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Future perspectives of run-of-the-river hydropower and the impact of glaciers' shrinkage: The case of Italian Alps

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HIGHLIGHTS

- We quantified the impact of climate-change on hydropower in Italian Alps.
- We provided the first country scale perspectives of run-of-the-river plants.
- We employed a semi-distributed hydrological model and nine climate scenarios.
- Median hydropower production is expected to reduce by 3% by 2065.
- Glacier retreat is the major driver of this reduction in hydropower production.

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ABSTRACT

We assess the impacts of nine climate-change scenarios on the hydrological regime and on hydropower production of forty-two glacierized basins across the Italian Alps, assumed exemplary of similar systems in other glacierized contexts. Each of these basins includes one (or more) hydropower plant, here treated as a run-of-the-river system. We implemented a semi-distributed hydrologic model that divides each basin in elevation bands and reconstructs orographic effects on both precipitation and temperature. The nine climate-change scenarios quantify the individual and combined effects of an increase in temperature and a change in liquid-solid phase partition. The simulation horizon is 2016–2065. Thus, we avoided long-term scenarios and worked at short-medium range to maximize the relevance of this work for decision makers. Our results predict a decline of about −30% in average summer runoff across all basins compared to present. Because most of this decrease in runoff occurs during high-flow periods when the run-of-the-river capacity of these plants is exceeded, this result translates into a median decrease of about −3% in hydropower production for run-of-the-river systems through 2065, across all the basins and all scenarios. The predominant cause of this decline is glacier shrinkage, whereas different temperature or precipitation trends plays a marginal role. Run-of-the-river hydropower production in basins where the current glacier coverage is less than 10% of total area is particularly robust to climate change.

1. Introduction

According to the fourth report of the Intergovernmental Panel on Climate Change (IPCC), average global temperature has increased by +0.7 °C compared to the preindustrial level, fast-tracking from +0.1 °C per decade over the last century, to +0.13 °C per decade over the past 50 years and up to +0.16 °C per decade over the last 10 years [1]. Since 1970, there has also been a marked increase in the radiative forcing compared to previous decades, +43% between 2005 and 2011 [2]. All over the world, glaciers are rapidly responding to this increase in radiative input. After three centuries of expansion (Little Ice Age), they have entered a phase of rapid shrinkage since the second half of the nineteenth century. Multiple studies in the literature [3–5] show consistent trends throughout the northern hemisphere.

Shrinkage of glaciers has many implications for glacierized catchments, including changes to the local hydrological regime and a decrease in slope stability due to permafrost thawing [6–8]. The two most significant impacts in ice- and snow-dominated regions are a reduction in seasonal runoff and the simultaneous depletion of snow water resources, with evident implications for hydropower and energy

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production [9–11]. There is widespread consensus that climate change will result in changes to other river-flow conditions such as streamflow timing and quantity [12], sediment load [13], water temperature [14,15], biological/ecosystem changes [16,17], and habitats [18,19], subsequently affecting hydropower production. Many regions in the world are expected to exhibit such effects based on studies conducted at a global scale [14,20–22] and at regional level such as in India [23–25], China [26,27], Ethiopia [28], Canada [29], the United States [30–32], Asia and the western United States [33], England [34], Mediterranean basins [35,36], and the European Alps [37–39], among others. In this context, future perspectives of hydropower in Italy have been never addressed on an Alpine scale.

Water storage is an important way to cope with seasonal variation in water supply and demand. Storage of water in reservoirs, however, affects streamflow and sediment seasonal patterns. The accumulation of sediments behind a dam is a well-known issue for several reservoirs worldwide because it both reduces available storage and lifetime of a reservoir and affects the natural flow of suspended material downstream [40,41]. The worldwide net reservoir capacity is declining as a result of sedimentation (5% of the installed capacity, [42]). Combined with an increasing need for storage, these losses challenge sustainable-management operations and water resources management in many regions. The most vulnerable hydropower plants are those with a strong seasonal flow pattern, such as those located downstream of glaciers. An example is the Ceppo Morelli dam (original reservoir volume 500,000 m^3), which is nowadays used in a run-of-the-river mode as its regulation capacity has progressively become negligible due to silting [43–45].

