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Opinion

The Recharge Channels of the Sierra Nevada Range (Spain) and the Peruvian Andes as Ancient Nature-Based Solutions for the Ecological Transition

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Abstract: Nature-Based Solutions for Integrated Water Resources Management (NbS-IWRM) involve natural, or nature-mimicking, processes used to improve water availability in quantity and quality sustainably, reduce the risks of water-related disasters, enhance adaptation to climate change and increase both biodiversity and the social-ecological system's resilience. United Nations and the European Commission promote their research as a cornerstone in the changeover to the Ecological Transition. In the Sierra Nevada range (Spain) and the Andean Cordillera, there is a paradigmatic and ancestral example of NbS-IWRM known as "careo channels" and "amunas", respectively. They recharge slope aquifers in mountain areas and consist of an extensive network of channels that infiltrate the runoff water generated during the snow-thawing and rainy season into the upper parts of the slopes. The passage of water through the aquifers in the slope is used to regulate the water resources of the mountain areas and thus ensure the duration of water availability for the downstream local population and generate multiple ecosystem services. This form of water management is known as Water Sowing and Harvesting (WS&H). As shown in this work, it is a living example of a resilience and climate change adaptation tool that can be qualified as a nature-based solution.

Keywords: careo; amuna; aquifer recharge; nature based solution; water resources management; ecological transition

1. Introduction

Water is an irreplaceable resource for life and human development on the planet. The 2030 Agenda for Sustainable Development, adopted by the United Nations General Assembly, underlines the obligation to ensure the availability and sustainable management of water for all [1]. Furthermore, sustainable water resource management is a guiding principle within the European Union's efforts to achieve an ecological transition towards a circular economy. Sustainable water management depends on water availability and thus on the rate of water renewal, which is marked by exogenous factors (e.g., the hydrological cycle) and to whose changes it is necessary to adapt [2]. Otherwise, the unsustainable use of water resources in economic activities may jeopardize our security and, paradoxically, the economic development it is intended to achieve. Therefore, it is necessary to manage water resources sustainably with solutions that involve their protection while safeguarding the biodiversity of dependent ecosystems and making them more resilient, thus improving human well-being.

Nature-based solutions are "solutions to challenges facing society that are inspired and supported by nature, are cost-effective, provide environmental, social and economic benefits, and help build resilience" [3]. Some solutions can be found among traditional water management practices developed by local communities in drylands (e.g., the inhabitants of the Alpujarras region on the slopes of the Sierra Nevada at the end of the Early Medieval Period [4–6], or the Chavín and Wari pre-Inca cultures in Peru [7]). Such practices aim to ensure sustainable access to water resources in times of low availability and high demand caused by climate and social changes [8,9]. Besides, these practices boost biodiversity conservation [10–14] and the recognition of rural communities' cultural identity and role as custodians of the land [11,15,16]. However, the functioning of many of these water management systems is threatened by globalization and or concentration in urban areas into which people are forced to migrate from rural communities. The reallocation of such people in urban areas may generate a significant impact on both the quantity and quality of water resources in such zones, which are typically reflected in (1) water shortages and (2) water quality issues because of pollution, thus aggravating both intensity and frequency of such water shortages. Nevertheless, the impact of people's migration on water resources is not limited to the urban zones. In rural areas, the abandonment of practices may result in the loss of traditional knowledge systems transmitted from generation to generation. To limit such impact at least in origin, it is essential to protect this knowledge from oblivion, as it provides age-old solutions for sustainable management of water resources to the recurrent problem of water scarcity, even in the most adverse social and climatic circumstances [4,5,17,18].

We present a traditional water management system that uses recharge channels for sowing water in mountain aquifers to be harvested later on downstream, for domestic supply and irrigation. The maintenance of such a system whose maintenance may help in the ecological transition. This highly efficient system [19,20] was developed independently by local communities south of the southeast of the Iberian Peninsula and in the Andes [8,21] to solve problems regarding scarcity. This paper describes the system functioning as a Nature-based Solution for Integrated Water Resources Management (NbS-IWRM) and postulates it as an adaptation measure to climate change.

2. Recharge Channels in Mountain Zones as NbS-IWRM for the Ecological Transition

The ecological transition refers to the process by which humans incorporate nature into society [22]. More recently, in the light of global change, it has developed into a broad set of objectives that seek the transformation of the energy, industrial, and agri-food sector [23,24] to adjust the demand of natural resources derived from human activity to the availability and production capacity of such natural resources. Its implementation seeks to curb the environmental crises threatening humanity's journey on Planet Earth.

