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D3.6

Optimized water resources models as a support to management strategies

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Changes with respect to the DoA
Not applicable

Dissemination and uptake
This report is public.

Short Summary of results (<250 words)
D3.6 – Optimized water resources models as a support to management strategies was developed by IWW, LNEC, NTNU, KWR, AQUATEC, CYI and all local partners within WP3 - Integrated analysis of the water cycle.

This report D3.6 provides an overview of the benefit of the BINGO modelling approach for 14 sites in 6 countries. Even though the sites are diverse, as they each tackle different water problems that are typical for Europe, the combination of bottom-up knowledge and data with top-down modelling strategies (climate change data, scenarios) has been successful. At the some of the sites, e.g. in the Netherlands and Germany, individual models had already been implemented, but have been further developed or joined by additional models within BINGO. At other sites, models have been applied for the first time. Both cases have created additional knowledge about local processes and enabled water stakeholders to learn more about their resources, to peek into the near and distant future, and finally to adjust their management strategies according to model applications and results.

Evidence of accomplishment
This report.

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1. INTRODUCTION

This document is developed as part of the BINGO (Bringing INnovation to onGOing water management – a better future under climate change) project, which has received funding from the European Union's Horizon 2020 Research and Innovation programme, under the Grant Agreement number 641739. The Project website (www.projectbingo.eu) represents Deliverable 3.6 of Work Package 3 (WP3) – D3.6 - Optimized water resources models as a support to management strategies.

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2. Summary

This report D3.6 provides an overview of the benefit of the BINGO modelling approach for 14 sites in 6 countries. Even though the sites are diverse, as they each tackle different water problems that are typical for Europe, the combination of bottom-up knowledge and data with top-down modelling strategies (climate change data, scenarios) has been successful. At the some of the sites, e.g. in the Netherlands and Germany, individual models had already been implemented, but have been further developed or joined by additional models within BINGO. At other sites, models have been applied for the first time. Both cases have created additional knowledge about local processes and enabled water stakeholders to learn more about their resources, to peek into the near and distant future, and finally to adjust their management strategies according to model applications and results.

3. Cyprus

Model frameworks

The BINGO climate-water research in Cyprus focuses on two watersheds along the northern slopes of the Troodos Mountains. The first watershed is the Peristerona Watershed, which is a rural and forested watershed; the second is the Pedieos Watershed, which has forests upstream, agriculture midstream and urban environments downstream (see D3.1). The main climate-water risk for Peristerona is drought and the main climate-water risk for Pedieos is flooding in the downstream urban area. The Peristerona Watershed research is presented in sections 3.1 to 3.4 and the Pedieos Watershed is presented in sections 3.5 to 3.8.

3.1. Objectives Peristerona Watershed

The overall goal of the Peristerona Watershed hydrologic research is to improve our understanding of the effect of climate change, especially drought, on the water balance components of the watersheds along the northern hillslopes of the Troodos Mountains. The rural communities in these watersheds rely on streamflow and groundwater for domestic water use and irrigation (see D3.3). The northern slope watersheds are located in the rain shadow of the mountains. Thus, climate change is expected to have a stronger effect on the northern slopes than on the southern slopes of Troodos.

The main objective of the hydrologic modeling research was to set-up the Weather Research and Forecasting (WRF) model with its hydrologic extension (WRF-Hydro) for streamflow simulations along the northern slopes of the Troodos Mountains (D3.3). WRF-Hydro was the selected modelling instrument because it allows the coupling of hydrologic and atmospheric processes, thus matching the overarching goal of the BINGO project of analyzing the effects of climate change on the hydrologic cycle. WRF-Hydro is one of the most complete model environments for the analysis of coupled atmospheric-hydrologic processes and has an active and growing user community (Givati et al., 2018; Gochis et al., 2018; Senatore et al., 2015). The WRF model is a well-established and widely used atmospheric model that was also used for the modeling of past and future climate in WP2 (D2.5, D2.7).

The calibration of the WRF-Hydro model for continuous simulations (1-year) was, however, constraint by the lack of accurate precipitation data with high temporal (hourly) and spatial resolution (1-km) for the distributed modeling of the hydrologic processes in these steep and narrow Troodos watersheds (D3.3), as explained below. Therefore, we re-calibrated WRF-Hydro, using hourly rainfall observations from 30-40 rainfall stations, and the WRF simulations from WP2 for two 15-day extreme events (January 1989, November 1994).

To improve our understanding of the water use of the *Pinus brutia* forest along the Troodos hill slopes, sapflow, throughfall, soil moisture and meteorological parameters in the forest on the edge of Peristerona Watershed were observed and analyzed (D3.5). The findings of the field research were incorporated in the daily, lumped, 4-parameter GR4J model application (Perrin et al., 2003). The GR4J model was used to simulate the long-term effect of climate change on streamflow and water resources in Peristerona Watershed (D4.3).

3.2.   Main results

In WP2, good results were obtained for the simulation of 15-day rainfall extremes for Cyprus, with ERA-Interim reanalysis data supplying the initial and boundary conditions (D2.5; Zittis et al., 2017). The best model performance was obtained for the extreme events of January 1989 and November 1994. A Nash Sutcliffe Efficiency (on absolute differences) of 0.72 was reached for the January 1989 event and 0.42 for the November 1994 event. The percent bias for these events was -9.6% and 4.4%, respectively (D2.5; Zittis et al., 2017). However, subsequent year-long simulations with the optimized WRF model ensemble, showed substantial precipitation biases and even for simulations with the application of grid or spectral nudging biases remained (Zittis et al., 2018).

In D3.3, the atmospheric forcing data of two year-long runs of the WRF model at 12-km resolution were used as input for the WRF-Hydro model calibrations. However, as explained above, the WRF-modeled rainfall did not confirm with the reality and could not be used for the WRF-Hydro model calibrations. Therefore, the precipitation input data for WRF-Hydro were derived from the observational 1-km gridded, daily rainfall data set over Cyprus (Camera et al., 2014). The WRF-Hydro model was calibrated for the Peristerona Watershed for the hydrologic year 2006/2007 and validated for 2000/01. A Nash Sutcliffe Efficiency (NSE) of 0.13 was obtained for the model calibration (see D3.3). The NSE values could not be improved, due to the lack of continuous (e.g., hourly) rainfall data.

To improve the WRF-Hydro model application, a 1-km, observational hourly rainfall data set was developed for the January 1989 and November 1994 extreme events, which were successfully modeled in D2.5. The hourly rainfall data set was created by combining hourly observations from 30 to 40 stations of with the daily, 1-km gridded observational data set, which was derived from 145 stations (Camera et al., 2014). All original rainfall data were provided by the Cyprus Department of Meteorology. The WRF-Hydro model was calibrated for the two extreme events for 22 watersheds along the northern slopes of the Troodos Mountains (Camera et al., 2019). The calibration focussed on the REFKDT parameter, which partitions rainfall between infiltration and runoff. Similar to other studies (e.g., Arnault et al., 2018; Givati et al., 2016), REFKDT was identfied as one of the most sensitive WRF-Hydro model parameters in D3.3.

The calibrated REFKDT values for the Peristerona and Pedieos Watershed for the January 1989 and November 1994 extreme events are shown in Table 1. The January 1989 event occurs under very wet conditions, after an earlier extreme event in January 1988, whereas the November 1994 extreme starts out under much drier initial conditions. Reasonable NSE values were obtained when different values of REFKDT were used for the two events. These results indicate that in the calibrated model the hydrologic processes are not modeled very well. The NSE values for the WRF-simulated rainfall over the watersheds are quite good. However, they are very sensitive to small shifts in time and place, as indicated by the low NSE for Peristerona in January 1989. The streamflow simulations with modeled rainfall and the calibrated model (REFKDT obtained from the simulations with observed rain) show fairly large biases. Although these simulations show reasonable model achievements, the WRF-Hydro model can obviously not yet be used for operational water management.

Table 1. Calibrated REFKDT values with Nash-Sutcliffe Efficiency (NSE) and percentage bias (PBIAS) for the streamflow of the 1989 and 1994 extremes; and the NSE and PBIAS of the WRF-modeled rain and the PBIAS of the streamflow simulated with the WRF rain for the two extremes at Peristerona and Pedieos Watershed.

Watershed	REFKDT 1989	REFKDT 1994	NSE 1989	NSE 1994	PBIAS 1989	PBIAS 1994
Peristerona	0.3	0.5	0.76	0.67	-54.5	-22.9
Pedieos - Agios Onoufrios	0.5	1	0.72	0.60	-39.1	-32.0
Pedieos near Kampia	0.5	3	0.80	0.47	-49.9	-58.4
	NSE rain 1989	NSE rain 1994	PBIAS rain 1989	PBIAS rain 1994	PBIAS flow 1989	PBIAS flow 1994
Peristerona	0.17	0.59	33.3	-8.3	-49.4	-60.2
Pedieos - Agios Onoufrios	0.60	0.59	7.0	-31.6	-19.8	40.1
Pedieos near Kampia	0.59	0.62	11.9	-13.9	-89.8	-97.5

The field observations and water balance computations in the forestry research site showed that the trees take up substantial water from the fractured bedrock. The percentage of the incoming rainfall that goes to evapotranspiration was 86% (2015), 88% (2016) and 90% (2018). However, in the 2017 drought year (220 mm rainfall) evapotranspiration exceeded the incoming rainfall, with water from the bedrock sustaining the transpiration of the trees (D3.5).

For long-term drought simulations of Peristerona Watershed, we used the daily, lumped GR4J model. Based on the findings of the field observations, the GR4J streamflow exchange parameter (X2) was set to zero and a NSE value of 0.82 was obtained for the calibration (1995-2010) and 0.71 for the validation (1980-1995) (D3.5). The RCP 8.5 simulations with the GR4J model for 2020-2050 showed a 27% decrease in streamflow for 2020-2050 in Peristerona Watershed, relative to 1980-2010 (D4.3). However, even though the simulations have become more robust through the findings from the field research, GR4J is an empirical model and may not capture future climate-related environmental changes very well.

3.2.1. Relevance for the water sector

The BINGO research helped to improve the awareness of the stakeholders about the effect of climate change on their water resources for domestic and irrigation water supply. Even though desalination was considered financially unfeasible by the Peristerona Watershed stakeholders during the first meeting, this option has now been accepted.

Knowledge about the water use of the *P. brutia* species on the northern slopes of the Troodos Mountains have been shared with the Department of Forests and the Water Development Department. The Department of Forests is hosting the ecohydrology research at the Agia-Marina-Xyliatou research site and have been interested and engaged in the research. They have used the research findings to obtain a better understanding of the functioning of *P. brutia* species. The streamflow observations in the downstream area have also been shared with the Water Development Department.

3.3. Outlook

The water authorities have recently designed the extension of the desalinated water supply network to the downstream area of Peristerona Watershed. Seawater desalination and the pumping of desalinated water from the coast to these inland areas require substantial energy, which are mainly supplied by fossil energy resources. The release of the brine from the desalination process back into the sea, can also negatively affect marine biodiversity. Thus, although this measure is understandable from a climate change adaptation perspective, it is not a very environmentally friendly and climate-neutral option. The smaller communities of Orounda and Kato Moni, just upstream of Peristerona community, remain reliant on groundwater, fed by streamflow recharge. Thus the optimal management of the groundwater recharge structures for optimizing both the quantity and quality of the water remains a topic for further research.

The coupling of high-resolution atmospheric and terrestrial hydrologic models is extremely important for the simulation of physically consistent rainfall events, hydrologic systems and feedback processes. This is especially important for topographically heterogeneous environments in semi-arid environments with high spatial and temporal variability of rainfall and flashy hydrologic responses, caused by the steep topography, shallow soils, fractured geologic formations and low moisture contents. The WRF-Hydro modelling research has become the topic of a new PhD study in Cyprus. The PhD research will include the development of an efficient ensemble of atmospheric process parameterizations for the simulation of precipitation and an in-depth analysis of the sensitivity of modelled runoff to the infiltration and drainage process parameterizations (Sofokleous et al., 2019).

3.4. Bibliography

Arnault, J., Rummler, T., Baur, F., Lerch, S., Wagner, S., Fersch, B., Zhang, Z., Kerandi, N., Keil, C. and Kunstmann, H., 2018. Precipitation sensitivity to the uncertainty of terrestrial water flow in WRF-Hydro–An ensemble analysis for Central Europe. Journal of Hydrometeorology, (2018).

Camera, C., G. Zittis, A. Bruggeman, I. Sofokleous. 2019. Testing the performance of a one-way coupled atmospheric-hydrologic model for the simulation of past extreme events over Cyprus. Geophysical Research Abstracts Vol. 21, EGU2019-2252.

Camera, C., A. Bruggeman, P. Hadjinicolaou, S. Pashiardis, M.A. Lange. 2014. Evaluation of interpolation techniques for the creation of gridded daily precipitation (1 × 1 km2); Cyprus, 1980–2010, Journal of Geophysical Research: Atmospheres 119(2): 693-712. https://doi.org/ 10.1002/2013JD020611

Givati, A., Gochis, D., Rummler, T. and Kunstmann, H., 2016. Comparing One-Way and Two-Way Coupled Hydrometeorological Forecasting Systems for Flood Forecasting in the Mediterranean Region. Hydrology, 3(2), p.19.

Gochis, D.J., M. Barlage, A. Dugger, K. FitzGerald, L. Karsten, M. McAllister, J. McCreight, J. Mills, A. RafieeiNasab, L. Read, K. Sampson, D. Yates, W. Yu, 2018: The WRF-Hydro modeling system technical description, version 5.0. NCAR Technical Note. 107 pages. Available online at https://ral.ucar.edu/sites/default/files/public/WRF-HydroV5TechnicalDescription_0.pdf

Perrin, C., Michel, C., Andréassian, V., 2003. Improvement of a parsimonious model for streamflow simulation. J. Hydrol. 279, 275–289. https://doi.org/10.1016/S0022-1694(03)00225-7

Senatore, A., Mendicino, G., Gochis, D.J., Yu, W., Yates, D.N. and Kunstmann, H., 2015. Fully coupled atmosphere-hydrology simulations for the central Mediterranean: Impact of enhanced hydrological parameterisation for short and long time scales. Journal of Advances in Modeling Earth Systems, 7(4), pp.1693-1715.

Sofokleous, I., A. Bruggeman, C. Camera. 2019. The effect of hydrologic process parameterisations on runoff from single soil column model simulations of a Land Surface Model. Geophysical Research Abstracts Vol. 21, EGU2019-15952.

Zittis, G., A. Bruggeman, P. Hadjinicolou, C. Camera, J. Lelieveld. 2017. The added value of convection permitting simulations of extreme precipitation events over the Eastern Mediterranean. Atmospheric Research, 191: 20-33. https://doi.org/10.1016/j.atmosres.2017.03.002

Zittis, G., A. Bruggeman, P. Hadjinicolaou, C. Camera, J. Lelieveld. 2018. Effects of meteorology nudging in regional hydroclimatic simulations of the Eastern Mediterranean. Atmosphere 9(12), 470; https://doi.org/10.3390/atmos9120470

3.5.   Objectives Pedieos Watershed

The downstream area of the Pedieos Watershed has been identified as an area of Significant Flood Risk potential under the European Flood Directive (WDD, 2014, I.A.CO LTD 2011) implementation. The goal of the Pedieos Watershed research was the simulation and assessment of flood events under future climate and land use changes, using the calibrated models and data from the competent authority (Water Development Department) for the Flood Directive study. This ensured that the model results are comparable and compatible with the analysis and reporting for the Flood Directive. The research used the HEC-HMS, HEC-RAS and HEC-GEO-RAS models (see D3.3). Future extreme events for 2015-2024 were identified from the global MiKlip decadal prediction system, based on large-scale circulation patterns and precipitation thresholds of observed past events (D2.7). Three severe future events were selected and dynamically downscaled to 12-, 4- and 1-km resolution over the broader region of the eastern Mediterranean and specifically in our case, Cyprus, following a "one-way nesting" approach, using the best performing five-member ensemble set, identified in D2.5 and Zittis et al. (2017). Land use change scenarios for the watershed were developed based on the SCENES story lines (D3.2).

3.6.   Main results

Two of the three simulated future extremes produced flows at the upstream gauging station that were approximately equivalent to 1 in 10 and 1 in 20 year events. The most extreme member of the largest future event (2023) resulted in a peak flow of 95 m3/s at the Pedieos upstream flow gauging station, which is estimated to be equal to a 1 in 100-year recurrence event. This event caused a 295 m3/s peak flow at the outlet of the watershed under study (D3.4).

The main land use changes for the Pedieos Watershed are an 18% increase in urban areas under the Sustainability-Eventually scenario and a 50% increase in urban areas under the Economy-First scenario (D3.2). These scenarios showed a 3% and a 5% increase in the flow at the outlet of the watershed for the most extreme modeled event. For these simulations the extent of the flooded area increased from 124 ha to 128 ha for the Sustainability scenario and to 129 ha for the Economy First scenario (D3.4). The relatively small impact of the increased urbanization on the flows is attributed to the fact that the proportion of the increased urban area is very small compared to the rest of the contributing watershed. Furthermore, the upper watershed in natural forested condition receives a much higher proportion of rainfall.

The simulations also showed that emptying the 2.8 Mm3 reservoir storage of the Tamassos dam, just upstream the urban area, could prevent downstream flooding for the 1 in 20 year event. Thus, advance knowledge of rainfall extremes could ensure the timely release of the reservoir storage for downstream recharge and prevent flooding.

The decadal predictions showed that a 1 in 100 year flood event can be expected within the near future. Such an event causes flooding of substantial residential areas adjacent to the Pedieos River and exceeds the capacity of a number of bridges and culverts. Therefore, flood protection measures and a redesign of hydraulic structures associated with the Pedieos River flows are deemed necessary to be considered.

3.6.1. Relevance for the water sector

The use of dynamical downscaling for the simulation of future rainfall extremes has proven to be a valuable approach. Based on the results and experience obtained in the BINGO Project, we are now applying a similar modelling approach for the urban area of Limassol, for the ERMIS-F Greece-Cyprus Interreg Project (www.ermis-f.eu). The ERMIS-F project is conducted with support from the Water Development Department and in cooperation with the Sewage Board of Limassol and Amathus.

The results of the simulations have been shared with the Water Development Department. The findings confirm the importance of flood protection measures for the Pedieos Watershed. The modeling work has improved the ability of water sector organizations (SME) to conduct similar flood modelling research within climate change adaptation strategies, programs etc.

