Review

Water Resources Management under Climate Change: A Review

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Abstract: Climate change affects water resources through the decrease of rainfall and the increase in temperatures and evapotranspiration. An indirect impact of climate change is also the increase of water uses by human activities. In this review, 320 papers were retrieved, of which 134 spanning five continents impacts and solutions to be used to better understand the effects of climate change on water resources, ecosystems, human health, security and socio-economic aspects were selected. Here, suggestions and proposals by scientists from around the world towards solutions, tips and ideas to deal with climate change and the best solutions for future water management were presented. The main solutions highlighted concern integrated water resources management, political direction, policies, increase in knowledge and new technologies. Furthermore, most of the papers analyzed underline that water resources management needs to incorporate protection and restoration of ecosystems and their services. Nature-based solutions need to be the starting point of new scientific and innovative ways to deal with climate change and towards future climate adaptation. In this complex evolution of the water resource, where is the management of the water resource in Italy going?

Keywords: Climate change; integrated water research management; water resources

1. Introduction

Since the early '90s, the Intergovernmental Panel on Climate Change (IPCC) identified an anthropogenic effect on climate that caused catastrophic changes at global level (such as temperature and sea level rises, ocean acidification, etc.) [1,2]. The new models developed in this period, started to incorporate the potential climate effects of human activities including the increase in sulfate aerosols and in the stratospheric ozone. In addition, a better definition in the natural variability of the climate system was developed [1,2]. Considering inland waters and their catchments, indirect climate change impacts can be present, with positive and negative effects on the amount of precipitations, the total riverine runoff, snow-fall and snowpack accumulation, evapotranspiration, lake levels and connecting channel flows reductions [3,4].

The first examination on climate change and on the consequences on freshwater resources availability conveyed there was an apparent increase in frequency of drought periods, mainly in summer, and probably these were a consequence of climate change [5,6].

Anthropogenic climate change is expected to have significant impacts on global freshwater resources. These impacts include increased evapotranspiration, resulting from higher temperatures, as well as a likely increase in the frequency and intensity of droughts, with reduction of snowpack and changes in the timing of spring runoff. In snowmelt-dominated river systems, higher winter temperatures resulted in reduced snowpack accumulation and lower snowmelt contribution to river discharge during summer [7]. As a result, climate change affects water supply, resulting in damage to infrastructures due to floods, water scarcity related to decreasing rainfall and increasing demand, sanitation services related to declining water quality, and the distribution of water resources.

Moreover, climate change affects soil moisture, groundwater recharge and frequency of flood or drought events and groundwater level in different areas. Studies on the socio-economic impacts of climate change, based on future scenarios and uncertainties assessment, highlighted: 1) the timing, magnitude and nature of climate change; 2) the ability of ecosystems to adapt either naturally or through managed intervention to the change in climate; 3) the future increase in population and economic activities have impacts on natural resources; 4) how society adapts through the logical responses of individuals, businesses, policy changes and security [8,9]. Freshwater security, in particular, concerns the capacity of water of produce and destroy, the economic, social, human health and ecosystem aspects [10]. Indeed, climate change affect rainfall quantity, increasing the precipitation variability with catastrophic consequences on groundwater recharge [11,12], rivers flow, water resource availability, agricultural production and economic growth in several countries [13,14,15]. Therefore, climate change combined with intensive human activities caused significant changes in precipitation and streamflow amounts worldwide [16].

In the era of climatic changes, it is clear that the management approach should also be changed, and the knowledge of the trend of rainfall temporal changes, population and storage should be at the base of the water management: the storage trend evolves in an opposite way to the rainfall gradient [6]. Several studies highlighted a certain amount of climate change is inevitable and the efforts and the challenges should be towards adaptations strategies. Some of these strategies should include changes in behavior, technological solutions, changes and improvements in laws and policies, and in water resources management [17,14]. The assessment of the availability of freshwater resources in the context of future national requirements and expected impacts of climate change and its variability is critical for national and regional long-term development strategies and suitable development [8,18]. Physical water shortage, or lack of water, probably will not be extensive, but, instead, the failure to meet multi-purpose water demands (or needs) will cause a profound water crisis due to climate change [7].

