gawne et al., 2012).

While a modelling platform such as WEAP can explicitly represent all water demands/requirements and hydrological risk elements discussed in sections 2 and 3, it does not explicitly handle sedimentation effects on reservoir capacity, nor political risk external to the production system. There seems to be some scope for using Bayesian belief networks as a 'meta modelling tool' (Barton et al., 2008) to integrate model simulation results on water availability with other risk sub-models. An object-oriented Bayesian network (OOBN) can be used to integrate different disciplinary sub-models (Barton et al., 2016). An OOBN is a hierarchical representation of a joint probability distribution over a set of random variables. It consists of a graphical structure describing dependence and independence relations between variables in the model represented as the nodes in the graph. The dependence relations are quantified using conditional probability distributions. The hierarchical structure is created through the use of instance nodes, which are realizations of self-contained sub networks within a network class. For example, Barton et al. (2016) used an OOBN to link the impact of upstream land-use management on nutrient run-off modelled in a SWAT catchment model, to the impact of nutrient loading on lake eutrophication in a 2D MyLake water quality model, linked to impacts on bathing water suitability, and finally to willingness-to-pay for different recreational water uses.

4.3 *World Bank – Decision-tree framework*

The Decision Tree Framework (DTF) developed by the Word Bank (Ray & Brown, 2015) is a decision supporting tool designed to assess climate risks of water resources projects and the importance of these risks relative to non-climate risks such as politic or demographic risks. The tool provides a hierarchical, bottom-up, and repeatable process that enables the evaluation of the sensitivity of water resources projects to climate risks and the implementation of risk mitigation when necessary. The methodology includes both climatological and decision-making approaches via the definition of project vulnerabilities-based climate scenarios and the involvement of stakeholders respectively.

The DTF consists in a succession of four stages (Phases 1 to 4) from which it is possible to exit when climate information is judged adequate to evaluate project performance. Phase 1 is called Project Screening and aims at identifying sensitivities of the project to different climate factors with the aid of the Climate Screening Worksheet. Projects with non-significant climate sensitivities go out of the decision tree, while projects with *potential climate sensitivities* will go to phase 2 for further analysis. Phase 2 is called Initial Analysis and consists in estimating the sensitivities of the project to changes in climate and assessing their importance relative to non-climate related stressors. The output of this phase is a Climate Risk Assessment which will contain estimates of the magnitude of potential climate stressors provided by a first-order water resources system model. Projects with small climate sensitivities relative to other factors will go out from the DTF while projects with *relatively significant potential climate vulnerabilities* will go to the next phase. Phase 3 is called Climate Stress Test. This phase aims at quantifying the climate and non-climate uncertainties that have been identified in phase 2 by applying a so-called climate stress test. The method consists in varying climate conditions and test the system performance against these changes. A wide range of climate scenarios based on both historical data and future climate projections are tested, beyond the typical range from General Circulation Models (GCMs), with the aid of a coupled hydrologic-economic model. This phase requires significantly more computational analysis than the previous ones. The output of phase 3 is a Climate Risk Report including a climate response map which present the sensitivities of the system to climate variations and an evaluation of the magnitude of the climate and non-climate risks. Projects will thus be evaluated as robust or vulnerable to changes in climate. Only projects with *demonstrated climate vulnerability* will be addressed in phase 4. In the last phase of the DTF, so-called Climate Risk Management phase, management risk tools will be selected and methods to reduce climate vulnerabilities identified in phase 3 will be developed. If the robustness of the project is improved, the design modifications and plan for addressing climate vulnerabilities will be reported in a Climate Risk Management Plan. In this case, the revised project will go back to phase 3. However, projects with high risk and limited mitigation can be abandoned at this stage of the decision tree.

4.4 *Comparison of approaches*

Table 1 attempts to evaluate the suitability/capability of the various approaches described in Section 4.1-4.3 in order to assess the hydrological risks. The criteria listed to the left in the table are assumed to be important functionality of the approaches/tools in order to support the development of integrated hydrological risk analysis. The suitability/capability of the approaches/tools are given a score from 0 to 3, where a score 0 indicates that this approach/tool does not support such analysis, while a score of 3 indicates that such analyses are supported very well.

Table 1. Evaluation of the suitability of three different approaches in assessing the integrated hydrological risks of hydropower projects. The scores are given from 0 to 3, where 0 is the lowest score and 3 the highest/best. The scores are given by the authors of this paper.

Criteria*	WEAP	Bayesian network	Decision Tree Framework (DTF)
Long-term simulations	3	2*	2**
Spatial variations	3	2*	2**
Multiple scenario simulations	3	3	3
Uncertainty/sensitivity	2	3	3
Wide set of water use	3	3	2
Risks defined qualitatively	0	3	3
Requires input from domain tools	No	Yes	Yes

* Spatial and temporal variation can be handled indirectly in BBNs by analysis carried out in domain tools which are then synthesized into conditional probability distributions in a ‘meta-model’ implemented as an OOBN.