The use of dynamical downscaling for the simulation of future rainfall extremes has proven to be a valuable approach. Based on the results and experience obtained in the BINGO Project, a similar modelling approach for the urban area of Limassol is applied, for the ERMIS-F Greece-Cyprus INTERREG Project (www.ermis-f.eu). The ERMIS-F project is conducted with the support of the Water Development Department and in cooperation with the Sewage Board of Limassol and Amathus.

A longer time series for extracting and deriving the probabilities of possible future rainfall extremes are simulated in the ERMIS-F INTERREG Project. The RCP8.5 (business-as-usual) scenario for the period of 2005-2100 has been selected. The bias-adjusted version of the CESM1 global earth system model to 12-km for the Eastern Mediterranean has been downscaled, for the period 1980-2100, with the optimized WRF model. 80 rainfall extremes from the 2020-2100 time series will be extracted and then a subset for downscaling to 1-km over Cyprus will be selected. Similar to the BINGO approach for the Pedieos Watershed, the calibrated HEC models and data of the Water Development Department for flood modelling will be used again, to derive results in line with the analysis and reporting for the Flood Directive.

3.7. Outlook

The BINGO research has confirmed the importance of and need for flood protection measures for the Pedieos Watershed. Research on the parameterization and evaluation of the WRF-Hydro model for Cyprus could lead to improved short-term forecasting of precipitation, stream flow and dam water storage. This could support the management of water storage and release of the Tamassos Dam reservoir and thereby contribute to reduced flooding in the downstream areas.

Further research in the use of early flood warning systems on the upstream river flow weirs and a system of adequate control releases from the Tamassos Dam is considered useful. Also, research on the best operation management of the reservoir to enhance its anti-flood role is needed.

Stakeholders should identify points along the Pedieos river that are prone to flooding, so that early warning steps are taken for the safety of the urbanized environment.

3.8.   Bibliography

Water Development Department (WDD). 2014. Areas of potentially significant flood risk. Available at: http://www.moa.gov.cy/moa/wdd/Wdd.nsf/all/9927D3D42AA70328C2257A3100308E44?opendocument

Zittis, G., A. Bruggeman, P. Hadjinicolou, C. Camera, J. Lelieveld. 2017. The added value of convection permitting simulations of extreme precipitation events over the Eastern Mediterranean. Atmospheric Research, 191: 20-33. https://doi.org/10.1016/j.atmosres.2017.03.002

4. Germany

Model frameworks

For the German research site, the following four frameworks were developed and implemented: In Framework 1, a TALSIM Model of the Dhünn catchment area was setup. Framework 2 included a NASIM and a SWAT Model of the Dhünn catchment area. Both Frameworks 1 and 2 address the case study "not enough water". In Framework 3, a NASIM Model of the Mirke Creek in the city of Wuppertal was developed for the case study "too much water". Framework 4 included a NASIM Model of the Leimbach catchment area, addressing also the case study "too much water". Further details on the four frameworks are included in Deliverable D3.4. All of the models were hydrological models, but with different focus and detailing.

4.1. Objectives [FRAMEWORK 1]

Framework 1 addresses the following objectives with respect to dry periods at the Dhünn catchment area, as described in D3.4:

- Establish how many times certain thresholds were exceeded / not exceeded at representative water gauges
- Determine duration of extreme dry events in terms of reservoir storage volume under a specified threshold (see Figure 1)
- Analyse the impacts of anthropogenic influences (socio-economic factors), such as land and water use on surface runoff and reservoir storage volume
- Analyse the impacts of future climate change scenarios on surface runoff and reservoir storage volume
- Analyse the impacts of future climate predictions in combination with land and water use scenarios

A detailed description of the Dhünn catchment area is included in D3.1.
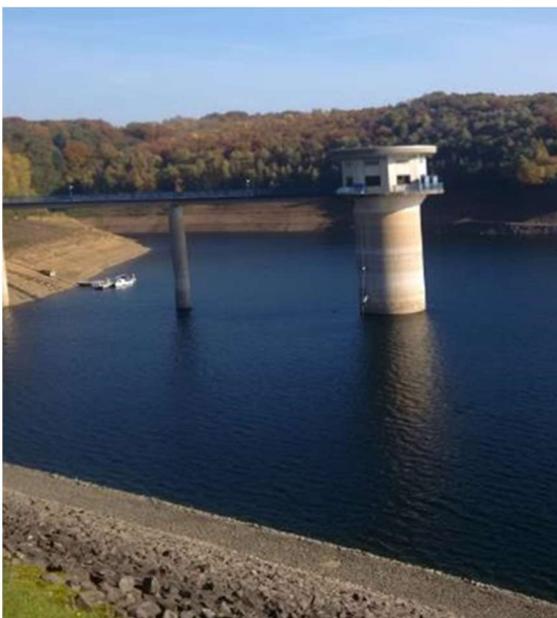
Figure 1 - Dry period at the Große Dhünn Reservoir: 2012 – 2015

4.2. Main results

Based on the detailed result analysis presented in D3.4, the following essential points summarise the main outcome of Framework 1:

- The decadal member R9 produced the most critical scenario of future conditions as far as the case study "not enough water" is concerned.
- Water quantity is not likely to undergo severe impacts due to changes on land use within the time range from 2015 to 2024.
- Changes on water use have significant impacts both on reservoir storage and downstream runoff.
- With respect to the simulated discharge values at the upstream hydrometric station "Neumühle (SNEM)" no major impacts were observed (this is related to the water protection zone and only improved conditions on the time line).
- The simulated discharge values of the main important downstream water gauges "Manfort (SMAN)" and "Schlebusch (SSLB)" show similar behaviour as far as future conditions are concerned. The future scenario "economy first" derived from the decadal member R9 appears to be the most challenging.
- Same conclusion was drawn regarding the simulated volume values at the GDT. The total duration of occurrences of the status at the GDT below the critical conditions concerning the storage volume tends to be significantly longer within the scenario "economy first" forced by the decadal member R9.
- With respect to the model simulation with past conditions, by an assumed constant water demand for the city of Düsseldorf the simulated storage volume reaches very often values under the critical threshold.
- Bias correction is very sensitive for the modelling. The procedures to fit areal data and point observations are still not suitable. In the practical use of modelling there is still a gap in using both and have comparable results. For the moment it might be better to compare relatively with the same sort of input for the past and the future or use statistical indices like SPEI.

4.2.1. Relevance for the water sector

- The analysis of Framework 1 with respect to its relevance and applicability in the water sector has resulted in highlighting the importance of the terms water use and land use. The impact of increasing water use in the future plays a major role in water management and most importantly in dealing with dry periods and water scarcity. However, changing of land use patterns in the future should not be neglected due to their limited impact on water quantity in the model results – there are also the questions of water quality. The development of strategies for sustainable water use in order to tackle the challenge of water scarcity is of crucial importance. The framework results constitute the base of the development of such strategies.
- Related to the model experiences itself, the used model came out as very applicable in handling different scenarios and ensemble time series. Very important is also the possibility to implement and compare different operating rules linked with given requirements or demands of water.

- A still highlighted challenge is the mentioned problem with the bias between the climate models and the observed data. There is still a need also of better exchange and understanding between both sides of modeler (climate and hydrology). BINGO helped a lot to improve that and set up a needed network.

- Very useful was the exchange, experiences and the testing of communicate uncertainty. To switch from the mostly used deterministic way of planning to a more probabilistic is a very important step to implement in the water sector. BINGO brought the modeler and the stakeholder closer together in understanding the approach and make use of it.

- The results of the modelling in WP3 (and the subsequent risk assessment in WP4) underlined the importance to deal with climate change related risks and the uncertainties for the future. This raise of awareness initiated lively discussions between the relevant stakeholders (not only the local ones) on potential adaption measures and on methodologies how the effectiveness of these adaption measures could be evaluated.

- The modelling itself as well as the modelling outcomes are largely applicable to other water stakeholders dealing with raw water scarcities in reservoirs. Both, the methodology applied as well as the gained results might serve as important input for climate change adaption processes in the water sector. The approach of combining climate and socio-economic factors are now discussed and by giving a good example of implementation in routines will help the water sector in evaluating decision support. The detailed description of the working procedure allows interested stakeholders to apply the process at their research sites in the same way as done in the Wupper case study. Thus it is possible to gain site-specific predictions of climate-change impacts on water availability, allowing a scientifically based decision for or against different adaption measures.

- The work carried out might primarily serve as an impulse for water stakeholders on regional, national and international level to initiate processes to evaluate climate change related risks of water scarcity and the effectiveness of potential adaption measures. Here not the takeover of the exact procedure and methodology is the important point but more the raising of awareness of the existing risks and the need to find suitable, cost-effective and socially-environmentally compatible adaption measures.

- The switch from the deterministic approach to the probabilistic one will be a huge one for the water sector. It means that there will be not just one result (which just seemed to be the "truth") but possibilities of impacts and related measures. Instead of pretending to know the "truth" we have to deal with uncertainties and that requires more flexibility on regulations.

4.3. Outlook

Next steps in the direction of sustainable water management in the catchment area of the Wupper are the following:

- Development of water use and land use strategies not only for the next decade but also for a longer timeframe. For long term amortisation measures like retentions basins - it is useful to extent the procedure from the actually investigated ten years (2015-2024) to a longer period to get more substantial information on potential climate change impacts.

- Re-modelling of the system under consideration of different climate change adaption measures or strategies to enable

- o the evaluation of the cost-effectiveness of the respective measures to enable a scientifically proofed and practical useable decision and weighing process for different adaption measures
- o the determination of the remaining risk under consideration of potential measures
- Raising awareness of policy framework, stakeholders (e.g. from the industrial sector) and private persons.
- Optimize information and commitment strategies for the local and regional stakeholders
- Operationalisation of decadal predictions and derived indices to use them in mid-term planning

4.4. Bibliography

Deliverable D3.1 – Characterization of the catchments and the water systems

Deliverable D3.4 – Model results for water and land use scenarios completed and analysed

4.5. Objectives [FRAMEWORK 2]

The following two objectives, which refer to dry periods at the Dhünn catchment area, are addressed in Framework 2, as described in D3.4:

- Analyse the effects of climate change (here: shifting of precipitation) on the inflow to a reservoir (see Figure 2: shifting to more summer events and the related reduced discharge)
- Analyse the possible variation of the simulated discharge by using all decadal members and learn about the effect of bias correction at different water gauges of the Dhünn catchment area
- Carry out a comparison between a water system (detailed urban drainage, basin control) orientated hydrological model (NASIM) and water balance (more detailed soil processes) orientated model (SWAT) for the catchment area corresponding to GDT inflow (UGD)
- Improve the models in simulating the soil processes and thereby the resulting runoff by using soil moisture measurements (see D3.5) and detailed soil investigations
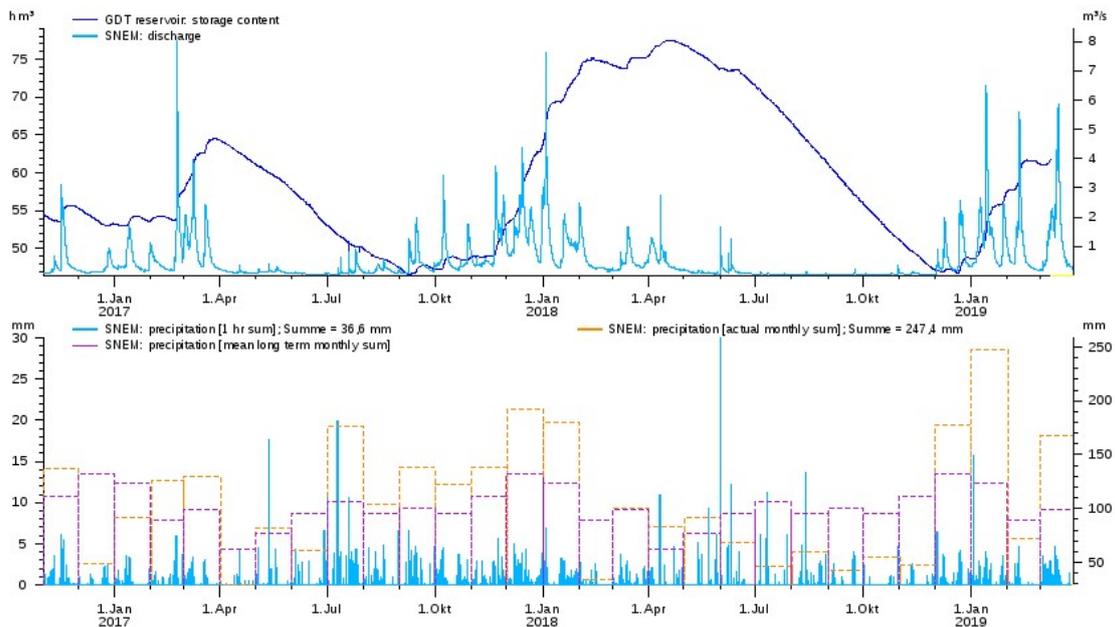
Figure 2. Runoff generation at the "Große Dhünn" reservoir related to season: in summertime only low discharge generation due to losses, despite heavy rainfall

The Dhünn catchment area is described in detail in D3.1.

4.6. Main results

In D3.4 the following outputs compile the main outcome of Framework 2:

-   The comparison between the SWAT and NASIM models showed a good output agreement. This consistency among the two model results indicated the ability of NASIM to capture the hydrological processes and future changes accurately. Hence model uncertainty was considered to be low.
-   Changes (with decreasing tendency) in runoff values were stronger during winter and spring in both models and showed significant differences compared to past runoff rates.
-   Increasing trends in the runoff rates during summer are low. Thus and because it is not observed so far, they were not considered to constitute a significant change with respect to historical data. This outcome is valid for both models.
-   Very good results from soil moisture measurements to improve the knowledge about runoff generation within the different seasons and different initial conditions
-   Standard model parameter are not well covering the soil moisture but can be calibrated by the observations
-   New network techniques (wireless) are enabling us to set up a more spread and thereby representative soil moisture measurement network – also for using it operational

4.6.1. Relevance for the water sector

-   The results of Framework 2 show the applicability and accuracy of both hydrological model in capturing hydrological processes and future changes. That means that in the praxis, both hydrological models could be applied in order to provide information on the impacts on possible further changes in the land use and water use patterns.

- The decreasing runoff values during spring and winter have a significant impact on the whole region, not only on the investigated Große Dhünn reservoir. In winter and spring a high amount of water is important for filling the reservoirs, thus here already one important cause for shortages of water availability can be found. As several more reservoirs for drinking water supply exist within the region and in comparable parts of Mid-Europe, these risks are likely to be transferable to those other reservoirs too. Thus the outcomes of framework 2 show a significant impact also on other water stakeholders in the region.

- The investigated shifting of weather patterns might also have a significant impact on water managers in general, also across the borders of the region. Especially the shifting of rainy and dry periods within a year might necessitate to rethink the existing water management practices in general to adapt to the predicted changes. This is not just an issue at the investigated research site in the Wupper area but of many research sites all over Europe, although the shift of weather patterns might express very different from the one investigated in the Wupper region.

- Therefore, we can learn from the BINGO project how to think impact related instead of just thinking about trends and changes in the forcing input (like temperature and rainfall). Linked to the specific impacts, catchment characteristics and climate changes suitable measures can be derived

4.7. Outlook

- The gained experiences and improved knowledge and tools show very good capabilities to support the planning and maintaining processes operational. Therefore the tested data set of decadal ensembles (2015-2024) should be implemented into the workflow continuously

- Also the field work shows very good benefits. Based on the first experiences the sensor network is enlarged and should also transferred to areas where flashfloods occur (framework 3).

- The results within BINGO helped a lot to communicate cause and impact. The tested method should be standardized.

4.8. Bibliography

Deliverable D3.1 – Characterization of the catchments and the water systems

Deliverable D3.4 – Model results for water and land use scenarios completed and analysed

4.9. Objectives [FRAMEWORK 3]

For Framework 3, which refers to extreme precipitation events and consequent flash floods, the model objectives are the following, as described in D3.4:

- Simulate future extremal episodes (downscaled in spatial and time scale) in order to determine if obtained discharge exceeds thresholds which are known damage causing at different hotspots for a typical catchment within the Wupper region (Mirke Creek) and if the actual trend (rising occurrence of flash floods) is confirmed for the whole decade

- How applicable is the available data to model convective events

- Determine the impacts of anthropogenic influences such as land use on a dense sealed catchment area

A detailed description of the Mirke Creek is included in D3.3.

4.10. Main results

The main results from the analysis of Framework 3, as described in D3.4, are the following three:

- Changes in the land use changes and particularly expected changes in the sealing degree for the next decade did not seem to have a significant impact on surface runoff formation for the Mirke Creek catchment area, based on the available data.
- To model convective rain storms - which forces flash floods – cannot derived from a spatial distribution of 12 km (see Figure 3). The small-scale structures are smoothed by the averaging procedures. Higher resolutions like the 2.2 km are needed. Also, the distribution in time must be subdaily (differently to framework 1 and 2).
- The amount of input data is hard to handle. By downscaling the data the computation time is rising rather high (not possible with every computer) and there is a need for some compromises, like only selecting the extreme event as a series above a defined threshold.
- Cause the forced discharge is driven by the initial conditions and predicted rainfall there is a need for some assumptions
- By using threshold instead of proportional trends of the driving forces a direct link to expected damage values (impact) is possible
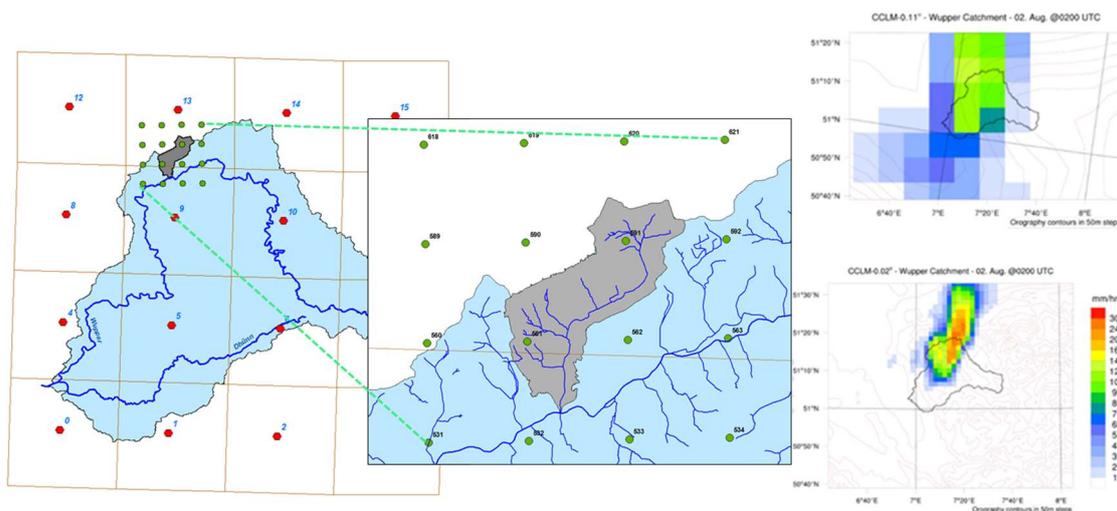
Figure 3. Distribution of the used (downscaled) data in relation to the tested catchment (left) and an example for the same event in 12 (top) and 2.2 (below) km distribution which shows the smoothening of the structures (right: source FU Berlin)

4.10.1. Relevance for the water sector

- With respect to retrieving information from the simulation of extremal episodes and its application in the practice, the results of Framework 3 show the importance of the accurate representation of convective extremal episodes. Gaining reliable simulation results for rainfall episodes of this nature is of major importance. It is essential that more focus is placed in this direction.
- The methodology for the determination of flood risks considering different climate change scenarios is largely adaptable to other research sites. In contrast, the results and consequent conclusions of the modelling are not easily transferable to other research sites as for each research site the conditions and modelling inputs might differ significantly. Thus conclusions like the minor impact of

increased sealed area are not transferable without restrictions. However, the modelling methodology itself is very promising to be used in different case studies all over Europe.