Over time, several solutions were proposed to counteract or to adapt to climate changes: such as integration of measures of climate resilience through water safety plans and water resources management, strictly connected with policy prescriptions and new technological solutions (e.g., wastewater treatment, pumping efficiency, renewable sources) [19]. Therefore, it seemed likely that adaptive management, integrated freshwater resources management, social learning and resilience thinking, have to be the new paradigms related to the political, institutional practices and national-international laws [20].

Thereafter, to evaluate the water resources and the water resources management a particular concept has been introduced: the Terrestrial Water Storage (TWS), a natural or manmade water storage that represents the freshwater global resource availability, both surface and ground waters, strictly linked to droughts, floods and sea level changes. It represents all the natural and artificial water storage present on the earth's surface, subsurface and underground, such as soil moisture, root zone, groundwater, snow, ice, water stored in vegetation, river and lake, reservoirs, ponds. The TWS is thus the capacity given by lakes, rivers, groundwater, soil moisture, glaciers, canopy water storage, to balance hydrological cycle, ecological, environmental and socio-economic aspects [21]. Recently, the Gravity Recovery and Climate Experiment model (GRACE) allowed to evaluate water resources, drought and floods phenomena and above all the impact of human activities on the water cycle such as ground-water depletion [22].

Different adaptation measures have been under study: increasing water supply, reducing demand through water saving, or with infrastructure as groundwater artificial recharge (water spread or impound on the land surface to allow infiltration and percolation to the aquifer or injecting directly water into the aquifer using wells), increasing water conservation efforts (through rain water harvesting, ponds, lakes, canals digging, water reservoirs expanding, and installing rain water catching ducts and filtration systems on buildings), with lining kilometers of unpaved canals, land-use changes, crop conversion

[7]. The increase of water storage capacity would seem to be the most viable solution: it could increase agricultural and economic productivity, contributing also to hydro-power generation and providing water supply to commercial and industrial enterprises. This solution has strong multi-tasking roles contributing to poverty reduction, sustainable development and adaptation to climate change [13].

The adaptation to climate change needs to be dynamic, and it is necessary to consider the socio-political contest, the biodiversity and the ecosystem services into integrated development-oriented processes [23].

In this paper, we analyze the effects of climate change as increase of evapotranspiration, of annual runoff, of water resources variability, in temperature and in longer drought periods and in the total number of extreme events with decreasing snowpack accumulation, with consequences on agriculture, socio-economic development, biodiversity and the ecosystem services in each continent. An in-depth bibliographic research in support is reported in the supplementary material (Tabel 1S) divided by country and topic.

The present overview aims 1) to summarize the effect of climate change on freshwater resource availability worldwide, and 2) to understand what kind of responses government are taking across countries, 3) to highlight the impact of different water management solutions on fields such as economy, society and nature to find strategies and smarter solutions which consider also the cost-benefit ratio and environmental aspects, and 4) to find out and offer to Italian policy makers possible appropriate solutions already applied in other countries to address water resource management challenges under climate change effect.

2. Materials and Methods

A total of 320 papers were retrieved from the internet using Google and Google scholar search engines in two steps.

The first search step was focused on climate change and its evolution in time and space analyzing papers from 1990 to 2022 and was performed using long-tail keywords involving more than a single word, namely "Climate change", then "Effects of climate change" then "Climate change and water resource".

The second step focused on water research management and on solution to water scarcity, water multiple uses, groundwater and water for ecosystems, considered papers from 2000 to 2022 to find the most recent research on climate change impacts and on smarter solutions to manage water resources, and was performed using the keywords "Water research management" then "Climate change and water storage" then "Water storage".

We retrieved 160 references for each step including scientific papers, books, memorandum, and grey literature of the collected references we only considered papers written in English, published in indexed international scientific journals, and fully related with the topics of interest. The exclusion criteria leaded to keep 134 relevant papers.

3. Results

The papers on climate change impacts on water resources are the most common and represent the 39.4% of the papers analyzed, while papers dealing with climate change impacts on biological aspects (17%), and climate change modelling (12.5%) are of second in number. Other papers are represented by percentages lower than 5% and include economical aspect of climate change effects, climate change related to medicine and health, climate change impacts on tourism, on the frequency of natural hazards, geological impacts, and sociological aspects.