Moreover, the European Green Deal, which is assumed as the "new growth strategy" for the European Union (EU), is developed using the ecological transition as one of the main drivers [25,26]. Water resource management is one of the cornerstones, both for the conservation of the environment and as a driver of the circular economy [2]. The sustainable management of water resources plays a crucial role in this ecological transition towards a "green" economy within the EU, and elsewhere. The quest for a society that is coexisting with nature without compromising our future abilities, while balancing the needs of a steadily increasing world economy, strongly depends on whether we will be able to adapt to the changes in the water cycle following climate change [27]. The ecological transition in the EU has obliged to strengthen coordination across the board and integrate all social sectors. All this is to change the management and sustainable use of land and water resources and fight desertification, drought, and non-recoverable resource depletion. This action is critical in the pan-Mediterranean area, where water resource availability is decreasing alarmingly [28].

Integrated water resource management (IWRM) is a concept that emerged in the UN's Mar del Plata conference of 1977 and was defined as a method to provide potable water and sanitation facilities to all and to accelerate political will and investment in the water sector. The transformations needed to implement such a concept were broadly envisaged in Mar del Plata and further elaborated, along with the IWRM concept itself, in Dublin, Rio, The Hague, Bonn Johannesburg, and Kyoto [29]. Currently, IWRM is defined as the method to promote the coordinated development and management of water, land, and related resources to maximize the resulting economic and social welfare equitably without compromising the sustainability of vital ecosystems [30]. This concept has become a paradigm for the UN 2030 Agenda for Sustainable Development, as Target 6.5 of the Sustainable Development Goals calls for the implementation of IWRM at all levels by 2030. IMRW is being embraced by many developed developing and transitional countries [31,32] This paradigm and the climate change context have raised interest among water managers, planners, and stakeholders in the so-called Nature-based Solutions for Water Integrated Resources Management (NbS-IWRM) [33]. This concept consists of the application of actions that mimic natural processes to improve water availability in quantity and quality, reduce water-related disaster risks, enhance adaptation to climate change, and increase socio-ecosystem resilience [34]. Contrary to this, the modern irrigation development where rainfall cannot cover crop growth needs has evolved from the introduction of new physical structures and equipment to a new scheme that looks for a transformation of the management of irrigation water resources, to improve the efficiency and productivity of the resources and services provided to the farmers [35]. This includes the Mediterranean region and other arid and semiarid zones. Unfortunately, this concept of modernization does not respond to the latest challenges of society, which include the depletion of resources, deterioration of the environment, population growth, and climate change [14]. Being aware of this problem, the United Nations Food and Agricultural Organization, the European Commission, and the Spanish Ministry for Ecological Transition and Demographic Challenge, among others, are promoting research on NbS-IWRM [3,36–38]. The Spanish Ministry for Ecological Transition joined World Water Day 2021 with an event entitled "Nature-based solutions for water management in Spain: challenges and opportunities". At this event, the Secretary of State for the Environment underlined the need to look for nature-based solutions to improve the use of water resources by conserving and protecting the headwaters of river basins, and/or by regulating natural flows [39]. Such nature-based solutions can complement conventional infrastructures and reduce the overall costs of water quantity and quality services.

Reported examples of NbS-IWRM applications around the world are scarce and relatively recent. However, in some mountain ranges, such as the Sierra Nevada (Spain) and the Andes (South America), there are good examples of conceivable NbS-IWRM based on the traditional knowledge of local populations [8,40]. The concept of Water Sowing and Harvesting (WS&H) was coined in these areas. WS&H describes the process by which surface runoff water from both snowmelt and rainfall is collected and infiltrated (sown) through a system of channels dug in the upper parts of the mountain basins (Figures 1 and 2) [19,41,42], to be recovered (harvested) elsewhere, sometime later, as a groundwater discharge, for irrigation or domestic use. The delay is due to the slow velocity of groundwater through permeable materials. Such aquifer recharge channels are locally known as "careo channels" in the Sierra Nevada range (Spain) and "amunas" in the Andean Cordillera (South America). The amunas are almost identical to the careo recharge channels in Spain, although developed independently by the pre-Inca cultures in Peru, Chavín initially, and Wari later [7]. The water that is not sown in the area leaves it and goes to the sea or evaporates in flat land downstream where the water cannot be recovered.

Figure 1. Careo recharge channel in the Bérchules watershed, located at Spain's southern slopes of the Sierra Nevada range (Photo: Sergio Martos-Rosillo).

Figure 2. Example of an area where water flowing through a careo channel is released for infiltration. The infiltration zone is 6 km from the beginning of the channel. When the photograph was taken (April 2021), a flow rate of 250 L/s infiltrated. The seepage water generates pastures in the neighboring infiltration zones. (Photo: Blas Ramos).

