Integrating a hydrological model into regional water policies: co-creation of climate change dynamic adaptive policy pathways for water resources in southern Portugal

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Highlights:

- Climate change will decrease water availability in Algarve region
- One of the first studies to use dynamic adaptive policy pathways in water resources
- Involvement of stakeholders to co-design an adaptation strategy
- Usage of hydrological model to quantify effectiveness of adaptation measures
- Combine hydrological model outcomes with dynamic adaptive policy pathways
- Adapting water resources sector to climate change in Algarve will require multiple measures

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Integrating a hydrological model into regional water policies: co-creation of climate change dynamic adaptive policy pathways for water resources in southern Portugal

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Abstract

Irrigation is essential for a large part of Mediterranean agricultural systems, but scarce resources may cause conflicts between agricultural and domestic uses. These conflicts might be exacerbated by climate change, which could bring a drier climate and thus increase irrigation water demands while lowering supplies. These issues were addressed when designing a climate change adaptation plan for water resources in the Algarve region (southern Portugal), which was co-created between hydrologists and local stakeholders and policy-makers, by using the Dynamic Adaptive Policy Pathways (DAPP) approach to synthetize and communicate the results from hydrological modelling of future scenarios.

The evolution of water availability and irrigation demands for key water assets in Algarve (southern Portugal) were simulated until 2100 for climate scenarios RCP4.5 and RCP8.5, using a modified version of Thornthwaite-Mather. The results show an increase in water stress, mainly in the RCP8.5 scenario. The results and need for adaptation were discussed with local and regional decision-makers and other stakeholders, and a set of adaptation measures was agreed upon. The discussed adaptation measures were then modelled and integrated the design of tailor-made DAPP. Finally, decision-makers and stakeholders were presented with DAPP and selected the most suitable and political reliable adaptation pathway that tackles projected climate change impacts in water resources until the end of the 21st century.

Stakeholders showed a strong preference for incremental and distributed small-scale measures, including the promotion of water use efficiency and landscape water retention, to large-scale measures such as wastewater recycling or new dams. A decrease in irrigation water use for agriculture was not considered socially desirable. Desalination was considered too costly for irrigation in the short term but kept in reserve in case other measures fail to keep water supplies at an acceptable level.

Keywords: Water availability; Climate change; Dynamic Adaptive Policy Pathways; Participative process; Thornthwaite-Mather; Mediterranean
Introduction

Water availability is currently challenged by population growth and rapid urbanization, which is leading to an increase in water demand for human consumption and agriculture (Iglesias et al., 2007; Mancosu et al., 2015). In addition, climate-associated changes, such as the increase in the spatial and temporal variability of precipitation, further threatens the sustainability of water resource use (IPCC, 2014).

Climate change can act as an extra pressure factor on hydrological systems, particularly in regions which already have strong demands. One of these regions is the Mediterranean area, where agriculture accounts for up to 80% of the water consumption (EEA, 2012). Together with recent trends for lower average precipitation and seasonal changes (Casanueva et al., 2014; van den Besselaar et al., 2013), higher temperatures (Hov et al., 2013) and increased drought frequency (Hoerling et al., 2012), the water sector is already under high stress. In fact, some regions in the Mediterranean experience severe water stress throughout almost the entire year (EEA, 2018a). As a result of both climatic changes and higher population pressure, renewable water resources decreased from 2 300 to 1 800 m$^3$ per inhabitant in southern Europe between 1990 and 2015 (EEA, 2018a). In these highly stressed systems, it is expected that even small changes in water availability or demand can have relevant outcomes for vegetation growth and water supplies (Wilhite et al., 2007).

The Mediterranean area is recognized as a hotspot of climate change, with future climate models anticipating the exacerbation of the recently observed trends (Giorgi, 2006; Seneviratne et al., 2016). Hydrological models are usually used to assess the impacts of climate change scenarios on water availability, and a large number of hydrological modelling studies for the Mediterranean region has been conducted in recent years. The results of this studies generally point to a future trend of lower water availability, combined with a larger contrast between the wet and dry seasons (Bangash et al., 2013; Bussi et al., 2014; Carvalho-Santos et al., 2016; Majone et al., 2016; Mourato et al., 2015; Nunes et al., 2013, 2008; Piras et al., 2014; D. Pulido-Velazquez et al., 2015; M. Pulido-Velazquez et al., 2015; Rodriguez-Lloveras et al., 2016; Sellami et al., 2013; Serpa et al., 2015; Stefanova et al., 2015a, 2015b; Zhang et al., 2019). Some studies have also focused on the water supply infrastructure, i.e. it’s capacity to capture enough water to meet existing demands (Carvalho-Santos et al., 2017; Garrote et al., 2016; Iglesias et al., 2011; López-Moreno et al., 2014; Mereu et al., 2016; Molina-Navarro et al., 2014; Nunes et al., 2017; Stigter et al., 2014). In general, these studies have shown that increasing water demands for irrigation are likely to be accompanied by a decrease in water supplies. Moreover, the absence of adaptation measures can lead to water availability in the Mediterranean region reaching a critical level, with water inflows not being enough to meet water needs, even under a 2° warming (Bisselink et al., 2018).

Although these models possess a high potential to support the design and test of climate change adaptation measures, they have seen limited application in collaboration with local stakeholders (Melsen et al., 2018; Srinivasan et al., 2017; Stigter et al., 2014). Some reasons have been pointed out as key barriers to wider use of modelling to support decision-makers in the water sector, such as the lack of communication between agents or the uncertainty related with climatic and hydrological models (Borowski and Hare, 2007; Hare, 2011; Webley et al., 2011). Additionally, stakeholders and decision-makers often face a large variety of adaptation measures, ranging from those that attempt to reduce the current vulnerability or to improve the efficiency of the existing systems (i.e. coping and incremental approaches, respectively), to measures that require the change of fundamental attributes of a system (i.e. transformative...
adaptation) (Barros et al., 2014; Chhetri et al., 2019). In such a complex system where different measures and options reflect a wide extent of effectiveness and uncertainties, the planning of water management resources may require different and new approaches (Buurman and Babovic, 2016). Some approaches have been created to help policymakers and system designers to develop climate change adaptation measures: adaptive plans that are flexible and that can react to new information or changes to environmental conditions. In the context of climate adaptation policy-making, one relevant approach is dynamic adaptive policy pathways (Haasnoot et al., 2012; Reeder and Ranger, 2011).