- The method to use thresholds instead of the probability of occurrence is relevant to communicate risk. To show the direct impact support much better to arise awareness and the motivation to implement measures. With the direct link to costs, a cost-effectiveness analysis is possible. This procedure is transferrable to every risk for all over Europe

4.11. Outlook

- It is useful to extent the procedure from the actually investigated ten years (2015-2024) to a longer period to get more substantial information on potential climate change impacts.
- At the moment the evaluation of different adaption measures to reduce existing flood risks, based on the results from WP3 (this and previous reports) for the different hotspots is ongoing.
- Included is the analysis of the cost-effectiveness of different potential adaption measures, both for the case of the current situation as well as under consideration of climate change (longer period)

4.12. Bibliography

Deliverable D3.3 – Calibrated water resources models for past conditions

Deliverable D3.4 – Model results for water and land use scenarios completed and analysed

4.13. Objectives [FRAMEWORK 4]

After the extreme events of May – June 2018, Framework 4 was implemented for the case study "too much water". The model objectives are the following, as described in D3.4:

- Determine whether the simulation with different ground precipitation and rain radar data captured the flood events, caused by convective rains
- Determine the effect on the statistical design values before and after the extreme event and the values for the available decadal prediction
- Determine the impacts of anthropogenic influences such as land use on a dense sealed catchment area for two decadal members (maximum and minimum)

A detailed description of the Leimbach catchment area is included in D3.4.

4.14. Main results

Based on the result analysis presented in D3.4 of Framework 4, the following points summarise its main outcome:

- The obtained results from the simulation with data from both available ground stations present either overestimation (for some events significantly strong) or underestimation of the discharge of that catchment – which shows the highly small-scale distribution of the rain cells.
- Therefore one of the two ground data time series are representative for the simulation of the analysed flood events, due to the convective nature of the extreme precipitation that characterised those events.

- The analysis of the radar data demonstrated that local nature of the three events and helped to better simulate it
- Although R1 displayed the highest accumulated volume, peak discharges were observed more often in the future scenarios forced by R9.
- Statistical design values are very sensitive to single extreme events and to be sorted in very carefully (see Figure 4)
- The soil wetness (initial conditions) is a highly sensitive parameter even in urban areas. The first event was extreme (80 mm in one hour over the whole catchment) but still caused only 25% as a discharge coefficient at the gauge due to low antecedent precipitation (6 mm for 30 days). The following events were forcing more discharge or effective precipitation (see Figure 5)
- With respect to the results of the simulations with decadal members, the higher accumulated volume as well as the highest deviation with respect to the current state corresponds to economy first.
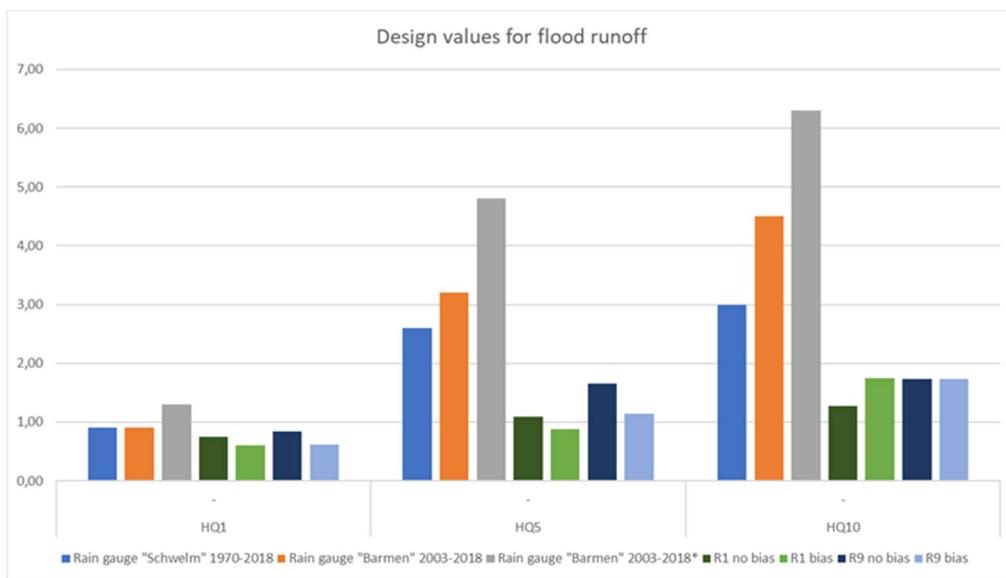
Figure 4. Statistical design floods with different ground stations – station "Barmen" before the event (orange) and after (grey) and values within the ten years of simulation derived from the decadal ensembles (R1 and R9)
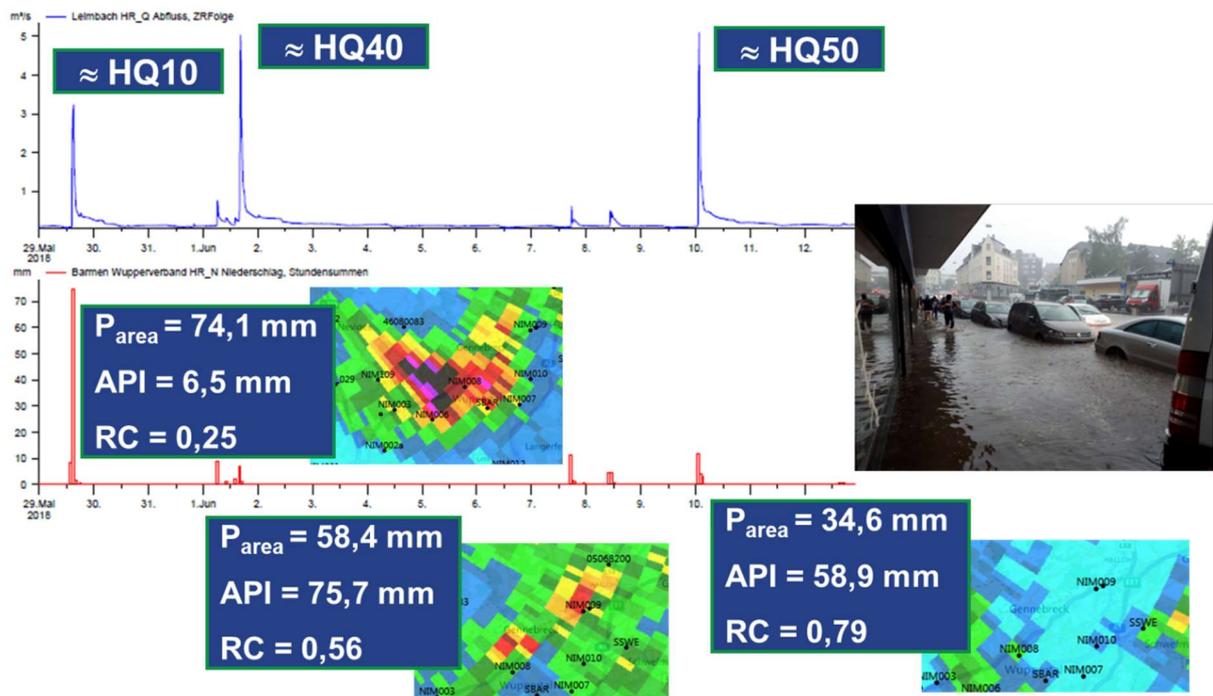
Figure 5. Ten days with 3 consecutive events and their different catchment reaction

4.14.1. Relevance for the water sector

- Framework 4 provides some insights with respect to dealing with ground station and radar data when it comes to local events of convective nature. The lesson learned from the analysis of Framework 4 is the fact that the use of radar data provides needed information regarding heavy rainfall of local nature.
- Soil moisture is highly relevant even in urban areas – sensitivity studies are necessary to analyze events and develop realistic scenarios for risk management
- Impact driven procedures are necessary to develop communication strategies with understandable risk definition (like Beaufort classes)

4.15. Outlook

- From the experiences standard procedures had to develop and define to make widely understandable and comparable risk definition

4.16. Bibliography

Deliverable D3.4 – Model results for water and land use scenarios completed and analysed

5. The Netherlands

5.1. Objectives

The Veluwe research site (ca. 1 250 km²) is located in the centre of the Netherlands and consists of ice-pushed moraine and fluvio-glacial complexes. It is an elevated sandy area, which contains a large aquifer of fresh groundwater. Most of the area is designated nature reserve and land use mainly consists of forests (predominantly pine), heather and drift-sand. Due to the expanse of the area and its large unsaturated zone, the groundwater system responds slowly to changes in meteorological conditions. Brooks and streams are found at the fringe of the sandy area, where water exfiltrates. Upward seepage also occurs in surrounding lower lying agricultural areas. No large drainage systems or surface water bodies exist in the central part of the area. A complete description of the site including historical information can be found in D3.1.

Precipitation shifts from summer to winter are expected in the future, combined with increased evapotranspiration demands in summer due to higher temperatures (KNMI 2014). This can lead to longer and more intense dry spells occurring more often across the Netherlands (KNMI 2014). These dry spells can pose a threat to the drinking water supply as well as to other land use functions, in particular agriculture and nature. In these circumstances the large groundwater body of the Veluwe becomes even more important. Groundwater abstractions from this area would then be increased. It is important to manage the groundwater system in a sustainable way to ensure enough water for the drinking water supply, and groundwater dependent nature and agriculture at the fringe of the Veluwe. Both land use and climate control the water balance of the Veluwe area. We evaluated the effects of land use and climate change on water resources of the Veluwe area and related functions within the BINGO project. This was done by analysing simulations with the AZURE groundwater model (D3.3 and D3.4), but also by performing measurements in the field. The model objectives of this research are to quantify the effect of climate and land use changes for i) historical conditions (Nijhuis 2017), ii) the recent past (1980-2015, D3.3), and iii) the near future (2015-2025, D3.4). The measurements in the field of actual evapotranspiration were used to adjust the evapotranspiration calculations in the AZURE model (D3.5). The model results give an indication of changes in the groundwater at the Veluwe in historic perspective and in the future as well as the effect of potential adaptation measures like land use change.

5.2. Main results

Field measurements

The measurements at the lysimeter station at the Veluwe of actual evapotranspiration of heather were used to adjust the evapotranspiration calculations in the groundwater model AZURE. A land use type 'heather' was added and the soil evaporation for dry nature was adjusted. This led to simulated evapotranspiration values that were more in line with literature and the measurements. A detailed description can be found in D3.5.

Historical conditions

Results from the analysis of historical conditions are described in Nijhuis (2017) and Nijhuis et al. (2018), here a short summary will be given. Based on historical maps and data, the land use of the Veluwe was

determined for 1850, 1900, 1960 and 2008. Considerable changes occurred in the period 1850-2008 with decreases in heather (-30% of the total area) and in drifts sands (-26% of the total area). These land use types were replaced with pine forest, which covered 44% of the total area in 2008. Measured meteorological data (temperature and precipitation) were available from the region close to the Veluwe from 1850. Both precipitation and temperature increased from 1850 to 2008. Potential evapotranspiration was derived from these data. To estimate the actual evapotranspiration, a Hydrus-1D model was used. The actual evapotranspiration increased with 175 mm/y between 1850 and 2008 (Figure 6). This increase is mainly caused by the land use changes. When land use changes are not taken into account (e.g. land use for 1850), actual evapotranspiration increased with only 25 mm/y (Figure 6). The increase in pine forest dominates the increase in actual evapotranspiration. The changes in actual evapotranspiration affect the groundwater recharge (Figure 7). Besides the evapotranspiration, groundwater abstractions also impact the groundwater levels. Groundwater levels were estimated from a linear model based on recharge, taking into account discharge from streams and groundwater abstractions, and groundwater mounding. Groundwater levels decreased from 1850 due to land use change and water abstractions (Figure 7). Land use change caused the largest decrease in groundwater level.
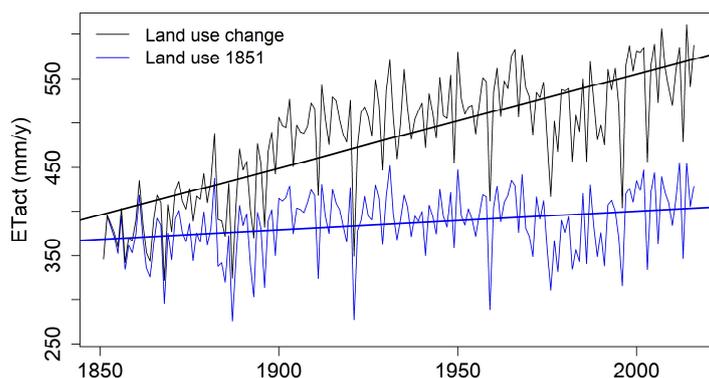
Figure 6. Actual evapotranspiration for the Veluwe over the historical period for scenario with changes in land use (black) and scenario with land use from 1851 (blue).
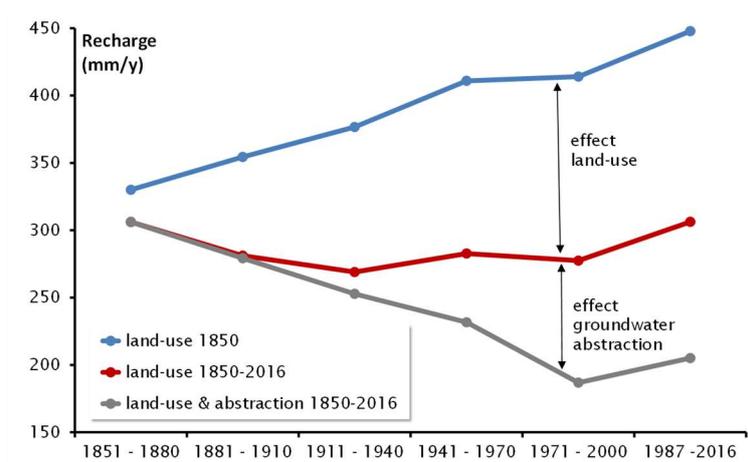
Figure 7. Groundwater recharge for the historical period based on three different scenarios: scenario with ETact based on land use 1850, scenario with actual evapotranspiration (ETact) based on actual land use, scenario with ETact with actual land use and including groundwater abstractions.

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Recent past

We have simulated the groundwater levels at the Veluwe with the groundwater model AZURE. The AZURE model was calibrated in 4 different stages on data of groundwater observation wells and on outflow data from 1995 to 2005 of different polder areas. Groundwater levels of the calibrated AZURE model are on average 20 cm lower than observed. Deviations are larger for elevated areas, and lower at the ridges of the ice-pushed moraine. The simulated dynamic range (the variation between the minimum and maximum groundwater heads) is on average 8 cm larger than the observed dynamic range. For the greater part, the residuals after calibration show a normal distribution. However, there are also clustered deviations, especially for elevated areas where simulated groundwater heads are too low. More detail can be found in D3.3. Considering the complex hydrogeological system, we are satisfied with the model performance. With the exception of observation wells in elevated areas, most observation wells show a good agreement with the observed groundwater head.

Near future

The effects of climate, land use and water use changes for the near future (2015-2024) on water resources were studied in D3.4. Here we give a short summary of the main results. The meteorological data for 2015-2014 were taken from MiKlip forced decadal predictions (D2.2). The data consisted of a bias-corrected dataset for the period 1980-2015 and an ensemble of ten decadal predictions for the near future Average groundwater levels in the near future (2015-2024) were compared with the average levels in the reference period (1984-2014). Five locations were selected to show the development of the groundwater levels over time. Model simulations were done with 3 climate ensemble members (wet, intermediate, dry), 2 land use scenarios (Sustainability eventually and Economy First), and 2 water use scenarios. These scenarios are described in D3.2.
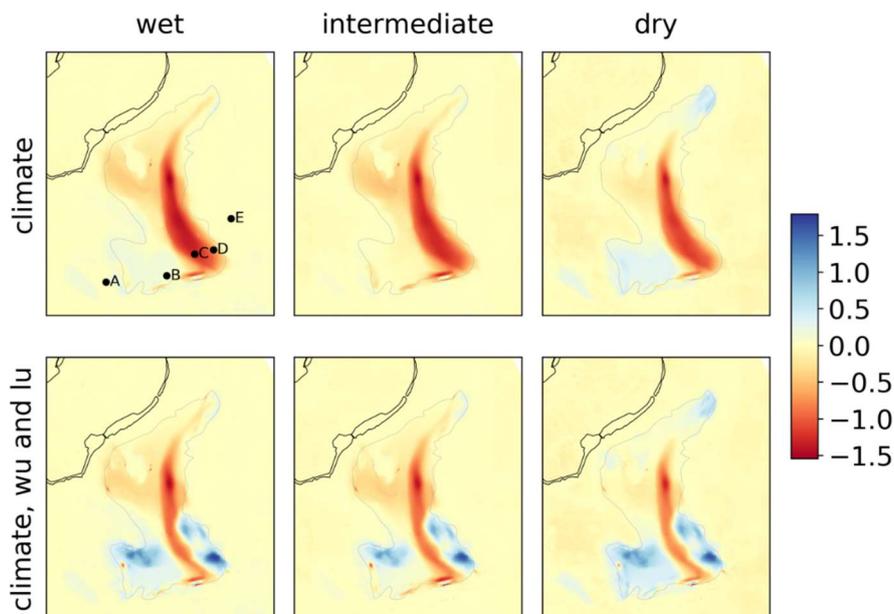
Figure 8. Changes in mean groundwater head (m) between the near future (2015-2024) and the reference period (1984-2014) for the three climate ensemble members without changes in land use and water use and with change in land use (lu) and water use (wu). The grey line indicates the area of the Veluwe.