For the second step search the overall results showed that papers dealing with water resource management are the most common, representing 47.3% of the analyzed papers. Less frequent are papers dealing with storage aimed to use solar energy or hydro-power generation production (12%), water quality status and chemical aspects related to water treatments for safe drinking water (10%). Papers on biological, ecological and

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microbiological carbon storage, or biological treatment of drinking water, modelling of changes in water availability, climate change impacts on global atmospheric circulation, and economical effects of water availability are uncommon (<10%).

In a second run, the analyses considered both the distribution of papers per continent (Table 1), and the solutions or proposal related to climate change or the adaptation to it, resulted from different Country in each Continent (Figure 1). In the continent list, we added two elements: “More Countries” which includes papers whose studies referred to the effects of climate change on water resources and the potential solutions in more than one country or Continent, and “No country” representing papers dealing with climate change in general, without specific relation to countries or continents.

Table 1. Number of papers per country. Middle East includes Bahrain, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Saudi Arabia, Qatar, Syria, United Arab Emirates, Yemen. No country: not geotargeted general aspects.

Continent and countries	No. papers
North America and Canada	21
South America	3
northern Europe and UK	11
central Europe	3
southern Europe	8
Africa	8
Asia	23
Australia	3
Middle East or Saudi Arabia only	3
China and Korea	6
India	6
Central Asia or Himalayan region only	8
More Countries	47
No country	7

Most of the selected papers (35.1%) are targeted to multiple countries debating the climate change effect across Asia and Eastern Europe or in developing countries or into arid, alpine or glacier zones. In the Americas and in Asia, massive research activity was devoted on climate change effects on water resources, water management, groundwaters, social, economic and environmental aspects (17.9% and 17.2%, respectively). In particular, 62.5% of the papers targeted on the Americas debated on impacts, effects and solutions concerning the United States, and 21.7% targeted on Asia addressed climate change effects on water resource management in China and India. Europe, is the third most referred continent, showing 16.4% of the papers on climate change impacts on agricultural and economic aspects, introducing proposals for shared legislations and management planning activities. Papers related to Africa only represent 6% of the total production, equally distributed between North and South Africa, and they mainly debate on changing in water resources and on social and political implications. Conversely, papers referring to Australia (2.2%) covered topics such as future climatic change scenarios and expected impacts on water resource management.

The selected papers, in addition to address climate change issues on water resources, also propose solutions to achieve sustainable water resource management (Figure 1). Solutions frequently include both reservoirs and TWS, or include political directions and popular participation in politics, or enhanced knowledge and groundwater management. Groundwater management is sometimes presented as the universal solution to achieve an integrated water resources management, while the enhanced knowledge is seen as an investment bringing remarkable improvements to any other addressed solution.

Natural Storage and Nature Based Solutions are viewed as innovative solutions and are therefore little treated and considered as a separate topic.

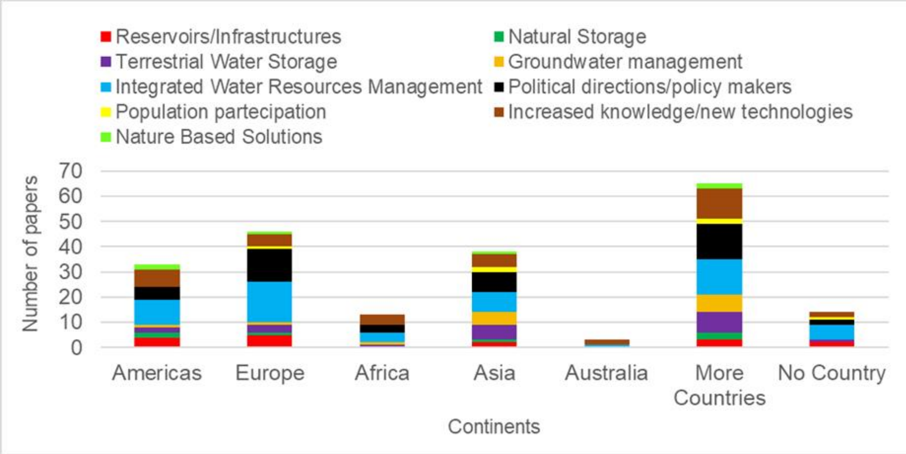

Figure 1. Solutions proposed to adapt or deal with climate change, by continents.