The Dynamic Adaptive Policy Pathways (DAPP) approach relies on the identification of adaptation tipping points (Kwadijk et al., 2010), allowing the selection of a set of adaptation measures by timing and sequencing them, considering a pre-chosen objective (Haasnoot et al., 2013). Because adaptation emerges as a “process rather than simply as abrupt events separate from social and political processes” (Fazey et al., 2016), this approach is considered a useful tool to enlighten decision-makers regarding the intensity of future adaptations (Tanaka et al., 2015), and to build consensus among entities. Although this methodology has been applied in different adaptation contexts (Campos et al., 2016; Haasnoot et al., 2012; Kwakkel et al., 2015), there is a lack of studies and applications for drought and irrigation management.

This work was developed under project PIAAC-AMAL1, a regional adaptation plan for the Algarve region (southern Portugal), and aims to address the issue of supporting the adaptation of water resources to climate change in this Mediterranean region. To this end, an approach was designed which combined hydrological modelling and DAPP and applied together with local water managers. The approach was applied to i) assess water availability and requirements in several reservoirs throughout the 21st century, under future scenarios of moderate (RCP4.5) and high-end (RCP8.5) climate change; ii) quantify the effectiveness of available adaption measures; iii) co-create a DAPP for the region based on the magnitude of water stress and the effectiveness of adaptation measures along the 21st century; and iv) select the most suitable adaptation pathway to cope with climate change.

Methodology

Case study site: the Algarve region

The Algarve region, located in southern Portugal (Figure 1), has a heterogeneous geography, subdivided into Serra (inland mountains), Barrocal (mountain footslopes) and Litoral (coast). The Serra region overlays relatively impermeable bedrock and is characterized by a mostly natural land cover, with poor and thin soils showing a limited aptitude for forest and agriculture and with signs of erosion and desertification (CCDR-A, 2007a). The Barrocal region overlays extensive coastal aquifers, including the Querença-Silves karst, providing an easily accessible water source for irrigation. The landscape is characterized by large areas of mostly permanent crops, either irrigated (e.g. orange trees, vegetable gardens) or rainfed (e.g. carob trees, almond trees, olive trees) (CCDR-A, 2007a), whereas the Litoral region is characterized by a highly modified landscape, with the largest urban areas of Algarve and the most intensive agricultural areas (CCDR-A, 2007b, 2007a).

The climate in Algarve is characterized by a Csa climate under the Köppen-Geiger classification (see e.g. Beck et al. 2018). Annual precipitation varies considerably along with the territory, reaching the highest values in the northwestern mountainous areas (around 1500 mm.y\(^{-1}\)), progressively decreasing towards the coast and towards the East (around 500 mm.y\(^{-1}\)). The amount of annual precipitation combined with dry and hot summers and the influence of North Atlantic Oscillation make the Algarve region prone to the occurrence of moderate to extreme droughts, estimated to occur approximately every 3.6 years (Santos et al., 2010). Such extreme events are known to bear important impacts, being an example the 2005 drought that was responsible for the loss of 60% and 80% of wheat and maize production, respectively (Isendahl and Schmidt, 2006), leading to costs that exceeded 500 million Euros (Vanneuville and Werner, 2012).

Six main water reservoirs located in five basins (Bravura, Odelouca, Funcho, Odeleite and Beliche) are used to supply public distribution systems and three large-scale irrigation infrastructures (Lagos; Silves, Lagoa and Portimão (SLP); and Tavira) (Figure 1). Groundwater is used to irrigate smaller croplands; the Querença-Silves aquifer is the most relevant groundwater supply, accounting for about 35% of groundwater resources in the region (APA, 2016a). These systems can supply most water demands except during severe drought years, such as 2005.

Agriculture alone accounts for 65% of the total water consumption volume, while public supply accounts for around 30% and irrigation of golf courses for around 6% (APA, 2016b, 2016a). Wastewater is collected and treated at large coastal treatment plants, and the effluents are currently discharged into the sea; in recent years, most inland treatment plants were closed and wastewater collection systems were connected with coastal plants in an effort to improve stream water quality.

Figure 1 – Location of the main water reservoirs, the Querença-Silves aquifer and the main irrigation areas. Data source: APA (2018a), DGT (2017) and EEA (2018b)
Climate and Geographical data

Meteorological data for monthly temperature and precipitation between 1995 and 2017 was used to force the hydrological model, taken from the meteorological stations shown in Figure 1 and available in the Portuguese Water Resources Information System (SNIRH; APA, 2018b). The data was harmonized and corrected using meteorological data from E-OBS version 16, at a resolution of 0.25° (Haylock et al., 2008). Temperature values were used to calculate monthly Potential Evapotranspiration (PET) using the Hargreaves method, which for this region is well correlated with calculations using the Penman-Monteith method (Stigter et al., 2014).

Land use was retrieved from Portuguese land use and land cover maps (COS2010), which is available from the Directorate-General of Territory (DGT, 2018); while the soil map was taken from the FAO 74 dataset (FAO/UNESCO, 2018). For the topography, the Digital Elevation Model (25 m) from the European Environmental Agency was used (EEA, 2018b).

The hydrological model was assessed using data from hydrometric stations between 1995 and 2017. Monthly water inflow data to the reservoirs and irrigation water use was taken from SNIRH (APA, 2018b) for the stations shown in Figure 1, with most stations only having data for part of this period. Water recharge estimates into the Querença-Silves aquifer were taken from the calculations by Stigter et al. (2014).