The careo recharge system has at least three functions:

(i) delaying the transit time of water through the ground to maintain the flow of rivers and springs at lower altitudes during the summers, when radiation and temperature favor crop growth, but rainfall is scarce, and the demand for drinking water increases,
(ii) watering the vegetation on the mountain slopes (Figure 2), favoring the growth of pastures, and enhancing biodiversity, and
(iii) improving water quality by diluting the salinity of evapo-concentrated groundwater and filtering runoff water. Therefore, the spatio-temporal regulation of water resources

for different uses and the associated ecosystem services qualifies this WS&H "green infrastructure" as an NbS-IWRM [43].

The importance of the careo recharge channels and their hydrological, environmental, and socio-economic services, belong to the ancestral knowledge and cultural heritage of the local population, which has kept them operational in the Southwestern Iberian Peninsula since at least the 11th century [4,5]. However, it is only very recently that water and environmental authorities have recognized their importance. The water authorities of the Guadalquivir River basin and of the southern basin of Andalucia (the two basins where recharge channels play an important regulating role), the provincial administration of Granada, the Sierra Nevada National and Natural Parks, and the Association of Historical and Traditional Irrigation Communities of Andalusia have just started to address the careo system by incorporating it into their planning, maintenance, and surveillance activities. Between 2008 and 2011, the Sierra Nevada National Park and the Department of the Environment of the Regional Government of Andalusia invested 5.3 million euros through the project "Conservation of the traditional careo recharge channels of Sierra Nevada". References to the economic interest of the careo channels are also found in the 2nd Plan for the Sustainable Development of the Natural Area for the Sierra Nevada, approved in 2018 by the regional government as a part of the Natural Resources Management Plan. Furthermore, at a national level, the collaboration between water management agencies and researchers has been sought to investigate similar NbS-IWRM in Guadarrama, Gredos and Sierra Morena ranges, and the Canary Islands. Interest in the careo recharge channels has also increased internationally. Examples are (1) the Research Network "Water Sowing and Harvesting in Protected Natural Areas" (https://www.cyted.org/es/syca (accessed on 30 August 2022)), funded by the Ibero-American Programme of Science and Technologies for Development, with additional support for training activities from the INTERCOONENTA program of the Spanish Agency for International Development Cooperation, which unites 76 researchers, water, and environmental planners from eight Ibero-American countries, (2) their relevance to the Focus Group "Nature-Based Solutions for water management under climate change" of the European Innovation Partnership for Agricultural Productivity and Sustainability [44], and (3) by UNESCO's Intergovernmental Hydrological Programme as Demonstration Site in its Global Network of Ecohydrology (http://ecohydrology-ihp.org/demosites (accessed on 31 August 2022)). This action reflects the applicability of such an NbS-IWRM system in many mountain areas with similar climate conditions to those prevailing in the Sierra Nevada range [45]. Such are as the southern slopes of the Alps in France and Italy, the Dinaric Alps in Croatia, Mount Etna in Italy, the Atlas Mountains in Morocco, the Taurus Mountains in Turkey, the Lebanese Cordillera, the Sierra Nevada range in the United States, or the Andes Cordillera in South America.