** Spatial and temporal variation can be handled indirectly in World Bank Decision Tree Framework by analysis carried out in domain tools which are then synthesized into a climate risk report.

5 CONCLUDING REMARKS

Water resources projects can in many regions be characterized by having ‘deep uncertainty’. Several studies have shown that there are potentially large hydrological risks related to hydropower projects, and the assumption that new hydropower projects can be planned exclusively based on historical observations of runoff may lead to a biased risk picture (Milly et al., 2008). A large set of risk factors, all potentially contributing to the overall risks, and the combination of these factors, should be taken into account when new hydropower projects are planned, as they might pose a large risk to the hydropower developer. The magnitude, spatial location and temporal variation of the individual factors will lead to different levels of risks and diverse risk profiles. Such projects will greatly benefit from methodologies that reveal the full spectrum of uncertainties which will guide decision-makers towards more robust decisions. This paper has presented some, selected tools that can be applied for the purpose of analyzing risks and ultimately control and reduce them. The use of such tools will hopefully lead to better investments and lower financial risks in planning and operation of hydropower projects.

WEAP is a highly advanced hydrological tool that offer an integrated approach for water resources management and supports the simulation of different water allocation scenarios, changes in water needs, and the effect on the water available for hydropower production. WEAP is not a risk analysis tool *per se*, but can be configured to simulate scenarios that are highly relevant in the preparation of results for assessing the hydrological risks in an integrated manner. Most of the risk factors and their internal dependencies described in previous sections can (and must) be described quantitatively, but WEAP does not allow the representation of qualitative factors. WEAP does not require input from ‘domain tools’ as most relevant processes and water demands should be included in the tool itself, but can still communicate with external and more dedicated tools (e.g. Modflow, Qual2K, SalMod) or utilize results from other tools as input or as boundary conditions. From this we conclude that WEAP is a feasible for analyzing integrated hydrological risks directly, or that the tool could provide useful input to other approaches, such as object oriented Bayesian networks.

Object oriented Bayesian networks offer some scope for extending hydrological risk analysis conducted in WEAP, but with some important caveats. For example, a sub-network could be set up using simulations from soil erosion and transport using SWAT linked to simulations of reservoir capacity conditional on sediment loading. This sub-network could be connected to nodes in an encapsulating network representing WEAP simulations, through an interface node for reservoir capacity. Such an OOBN could be augmented with decision and utility nodes representing exogenous policy decisions’ costs and benefits. A further, sub-networks could be used to specify individual policy risks more explicitly, based on consultations and formalization of expert policy judgements. In principle, the OOBN could then be used to identify decisions with optimal utility considering all the joint probabilities.

While authors applying OOBNs to integrated environmental appraisal find it a useful framework for transdisciplinary communication risk, a challenge faced by all serially coupled models is uncertainty propagation and uncertainty accumulation (Barton et al., 2016). In such coupled probabilistic model systems there are no negative feedback loops reflecting for example risk mitigation actions, which may also reduce uncertainty over time. For example, water saving or erosion control measures may increase thanks to other policy sectors climate action plans. Without such negative feedback loops the modelled system tends towards greater uncertainty as one moves down the causal chain. Integrated risk analysis models of this kind can therefore be biased towards ‘no action’ or status quo decisions, as the modelled ‘signal’ of potentially large benefits is attenuated by layers of modelled climate change uncertainty, while the costs are well known and immediate. Such biases may also be uncovered through extended risk modelling exercises with Bayesian belief networks. Such integrated models improve the decision-making process, usually not by pointing to an optimal decision, but by uncovering where in the causal chain investment in monitoring provides the greatest information value for future decision-making.

The World Bank Decision Tree Framework (DTF) is a decision tool developed which, contrary to OOBNs, has the advantage to be especially designed for water resources projects. The DTF allows the identification and the quantification of potential climate vulnerabilities of water resources projects relative to other type of vulnerabilities (non-climate). The tool handles risk assessment of climate vulnerabilities by providing a detailed methodology to address climate risk but it also helps the project manager to develop risk management strategies for projects at high risk. Contrary to other approaches, the effort expended when applying DTF is proportional to the relative importance of climate vulnerabilities relative to non-climate vulnerabilities. For example, projects with small climate risks will exit the DTF after phase 1 and will not require any climate assessment risk. The DTF is however neither a hydrological nor an economic simulation tool and requires like OOBNs inputs from external simulation tools in the further phases of the decision process. Results of climate scenarios simulations using WEAP can for example be used in phase 3 when analyzing the response of the system to a large range of climate scenarios. Additional tools for decision making or risk management that may be needed are well referenced in the description of the DTF (Ray & Brown, 2015).

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