Future climate change scenarios were derived from nine Regional Climate Models (RCMs) for Europe (Table 1), downscaled under the Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) (Jacob et al., 2014). These climate models were selected to match those previously selected to build the Portuguese Climate Portal (IPMA, 2018). Monthly temperature and precipitation projections were downloaded for the EUR-11 domain, both for historical simulations (from 1970 to 2005) and for future climate projections under Representative Concentration Pathway (RCP) 4.5 and 8.5 (from 2006 to 2100), at high spatial resolutions of 0.11° (=12km). RCM projections were not bias-corrected; instead, RCM bias was addressed during the hydrological modelling stage (see below).

<table>
<thead>
<tr>
<th>GCM</th>
<th>RCM</th>
<th>Driving ensemble member</th>
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<tbody>
<tr>
<td>CNRM-CERFACS-CNRM-CM5</td>
<td>CLMcom-CCLM 4-8-17</td>
<td>r1i1p1</td>
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<td>SMHI-RCA4</td>
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<td>MPI-ESM-LR</td>
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Water resources assessment under observed and climate change conditions

Water availability and demand were assessed using the Thornthwaite-Mather water balance model (Thornthwaite and Mather, 1957) as described by Stigter et al. (2014), modified to account for daily rainfall variability following Zimmermann (2006). The model calculates water balance from rainfall, PET, and soil and vegetation hydrological properties; the results include soil water content, actual evapotranspiration, surface runoff and aquifer recharge. Plant water requirements are calculated from PET and crop development stages following Allen et al. (Allen et al., 1998). Direct runoff is calculated from a statistical disaggregation of daily rainfall using Curve Numbers (Zimmermann, 2006). The remaining water is partitioned into soil storage, actual evapotranspiration and water yield; water yield is further partitioned between streamflow (in this case, baseflow) and aquifer recharge according to the underlying lithology and hydrogeology. In irrigated areas, irrigation requirements are calculated as the deficit between crop water requirements and actual evapotranspiration, using an efficiency coefficient for each irrigation area taken from the Portuguese Irrigation Information System (SIR, 2019); excess irrigation was considered as water yield and therefore also partitioned between streamflow and aquifer recharge.

The hydrological model was applied to the areas shown in Figure 1, considering:

- Five watersheds draining into reservoirs: Bravura, Odelouca, Funcho/Arade, Odeleite and Beliche. As these watersheds overlay relatively impermeable bedrock, all water yield was assumed to be streamflow and, thus, water resources available for each reservoir.
- Three irrigation infrastructures: Lagos, SLP and Tavira. Here, the model was only applied to calculate irrigation water requirements.
- The Querença-Silves aquifer. Most of the water yields were considered to be groundwater recharge (Stigter et al., 2014). In this case, both water yield and irrigation were calculated, with excess irrigation allowed to re-enter the aquifer.

The model was applied for individual land-use types inside each area. For the watersheds and aquifer, land-uses included dense shrublands, Mediterranean dryland forests, plantation forests (eucalypt and maritime pine), uncultivated lands and rainfed orchards. For the irrigated area, crops included irrigated orchards, corn, rice, vegetables, vineyards and permanent grasslands (golf courses). The model was calibrated and validated using the hydrometric and water use data described above. A full description of the calibration and validation process is available in Appendix A.

To assess climate change impacts, the model was applied using climate simulations for historical (from 1970 to 2005 – period of the historical simulations) and future (2006-2100) climate projections for each RCM shown in Table 1. The hydrological model results for each RCM, including changes to soil water content, actual evapotranspiration, surface runoff and aquifer recharge, were used to calculate monthly average anomalies of water availability and irrigation demand for three future periods: 2006-2040, 2041-2070 and 2071-2100; an ensemble monthly anomaly was taken from the median of the anomalies obtained from running all RCMs, and applied over present-day water availability and irrigation demand to calculate future scenarios for these three periods. This method follows Stefanova et al. (Stefanova et al., 2015a, 2015b), and replaces a bias-correction of the RCM results with what can, in effect, be considered as a bias correction of the hydrological model results.
To extrapolate the hydrological model results to the entire Algarve region, the water yield and irrigation requirement estimated for each land use were summarized at the average annual scale, both for present-day conditions and for future climate scenarios. The low variability across the region allowed the calculation of a single value for each land use type. These results were then used to calculate water availability and irrigation requirements outside the simulated areas shown in Figure 1. Water yield over coastal aquifers was partitioned between streamflow and groundwater recharge following the recharge rates reported in the local water resources management plan (APA, 2016a).

Water stress was evaluated using the Water Exploitation Index (WEI), which can be defined as the rate of water abstractions over water availability and is obtained as the percentage of the mean annual total demand of water with the long-term mean annual water resources (EEA, 2012). Values of the index between 0%-20% represent a situation without stress; between 21%-40% represent moderate stress; between 41%-70% represent severe stress; between 71%-100% represent extreme stress; and above 100% represents a situation of scarcity (Nunes et al., 2017; Stigter et al., 2014). In this work, water abstractions were equated with water demand, given the ease of groundwater access, and the lack of calculation of future water abstractions which would require the use of reservoir or groundwater models (see Hugman et al., 2017; Nunes et al., 2017). The above levels of water stress were instead used as indicators of the potential for future supply disruptions due to insufficient abstractions, caused by issues such as water competition or limited storage capacity (Alcamo et al., 2003). These model limitations also prevented the calculation of a monthly WEI, which was not considered important due to the large natural and artificial water storage capacity in local aquifers and reservoirs, capable of collecting most water available in the wet season for use in the dry season. The present-day WEI was estimated to be 43%.

Water demand for public supply was taken from the local water resources management plan (APA, 2016a) and assumed to be constant in the future. Water demand for agriculture was calculated from the hydrological model extrapolation for the Algarve, considering no changes in irrigated crops. This assumption results from a compromise between stakeholders expectations at the beginning of the study, since some foresee an intensification of existing irrigated areas without further expansions (e.g. farmers) (see Stigter et al., 2017), while others envision a more sustainable use of water, even if it implies a decrease in the areas of irrigated agriculture (e.g. environmental or water sector). Water availability was also calculated using the model extrapolation. Agricultural demand and water availability were calculated for present-day conditions, future climate scenarios and adaptation scenarios (see below), assuming no changes in land use.