Most parts of the Veluwe showed a decrease in mean groundwater level for all three climate ensemble members (Figure 8). The last part of the reference period (2005-2014) was relatively dry and caused a sharp decline in groundwater levels (Figure 9). The groundwater levels did not recover completely during the near future period, especially in the highest parts of the Veluwe. Therefore, mean groundwater levels in those areas decreased in the near future, even though groundwater levels at specific locations increased during the near future period. The response of the elevated parts of the Veluwe to the three ensemble members (dry, intermediate, wet) was fairly similar, except for an increase in groundwater levels in some regions in the dry ensemble member (Figure 8). All ensemble members showed a similar interannual variability, whereby wet and dry years alternated between the ensemble members. In order to see the long-term effect of climate change on the Veluwe, the model simulations have to be expanded towards the far future. The low-lying agricultural regions next to the Veluwe did show a difference in response between the ensemble members with decreases in groundwater levels for the dry ensemble member that did not occur for the wet ensemble member. In contrast to the elevated areas, these low-lying regions are thus prone to water shortages, especially in summer.

At some of the five selected locations (located at higher elevations) and parts of the elevated areas, the dry ensemble member gave higher groundwater levels by the end of the near future than the other ensemble members (Figure 8). The uncertainty in potential and actual evapotranspiration and the distribution of the precipitation over the year could be an explanation for these results. When soil moisture is limited, the soil will not be able to deliver enough water to meet the demands of the higher potential evapotranspiration in the dry ensemble member. This phenomenon especially occurs in the elevated sandy regions. In combination with higher winter precipitation, this reduction in evapotranspiration will lead to higher recharge compared to the other ensemble members. The dry ensemble member had the lowest recharge values in the near future, but precipitation mainly occurred in winter. The amount of precipitation in winter is thus very important for the recharge of the groundwater reservoir.

The changes in land use in the Economy First scenario had a large effect on the groundwater heads across the southern part of the Veluwe (Figure 8 and Figure 9). Groundwater levels increased due to reduced evapotranspiration and the associated increase in recharge.

Over a large region of the Veluwe and the surrounding low-lying agricultural areas, the impact of changes in climate dominates the response of the groundwater level. These regions could therefore be vulnerable to water shortages. In regions closer to areas where land use changes were applied, the effect of the land use changes determines the future changes. The impact of water use changes was limited compared to the land use changes and mainly concentrated to regions around the groundwater abstraction wells. However, in these regions groundwater levels decreased, especially when no land use changes were applied. Therefore, increasing abstractions could damage nature areas at the fringe of the Veluwe and reduce agricultural productivity in surrounding agricultural areas.
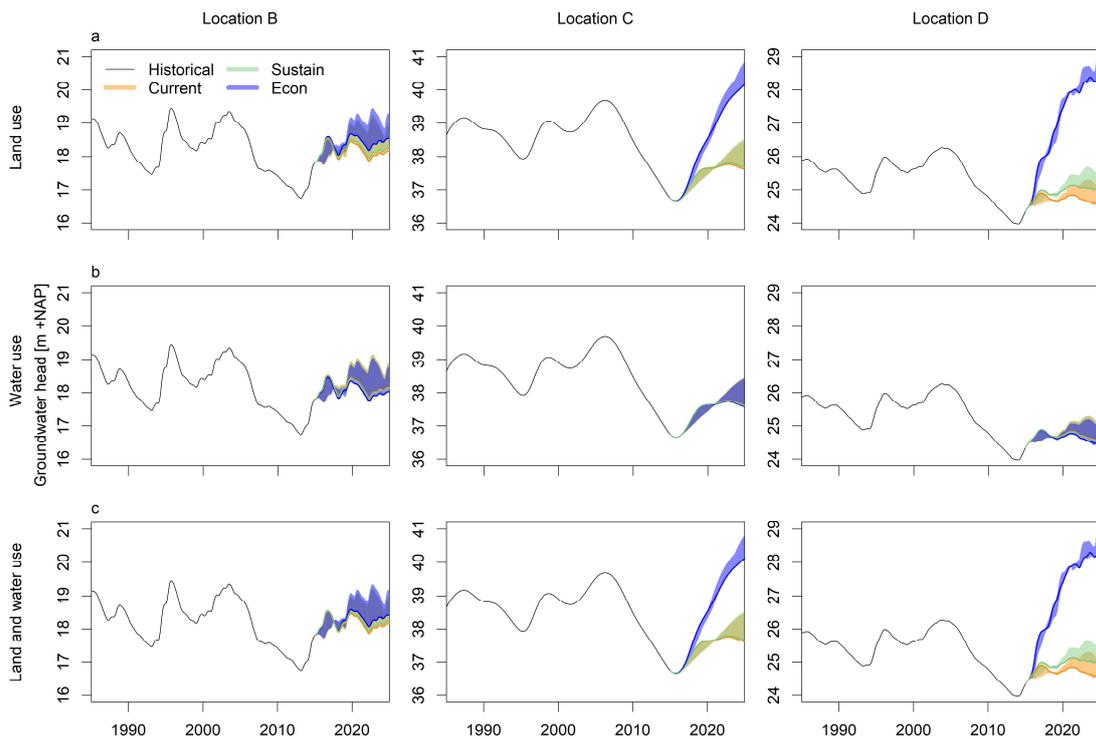
Figure 9. Groundwater heads for locations B, C and D for, a) land use scenarios (current land use, Sustainability eventually, Economy first), b) water use scenarios, and c) land and water use combined scenarios. 'Historical' refers to the reference period. The colour range indicates the range resulting from the different climate ensemble members, the lines show groundwater levels from the intermediate ensemble member.

5.2.1. Relevance for the water sector

The model framework used in the BINGO project provided the stakeholders with information about the effects of changes in climate, land use and water use on the groundwater levels at the Veluwe based on historical results and projections for the near future.

The field data were used to evaluate the simulated evapotranspiration values from AZURE and to adjust the model parameters based on this evaluation. The accurate simulation of the evapotranspiration is very important for the Veluwe, because the evapotranspiration directly influences the groundwater recharge. The field data provide important information to the stakeholder partner Vitens to assess their model and adjust it accordingly.

The information provided about the effect of climate change at the Veluwe in combination with a drought that occurred in the Netherlands in 2018, which also impacted the Veluwe area, has increased the awareness of stakeholders. The BINGO results have made it clear that not only drier conditions in summer can be expected in the future, but also increases in precipitation during the year leading to wetter conditions. This means measures have to take both extremes into account.

Based on the model results, potential measures were identified, which were also analysed during the BINGO project. One of these measures, for example, is changing the land use at the Veluwe. The historical analysis and the projections for the near future provided information about the expected changes in actual

evapotranspiration and groundwater levels following this measure. This could impact the management of the Veluwe area in the future.

Besides the potential of the results for identifying measures that impact the management of the Veluwe area, the results are also valuable for the drinking water company at the Veluwe (Vitens). The results are used, for example, to determine possible locations for a replacement of one of the current drinking water abstraction wells. The information provided is also important for Vitens to identify additional strategical water reserves for drinking water.

The involvement of the drinking water company Vitens and the stakeholder Province Gelderland within BINGO made it possible to select model simulations that were directly linked to relevant water management questions. All model simulations were done by Vitens, which means that the results can immediately be used for implementation. The cooperation within BINGO ensured a close link between science and practice.

5.3. Outlook

Based on the results within the BINGO project, several next steps to improve the understanding of the Veluwe system and the groundwater model framework can be taken:

- Analysis of the data collected during the experiment at KWR (D3.5) on transpiration and rainfall interception of trees. These data can be used to evaluate the simulated evapotranspiration values similar to the analysis done for heather.
- An outlook into changes to the groundwater at the Veluwe has been given for the near future. Due to the slow response of the Veluwe, however, it is important to expand the outlook towards the future with model simulations till 2050 to get a better understanding of the effects of changes in climate.
- During the BINGO project, only selected output variables from the AZURE model were recorded for all simulations, because of the computational effort that was needed to provide all relevant variables over a longer period. It was, for example, not possible to evaluate the simulated evapotranspiration values over a period longer than two years. Improving the computational efficiency of the model would make it possible to gain more insight into the Veluwe system and study other variables besides groundwater levels.
- The rooting depth values in the AZURE model could have a large influence on the simulated evapotranspiration. Compared to field observations the rooting depths in the model are shallow. Large trees across the Veluwe did not show damage from water stress during the drought in 2018, while the rooting depth in the model would lead to transpiration reduction. Remote sensing images could provide more detailed information about the drought response of the vegetation. This can be used to evaluate the model results.
- In general, the results indicate that the AZURE model could still be improved, especially the simulation of the fluxes to the surface water and the resolution of the model (currently 250 by 250 meter).

5.4.   Bibliography

KNMI (2014). KNMI'14 climate scenarios for the Netherlands; A guide for professionals in climate adaption. De Bilt, The Netherlands, KNMI.

Nijhuis, K. (2017). Historisch landgebruik van de Veluwe in hydrologisch perspectief. MSc internship. Nieuwegein, KWR Watercycle Research Institute.

Nijhuis, K., B. Voortman and J. P. M. Witte (2018). "Effecten van historische landgebruik op de waterbalans van de Veluwe." De Wijerd 39(1): 22-26.

6. Norway

Model frameworks (as overview)

The city of Bergen is known for its generous rainfall amounts. The climate is usually mild and wet putting much strain on the city's infrastructure to capture and safely transport stormwater. At the same time, the city has experienced drought incidents threatening the reliability of the city's water supply. The outlook for future precipitation patterns is of high interest to the Municipality in Bergen in order to plan for a sustainable stormwater management and drinking water supply. Thus, the research objective has been two-fold, covering both stormwater management and water supply. Two model frameworks for 1) urban drainage and 2) drinking water availability have been used in order to address this. Sections 6.1-6.4 cover the first model framework, which is a SWMM model built for the Damsgård city-area in Bergen. The model comprises a hydrological routine for surface water coupled with a hydraulic model of the combined sewer system in the area. Further sections, 6.5-6.8, cover the second model framework for drinking water supply, which include hydrological models of reservoir inflow and a hydrological routing for water storage estimations. Both model frameworks are briefly described in the following sections, but the reader is referred to BINGO D3.1 for detailed catchments descriptions, BINGO D3.3 for complete model descriptions and calibration strategies, and finally BINGO D3.4 for presentation and analyzes of simulation results.

6.1.   Objectives [Urban drainage]

The Damsgård area is located at the foot of Mount Løvstakken close to the city center and is characterized by its steep slopes. A combined sewer system handles the stormwater generated in the urban area and the upstream mountain. CSOs are present in the downstream parts of the system, discharging mixed stormwater and sewage to the subjacent fjord, Puddefjorden. The areas close to the fjord are undergoing a large transition from being dominated by industrial activities to new housings, public spaces and increased leisure activities in and around the fjord. In order to achieve a holistic urban development and upgrade of the area, the municipality wish to address the issue of CSOs such that pollution to the fjord can be minimized. For this purpose, a SWMM model of the drainage network has been set up. The CSOs were simulated and analyzed using 10 scenarios of decadal precipitation predictions for the period 2015-2024 prepared by the FUB in the BINGO project.

6.2.   Main results

Stormwater and CSO are quick hydrological responses to rainfall events in urban areas. This requires a fine-scaled model time-step. Due to this, the SWMM model was set-up and run at a temporal resolution of 5 minutes. Thus, the simulations performed covered 10x10 years of continuous series at a 5 minute time step. The results of the simulations are thoroughly described in BINGO D3.4 and can be summarized as following:

- The predicted precipitation is substantially increased compared to long, historic records of observations in Bergen. They are, however, in agreement with observed trends of precipitation increase and not considered unrealistic for the site.
- Due to increased precipitation, an increase in CSO is also projected, both in terms of number of CSO occurrences, volume discharge, and active hours of the CSOs.

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- The magnitude of the increase varies across CSOs and the most problematic CSOs has been identified and located.
- The simulated CSO is linked to higher risks and negative impacts on aquatic leisure activities, the marine environment and the public's trust in the municipality.

6.2.1. Relevance for the water sector

The work performed in WP3 of the BINGO project has produced results helpful to the water management in the Damsgård area in three categories:

- Model development
- Simulation strategies / model execution
- Decision-support

Model development

The municipality lacked a model of the drainage network in the Damsgård area. Since the model has been set up using the SWMM environment, the municipality now have access to a model that does not depend on costly software subscriptions. The model is also set up in such a way that it easily can be coupled with the municipality's own models of surface water (floodings) and drainage lines.

Large drainage system models usually requires large amounts of observations in order to be properly calibrated. To combat this when building the Damsgård drainage model, a calibration routine based on parameter regionalization was developed (BINGO D3.4, Mittet 2017). The methodology can be useful to other sites facing similar calibration challenges.

Simulation strategies / model execution

Running 10x10 years of 5 minute time-step resolution for a large drainage system is a demanding task and expensive in terms of the knowledge level, human resources and computer power required. In addition, the applied software SWMM pose some barriers, such as run time, storage constraints and limitations to number of open files (among others). In order to be able to run the high-resolutions simulations some recompiling of the SWMM source code and subdivision of modeling tasks were necessary. This involved 1) increasing the number of files that are allowed open at a time, and 2) separate the hydrological routine from the hydraulic routine and run them independently.

One of the key take-away's from this, is that although long-term continuous simulations of urban drainage systems are not so common, it is fully possible. It does, however, require expert knowledge both within the field of hydraulics/hydrology and data science (due to e.g. modification of software source code etc.). In Norway, this skillset is not the most common, although it might be in the future. The practical value for stakeholders is therefore debatable when the model is needed specifically for long-term, high-resolution and continuous simulations. It is expected that the built model will have more applied value to the stakeholder if used for event-based simulations.

Decision-support

Model simulations resulted in long-term projected time-series of CSO at the Damsgård research site. This provides a unique opportunity to study the timing, frequency, magnitude and severity of CSO events given projections of a future climate. By assessing this within risk management frameworks, a solid and detailed

decision-support is provided. On this basis, concretized solutions and strategies for minimizing and treating the identified risks can be developed.

6.3. Outlook

As described, the results of the modelling work in Workpackage 3 of the BINGO project provide a good basis for suggesting climate adaptation measures and strategies. Running such scenarios of adaptation options is part of ongoing work within the BINGO project. Furthermore, the model should be coupled with aforementioned surface models held by the municipality and stakeholders should be trained in using the model for continuous and event-based simulations.

6.4. Bibliography

BINGO D3.1

BINGO D3.3

BINGO D3.4

Mittet, Jonas. "A regionalisation technique for urban ungauged catchments-A case study from Norway." Master's thesis, NTNU, Trondheim, Norway, 2017.

6.5.   Objectives [Water resources]

The city of Bergen experienced a winter drought 2009/2010 that raised questions with regards to the city's water supply safety and coverage. It was therefor included as an objective in the BINGO project to investigate the risk of similar droughts under climate change. Since then, Bergen K has increased their storage potential substantially and, by this, coped with the issue already. The modelling objectives in the BINGO project has thus been limited to project future water availability under climate change using existing models of the water resource network in Bergen. The existing model framework consists of HBV-models for reservoir inflow to the surface waters comprising the water supply in Bergen and a simple hydrological routing for projection of future water availability (Kristvik and Riisnes 2015).

For a detailed description of the catchments and water supply system in Bergen it is referred to BINGO D3.1 while BINGO D3.3 presents the modelling framework used.

6.6.   Main results

As described in Section 6.2, the precipitation projections for Bergen in the period 2015-2014 show a clear increase. The projected temperatures are mostly more stable and similar to current climate (BINGO D3.4). Along with scenarios of water demand for the same time-frame, this gave the following main result when simulation future water availability:

- Generally increased inflow for all seasons except for a few scenarios during summer months
- The minimum storage reserve observed in the simulation amounts ~92% of the total storage capacity
- The projected water supply in Bergen is reliable and well covered despite of increased water demand caused by population growth and leakages in the distribution network. The main reasons for this are 1) increased inflow to reservoirs, and 2) better ability to save water to dry periods due to increased storage capacity.

6.6.1. Relevance for the water sector

The municipality in Bergen has been provided with a framework for assessing future water availability given different scenarios for climate change and water demand. Through simulations, and analyzes of such, they have confirmed the reliability of their system. The frame-work is easy to use and adaptable to other research sites facing similar challenges.

6.7.   Outlook

Because of the limited focus on the water resource within the BINGO project, further analyzes and use of the water resource simulations was outside the scope of the project. The analyses and framework provided is, however, ready for use if further stress-testing of the system under different climate, water demand and adaptation scenarios becomes necessary in the future.

6.8.   Bibliography

BINGO D3.1

BINGO D3.3

BINGO D3.4

Kristvik, Erle and Riisnes, Birthe. "Hydrological Assessment of Water Resources in Bergen - Climate Change Impacts". Master's thesis, NTNU, Trondheim, Norway, 2015.

7. Portugal

Model frameworks (as overview)

The Portuguese contribution to the BINGO objectives of testing different systems' vulnerabilities to climate change is fourfold:

1. Test climate change impacts in the Tagus estuary bordering lands where expected sea level rise, possibly associated with more frequent storm surges, and salt water intrusion are the driving forces;

2. Determine how potential reduction in aquifers recharge and, in coastal lowland areas, possible saltwater intrusion, may reduce the availability of groundwater to agricultural uses and water supply;

3. Estimate how vulnerable communities will become to increase floods frequency and magnitude in urban areas;

4. Assess how the potential changes in surface water flow regimes will jeopardize the current and future planned water uses.

7.1. Objectives [Tagus estuary]

With a surface area of about 320 km^2, the Tagus estuary is one of Europe's largest estuaries (see D3.1 for details, Figure 10). Two main problems in the Tagus estuary are tackled in BINGO: i) the inundation of rich agricultural lands by the combined action of tides and storm surges; and ii) the salt water intrusion in the upper reaches of the estuary where a major water intake for irrigation is located (Conchoso). Both problems can have negative social, economic, and environmental implications, and can potentially be aggravated by climate change (e.g., through sea level rise or reduced river flow).