3. Science to Understand Better Recharge Channels

The first scientific publications on the hydrology and hydrogeology of these ancestral water recharge systems are recent. The earliest paper by Pulido-Bosch and Sbih (1995) [41] described careo recharge channels in the southern slopes of Sierra Nevada (SE-Spain) and measured groundwater residence times from 5 to 10 days by applying dissolved lithium chloride (LiCl) to the water flowing in the Cástaras careo channel, which is located in the Trevélez River basin. In the same basin, Oyonarte et al. (2022) [14] measured for the Busquístar channel a mean infiltration rate per unit length of channel ($\hat{q}$) of 9.32 L/s/km. In the neighboring Bérchules Basin, Martos Rosillo et al. (2019) [19] obtained a $\hat{q}$ value of 20.2 L/s/km in the Espino channel. Here, they measured infiltration rates up to 400 L/s in some channel zones. In the Peruvian Andes, Cárdenas-Panduro (2020) [46] obtained a $\hat{q}$ value of 88.7 L/s/km for the Saywapata channel. Such high $\hat{q}$ values evidence the high infiltration capacity of the recharge channel system. Analyzing the importance of the channel recharge with respect to that of the natural water cycle, Jódar et al. (2022) [20] showed that the total channel recharge in the Bérchules watershed during the hydrological year 2014–2015 was 3.66 hm^3, which is equivalent to 70% of the river water flow at the outlet of the basin (5.3 hm^3) and amounts 48% of the total aquifer recharge for this period (7.62 hm^3). They have demonstrated that this ancestral aquifer recharge system can double natural recharge rates as it increases the average and base groundwater discharge of downstream springs and the mainstream during the summer [6,20,47,48]. Yapa (2016) [21] and Martos-Rosillo et al. (2020a) [8] described similar ancestral methods of water recharge in the Americas since pre-Columbian times. In addition, Ochoa-Tocachi et al. (2019) [7] studied a 1400-year-old rainfall-runoff infiltration enhancement system in the Andes, which is based on amunas. These authors used eosine to trace the recharged water, obtaining that groundwater is held for an average of 45 days before resurfacing, and assessed the effects of this water management technique on the water supply of Lima using a rainfall-runoff model. As research results are very promising, Peruvian local water planners are encouraging the use of this green infrastructure through Mechanisms of Rewards for Ecosystem Services, which allows financing such NbS-IWRM practiced by local peasants but benefiting other downstream water users. However, the greater or lesser impact of these solutions is location-specific and therefore requires deep scientific or traditional knowledge. For instance, Somers et al. (2018) [49] measured scant recharge from recharge channels also in the Peruvian Andes, likely because the water available for recharge in their case study was only from rainfall runoff, which is available only a few days per year compared with snowmelt runoff, that may last months. Nevertheless, the hydrological parameters that control the hydrodynamic, hydrogeochemical, and isotopic responses of the slope aquifers in the Sierra Nevada and the Andes, where traditional recharge channels remain operational, are rather unknown.

The effects of these ancient groundwater recharge systems on terrestrial ecosystems are various and not fully understood. Remote sensing observations show an extension of the growing season and an increase in chlorophyll activity of vegetation in areas where the careo recharge is conducted [50–53]. However, there are no data regarding how the system contributes to increase vegetation productivity and carbon sequestration, nor to characterize its role to sustain threatened drought-intolerant species associated with the channels. Moreover, the positive or negative effects on fluvial and riparian ecosystems appear to vary, depending on the altitude of the river reach considered. Water withdrawal in the upper zone of the basin from the river to feed the recharge channels likely impacts the functioning and biodiversity in the reaches immediately downstream of the diversion site. The regulation of river flow has strong effects on the functional diversity of riparian vegetation [54,55] and aquatic communities such as amphibians and fish [56]. Ecosystem functioning (i.e., primary production, organic matter decomposition, nutrient cycling) can also be impacted by the river flow regulation, particularly in streams from semiarid regions, which are characterized by a high rainfall seasonality [57]. These alterations will worsen in Mediterranean streams as climate change proceeds as suspected (e.g., Salinas et al., 2018 [58]). In either case, there is a need to investigate the magnitude and positive or negative direction of such impacts, in terms of flow regulation as a function of the relative volume and seasonality of water withdrawal.

On the other hand, downstream reaches receiving groundwater from slope aquifers recharged by channel recharge systems could likely provide better conditions for biodiversity and ecosystem functioning and services. In these lower river reaches, groundwater inputs produce higher discharge and relatively low water temperature, improving habitat quality, particularly during summer, for many cold-stenothermal species typical of these rivers (e.g., brown trout). Nevertheless, as this groundwater has passed through slopes with agricultural use (Figure 3), it could transport nutrients (i.e., nitrogen and phosphorous) to the river, favoring eventually eutrophication. Such effects, which may have a positive and/or negative environmental impact, remain unknown. More research is needed to fully understand the behavior of recharge channel systems and their impacts on the associated downstream ecosystems.