**Stakeholder engagement, climate change adaptation and Dynamic Adaptive Policy Pathways**

More than 55 local, regional, or national institutions were involved in the study (full list of participating institutions per domain in Appendix B). These included water supply managers, technical staff from 15 of the 16 municipalities which integrate the Algarve region, as well as representatives from the regional water and agriculture management authorities, the regional public water supply utilities, and from farmers and nature conservation organizations.

The stakeholder engagement process was conducted in a total of four workshops throughout one year; the process is summarized in Figure 2. In an initial step, stakeholders were presented with scientific information concerning climate and hydrological processes, followed by an exchange of perspectives and knowledge with the modelling team regarding current and future
vulnerabilities, models’ outcomes, and adaptation options. The adaptation measures to be modeled and included in the DAPPs were selected with the stakeholders. Stakeholder engagement culminated in a final workshop where an adaptation pathway that aims to tackle water scarcity in the region was selected.

As stated above, the DAPP approach relies on the identification of adaptation tipping points. Kwadijk et al. (2010) defined tipping points in the context of DAPPs as the moment "where the magnitude of change due to climate change (…) is such that the current management strategy will no longer be able to meet the objectives". Hence, tipping points inform decision-makers when a given management strategy or policy is no longer effective and others are required (Campos et al., 2016; Haasnoot et al., 2019, 2013; Kwadijk et al., 2010). In practice, DAPPs usually emerge from the combination of modelling outcomes and experts’ opinion (Buurman and Babovic, 2016), being used to help stakeholders and policymakers to evaluate different measures and strategies, supporting the decisions over time. Hence, this approach is considered a useful tool to promote debate and awareness of future adaptation measures (Barnett et al., 2014; Bloemen et al., 2018; Tanaka et al., 2015), as it provides a tool to support stakeholders and policymakers in the identification of opportunities, no-regret actions, lock-ins, and the timing of an action, under a given environmental condition (Haasnoot et al., 2013).

The process of designing the DAPP was based on the tipping point of each of these measures, considering a previously defined adaptation objective: to ensure that future levels of water availability do not fall below the current level. For the purposes of this project, this meant that the adaptation objective was to meet water demands without exceeding current water exploitation. This adaptation objective was first suggested by the research team after some discussions between stakeholders, and later agreed upon by the stakeholders. Adaptation measures were considered which decreased water demands, satisfied water demands more efficiently, or increased water abstraction sources. Tipping points were calculated from the hydrological model results for water supply and demand for each RCP scenario; water supply and demand were recalculated for each adaptation measure by recalculating public water demand, irrigation demand or water supply as needed.

Following Walker (2000) and Haasnoot et al. (2013), this process was further complemented with the creation of a scorecard for the adaptation measures, designed through quantitative and qualitative metrics, including a detailed characterization of each measure, the costs for implementation and maintenance, the effectiveness in years, i.e., until when a given measure will ensure that the adaptation objective is fulfilled (derived from hydrological models), externalities with other sectors (e.g. economy, biodiversity, the safety of people and properties, human health) and uncertainty related with the implementation of each measure (see Appendix C for full description). This document was shared with stakeholders during the discussion of the DAPP.
Figure 2 – Schematization of the adopted methodology, with the identification of moments of interaction between stakeholders and the modeling team. Modeling processes are represented in grey and dashed boxes. Each of the white boxes represent one of the four workshops.

Results

Climate change projections for the Algarve (rainfall and temperature)

The projections of the climate models used in this study are shown in Figure 3. Results point to a progressive decrease in precipitation for the entire Algarve region throughout the 21st century, reaching reductions between -9% and -23% by the end of the century, for RCP4.5 and RCP8.5, respectively.

Coupled with the decrease in overall precipitation, an increase in minimum, the average and maximum temperature are also projected. The average temperature is expected to increase between +1.6°C and +3.2°C in the long-term, under RCP4.5 and 8.5, respectively, with similar trends for minimum and maximum temperature.

Figure 3 – Changes in average temperature (ΔT, in degrees Celsius; on the left) and precipitation (ΔP, in percentage; on the right) for short, medium and long-term, under RCP4.5 and RCP8.5. Dots: average; whiskers: minimum and maximum range; boxes: 25%-75% range; horizontal lines: median

Stakeholder engagement, water availability assessment under climate change scenarios and evaluation of adaptation measures

The informed discussion between different stakeholders allowed for the co-creation of six main groups of adaptation measures for the region: i) build a desalinization plant; ii) improve water use efficiency; iii) build a new reservoir; iv) creation of water retention landscapes; v) improve wastewater recycling, and vi) decrease the use of water by irrigated agriculture. The proposed measures combine different climate change adaptation approaches: i), ii), iii), iv) and v) are considered as incremental adaptation, while vi) is considered a transformative adaptation.
Transformative adaptation refers to “changes that fundamentally alter the entire system’s ecological and/or social properties and functions” (Fedele et al., 2019), hence reducing the main causes of vulnerabilities due to climate change (Fedele et al., 2019; Kates et al., 2012). On the other hand, incremental adaptation refers to the extensions of actions “that already reduce the losses or enhance the benefits of natural variations in climate and extreme events” (Kates et al., 2012).