For each of these two problems, we aimed to: i) implement, calibrate and validate appropriate process-based models; iii) use these models to characterize the present conditions, in particular extreme events; and iii) determine how the conditions will change in the near future.

Figure 10. General overview of the Tagus estuary and detailed view of the Lezíria Grande de Vila Franca de Xira Public Irrigation Perimeter.

7.2.   Main results

Inundation by tides and storm surges

The shallow water model SCHISM, including its wave module WWM, was implemented, calibrated and validated in the Tagus estuary in 2D depth-averaged mode. Extensive comparisons with field data showed that the model has an excellent accuracy, with elevation errors on the order of 10 cm (D3.3, D3.5, Fortunato et al., 2017). This accuracy was considered adequate to analyze inundation of the margins under extreme events.

The worst storm to hit the Tagus estuary since the beginning of the 20th century occurred on February 15, 1941. This storm was devastating in the Iberian Peninsula. In the Tagus estuary, it caused tens of casualties and sunk 150 ships. It was therefore used to characterize the present hazard in the estuary. A detailed description of the model application and the results is given in D3.4 and Fortunato et al. (2017a). Two scenarios were considered: 1) the same atmospheric, riverine and oceanic conditions that occurred in 1941; and 2) the same atmospheric and riverine conditions as in 1941, but combined with a major spring tide. In both cases, the bathymetry and configuration of the margins were the present ones. Inundation maps for the two scenarios indicate that dikes can be overflown and extensive areas can be inundated (Figure 11).
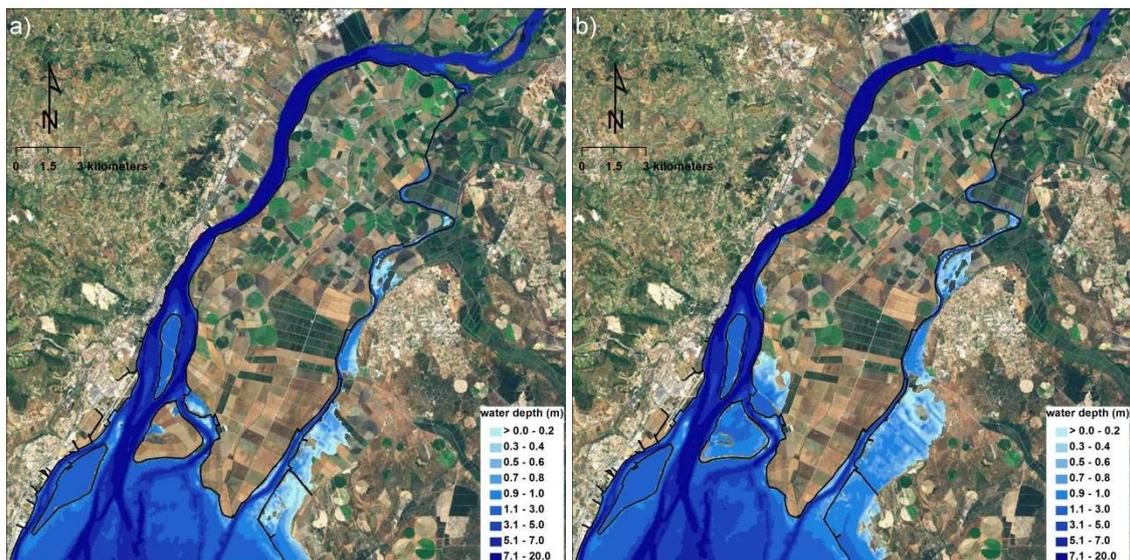
Figure 11. Inundation of the upper Tagus estuary for the 1941 storm: a) extreme surge scenario; b) worst case scenario, obtained by combining the 1941 storm with an extreme spring tide. Extracted from Fortunato et al. (2017a).

Finally, decadal predictions were used to assess how storms (hence inundation) may or may not change in the near future in the Tagus estuary region. This study is described in detail in D3.4 and Fortunato et al. (2018). Extreme value statistics were performed on multi-decadal time series of both atmospheric pressure and storm surges along the Atlantic Iberian coast, thereby extending the geographic extent of the analysis. Results (Figure 12) indicate that there is no evidence that storm surges will change significantly in the vicinity

of the Tagus estuary in the coming years. We conclude that the inundation hazard will only increase marginally, due to sea level rise.
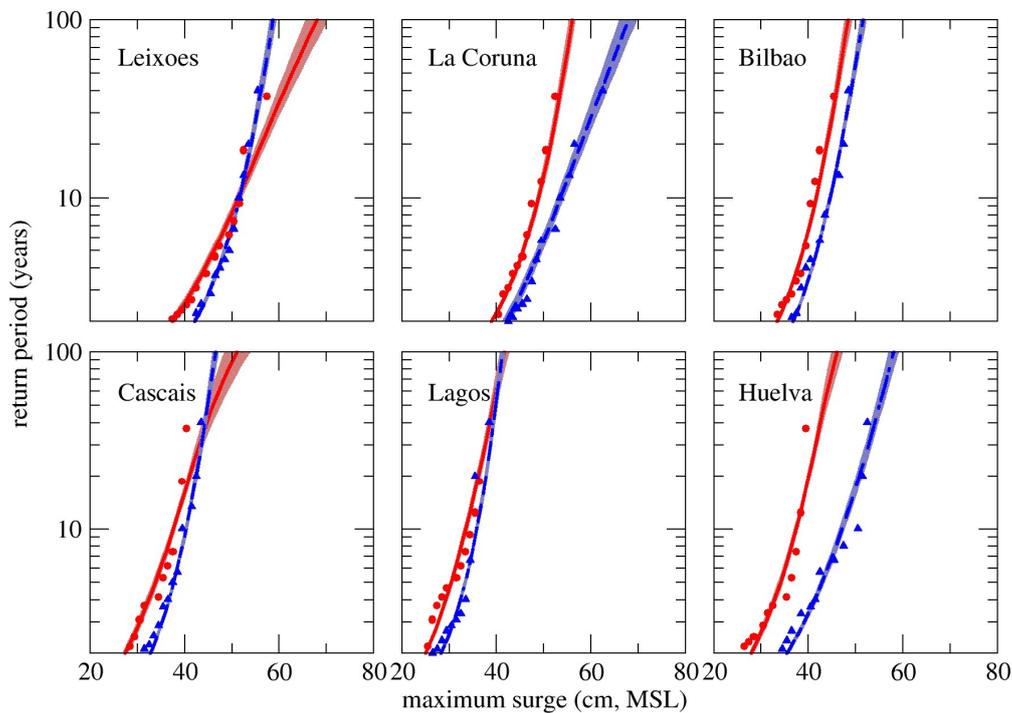
Figure 12. Changes in extreme storm surges at selected stations between the present (1980-2016, circles and solid lines) and the future (2021-2024, triangles and dashed lines). The symbols represent the empirical distribution law, and the lines are adjusted GEV functions. The shaded areas represent the 95% confidence limits, obtained by bootstrapping with replacement (extracted from Fortunato et al., 2018).

Salinity intrusion

The three-dimensional model of the Tagus estuary was implemented using the system of models SCHISM. The numerical model is forced by tides at the oceanic boundary, river flows at the riverine boundaries (Tagus and Sorraia) and atmospheric data at the surface. A detailed description of the model implementation and validation can be found in D3.3 and Rodrigues and Fortunato (2017). The model was then used to characterize the present and near-future conditions for droughts (see D3.4 for details and Table 2).

Preliminary validation assessments suggested that the model tends to overestimate the salinity intrusion in the upper reaches of the estuary and that the errors in the river flow data used to specify the boundary conditions constitute a major source of uncertainty in the model results (see D3.4 and D3.5), which should be taken into account when analyzing the results.

Results (Figure 13 and Figure 14) suggest that for climatological conditions salinity does not reach the Conchoso water intake, which is consistent with empirical knowledge. For conditions similar to the worst recent drought (2005, mean river flow in July estimated as 22 m³/s), salinity reaches about 10 at Conchoso and exceeds the thresholds acceptable for irrigation, which is consistent with testimonies from the stakeholders and provides confidence in the results. For lower river flows, salinity increases significantly and potentially aggravates the consequences for agriculture. At Rio do Risco, the salinity exhibits very little tidal oscillations and is similar to the minima observed at Conchoso at each tidal cycle, which suggests that the

same water mass sloshes back and forth, with small exchanges with the Tagus River. However, creating an alternative source for water irrigation in this area would not solve the water shortage problem during a drought since this water mass is fairly small and would probably only provide water for less than a week (see D3.4 for details). The tidal signal present in the salinity time series suggests that, under drought conditions, water should only be abstracted from the main water intake at low tide, in order to provide fresher water. Results also show that salinity intrusion in the upper estuary depends not only on the river flow alone, but also on the duration of the droughts since the tidally-averaged salinities display a rising trend.

Table 2. Summary of analyzed scenarios.

| Scenario	River flow (m³/s)
S0,climatological	132
S1, worst recent drought	22
S2, minimum river flow	16.5
S3, worst case scenario	8
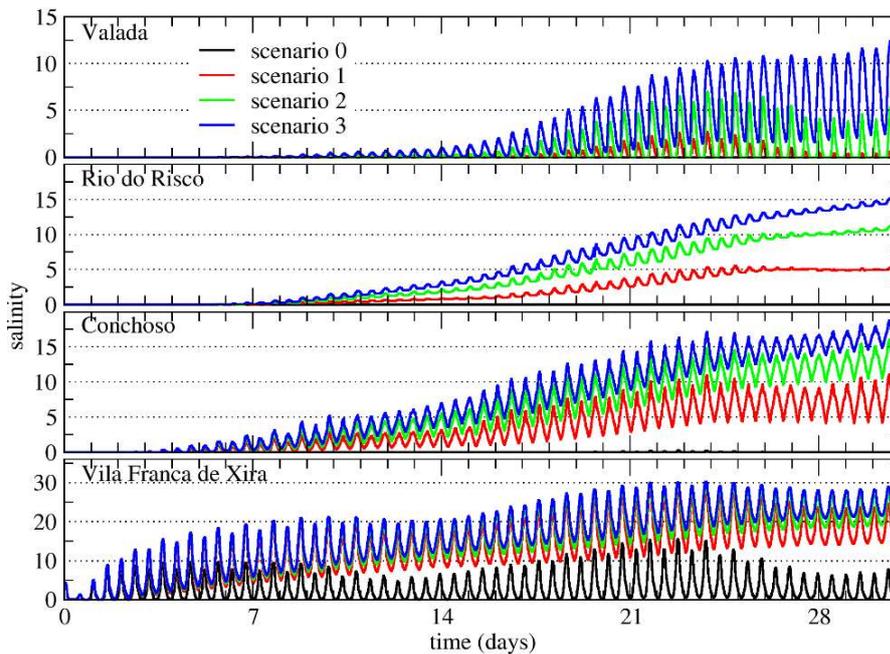
**Figure 13. Salinity in the upper Tagus estuary.**
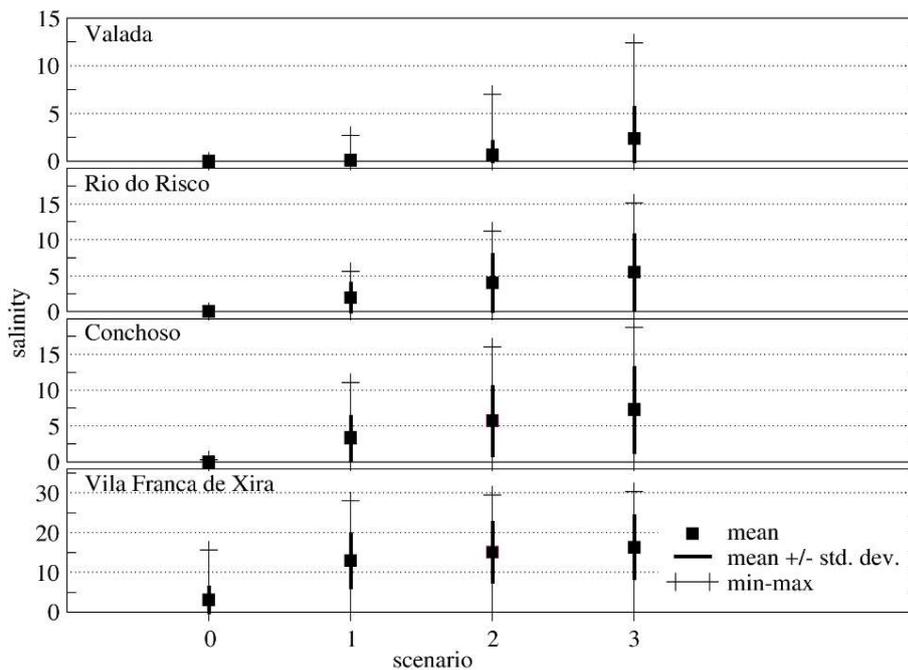
Figure 14. Statistics of surface salinity for the analyzed scenarios.

7.2.1. Relevance for the water sector

BINGO provided new and useful information for the stakeholders dealing with agricultural activities and water supply in the upper Tagus estuary. A better understanding of the inundation and salinity dynamics was achieved, which provides the stakeholders with information that may support decision-making during the development of their activities:

- Extreme storms were shown to lead to the overflowing of existing dikes and the inundation of extensive agricultural land. Although storminess is not expected to increase in the near future, the hazard will increase marginally due to sea level rise.
- The river flow was shown to be the main driver of salinity intrusion in the upstream areas of the estuary. Low river flows prevent the water uptake for irrigation and the problem is aggravated for longer drought periods. Since the river flow in the Tagus River is mainly controlled by decisions on the operation of dams, salinity intrusion should be taken into account when managing the water resources in the Tagus basin.

The modelling approach used herein for both inundation and salinity intrusion can be used to assess similar problems in other regions.

7.3. Outlook

To support the daily management of the agricultural activities in the upper estuary it would be useful to the stakeholders to have timely information regarding inundation and salinity. This could be achieved by implementing the developed numerical models in operational mode. Forecast systems are fundamental components of emergency response and routine management. They provide accurate and timely predictions on water conditions (e.g., water levels and velocities, salinity), supporting multiple uses. For over 10 years LNEC has been developing and deploying a forecast framework, denoted WIFF – Water Information

Forecast Framework (http://ariel.lnec.pt/), applicable from the ocean to the hydrographic basin, including the urban interface (e.g., Fortunato et al., 2017b).

Moreover results also show that accurate and timely information regarding the river flows in the Tagus basin is essential to support the management. Presently, the accuracy of the river flow measurements in the lower Tagus River is questionable. It is important therefore to improve the accuracy of these river flow measurements.

7.4. Bibliography

Fortunato, A.B.; Freire, P.; Bertin, X.; Rodrigues, M.; Ferreira, J.; Liberato, M.L. 2017a. A numerical study of the February 15, 1941 storm in the Tagus estuary, *Continental Shelf Research,* 144: 50 - 64.

Fortunato, A.B., A. Oliveira, J. Rogeiro, R. Tavares da Costa, J.L. Gomes, K. Li, G. Jesus, P. Freire, A. Rilo, A. Mendes, M. Rodrigues, A. Azevedo, 2017b. Operational forecast framework applied to extreme sea levels at regional and local scales, *Journal of Operational Oceanography*, 10/1: 1-15.

Fortunato, A.B.; Meredith, E.P., Rodrigues, M., Freire, P., Feldmann, H. 2018. Near-future changes in storm surges along the Atlantic Iberian coast, *Natural Hazards*, https://doi.org/10.1007/s11069-018-3375-z

Rodrigues, M., Fortunato, A.B. 2017. Assessment of a three-dimensional baroclinic circulation model of the Tagus estuary (Portugal), *AIMS Environmental Science* 4/6: 763-787.

7.5. Objectives [Lower Tagus aquifers]

The aquifer systems studied (Aluviões do Tejo, Tejo – Margem Direita, Tejo/Sado – Margem Esquerda, and Ota-Alenquer) are located in the Lower Tagus. The first three aquifer systems, which were modelled for groundwater flow, occupy an area of 8.58x 10^9 m^2 and a volume above 157x10^{12} m^3, forming a multi-layered aquifer system where these three aquifers are hydraulically connected and connected also to the river network and the estuary (see D3.1 for details, Figure 15). These aquifers supply water for domestic, agriculture and industry demands, in particular in Tagus left margin area. The main problem analysed in BINGO was the impacts of recharge modifications under climate change and the ensuing impacts on groundwater levels and the ensuing consequences in water availability. Groundwater levels' changes due to recharge changes can have negative or positive social, economic and environmental impacts, that depending if recharge decreases or increases.