An alternative technology is run-of-the-river hydropower, which has no (or marginal) storage capacity, meaning that the plant only relies on concurrent discharge for producing hydroelectricity by diverting flow from a natural river up to a certain threshold. The energy production in run-of-the-river plants is thus constrained by the natural river discharge and the need for protecting both the downstream ecological life and the plant equipment [46]. Run-of-the-river plants generally operate at the base of the load curve, as compared with storage plants operating at the peak of the load curve. Run-of-river hydropower plants have a relatively low environmental impact as long as the entire ecosystem is adequately protected [47]. Although hydropower generation capacity as a whole may benefit from storage, expansion of this technology (for example, by building new reservoirs) may not be economically or environmentally justified [48]. While run-of-the-river plants may thus represent a less invasive alternative to classic storage hydropower, their future perspectives in a warming climate have been generally poorly addressed [9,49,50], as most of the existing literature on hydropower and climate change focuses on storage systems. The few existing examples discuss either single plants such as the Ceppo Morelli dam in Italy [43,45] or the Falls Creek run-of-the-river plant in Oregon, USA [49], or regional studies such as the one carried out over Austrian Alpine catchments [9]. Major efforts are still needed to provide a coherent picture of run-of-the-river fate over large mountain chains and using easily-transferable metrics.

To assess perspectives of run-of-the-river plants over a much larger scale than existing works and using a standardized, transferable approach, we selected forty-two glacierized catchments with hydropower plants distributed across the Italian Alps, a heavily glacierized context. With an installed power of 22.4 GW, Italy settles in eleventh position on a world scale and fourth in Europe, behind Russia (47 GW), Norway (31 GW), and France (25 GW) [51]. In 2016 alone, the Italian electricity production from plants powered by renewable sources was 52.3 GW [52]. Almost 36% of this production came from hydropower (18.6 GW). Despite the importance of hydropower production at national scale, an assessment of run-of-the-river potential across the Italian Alps is still lacking. Filling this gap will provide a standardized flow to both assess perspectives of these systems elsewhere and assist decision makers at regional scale.

We applied a conceptual semi-distributed hydrological model to each of these basins to predict future scenarios of incoming flow at each reservoir, assumed to work as run-of-the-river systems. The model is specifically conceived to be applied in non-instrumented basins and therefore all parameters are estimated *a priori* basing on physiographic properties. Assuming nine possible climate-change scenarios over the next 50 years, we quantified the effects of changes in climatic conditions on the hydrological regime and on glaciers, hence on the production of hydroelectric energy. The input climate scenarios were defined starting from observed trends, thus avoiding the use of global or regional circulation models, which may suffer from high uncertainty in mountain areas and necessitate the formulation of further hypotheses regarding future emissions. We quantified the impact of climate change on the Italian hydropower vulnerability in terms of variation with the glacial extent ratio, i.e., the proportion of glacier area over the total area of the basin. Our work considers a medium-term perspective and shows that in catchments where this ratio is currently greater than 10%, run-of-the-river systems are more exposed to the impacts of climate change.

The three novel contributions of this paper are *(a)* that it extensively assesses the impacts of climate change on run-of-the-river systems in ice- and snow-dominated contexts; run-of-the-river systems have been less investigated than storage hydropower and comprehensive analyses and guidelines for decision-makers are therefore lacking; *(b)* that it quantifies the vulnerability of run-of-the-river systems as a function of the current glacier area of the basin, which allows one to easily generalize these results in other regions; from this standpoint, an important results regards the different fate of systems built in areas where glaciers represent less (or more) than 10% of total basin area; *(c)* to our knowledge, that it represents the first Alpine-scale study of future perspectives of run-of-the-river systems in Italy, a country where hydropower represents about 15.6% of national energetic production [52]. The study is organized as follows: Section 2 describes the study area and the data used. Methods are presented in Section 3. Section 4 evaluates the model, while results obtained through the climate scenarios are presented in Section 5. Section 6 concludes and gives some outlooks for future works.

2. Case study

The analyzed sample covers about 8% of the hydropower plants associated to large dams in Italy and 13% of those used for energy production (in Italy, a dam is classified as “large” if dam height exceeds 15 m or the reservoir capacity is larger than 10^6 m^3). The plants

Table 1
Regional characteristics of the dams analyzed (average across all dams in the region). Q_{1000} is the 1000-year flood quantile, Qd_max is the maximum flow rate from spillways.

Region	Number of dams	Maximum water level (m.a.s.l.)	Dam height (m)	Reservoir storage (10^6 m^3)	Catchment area (Km^2)	Q_{1000} (m^3/s)	Qd_max (m^3/s)
Piemonte	13	1786.86	43.85	13.21	33.1	286	8.26
Valle d’Aosta	5	2043	83.6	28.78	48.45	379	7.96
Lombardia	12	1715.44	69.41	21.55	32	256.90	24.86
Trentino	11	1489.16	59.27	27.83	135.28	532.28	12.42
Veneto	1	855.25	42	1.4	324.14	937	10

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