Water availability was then calculated for all the adaptation measures as follows (see also Appendix C for more detailed information):

- Wastewater available for recycling was estimated as 85% of municipal supply (Economopoulos, 1993).
- Water available from new reservoirs was calculated from the proposed watershed area for the Foupana dam in NE Algarve (382 km²) using the above-mentioned extrapolation for the Algarve.
- Increases in efficiency of water use were estimated as a 15% decrease in water requirements for municipal supply and irrigation, based on reported transmission losses of 20% in municipal supply systems (ERSAR, 2016) and 5% in all irrigation systems except Portimão, with 30% (SIR, 2019); the return of losses to the system was not considered.
- Decreases in water use by irrigated agriculture accounted for modifications on water requirements due to changes towards less water-demanding crops; this was calculated by completely replacing orange trees (which accounts for around 87% of agricultural water use in the region) with dryland tree crops such as olives, carobs or almonds, estimated from the irrigation requirements for rainfed orchards calculated by the hydrological model. This measure was further complemented with the progressive reduction of agricultural irrigated areas.
- Uncollected streamflow was calculated from the extrapolation of streamflow for the Algarve calculated above, and a conservative estimate of the water available for capture with distributed methods (e.g. small dams, water retention landscapes, aquifer recharge points) of 5%.
- A desalinization plant was considered to be capable of responding to all potential increases in water demand and decreases in water availability in the Algarve region.

Figure 4 shows the results for: (i) water available for abstraction from present-day sources (surface and groundwater) and new sources made available from adaptation measures; (ii) water demand, also present-day and after adaptation measures; and (iii) for each level of demand, the water sources required to keep extraction at a maximum of 43% and, hence, WEI at present-day levels. Water available for abstraction from present-day sources is expected to decrease, in 2100, by -9% in scenario RCP4.5, and by -36% in scenario RCP8.5. At the same time, water demand by present-day crops is expected to rise by 11% and 21% in scenarios RCP4.5 and RCP8.5, respectively. Compared with a present-day WEI of 43%, this would result in WEIs of respectively 51% and 78% by the end of the 21st century; in the second case, water stress would increase from severe to extreme.

As for the calculations for adaptation measures in water demand, the increase in efficiency showed relatively modest effects (15% as discussed earlier), while replacing orange trees with less water demanding crops showed a decrease in water demand of -27%. Crop replacement alone represented a decrease in WEI, to 31%, 37% and 57% for present-day, RCP4.5 and 8.5, respectively, changing the first two water stress situations from severe to moderate, and the
last one from extreme to severe. When complemented with the decrease in irrigated areas, this measure is effective until the end of the century, providing an alternative to the desalinization plant.

The calculations for adaptation measures in water supply sources showed modest effects. The use of recycled wastewater increased supplies by 8% in present-day, although the relative effect was larger for RCP8.5, with an increase of 12% by the end of the 21st century since wastewater remains constant, while total available water supplies decrease. The construction of the planned reservoirs and runoff retention could increase water availability for abstraction by respectively 14% and 5%, although the effectiveness of the reservoir tended to decrease towards the end of the 21st century, particularly in scenario RCP8.5. Overall, these three measures could increase the water available for abstraction by 26% to 29%. WEI would decrease from 43% to 34% in the present, 51% to 40% in RCP4.5, and 78% to 60% in RCP8.5, an effect comparable to that of crop replacement. About 45% of total available water would remain uncaptured, mostly surface runoff, and therefore not available for abstraction unless if captured with the distributed methods described above.

Figure 4 – Results of the hydrological model projections for historical conditions and three 30-year time slices in the 21st century for emission scenarios RCP 4.5 (left) and 8.5 (right); stacked bars represent available water for extraction from different sources, blue lines represent water demands, and brown lines represent the amount of water sources required to keep WEI at or below current levels.

Designing dynamic adaptive policy pathways

The effectiveness (in years) calculated for each adaptation measure is identified in Figure 5. The effectiveness reflects the calculated increase in water availability, based on WEI (either due to a decrease in water demand or an increase in the water supply). At the current state, the options ‘build a desalinization plant’ and ‘decrease the use of water by irrigated agriculture’ are unavailable, as they require a prior detailed study or represent an unrealistic change in the current policy, respectively. The measure ‘improve wastewater recycling’ is also unavailable, since the option requires that the large majority of wastewater treatment plants possess tertiary treatment (currently, from a total of 66 plants, only 7 have tertiary treatment - Águas do Algarve, 2019). Hence, at the end of each measure (i.e. when the tipping point is reached), stakeholders
could guide the adaptation pathway to one of the available measures (as explained above) that was not previously chosen (or implemented).

It is important to note that the measures’ effectiveness was found to change with the scenario considered (which influences water availability) and with the moment they are implemented (Figure 5). For instance, the creation of water retention landscapes had higher effectiveness when implemented in an early stage than in the second half of the century, since there is more precipitation and more water available. The sequence of implementation was also found to impact the tipping point of the next measure to implement, assuming a cumulative and dynamic adaptation pathway. An example of this situation is depicted in the highest effectiveness of ‘Build a new reservoir’ when implemented after ‘Improve water use efficiency’ measure, since the measure ‘Improve water use efficiency’ considers improvements in conveyance systems (urban and agricultural). This allows reducing the amount of water from the reservoir that is needed to fulfil the demand.

Finally, the calculation of the tipping points revealed that, under the RCP8.5 scenario, only the measures ‘Build a desalinization plant’ and ‘Decrease the use of water by irrigated agriculture’ can maintain the water availability constant at current levels, and hence achieving the adaptation objective. As expected, the RCP4.5 scenario causes lower stress on water resources and, consequently, leads to higher effectiveness of studied measures than in the RCP8.5 (Figure 5).

**Figure 5 – Dynamic Adaptive Policy Pathways with 6 different measures and tipping points, under RCP4.5 and RCP8.5 scenarios**

**Selection of the adaptive pathway by stakeholders**

Figure 6 summarizes the adaptation pathway selected by the stakeholders. As priority measures to deal with water scarcity by the end of the century, stakeholders agreed on improving water use efficiency and, simultaneously, creating water retention landscapes, as these are distributed small-scale measures and more easily implemented. While these two adaptation measures are being implemented, wastewater recycling should be studied and implemented in the wastewater treatment plants that already have tertiary treatment. This approach would
motivate decision-makers to promote more tertiary treatment plants, aiming at full implementation of this treatment in Algarve by 2035, when the full recycling of wastewater could start to be implemented. This pathway is estimated to be enough to achieve the adaptation objective for the RCP4.5 scenario, i.e. maintaining water availability at current levels throughout the century.