To analyse such impacts the following tasks were performed: i) build, implement, calibrate and validate a FEFLOW flow model for the three aquifers altogether; ii) use this model to characterize present conditions and a 1 year severe drought (2004/2005 year drought); iii) determine how the groundwater levels will change in the near future, due to climate change.
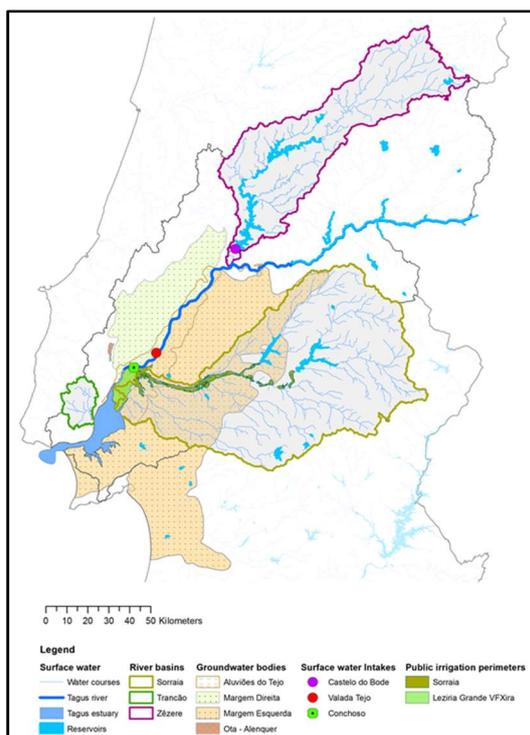
Source: Deliverable 3.4

Figure 15. Location of Lower Tagus river aquifers (solid dotted areas) and their spatial relationship with the other water masses studied

7.6. Main results

The impacts of climate change upon the aquifers are indirect, mainly thorough the respective recharge changes for each climate scenario. Recharge was simulated with BALSEQ_MOD (Lobo Ferreira, 1981; Oliveira, 2004) and detailed data are present4ed in D3.4. The 10 decennial realizations show a large variation of annual average precipitation, and the average of the realisations (ensembles scenario, red line)

shows an increase of the decennial average precipitation between 2 and 4%. This variation generates a parallel variation of recharge and to analyse the possible variation range in recharge the R1 realization (larges precipitation scenario), R3 (lowest precipitation scenario) and the average of all realisations (ensembles scenario) were analysed for each aquifer.
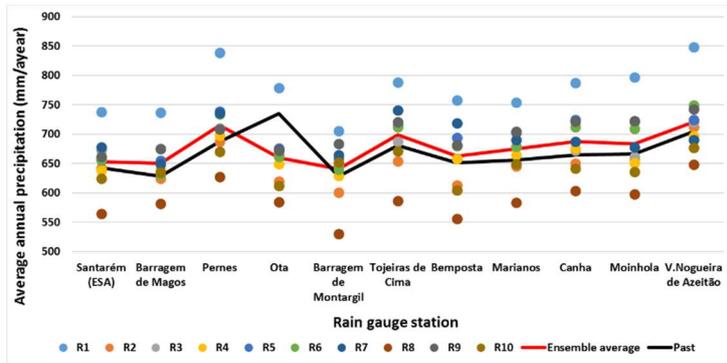
Figure 16. Annual average precipitation for each realization and each rain gauge station

The results show that recharge variations in each aquifer for each of the 10 realizations – each having the same occurrence likelihood – show a wide annual average recharge variation (Figure 17) which is illustrated by Table 3 for maximum (R1), minimum (R3) and ensembles realizations used in the groundwater flow model.
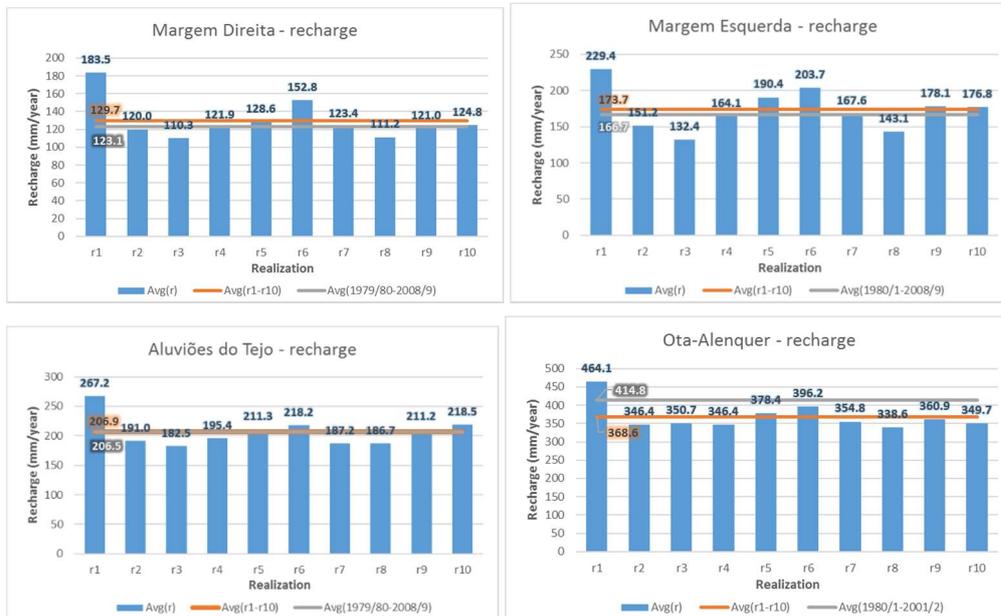
Figure 17. Annual average recharge in each aquifer for each climate realization (grey – 1979/2009 time series average recharge; orange – 2025/2024 time series ensembles average recharge)

Table 3. Summary of annual average recharge change from the historical period's values for each aquifer and climate realization

Realization	Margem Direita	Margem Esquerda	Aluviões do Tejo
R3	-10.4%	-20.6%	-11.6%
R1	+49.1%	+37.6%	+29.4%
ensembles	+5.4%	+4.2%	+0,2%

The spatial distribution of these recharge changes for high low and ensembles recharges are given in Figure 18.
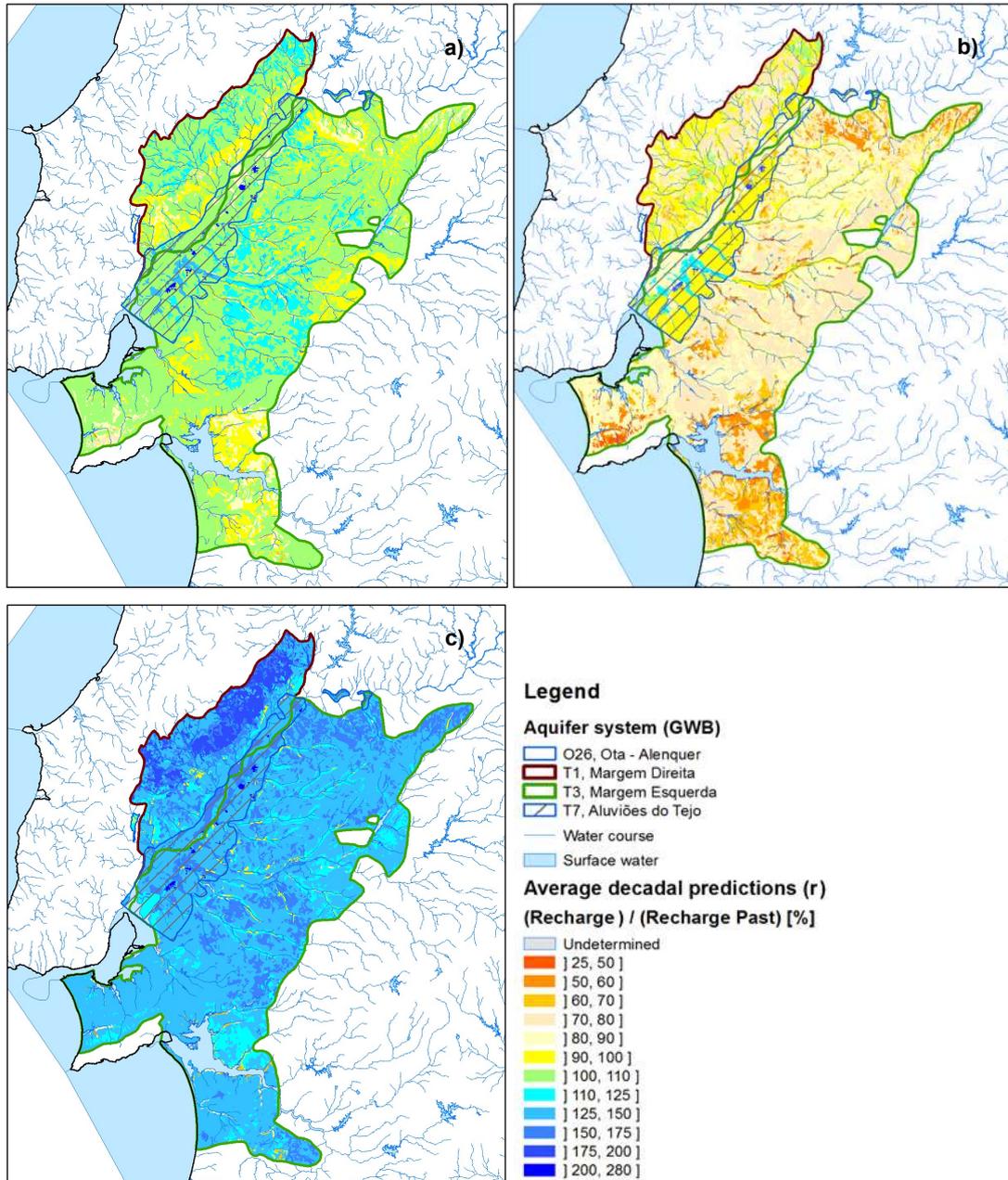
Figure 18. Spatial distribution of the recharge variation: a) ensembles, b) R3, c) R1

Groundwater FEFLOW 3D flow model was built, implemented and calibrated under pumping conditions (2289 abstraction wells) with the recharges for the historical period (1979 – 2009) and groundwater levels from a network of 501 observation wells and a total of 26 slices (25 layers). After calibration, the model was run in steady state for the three climate/recharge scenarios R1, R3 and ensembles. This work is described in detail in D3.4 and Novo et al. (2018). The groundwater levels' variations in Slice 1 for each of the three scenarios are presented in Figure 19 and Table 4.
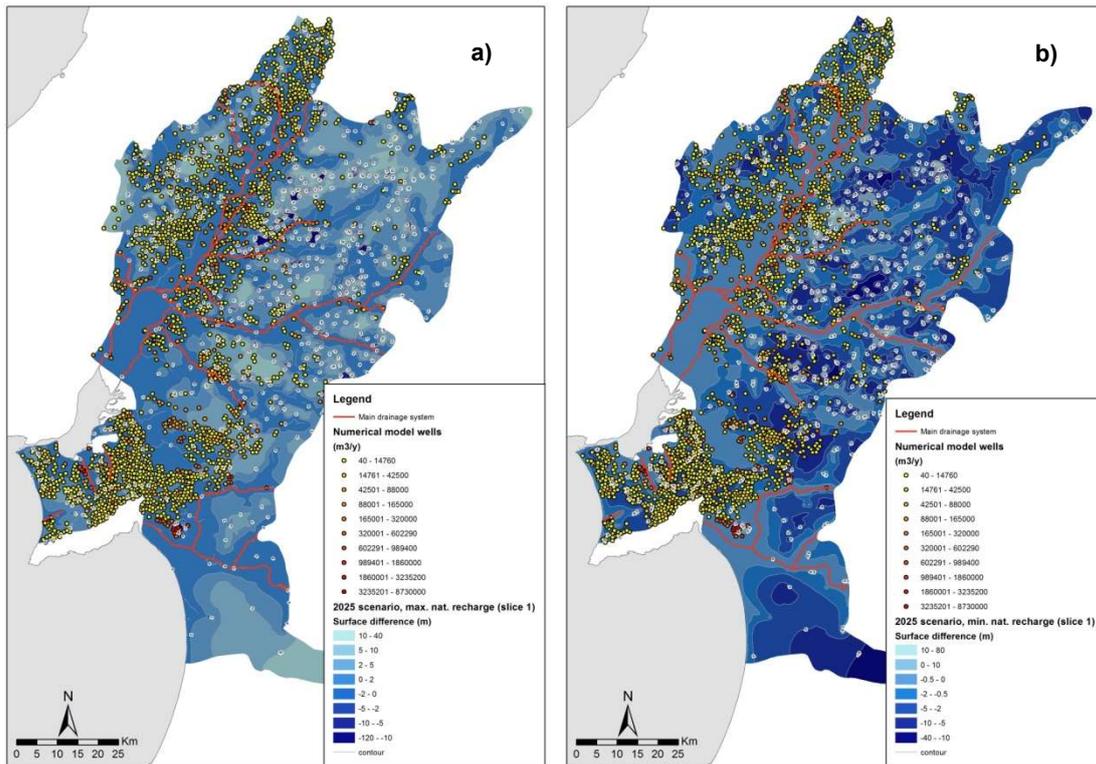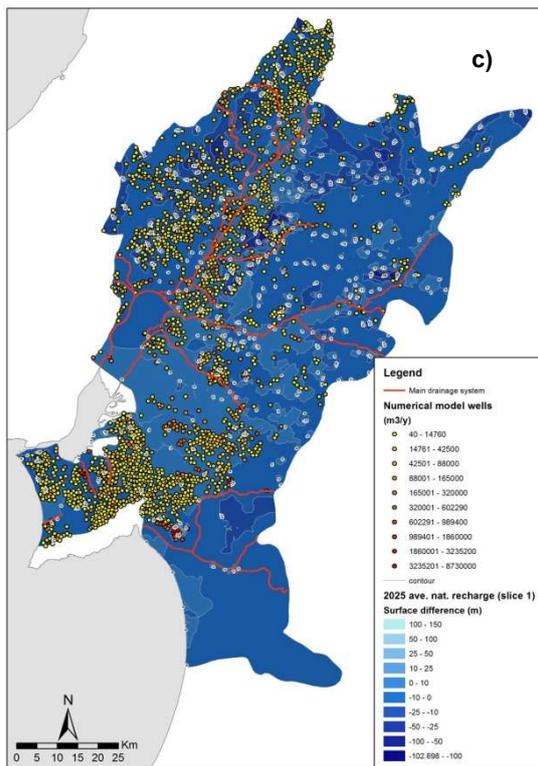
Figure 19. Groundwater levels difference between the average groundwater levels of historical series and: a) R3, b) R1, c) ensembles climate/recharge scenarios

These results show that impacts range widely from positive (rise of the groundwater levels' levels) to possible negative impacts (flooded areas) for the climate/recharge R1 scenario to negative impacts (groundwater levels' drawdowns) for the climate/recharge R3 scenario. For the ensembles scenario, groundwater levels' variation is negligible, so the impacts expected are irrelevant. Although all the 10 scenarios have the same likelihood, if it is assumed that ensembles scenario is an average of the possible climate outcomes, then the impacts expected are irrelevant. However, from the precautionary point of view, adaptation should be flexible to accommodate positive recharge changes (and ensuing inundations) or negative recharge changes (lesser groundwater availability) outcomes.

Table 4. Summary of average groundwater levels' change (in Slice 1) from the historical period's values for the whole of the aquifers taken together under each climate/recharge scenarios

Aquifer's zones	R3	R1	ensembles
Valleys; low areas	-0.5 m to -2 m	< +2 m	
From low to hilly areas	-2 m to -10 m	+2 m to + 5m	≈ 0 m
Upstream hilly areas	> -10 m	> +10 m	

Drought was also simulated – under transient state, and using the 2005 drought conditions – for 1, 3, and 5 years drought length to account for the normal (1 year) and the most pessimistic scenario (5 years drought). The results for Slice 1, the most likely to bear the largest impacts due its shallow nature, show moderate groundwater levels drawdowns, increasing as the drought lengthens (Table 5; Figure 20), which might be a bit off mark in some localized areas.

Table 5. Groundwater levels change under drought scenarios

| Aquifer's zones	1 year	3 years	5 years
Valleys; low areas	< -0.5 m	< -0.5 m to -1 m	< -0.5 m to -1 m (river areas)
From low to hilly areas	-0.5 m to -1 m	-1 m to -2 m	-2 m to -3 m
Upstream hilly areas	-1 to -5 m	-3 m to -5 m	> -5 m
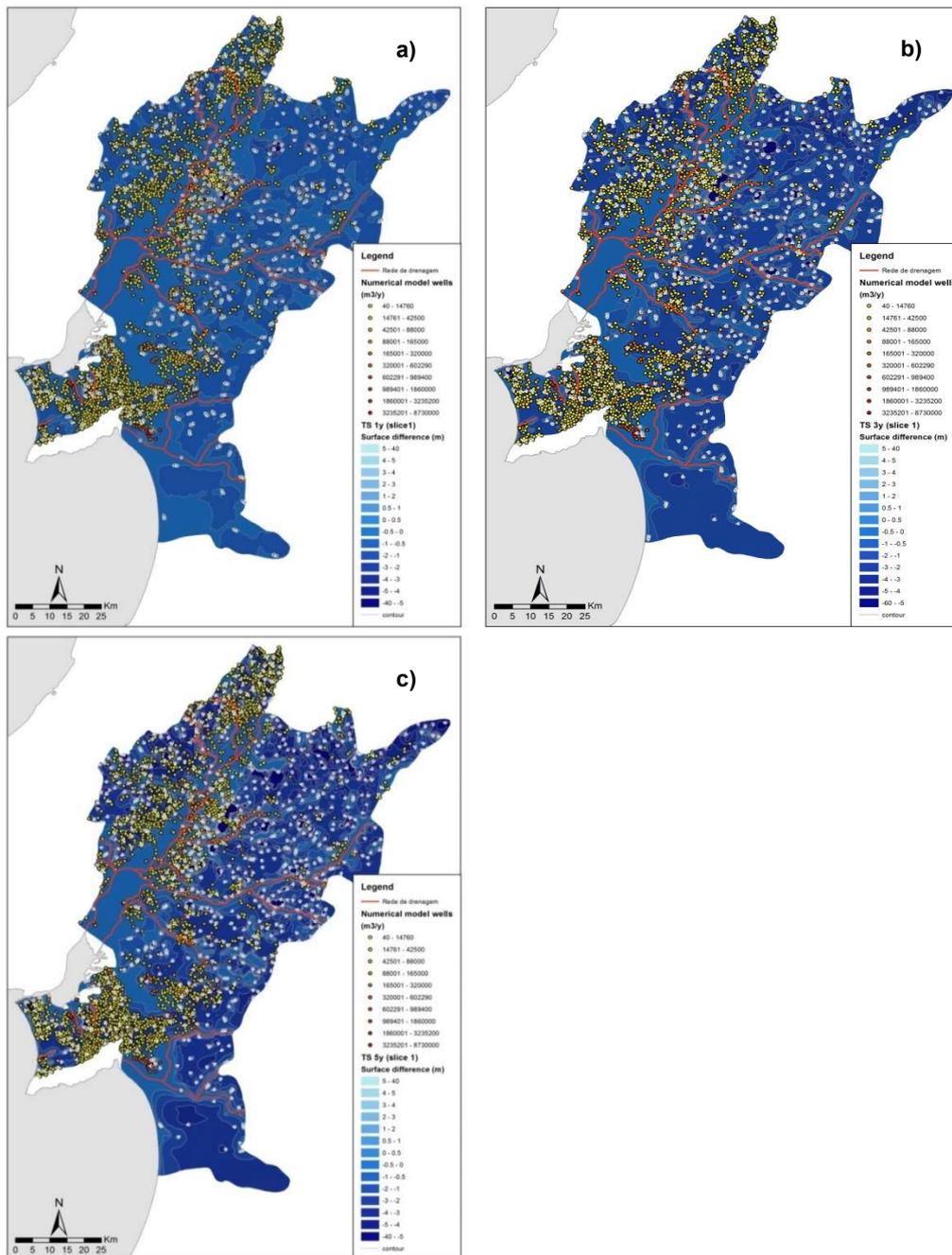
Figure 20. Groundwater levels' difference between the average water levels of the historical series and water levels' for drought recharge scenario (recharge conditions of drought year 2005) under transient state conditions: a) drought lasting 1 year; b) drought lasting 3 years; c) drought lasting 5 years.