In general, the more frequent proposal is based on an Integrated Water Resources Management (27.8%), followed by political directions or decisions (21.2%), and by enhanced knowledge or new technologies (17.5%). Innovative solutions are poorly represented, therefore Terrestrial Water Storage, reservoirs/infrastructures, groundwater management are addressed only in less than 10% of the papers, and natural storage, popular participation and Nature Based Solution are even less considered (<5%).

Among the proposed solutions, the Integrated Water Resources Management (IWRM) represents a new approach to manage the water resources including all the water-related components such as ecosystems, natural resources, social and economic aspects, land uses, agriculture, drinking water, water quality for sustainable development, human health and safety, and high-quality ecosystem services derived from vital ecosystems. This means that the traditional fragmentary approach is overcome by a more holistic and coordinated development to water management with the ultimate purpose of maximizing the resulting economic and social well-being, supporting equity and without compromising the sustainability of ecosystems.

Solutions related to reservoirs are often associated with smart water technologies and infrastructures, rather than building more reservoirs, in particular enlarging already existing reservoirs with volume optimization and/or improving their management and their distribution network. Thus, new technologies become crucial to improve irrigation distribution and water use efficiency, by acting also on the water demand, to monitor and prevent pollution, to improve water quality, to fight diseases through water sanitation, to desalinate seawater for water reuse, and gain importance in recent years in countries under water scarcity.

Lastly, Nature Based Solutions include strategies, actions, interventions in support of nature that provide environmental services and socio-economic benefits allowing an increased resilience of the environment in which we live. Increasing the sustainability of urban systems, the recovery of degraded ecosystems, the implementation of climate change adaptive and mitigation interventions and the risk management improvement and the resilience implementation, include also actions to protect, manage or requalify ecosystems in a sustainable way which provide benefits to human well-being and biodiversity. All this cannot be achieved without an enhancement of the public knowledge on the relationships between land use and water resources availability, on climate change trend and future scenarios thanks to new modelling or through time series analyses, on climate change effects on ecosystems, their sensitivity and response to climate change, on the need to have more publicly available and shareable hydrological data.

In Europe, Asia and More Countries, all the solution analyzed (Reservoirs/Infrastructures, Terrestrial Water Storage, Integrated Water Resources Management, Population participation, Nature Based Solution, Natural Storage, Groundwater management, Political directions/policy makers, Increase knowledge/new technologies) are considered. In the Americas, "Population participation" and "Groundwater management" are not considered as individual solutions, but they are included in the "Integrated Water Resources Management" representing the 19% of all the papers, versus 27% in Europe, 13.6% in Asia, and 7% in Africa.

In Africa, the analyses performed are quite comprehensive including "Terrestrial Water Storage", "Groundwater management", "Integrated Water Resources Management", Political directions/policy makers", "Increased knowledge/new technologies" (representing <10% of the total amount of papers).

In Australia we only found papers dealing with "Integrated Water Resources Management" and "Increased knowledge/new technologies".

In Asia suggested solutions included "Reservoirs/Infrastructures" (5.3%), "Terrestrial Water Storage" (15.8%), "Groundwater management" (13.2%), "Political directions/policy makers" (21%), "Population participation" (5.3%), "Increased knowledge/new technologies" (13.2%), "Nature Based Solutions" (2.6%).

Clearly, countries historically experiencing water scarcity (such as in Africa and Asia), the more efficient way to manage water is to distribute water in larger areas through artificial or natural canals (thinking about Groundwater management or Terrestrial Water Storage), and the involvement of the public and of stakeholders in decision making on the water resource management process.

In all countries, Integrated Water Resources Management and Increase knowledge/new technologies (since 2000 and 2004) are recognized as the more effective and efficient solutions. Increased knowledge is pivotal to implement the awareness on the impact of climate change on water resources and on ecosystem services, with cascading effects also on social and economic aspects. The increase in knowledge will also contribute to understanding that Integrated Water Resources Management can be key solutions to tackle climate change and to be more resilient to it.