However, under scenario RCP8.5 it would only fulfil the objective until 2060 and more adaptation measures would be required. Acknowledging RCP8.5 as a severe scenario with extreme impacts, and after some discussion and negotiations, stakeholders chose to build a new reservoir in 2060, which would be effective until 2080; this choice was made by weighting the consequences of the remaining measures, and was considered by the stakeholders as the “least bad”. This measure would be followed by the construction of a desalination plant as a last resort measure. Although some participants did not fully agree with these measures (e.g. NGOs), they were unable to provide viable alternatives which could address the magnitude of projected impacts. Some stakeholders considered that the measure ‘Decrease the use of water by irrigated agriculture’ would represent a too profound change to be reliable under the current policy in all considered scenarios, while others considered that the use of water by agriculture will most likely decrease due to socio-economic factors (e.g. ongoing rural farmland abandonment; advances; wide implementation of new techniques and technology in agriculture).

![Figure 6 – Adaptation pathway chosen by stakeholders, under RCP4.5 and RCP8.5 scenarios](image)

**Discussion**

As expected, climate projections for the Algarve region point to a progressive reduction of precipitation throughout the century, as well as a progressive increase in temperature. Such changes can have a severe consequence for water availability, due to the lower water availability and higher evaporative demands. The results obtained from the hydrological model predict a decrease in the water supply of 36% by the end of the century in the most severe scenario (i.e. RCP8.5); such decrease is larger than the anticipated decreases in rainfall, as already expected from previous works (Stigter et al., 2014). Our findings are in line with those found in previous research for the region, of around -40% in the SRES A2 scenario (Iglesias et al., 2011), and -39%
in the SRES A1b scenario (Stigter et al., 2014). This would represent an increase in water stress to extreme levels, keeping the Algarve as a water-stressed region (see e.g. Bisselink et al. 2018), particularly under the RCP8.5 scenario.

In this study, the Dynamic Adaptive Policy Pathways (DAPP) approach was applied to design a strategy that tackles water scarcity in the region. The discussion and involvement of stakeholders throughout all the process allowed for a pre-selection of a diverse set of adaptation measures. Such exhaustive involvement of stakeholders helped avoid a narrow and conservative framing of DAPP (see Lin et al. 2017).

As expected from previous research (Garrote et al., 2016; Nunes et al., 2017), the calculation of tipping points under the most severe scenario showed that adapting the water sector to climate change in the Algarve region will require the combination of several measures, based on managing both supply and demand. In this context, none of the initially available set of measures can alone fulfill the adaptation objective beyond mid-century; and only two sets of measures allow to prevent high levels of water stress until the end of the century: Build desalinization plant and decrease the use of water by irrigated agriculture. Reducing the irrigation demand and farmland areas was previously reported to prevent the cross of the critical state beyond sustainability at the end of the century in Algarve region (Hugman et al., 2012; Stigter et al., 2017). Moreover, this reduction in irrigated areas and water demand was considered to be likely (but undesirable) by the farmers (Stigter et al. 2017).

When selecting the most suitable adaptation pathway, stakeholders demonstrated an initial preference for measures that focus on water use efficiency and increasing water supply. The choice of an adaptive pathway usually allows prioritizing individual measures. However, in this case, the stakeholders selected the implementation of three measures. This may reflect a precautionary approach to deal with uncertainty associated with climate change projections and impacts and policy-making process (Kundzewicz et al., 2018). In the long-term, stakeholders avoided decreasing the use of water by irrigated agriculture, revealing a preference for incremental measures rather than for transformative ones. Such preference for non-transformative measures in the region was previously reported by Stigter et al (Stigter et al., 2017). This can be explained by the disruptive change of status quo that it implies (Lonsdale et al., 2015; Pelling et al., 2015; Rickards and Howden, 2012), by the risk of maladaptation (Rickards and Howden, 2012), by being a source of discomfort and lifestyle changes (Thornton and Manasfi, 2010) or by the uncertainty in the data and consequences (Marshall, 2014). The fact that incremental measures would maintain water availability at the current levels until the end of the century under RCP4.5 may also discourage the adoption of transformative measures at an early stage.

Is it important to note that, although the evolution of water availability and consumption can be mainly dependent on climate change (Bisselink et al., 2018; Huang et al., 2019), the social and economic context can add more pressure to an already vulnerable system, particularly in Southern Europe (Harrison et al., 2016; Stigter et al., 2017). Together with the fact that extreme events (such as long-term droughts) were not accounted for, it is possible that the efficiency of adaptation measures can be further reduced (and the tipping points anticipated) and the effects of climate change more severe (Pedro-Monzonís et al., 2015). The use of a more detailed modelling approach for the impacts of droughts would require complex modelling of reservoir and groundwater storage (Nunes et al. 2017, Hugman et al. 2017) which could be complicated in multidisciplinary studies such as this one, where resources and time must be distributed by multiple subjects. Nonetheless, the DAPP approach was designed to account for such
uncertainties; the exact timing of a tipping point is not crucial, as changes in climate, social or economic scenarios or in the methodology used to calculate them will change the timing of actions, rather than the actions themselves (Walker et al., 2013). Such characteristic makes DAPP a flexible and adaptive strategy, better suited to deal with deep uncertainty in climate change adaptation (Buurman and Babovic, 2016).

This study presents an example of how water resource models and stakeholders can interact and hence contributes to further reduce this previously identified gap (Melsen et al., 2018; Srinivasan et al., 2017). Furthermore, the Algarve has a large set of characteristics similar to other Mediterranean areas and faces similar pressures (i.e. climate change and water scarcity, conflicts between water users, namely agriculture and tourism, and overexploitation in some aquifers); these results and conclusions can be useful for both researchers and policymakers in the Mediterranean region, especially when considering that fewer than 20% of the European Mediterranean basins have adequate policies to face climate change (Garrote et al., 2016).