7.6.1. Relevance for the water sector

Information provided by BINGO concerning groundwater is ambiguous, underlining the need of adapting to a wide range of possible outcomes. This is useful information for the stakeholders but might be difficult to deal with, due to the wide range of groundwater levels' outcomes under climate change. A better understanding of groundwater levels' sensitivity to recharge changes was obtained, providing important information to support stakeholders' decision-making. However, such wide-ranging possible futures might lead to no action, due to the large uncertainty of the results.

On the whole, groundwater levels' changes are moderate for the whole aquifer's area and the hazard of low groundwater availability is moderate to low. In the case of ensembles scenario, the hazard is just marginal. However, these are large aquifers, with large resilience, so moderate changes in recharge bear little impact on groundwater levels and water availability. During larger recharge changes (e.g. drought scenarios) groundwater levels show larger changes, suggesting that for medium to long range time horizons (2070, 2100) which might have larger recharge changes, groundwater levels (and groundwater availability) can significantly change. Recharge change, coupled with pumping rates changes, is the main driver of groundwater levels' change.

The modelling approach used to analyse groundwater levels and groundwater availability changes can be used to assess similar problems in other regions.

7.7. Outlook

To support the management of water supply from the aquifers, in particular in Tagus left margin, where groundwater dependence is strong, groundwater levels' information at a monthly base, generated from monthly average weather forecasts, would be useful to the stakeholders to adapt to contingency situations and plan the best management alternatives. This could be achieved by implementing the flow numerical model in operational mode. Under extreme events, when water surface sources fail (e.g. due to droughts), groundwater becomes an important water supplier. This might generate significant groundwater depletions at a local level, which are difficult to forecast in a regional model, although this model is a good starting point to develop such local flow models.

The lack of groundwater levels' data along the river network impairs the correct simulation of groundwater/surface water interaction, with impacts on environmental management. It is important therefore to obtain these river water levels' data. As far as climate change is concerned, the short range approach for groundwater systems with large resilience shows highly variable outcomes. Due to this, decision-makers should shift their usual paradigm and start action now for goals on the long range, as far as large aquifers are concerned.

7.8. Bibliography

Lobo Ferreira J.P. (1981) "Mathematical Model for the Evaluation of the Recharge of Aquifers in Semiarid Regions with Scarce (Lack) Hydrogeological Data". Proceedings of Euromech 143/2-4 Setp. 1981, Rotterdam, A.A. Balkema (Ed. A. Verruijt e F.B.J. Barends). Também: 1982, Lisboa, Laboratório Nacional de Engenharia Civil, Memória Nº 582.

Novo, M.E., Oliveira M.M., Martins T., Henriques M.J. (2018) Projecto Bingo: O Impacto das Alterações Climáticas na Componente Subterrânea do Ciclo Hidrológico. Revista Recursos Hídricos da APRH, Vol. 39,

nº 2, pp. 59 – 74, Outubro 2018, pp. 65-80. DOI: 10.5894/rh39n2-cti3. In: http://www.aprh.pt/rh/v39n2_cti-3.html (consulted 15/1/2019).

Oliveira M.M. (2004) Recarga de águas subterrâneas: Métodos de avaliação. Doutoramento em Geologia (Hidrogeologia), Universidade de Lisboa, Faculdade de Ciências, Departamento de Geologia, 440 pp., 2004. Também: Teses e Programas de Investigação - TPI 42, ISBN 972-49-2093-3, Editora LNEC, 2006.

7.9.   Objectives [Surface Waters]

The main objective for the surface waters' component was to study the impacts of climate change on water resources and detect vulnerabilities in the current water uses due to water scarcity induced by new rainfall regimes.

Two case-studies were selected to test the water management practices' adaptability in different water sectors: water supply and hydropower generation; and agriculture.

Both of the study areas, described in detail in D3.1 (Alphen et al., 2016), have high capacity reservoirs in the headwaters, although their impact on the natural flow regime modification is diverse:

- In the Zêzere River basin (major northern Tagus tributary), a cascade of reservoirs generates hydropower – the main water use, which is not consumptive – and a water supply intake is placed in the downstream reservoir, but the volume abstracted is not significant when compared to the Zêzere's natural flow;
- In the Sorraia River basin (major southern Tagus tributary), two main reservoirs in the headwaters, with interannual water transfer capacity, are used for irrigation purposes in the downstream valley.

Two hydrologic models were tested and calibrated for past climate conditions (in D3.3 – Alves et al., 2016) and the more robust one was use to simulated the inflows to the reservoirs for the project's 10 years horizon, based on the climate estimates generated in WP2, in order to evaluate the vulnerability of the water demands to the projected water availability.
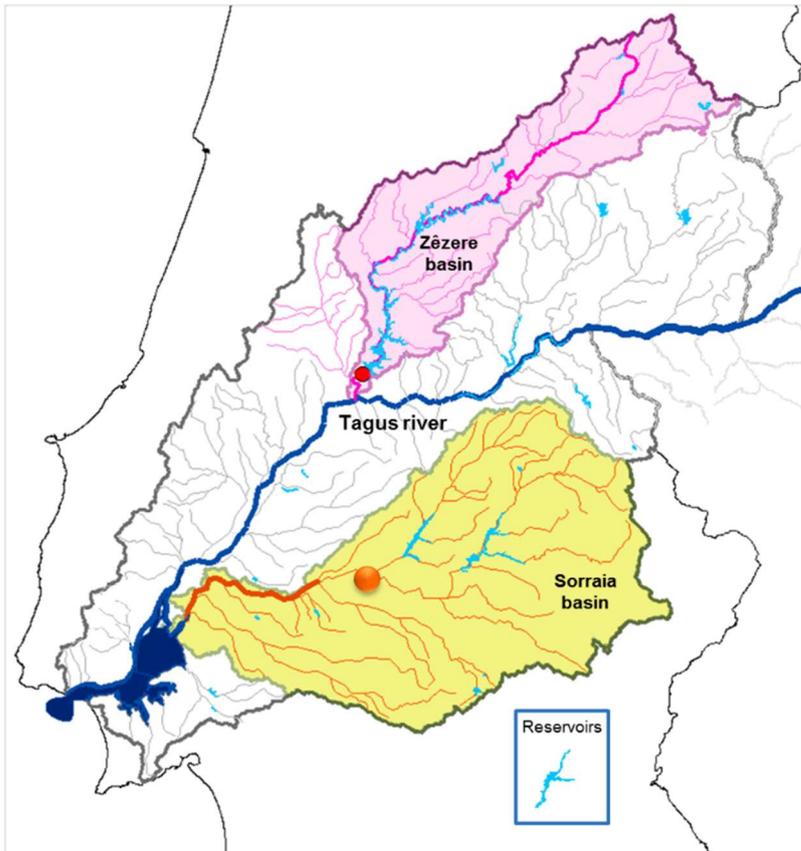
Figure 21. Zêzere and Sorraia river basins with its high capacity reservoirs and the points integrating their combined drainage areas of influence.

For each control point and input of 10 climate replicas the correspondent 10 flow regimes were simulated for the 2015-2024 period thus creating a the matrix of possible scenarios. Figure 22 synthesizes the 10 probable annual flow amounts simulated for the 2015-2024 period in the Zêzere basin where some of the minimums can be identified (e.g. 1-yr lows for replicas 4 and 10).
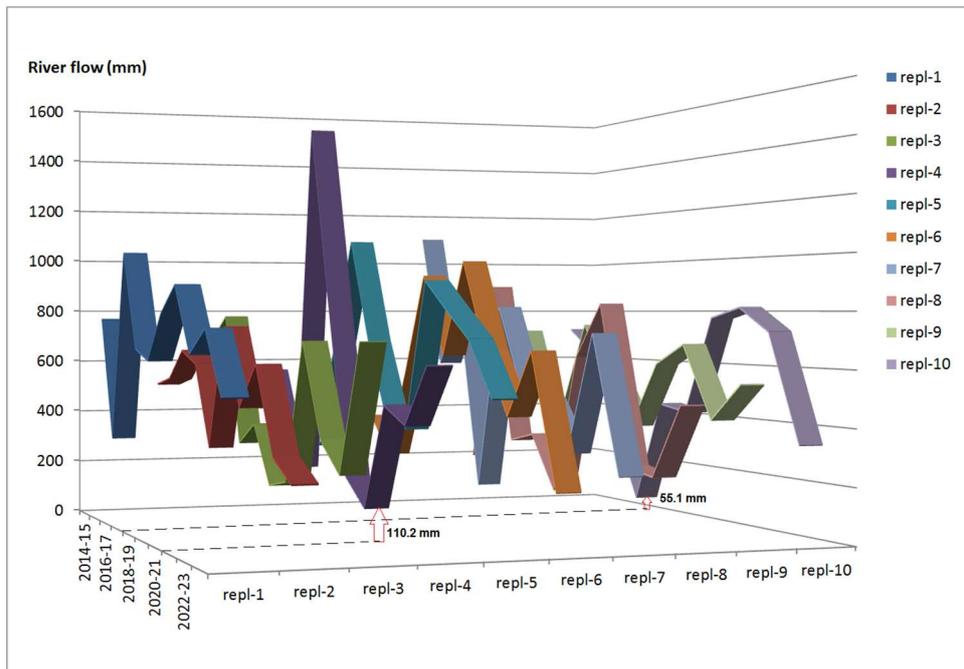
Figure 22. Ten replicas of probable flow annual totals simulated for the 2015-2024 period in the Zêzere basin

7.10. Main results

The significant result of the modeling procedure was the capability of translating potential impacts of climate predictions into the concrete domain of hydrologically meaningful water resources estimates. The equally-likely successions of 10 near future sequences generated in BINGO-WP2 module were transformed into correspondent flow sequences that enabled the subsequent testing of the adaptability of current management water resources management practices and policies. By preserving the chronology of each replica time sequence, management thresholds expected to be operational throughout the next 10 years could then be tested.

Additionally, the subversion of the series time chronology through duration curves allowed the analysis of changes in terms of flow regimes, e.g. the statistical persistence of a certain magnitude of flows during a fraction of the year (not necessarily uninterrupted time), Figure 23.
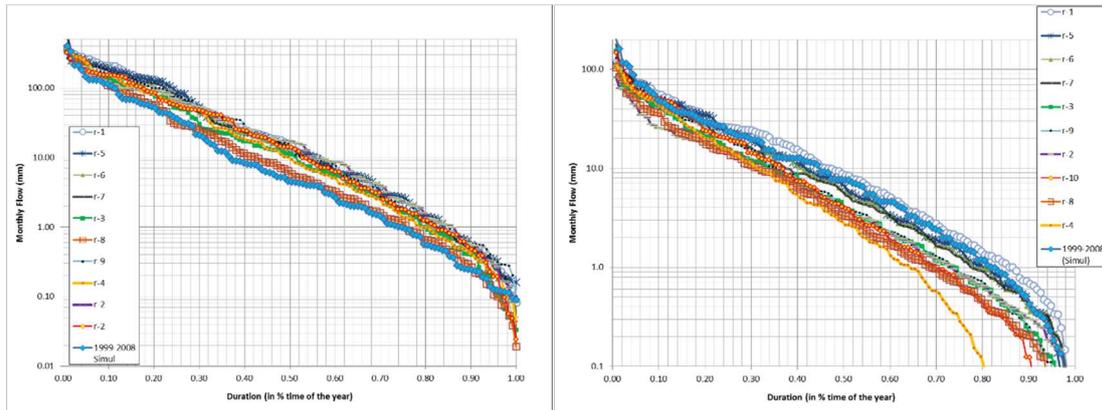
Figure 23. Duration curves for the 10 rainfall-replicas' input to the model and comparison with the last monitored decade data (1999-2008) in the Zêzere basin (left) and Sorraia basin (right).

The modelling activity (with methodology described in D3.4 − Aus der Beek et al., 2018) detected a stronger weight of the non-linear components of the water cycle in the southern basin of the Tagus (the Sorraia river basin) probably due to the higher temperatures and less steep slopes of this area when compared with the Zezere (further north). In fact, although the average annual rainfall predicted for the period 2015-2024 in both basins was higher than the average amounts registered in the 1999-2008 decade, the way monthly sequences of rainfall unveiled through time in the Sorraia basin were very determinant in reproducing dryer outputs in the southern region, putting more weight on the soil water component.

Based on runs of dry periods (mostly yearly runs) it was also possible to evaluate vulnerability of current storage capacity in the reservoirs to water stresses. Minima selection in each replica for multiannual dry periods (1-yr, 2-yr, 3-yr, 4-yr) enabled statistical drought analysis in the WP4-risk module (Figure 24).

7.10.1. Relevance for the water sector

The capacity to retrieved from a matrix of flow replicas dry sequences of inflows to reservoirs and identify the worst dry-runs' situation for stress-tests on water demand strategies was acknowledge as relevant from water sector agents.

Most of these agents have already management triggers and contingency plans for storage conditions at the end of a hydraulic year or at the beginning of the irrigation period but the possibility of coupling their strategies with multi year probable progression of a determined residual storage is a benefit.

Figure 24 represents the flow replica containing the worst 1-yr to 3-yr dry sequence generated for the Sorraia basin (replica 4). Nevertheless it was also found interesting from the agriculture sector to test the flow sequence coming from replica 2 (Figure 25), not only because it comprises the lower 4-yr value of all replicas but also because the sustained annual sequence of keeping with low values throughout the entire 4-yr period is probably more stressable economically.
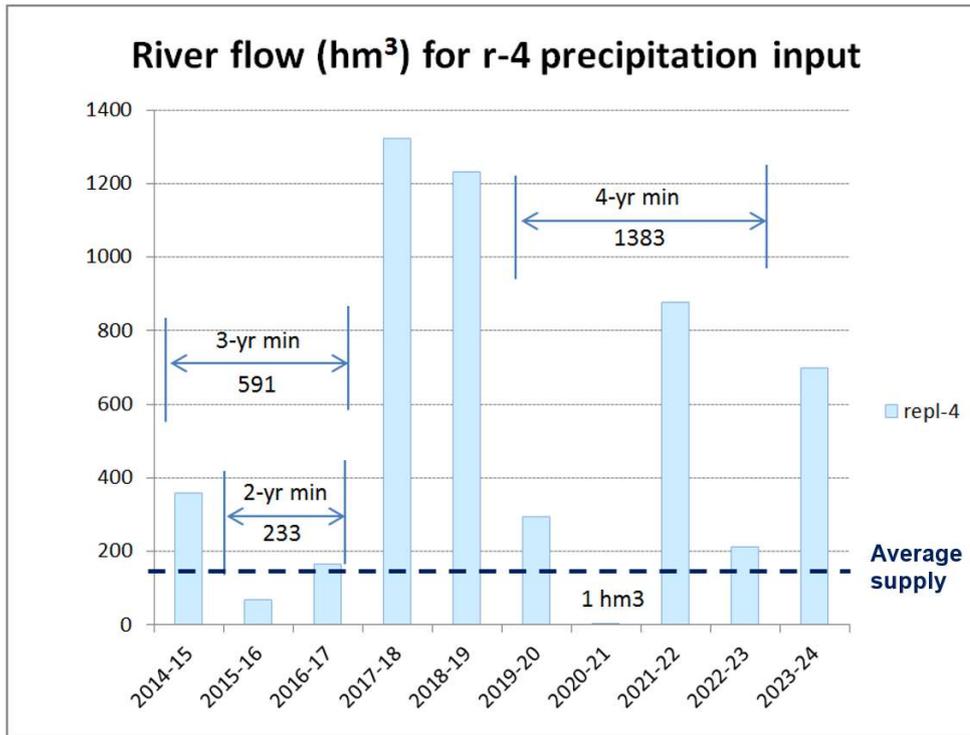
Figure 24. Annual flows for the Sorraia inflows to Montargil and Maranhão reservoirs in the period 2015-2024 from climate replica 4.
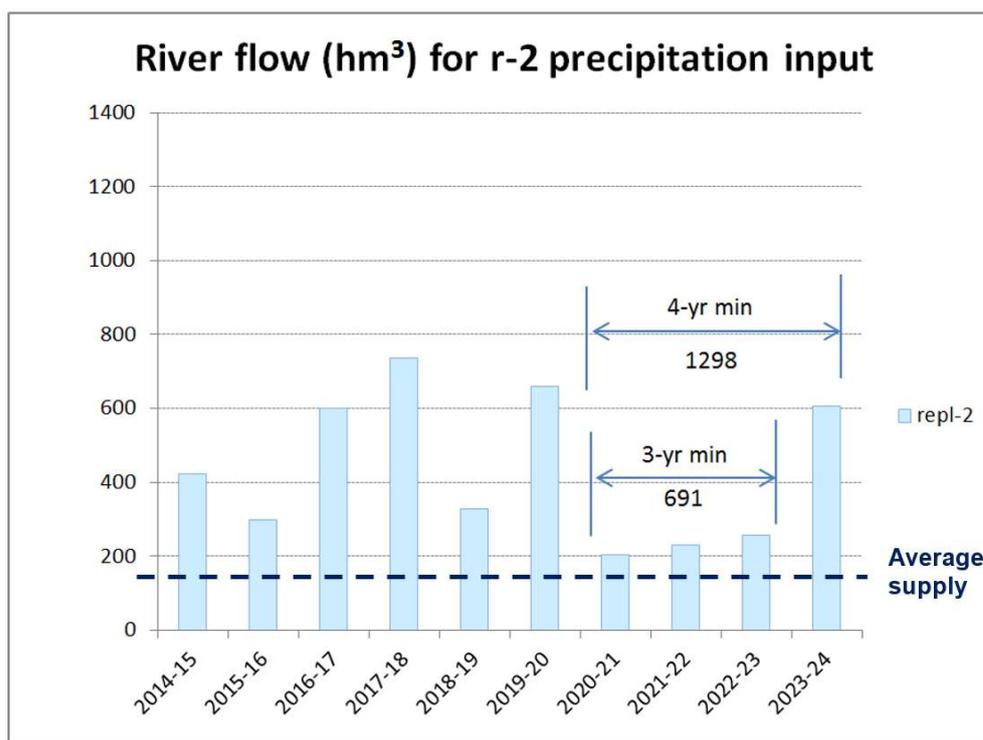
Figure 25. Annual flows for the Sorraia inflows to Montargil and Maranhão reservoirs in the period 2015-2024 from climate replica 2.

The big picture then is to keep approaching the climate change adaptability design investing in the improvement of short term climate predictions with statistical likelihood and, through hydrological transformation, updating water management and policies accordingly.

7.11. Outlook

All the work done was based on data coming from hydrological networks where the quantity and quality of data is being reduced due to budgetary constraints and lack of scientific sensitiveness.

It was difficult to get data to check the recent evolution of water resources availability in the selected case studies: rainfall data, evaporation data and flow data, particularly in the southern tributary of Tagus (Sorraia).