Nature Based Solutions appears as a topic in 2009 in United Kingdom and later in 2018 in China, 2019 and 2021 in the United States and in 2020 applied into More Countries. Nature Based Solutions represents innovative solutions, namely the right way to solve the water resource management to preserve the human future. In Italy the solutions suggested are different, with diverse directions: Integrated Water Resources Management, Political directions, Natural Storage and Reservoirs.

4. Discussion

Generally, the studies on climate refer to the average long-term changes over the whole planet and to climate variability as model system. In this way, a complete view of climate change effects on biological assemblages and human society cannot be reached. These impacts are significantly underestimated, and little considered as costs for the population as increasing food insecurity and pest disease [24], streams, groundwater and lakes water quality [25,26].

For this reason, we focused on studies describing scientifically and technically feasible solutions to better address primarily climate change and its effects on water resources, but also on ecosystems, socio-economic aspects, health and food security. The whole list of references is reported in the supplementary material (Table 1S). Furthermore, we provided a broad panoramic view of several forms of managing water resources in the world so as to offer scientific bases for future political and social decisions that the ministries and the Italian Government will have to take in the field of water resources.

Several papers [27,28,15] highlighted that the construction of new large dams in industrialized countries is not feasible due to the lack of adequate sites and of the legislation for environmental sustainability. Large dams have social and economic benefits but, at the same time, negative environmental and social impacts [13].

Therefore, it is proposed to improve the efficacy of reservoirs using water storage solutions based on auxiliary infrastructures, such as the height elevation of an existing dam and the aquifer recharge system based on the artificial recharge of groundwater.

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Other possible Natural Storage for water can be natural wetlands, soil moisture, groundwater aquifers, ponds and small tanks [13]. The last one, represent a water supply solution in developing countries, even if their use for drinking water may create quality problems [29].

Other papers show the importance of increasing Groundwater reservoir capacity in local aquifer [30], to manage aquifers as natural storage reservoirs preventing evaporation losses and ecosystem impacts related to the presence of large reservoirs [31].

Groundwater management must consider groundwater and its relationships with surface water, in order to reduce human vulnerability to climate change, maintaining or increasing water storage capacity (natural and artificial) [32]. These different water supplies can have different origins, with different annual variability and availability, and need to integrate a large number of demands, supply sources and to answer to different drought periods, and purposes such as an increase of water for ecosystem health [33].

Increased knowledge and new technologies can make groundwater recharge more efficient, or support the increase in water storage, for example using biodegradable hydrogel materials [34].

In addition, remote sensing can also be used to map the elevations of surface waters for deriving changes in water storage (lakes, reservoirs, wetlands) and trends in major rivers flows [35] to give indication for improved water management.

New technologies can deal with water scarcity, solicits deep research and modelling water quality, water uses, irrigation management to improve efficiency, waste and saline waters treatments, changes of agricultural practices or introduction of new cultivars to minimize the negative effects on crop [36], on human health and the environment due to overirrigation and salt intrusion [37].

The above-described technical solutions can help in improving resilience to water shortage, but it becomes evident that climate change emphasizes the urgent need of a new paradigm to the management of water resources, and of goal-oriented management plans with special attention to mitigation and adaptation strategies [38].

Water Resource Management with Integrated strategies needs to be implemented and supported from a holistic point of view with different adaptation strategy such as: water storage and green infrastructures, agricultural practices, water governance and policies, disaster risk reduction, economic diversification [39], distribution efficiency, leakage control, pressure management and influencing demand. An Integrated Water Resources Management also has the purpose to avoid the degradation of natural resources and ecosystems, to obtain a sustainable development with long-term productivity for the economic growth and in support of ecosystem services. The management plan should also take in account regional differences because each country has its own characteristics and issues to deal with such as coastal and inland areas, island, or desert regions [40].

However, Integrated Water Resources Management is also a political process of decision making [41], that included the four pillars of sustainability: social, economic, environmental, and institutional areas, and must consider physical, biological, chemical, socioeconomic aspects and their relationships [42].