Conclusions
This study aimed to provide an impact assessment of the projected climate change on water availability and requirements for the Algarve, a Mediterranean region, under RCP4.5 and RCP8.5, as well as co-create dynamic adaptive policy pathways with stakeholders to select a strategy to tackle water scarcity in the region. DAPPs were designed using the results from the water resources model and the effectiveness of the adaptation measurers assessed under the objective of maintaining water availability at the current levels throughout the century. As expected, results indicate an increase in water stress to extreme levels in the RCP8.5 scenario. To cope with such projections, stakeholders showed a strong preference for distributed small-scale measures, as they are more easily implemented and require less economical and/or societal costs; adapting Algarve region to climate change will likely depend on managing both supply and demand. In contrast, decreasing the use of water by irrigated agriculture was considered not socially desirable due to disruption it implies in the current system with perceived reputational damage for local governmental institutions.

Although much uncertainty remains regarding Hydrological modeling and climate change projections (even when using multi-scenario and Ensemble climate change models – see Pastor et al. (2020)), DAPP was proven to be able to satisfactorily integrate results from numerical models, to make them easily understandable by stakeholders, and consequently promote discussion over a complex subject.

Acknowledgement
The authors would like to thank all stakeholders who have participated in this research, and especially to the Algarve Intermunicipal Community, namely to Sérgio Inácio, João Graça and Joaquim Brandão Pires for their support throughout the process. We also thank the anonymous reviewers, whose comments helped improving the clarity and quality of our manuscript.

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Appendix A

Model calibration and validation

A split-sample approach was used to calibrate and validate the hydrological model, with the streamflow calculations calibrated for Bravura and validated for Arade and Beliche, and the irrigation calculations calibrated for Tavira and validated for Lagos and SLP. The main calibrated parameters were the crop coefficients, soil water retention capacity, and curve numbers. The model was evaluated using statistics between predictions and observations: the coefficient of determination ($r^2$), relative bias, the ratio between the root mean square error and the standard deviation (RSR), and the Nash-Sutcliffe Efficiency index (NSE), calculated and assessed following Moriasi et al. (Moriasi et al., 2007). The model presented a good performance for water yield (Table A1), with $r^2$ between 0.61 and 0.78, bias between -1.1 and 1.7%, RSR between 0.5 and 0.68, and NSE between 0.54 and 0.74. Model performance for irrigation requirements was also good (Table A2), with $r^2$ between 0.83 and 0.87, bias between 3 and 4%, RSR between 0.38 and 0.68, and NSE between 0.53 and 0.86.

Table A1 - Model performance for water resources. $R$: correlation coefficient, $R^2$: coefficient of determination, RMSE: root-mean-square deviation, StDev: standard deviation, RSR: RMSE-observations standard deviation ratio, NSE: Nash-Sutcliffe efficiency

<table>
<thead>
<tr>
<th></th>
<th>Bravura</th>
<th>Arade</th>
<th>Beliche</th>
<th>Querença-Silves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.79</td>
<td>0.78</td>
<td>0.86</td>
<td>0.89</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.62</td>
<td>0.61</td>
<td>0.74</td>
<td>0.78</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>0.1</td>
<td>0</td>
<td>0.3</td>
<td>-0.2</td>
</tr>
<tr>
<td>Bias (%)</td>
<td>0.4%</td>
<td>0.10%</td>
<td>1.7%</td>
<td>-1.1%</td>
</tr>
<tr>
<td>RMSE (mm)</td>
<td>18.5</td>
<td>43.2</td>
<td>15.4</td>
<td>12.7</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>120.2%</td>
<td>197.80%</td>
<td>103.2%</td>
<td>58.4%</td>
</tr>
<tr>
<td>StDev (mm)</td>
<td>27.3</td>
<td>66.4</td>
<td>30.6</td>
<td>22.8</td>
</tr>
<tr>
<td>RSR</td>
<td>0.68</td>
<td>0.65</td>
<td>0.5</td>
<td>0.56</td>
</tr>
<tr>
<td>NSE</td>
<td>0.54</td>
<td>0.57</td>
<td>0.74</td>
<td>0.69</td>
</tr>
</tbody>
</table>

Table A2 - Model performance for irrigation requirements. $R$: correlation coefficient, $R^2$: coefficient of determination, RMSE: root-mean-square deviation, StDev: standard deviation, RSR: RMSE-observations standard deviation ratio, NSE: Nash-Sutcliffe efficiency

<table>
<thead>
<tr>
<th></th>
<th>Lagos</th>
<th>SLP</th>
<th>Tavira</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>0.93</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.87</td>
<td>0.83</td>
<td>0.83</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>4.7</td>
<td>27.2</td>
<td>38.9</td>
</tr>
<tr>
<td>Bias (%)</td>
<td>4.0%</td>
<td>3.4%</td>
<td>3.0%</td>
</tr>
<tr>
<td>RMSE (mm)</td>
<td>48.3</td>
<td>390.8</td>
<td>595.4</td>
</tr>
<tr>
<td>RMSE (%)</td>
<td>41.1%</td>
<td>48.8%</td>
<td>49.6%</td>
</tr>
<tr>
<td>StDev (mm)</td>
<td>127.8</td>
<td>956.1</td>
<td>869.3</td>
</tr>
<tr>
<td>RSR</td>
<td>0.38</td>
<td>0.41</td>
<td>0.68</td>
</tr>
<tr>
<td>NSE</td>
<td>0.86</td>
<td>0.83</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Figure A1 - Comparison between simulated and observed values for water resources.