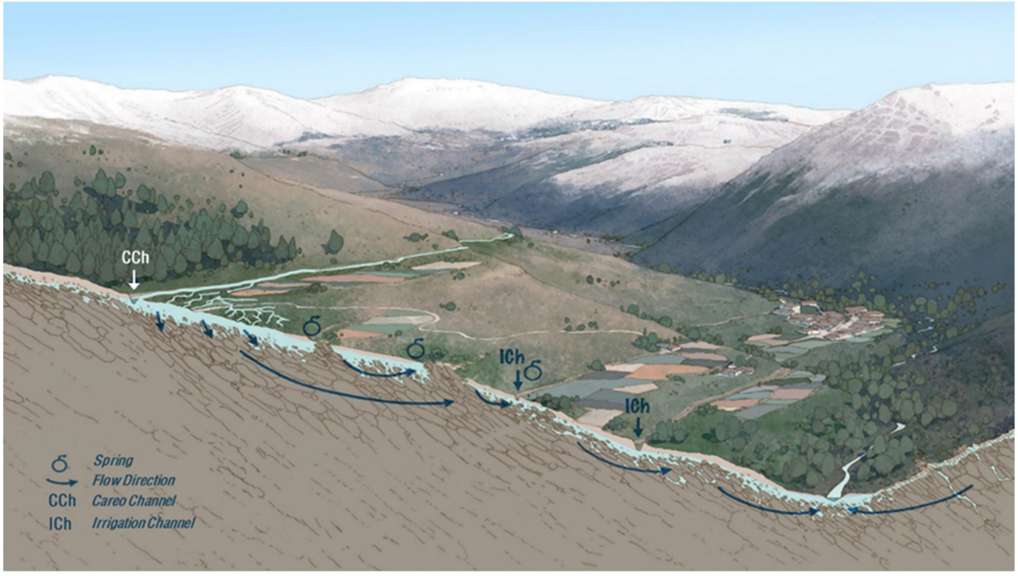

Figure 3. Conceptual scheme of hydrogeological behavior of the recharge with careo channels during the snow-melting period in an idealized watershed of Sierra Nevada (Spain). The geological substratum is made up entirely of schists, with a surface alteration zone (Author: Rocío Espín and Sergio Martos-Rosillo).

4. Current Challenges

Demographic and climate changes are threatening the provision of ecosystem services with foreseeable trade-offs that must be considered in the management of the territory's resources. One of the challenges is the exodus of the rural population and the incorporation of new stakeholders. While farmers and shepherds were the lands, water, and careo channel managers for centuries, current actors also seek conservation objectives, such as biodiversity protection, ecotourism, or freshwater provision for growing populations in the lower parts of catchments. In addition, agriculture is intensifying in some areas of the southern slopes of Sierra Nevada (i.e., the Bérchules and Mecina watersheds) in response to favorable market conditions. This may lead to increased demand for irrigation water and the claim for customary water rights, with effects on the availability of water resources similar to those reported in other regions [59,60].

Recharge channels in mountain regions have successfully overcome drastic social [4,5] and climatic changes that have occurred in the Sierra Nevada range since the Middle Ages [17,18]. Further back from as early as the 5th century in the Peruvian Andes [7], recharge channels have played an important role. According to palaeoclimatic reconstructions of the last two millennia, the period from 700 to 1200 was dry and prone to severe drought. After that, the climate became somewhat wetter (Åkesson et al., 2020 [61], and references therein), but not very different from the current climate conditions in the Andean Cordillera at the same latitude, where arid to hyperarid conditions still prevail [62]. The question is how, by delving into the hydrology and hydrogeology of these systems, valuing their ecosystem services, and understanding the effects that socio-economic changes have on traditional organizational structures, we can adapt these WS&H systems to the current context, harnessing their climate change adaptation values and ensuring the resilience that they have shown historically.

The careo channels may become an adaptation measure to climate change. Delineating their role in this regard, when implementing them in dissimilar conditions, including different (1) climate change projections, (2) forcing levels (greenhouse gas emission pathways), (3) socio-economic scenarios, and (4) management alternatives, vulnerability models may be helpful (Joyce y Janowiak, 2011 [63]). They make it possible to analyze the degree to which an ecosystem is affected by climate change and to evaluate the consequences of different adaptation strategies. This information, together with an adequate evaluation and communication of the uncertainties associated with the different scenarios, is the cornerstone for an adequate decision-making process and the implementation of the careo channels as an effective adaptation measure.

5. Conclusions

The careo recharge as NbS-IWRM may enhance biodiversity and ecosystem functioning, both terrestrial and aquatic, at the basin scale. Therefore, to understand the inner workings of the "Recharge channel-Soil-Aquifer-River" system, its social and environmental repercussions, and to maintain and replicate this NbS-IWRM system in other areas with similar characteristics, more in-depth and multidisciplinary research is needed. This research should provide information on (1) how to adapt the careo channels to the new social and climatic scenarios, (2) the hydraulic and hydrogeological variables to take into account when designing new recharge systems in other mountain areas with similar characteristics, and (3) how to maximize the ecosystem services provided. This historical water management system, based on local ecological knowledge and communal practices, in which a balance between land and water use has been attained, should become an adaptation measure to climate change, but also to build a better, more secure, and equitable future through the ecological transition path towards the objectives of the European Green Deal. This is especially important to stabilize the rural population and to preserve the environmental, hydrological, ecological, cultural, and economic conditions in mountainous areas and make compatible the roles of the local economy and "nature gardeners".

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