Political direction and policy makers have to address mitigation strategies to minimize the impacts of climate change, and adaptation actions to look at how to reduce the negative effects that climate change imposes and how to exploit the opportunities that arise.

Mitigation strategies balancing global water availability and water demand can reduce the vulnerability of people (at risk for poor health), of society and of ecosystem services [43]. Adaptation measures should incorporate climate considerations into long-term planning and management, and monitoring and advanced modelling to reduce waste, to use and reuse water more efficiently for protecting and restoring biodiversity and natural habitats [26], reducing demands, increase the amount of water expanding reservoir size, reducing water transport outside the catchment, and increasing pumping rate to the reservoir [44].

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Therefore, only considering a Population participatory approach to planning and management of water resources, it is possible to minimize the impact and to improve our resiliency to climate change [45]. This is also fulfilled to avoid that rural people, above all in the less-developed countries, remain excluded from decisions concerning natural resources [46]. A bottom-up assessments of vulnerability hold promise as a means of responding to local priorities and complexities [23].

Finally, recent studies [47] on Nature Based Solutions on natural and semi-natural ecosystems show decreasing climate change impacts and supply support to people adaptation [48]. Protected, restored and well-managed natural or semi-natural ecosystems have positive effects on the local economy, supporting the public adaptation to climate change and creating climate resilient communities. An example of a new strategy to solve water management issues in urban context where rapid urbanization, waterlogging, water pollution, ecosystem degradation has caused severe problems, is the Sponge City [49]. This is a holistic integrated urban water management approach using NBS, a starting point for new scientific research to deal with climate change in an innovative way.

A further example of NBS such as natural water retention ponds were developed as a solution to the assessment of water management in agriculture [50]. Ponds showed positive effects on the agricultural landscape, the water availability and on the environmental quality. The presence of ponds increases the water availability for irrigation during the dry season, adding secondary economic benefits improving the product quality under climate change scenario.

Therefore, considering what emerged from the analysis of the 134 papers, we can indicate practicable solutions to be adapted to the Italian context. Considering the climate features of the Italian territory, nature-based solutions are the more effective to deal with water scarcity and floods events. The possibility to define floodplain areas or ponds along rivers so as to distribute the water resource as much as possible, can help to storage water when abundant and to be used when scarce. Another effective solution is to consider groundwater and groundwater management to use as distributed storage, improving infiltration. The political direction towards Integrated Water Resources Management is an important element with whom to define the future actions and solutions to be taken at the government level, to deal with climate change and to preserve ecosystems services, biodiversity and our future.

5. Conclusions

Worldwide, due to the increase in population and in water demand for human purposes (i.e. agriculture, industry, hydro-power generation, tourism), the water crisis is a problem even in those areas characterized by high precipitation amount. In some countries, drought and water scarcity are characteristic, affecting the population distribution and causing devastating problems due to the consequences they have on populations well-being and health. Therefore, it becomes crucial to highlight solutions, methods and approaches to better respond in a sustainable way to water scarcity, to food security and health, to ecosystem and biodiversity protection in support of governments and their political decisions.

Water resources management under climate change is a complex issue. Across the world, climate change effects and impacts on water resources have different consequences on the environmental, social and economic aspects. Scientists from different countries suggested several strategies and solutions according to the physical, morphological, social and political characteristics of their territories, but all together they agree that integrated water resources management, political and planning process, increasing knowledge and applying new technologies are the best approaches to deal with the problem of water resource sustainability. Most of the papers we collected also highlight that the management of water resources must take into account not only the economic and social point of view but also, or above all, ecosystems and their services. Climate change and the lower availability of water resources require a radical change in the management of water resources where ecosystems and their services must be placed at the core of the system. Only by respecting the recharging capability of the earth's natural resources we will have the possibility of a sustainable and long-lasting future. That is even more true regarding Italian natural resources, water and biodiversity, where only a new enlightened vision of territorial planning could be the solution to water resource management.

Supplementary Materials: It is submitted along with the manuscript. Table 1S. List of references analysed divided per Country, Topic, and solutions proposed.

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