Figure A2 - Comparison between simulated and observed values for irrigation requirements.
### Appendix B

### Institutions participating in the study

#### Table B1 – Main institutions that participated in the study, aggregated by typologies*

<table>
<thead>
<tr>
<th>Class of institution</th>
<th>Number of institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipalities or parish</td>
<td>20</td>
</tr>
<tr>
<td>Irrigators associations, agricultural&lt;br&gt;cooperative and similar</td>
<td>10</td>
</tr>
<tr>
<td>Municipal/Regional water supply services</td>
<td>5</td>
</tr>
<tr>
<td>Research institutions</td>
<td>3</td>
</tr>
<tr>
<td>Regional directorate for land use&lt;br&gt;management and planning</td>
<td>3</td>
</tr>
<tr>
<td>National/Regional directorate for environmental or water sector</td>
<td>1</td>
</tr>
<tr>
<td>National/Regional directorate for agriculture</td>
<td>2</td>
</tr>
<tr>
<td>Nature conservation organizations</td>
<td>1</td>
</tr>
<tr>
<td>National/Regional environmental NGOs</td>
<td>5</td>
</tr>
<tr>
<td>Tourism sector</td>
<td>6</td>
</tr>
</tbody>
</table>

* full list can be retrieved from https://sapientia.ualg.pt/bitstream/10400.1/12870/3/PIAAC-AMAL_Anexos.pdf (document in Portuguese)
Appendix C

Scorecard

The scorecard table was built to inform stakeholders about the costs, effectiveness in years, externalities, and uncertainties of each measure. Effectiveness was obtained through hydrological modeling as described in the main body of this article. The costs, externalities, and uncertainty results from literature review (see e.g. Bertule et al., 2017).

Table C1 – Scorecard for climate change adaptation measures, considering water availability projections until 2100

<table>
<thead>
<tr>
<th>Actions</th>
<th>Investment</th>
<th>Costs Maintenance</th>
<th>Effectiveness (years) RCP8.5</th>
<th>Externality</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Build a desalinization plant</td>
<td>$$$$$</td>
<td>$$$</td>
<td>NA</td>
<td>----</td>
<td>?</td>
</tr>
<tr>
<td>Notes:</td>
<td>Construction by modules as needed. Investment costs are currently high but expected to decrease throughout the century (mainly related to technological advances). High negative externalities: biodiversity and energy sectors; increase in the water price for agriculture; visual impact on the landscape. It is also expected that these negative impacts decrease throughout the century. This measure includes the study of locations for brine discharge. The uncertainty is low since there are already detailed studies for the Algarve region.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Improve water use efficiency | $ | $ | 15 - 25 | ++ | ? |
| Notes: | Rehabilitation and modernization of irrigation and urban infrastructures. This would lead to a decrease in water loss in the system (either by ruptures and/or evaporation). It was estimated that the implementation of the measure would represent a saving between 43.9 hm³/year and 50.9 hm³/year (at the end of the century and under RCP8.5). The measure also includes the replacement of current vegetation present in urban public spaces for species adapted to observed and projected climatic conditions, leading to savings of 1.5 hm³/year under current conditions and 1 hm³/year at the end of the century, under RCP8.5. Positive externalities on the safety of people and properties and transportations. The uncertainty for this measure is low since it is in line with current policies in the region and its effectiveness can be easily monitored. |

| Build a new reservoir | $$$ | $$$ | 35 - 25 | --- | ? |
| Notes: | Increase in water availability between 92 hm³/year (for observed conditions) e 54 hm³/year (by the end of the century, under RCP8.5); increase in 14% the water availability in the Algarve region. The uncertainty is low since there are already detailed studies regarding a new reservoir in the Algarve region. |

| Creation of water retention landscapes | $ | $ | 15 – 5 | ++++ | ???? |
| Notes: | Water retention landscapes decrease urban floods and soil erosion, restore the hydrologic cycle and promote water quality. The effectiveness is high for small agriculture exploitations, but it contributes to the overall water availability in the region is low (here estimated as 5% of the total uncollected streamflow, varying from 31.7 hm³/year under observed conditions and 20.2 hm³/year by the end of the century, under RCP8.5 scenario. The measure represents positive externalities to biodiversity and human health. This measure has a high uncertainty, which reflects a lack of studies for the region and possible barriers to the wide implementation in the Algarve region. |

| Improve wastewater recycling | | | | | |

28
- Promote tertiary water treatment on existing Wastewater treatment plants with only primary and secondary treatment;
- Construction of a dedicated water supply system

<table>
<thead>
<tr>
<th></th>
<th>$$$</th>
<th>$$</th>
<th>25 - 15</th>
<th>NA</th>
<th>???</th>
</tr>
</thead>
</table>

Notes: This measure represents an increase of 54 hm³/year in water availability. This increase in water availability is constant since we did not assume changes in the population (and consequently in urban consumption) throughout the century. Currently, investment costs are high, but it is expected to decrease throughout the century (it is assumed a progressive and autonomous transition to tertiary treatment). The complete fulfillment of the measure represents 8% of the current water needs. For this reason, it presents a moderated effectiveness. The measure has a moderate uncertainty since changes in population and population dynamics (e.g. tourism) were not considered.

---

**Decrease the use of water by irrigated agriculture**

- Progressive decrease in water use for irrigation, by completely replacing orange trees with less water-demanding crops, such as olives, carobs or almonds.
- Progressive decrease in water use for irrigation, by reducing the area of irrigated agriculture

<table>
<thead>
<tr>
<th></th>
<th>$$</th>
<th>$$</th>
<th>≥ 100</th>
<th>----</th>
<th>???</th>
</tr>
</thead>
</table>

Notes: Replacement of orange trees with other cultures adapted to observed and projected climate. This measure is further complemented with the reduction of irrigated areas. Implementation and maintenance costs are expected to decrease in the last period of the century, following more awareness from the sector. Negative externalities associated with a high sociologic and economic impact. The uncertainty in this measure is high, reflecting the potential sociological, economic, and political barriers and consequences to its implementation.

---

**Legend:**
- $ Reduced cost
- $$ High cost
- ----- Negative externalities
- ++++ Positive externalities
- ? Low uncertainty
- ???? High uncertainty