Strangely one of the main obstacle to progressing in this field is a basic one.

Good models still need data. Like Mark Twain once said: Too much of anything is bad; too much data is just enough".

7.12. Bibliography

Alphen, H-J., Alves, E., Beek, T., Bruggeman, A., Camera, C., Fohrmann, R., Fortunato, A., Freire, F., Iacovides, A., Iacovides, I., Kristvik, E., Kübeck, C., Lorza, P., Muthanna, T., Novo ,E., Rocha, F., Rodrigues, M., Rodrigues, R., Russo, B., Sánchez, P., Scheibel, M., Spek, T., Witte, F., Zoumides, C. (2016). Characterization of the catchments and the water systems, Deliverable 3.1, BINGO - Bringing innovation to ongoing water management – a better future under climate change assessment, 89 pp.

Alves, E., aus der Beek, T., Bruggeman, A., Camera, C., Fortunato, A., Freire, P., Grange, A.S., Iacovides, A., Iacovides, I., Kristvik, E., Lorza, P., Montes, J., Mouskoundus, M., Muthanna, T.M., Nottebohm, M.,

Novo, E., Oliveira, M., Rijpkema, S., Rodrigues, M., Rodrigues, R., Russo, B., Sánchez, P., Scheibel, M., Sunyer, D., Viseu, T., Voortman, B., Witte, F., Zittis, G., 2016. Calibrated water resources models for past conditions, Deliverable 3.3, BINGO - Bringing innovation to ongoing water management – a better future under climate change assessment, 183 pp.

8. Spain

Model frameworks (as overview)

The aim of the WP3 BINGO case study of Badalona is to develop a full hazard assessment for both flooding and Combined Sewer Overflows (CSOs) through the development and calibration of advanced models to simulate the combined behavior of sewer systems and urban surfaces in case of floods events and the bathing sea waters quality of Badalona affected by CSO spills produced during rain events. In this context, D3.1 described the main characteristics of the case study, D3.2 the future land use and water use scenarios, D3.3 the integrated model setup and calibration, D3.4 the model results in terms of simulation results and hazard maps and D3.5 the field work research and data collections. This deliverable summarizes the main results and their utility for the water sector.

8.1.   Objectives [FRAMEWORK 1]

The objective of the flood framework is to develop a full flood risk assessment and, particularly, to produce spatially distributed risk maps for pedestrians, vehicles and buildings. This is done using the 1D/2D model that aims at simulating the spatial distribution of maximum surface flow velocities and depths in Badalona during selected design rainfall events.

According to the European Flood Directive, traditional 'flood control approach' is being replaced by 'flood risk management' (Merz et al., 2010a). The focus is towards flood risk rather than on flood hazard. Therefore, vulnerability can be considered as having a similar weight as hazard. Flood damage assessments are also gaining importance within the context of flood risk management (Merz et al., 2010b). Moreover, the European flood directive (part of the Directive 2007/60/CE) and its adaptation to Spanish regulations (Real Decreto 903/2010) focuses on the flood risk from river floods and coastal floods, while sewer and flash floods in urban areas are not explicitly included. Urban flood risk is thoroughly analyzed in BINGO. This urban flood risk assessment is a pioneering study in Spain since only flood risk from river and coastal floods is contemplated by Spanish regulations.

8.2.   Main results

Both the main results from D3.4 and D3.5 and also take home messages for the flood analysis from WP3 are summarized.

The rainfall analysis results of D3.4 (that build on the results of WP2) showed that rainfall intensities are likely not to increase within the next 10 years. As a consequence, flood hazard in Badalona is likely not to increase in the next 10 years. Nevertheless, rainfall intensities are likely to be higher than the actual ones in the future period 2050-2100 according to RCP 2.6 and 8.5 (RCP 4.5 showed a decrease in future rainfall intensities), producing an increase of the future flood hazard. Since the RCP 2.6 scenario is nowadays considered unrealistic by the European commission (the latest year trends in global CO_2 emissions show that the emission assumptions of RCP 2.6 were too optimistic) flood hazard was estimated based on RCP 8.5. The climate factors obtained for the scenario RCP 8.5 (see D3.4) were in the range of 1-15% increase of actual rainfall intensities (the highest climate factors are for the lowest return periods and vice versa).

The high hazard areas for pedestrian and vehicles obtained from the flood analysis based on RCP 8.5 precipitation are shown in Figure 26. The results show a 10-23% increase of pedestrian and vehicle high hazard areas for rainfall return periods of 2 and 10 years and a 1-4% increase of high hazard areas for return periods of 100 and 500 years. It is noted that hazard analysis is just an intermediate step toward the elaboration of risk maps, therefore an increase of high hazard might not result in a similar increase of risk. Overall, the drainage network of Badalona was designed to flood the streets of Badalona approximately once every 10 years; nevertheless, rainfall events of lower return periods were shown to produce flooding. Moreover, the rainfall intensities of the events with a return period of less than 10 years are expected to increase more than the intensities of the events with return periods such as 100 and 500 years (according to the selected climate predictions of the RCP 8.5).


	T2	T10	T100	T500
Pedestrians	20%	12%	4%	1%
Vehicles	23%	10%	3%	1%
CC Coefficients	15%	7%	2%	1%
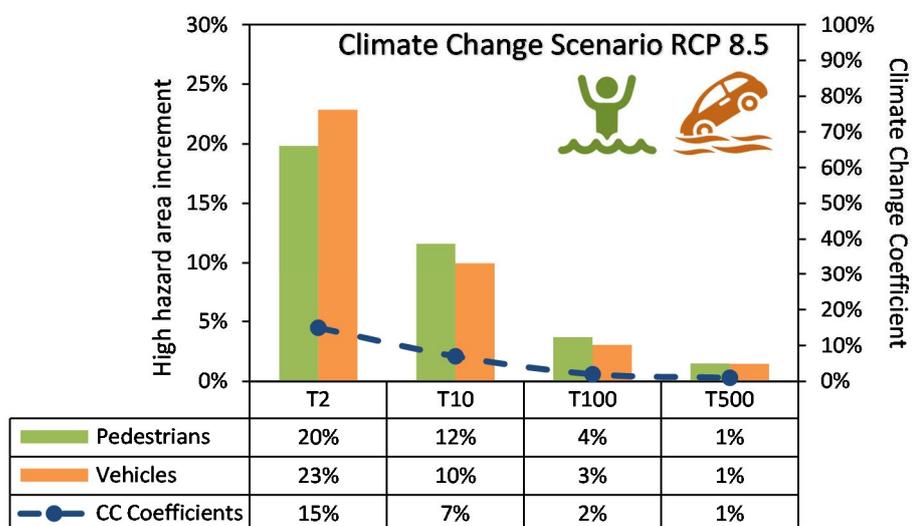
Figure 26. Pedestrian and vehicle hazard area increments due to climate change.

The field campaigns to collect local data shown in D3.5 were shown to be relevant to improve model performance and stakeholders' reliability on the flood models.

8.2.1. Relevance for the water sector

The BINGO results related to flood analysis helped improving several aspects of the water management of Badalona:

- Flood risk maps for pedestrians, vehicles and buildings were developed for different rainfall return periods (T=2, 10, 100, 500 years) both without and with the effect of climate change. In the WP3 of Bingo the hazard maps were developed. These maps were generated using the 1D-2D model presented in D3.3 to simulate surface flow velocity and flow depth thorough the streets of Badalona. Further, these hydrodynamic results were coupled to the hazard criteria presented in D3.4 for both pedestrians and vehicles. Figure 27 shows an example of a pedestrian hazard map with three different levels of hazard: low, medium and high.

  These maps will be made publically available for citizens through the civil protection web platform of the government of Catalonia. Several meetings with the civil protection department of Badalona

were organized in order to discuss the outputs of the hazard, vulnerability and risk maps for vehicles and pedestrians. Also, these maps can contribute to improve actual flood protocols of the civil protection.

These kind of urban flood maps are novel and pioneering in Spain since the current legislation only requires information about rivers and coastal flood maps. The current plans (_http://interior.gencat.cat/ca/arees_dactuacio/proteccio_civil/plans_de_proteccio_civil/plans_de_proteccio_civil_a_catalunya/#bloc18_) and the interactive maps (_https://pcivil.icgc.cat/pcivil/v2/index.html#41.4473,2.24363,7z_) of the civil protection in Catalonia show the risk areas in Catalonia, however they do not have the detailed urban resolution of the maps elaborated in the BINGO project (see the example of Figure 27).

Figure 27. Example of a pedestrian hazard map of Badalona.

- The models of the drainage network were updated with the inclusion of the latest construction works, the simulation of surface runoff flows and better reproduction of sewer flows. A new model calibration and validation was performed.
- The sediment field campaigns improved the understandings of the origins of the sediments deposited in the drainage network. Also the developed sediment transport models provide an initial step towards an improved management of the sediments and associated consequences regarding cleaning, pollution, odors and maintenance costs.
- The methodologies and the results obtained are useful for other national and European case studies. The methodologies are generally applicable, while the results are local. Nevertheless, the local results are a valuable source of comparison for other case studies.
- A state of the art and detailed flood risk assessment was performed bringing useful knowledge to both water managers and local population.
- Overall, the work made in BINGO provided advanced applications of the latest scientific tools and methodologies to improve flood risk management in urban areas.

8.3. Outlook

Local stakeholders have a new set of tools and methodologies to assess the costs and consequences of urban floods and related climate change impacts. Flood hazard and risk were evaluated for both actual and climate change scenarios. This is fundamental for improved decisions making, future investments,

emergency management and public awareness. Further, the hazard and risk maps developed in BINGO will be made publically available to citizens through the civil protection web platform.

Future work could focus on building flood awareness; maintaining the models developed and the sensors installed to collect data; spread the concepts of cost-benefit analysis; integrate flood management with other disciplines (urban traffic, ecosystem services) and emergency managements (fire, electricity, heat waves) to improve overall societal benefits.

8.4. Bibliography

Merz B., Hall J., Disse M. & Schumann A. Fluvial flood risk management in a changing world. Natural Hazards Earth Syst Sci 2010a, 10, 509–527.

Merz B., Kreibich H., Schwarze R. & Thieken A. Review article "Assessment of economic flood damage". Natural Hazards Earth Syst Sci 2010b, 10, 1697–1724.

8.5.   Objectives [FRAMEWORK 2]

The aims of this section is to develop a health risk assessment derived by CSOs that contaminate the recreational bathing waters of Badalona. CSOs discharge water with high bacteria concentrations to the sea water of Badalona and this is considered a hazard for people health and safety. Hazard for people bathing in the sea and the impact of future rainfall patterns on CSO were quantified in D3.4. An urban drainage and a sea water quality model were used (see D3.3) to develop this analysis. Other studies used similar models for bathing water purposes (Andersen et al., 2013; Marchis et al., 2013; Suñer et al., 2008).

8.6.   Main results

Both the main results from D3.4 and D3.5 and also take home messages for the CSO analysis from WP3 are summarized.

The rainfall analysis showed that no significant changes in both rainfall intensities and annual precipitation volumes are expected for the period 2015-2024 compared to the past period 1996-2014. The actual number of CSO spills varies between 3 and 9 with an average of 5-6 CSOs spills every bathing season (D3.4).

The future scenario based on the selected average future rainfall showed that there would be an increase in the number (12-14%) of CSOs and a decrease of CSO volumes (0-6%) in Badalona. The worst case scenario, instead, showed that there would be an increase in the number (0-33%) of CSOs and an increase of CSO volumes (22-53%) in Badalona.

The hazard analysis for people swimming in the sea of Badalona showed that high hazard can last up to 24-72 hours following CSO events. The time it takes to re-establish low hazard after a CSO event depends mainly on: discharged CSO volume, *E. Coli* concentration of the CSO, wind conditions that generate coastal sew water currents.

Salinity concentration measurements were also analyzed and simulated after the hypothesis risen during stakeholder meetings that salinity could be used as an indirect measure of sea water quality (bacterial contamination) since it can detect the presence of fresh water coming from CSOs. The results showed that sea water salinity indeed significantly drops as a consequence of CSOs, however it recover to undisturbed sea water values (37-38 ‰) much faster compared to sea water bacteria contamination caused by CSOs. Therefore, this indicator seems not to be appropriate for such use.

In WP4 the risk from CSOs was further developed and quantified using two indicators: seasonal time with unacceptable bathing water quality and time duration of unacceptable bathing water quality as a function of the rainfall volume. The seasonal time with unacceptable bathing water quality was shown to significantly vary from year to year and it could be up to 10% of a bathing season and with a high correlation to rainfall volumes and episodes fallen over the bathing season.

8.7.   Relevance for the water sector

The BINGO results related to CSO analysis helped improving several aspects of the water management of Badalona:

-          A coupled urban drainage with sea water quality model to simulate the sea water bacterial contamination after CSOs was calibrated and validated using data from BINGO.

- The risk analysis (WP4) quantified the seasonal time with unacceptable bathing water quality. This is relevant since the new Spanish regulations impose thresholds on this indicator. Further, the time duration of unacceptable bathing water quality as a function of the rainfall volume is a useful tool that the municipality decided to use in order to improve the management of bathing water quality. Particularly, to better estimate the duration of insufficient bathing water quality after CSO events. The novel link between rainfall volume and the duration of unacceptable bathing water quality was developed in BINGO. Figure 28 shows the duration of sea water contamination caused by CSOs as a function of the rainfall volume. This is useful to predict how long bathing should be forbidden and is currently being discussed with the municipality of Badalona for potential use in the current bathing water quality protocols in case of CSOs.
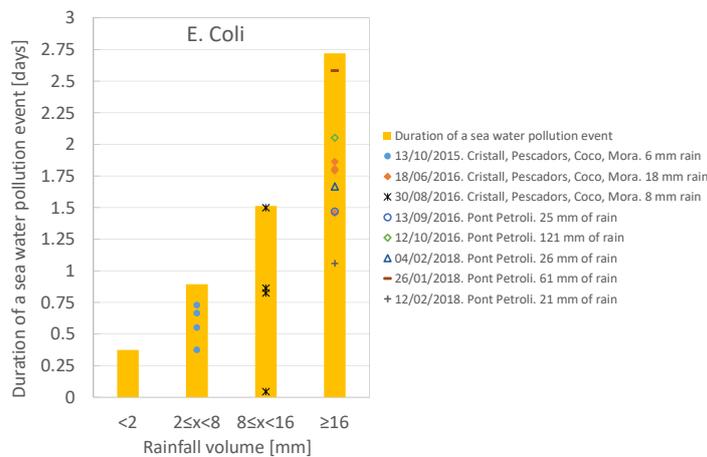

Figure 28. Duration of sea water *E. Coli* contamination as a function of the rainfall volume.

- The sea water quality model was updated with a new calibration and validation that used the sea water quality data and the measurements at the CSO points of the urban drainage network collected as part of the BINGO project.

- The methodologies and the results obtained are useful for other national and European case studies. The methodologies are generally applicable, while the results are local. Nevertheless, the local results are a valuable source of comparison for other case studies.

- A novel and detailed CSO risk assessment with focus on bathing water quality was performed bringing useful knowledge to both water managers and local population.

- Overall, the work made in BINGO provided advanced applications of the latest scientific tools and methodologies to improve bathing water management of urban areas affected by CSOs.

8.8.   Outlook

Local stakeholders have a disposition new tools and methodologies to assess the impacts of combined sewer overflows on bathing water quality and related climate change impacts. This is fundamental for improved decisions making, future investments, emergency management and public awareness.

Future work could focus on building environmental awareness; maintaining the models developed and the sensors installed to collect data; spread the concepts of cost-benefit analysis; integrate the management of

pollution derived from CSOs with other disciplines (e.g., urban traffic, ecosystem services) and emergency managements (fire, electricity, heat waves) to improve overall societal benefits.

8.9. Bibliography

Andersen, S.T., Erichsen, A.C., Mark, O., Albrechtsen, H.J., 2013. Effects of a 20 year rain event: A quantitative microbial risk assessment of a case of contaminated bathing water in Copenhagen, Denmark. J. Water Health 11, 636–646.

Marchis, M. De, Freni, G., Napoli, E., 2013. Modelling of E. coli distribution in coastal areas subjected to combined sewer overflows. Water Sci. Technol. 68, 1123–1136.

Suñer, D.; Malgrat, P.; Leitão, P.; Clochard, B., 2008. COWAMA - Integrated and real time management system of urban drainage to protect the bathing waters. 11th ICUD, Edinburgh, Scotland.

9. Conclusions

The BINGO approach had a large impact on improving water management at the 14 sites in the 6 countries. The following conclusions have been derived (selection):

Cyprus:

- Raising awareness of stakeholders concerning the effect of climate change on water resources
- Acceptance of desalination as a future option
- Improvement of and cooperation with forest management
- Implemented transfer of the BINGO modelling approach to another region
- Demonstration and support of SME in the water management sector
- Improved reporting for the Flood Directive

Germany:

- Gained experience with climate change ensemble data and their bias
- Closer collaboration of modelers and stakeholders
- Raising awareness of stakeholders concerning the effect of climate change on water resources
- Importance of transferability of BINGO approach for stakeholders
- Start of dialogue with stakeholders concerning climate change adaptation
- Models implemented in BINGO will be further used for additional purposes
- Better understanding of and management of reservoirs
- Further need for research identified

Netherlands:

- Increased awareness of stakeholders concerning the effect of climate change on water resources
- Model results were used to derive new measures concerning management
- Model results provided possible locations for new drinking water abstraction wells
- Established a close link between science and practice

Norway:

- Municipality now has models to analyse urban drainage network and water availability

- Further development of the SWMM model to be applicable for the task
- New long-term study on urban drainage as a best practice example for Norway
- Decision support to identify risks and measures
- Confirmation of the reliability of the water supply/resources in Bergen

Portugal:

- Better understanding of inundation and salinity dynamics
- Decision support for multiple stakeholders
- Communication of uncertainties concerning climate change and groundwater resources
- Availability of multi-year probable progressions of water flows

Even though the water problems at the various sites were diverse, water management (e.g. process understanding, model application and improvement, risk and measure identification, awareness raising) has been improved at all sites due to BINGO. It can be stated that these different local bottom-up approaches (e.g. models, data, knowledge, stakeholders) within a top-down BINGO framework (e.g. climate data, scenarios, model strategies) have led to multiple benefits for the water sector, of which many hold true for all sites and are thus likely to be transferable to other sites in Europe with similar problems. BINGO has shown that it is crucial to involve stakeholders in water resources assessment/modelling right from the start in order to iteratively analyse risks, derive measures and implement changes in water resources management.