BINGO
a better future under
CLIMATE CHANGE

BRINGING INNOVATION TO ONGOING
WATER MANAGEMENT

Guidelines

Application of hydro models

April 2019

www.projectbingo.eu

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Horizon 2020 Societal challenge 5:
Climate action, environment, resource
efficiency and raw materials

BINGO

Bringing INnovation to onGOing water management – a better future under climate change

Grant Agreement n° 641739, Research and Innovation Action

Short Summary (<250 words)

Hydro models are generally used to represent and predict water fluxes in the past, present and future, from near-real time to long term modelling, e.g. until 2100. The choice of the model is based on the type of water flux to be investigated/predicted. After setting up the model it needs to be calibrated and validated with observed data in order to assess its suitability to represent all relevant natural, anthropogenic and technical processes that drive the water fluxes. Once the model performance is considered to well represent past and present conditions, it can be applied for predicting future water fluxes. Usually, depending on the temporal horizon of the prediction, different climate scenarios/predictions can be used to drive the model, e.g. from hourly/daily forecasts to decadal predictions to RCPs (Representative Emission Pathways) until the end of the century.

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1. INTRODUCTION

BINGO stakeholders, such as water managers, rely on robust planning of their local resources and the assets involved. Although natural hydro resources systems have always been dynamic in space and time, climate and anthropogenic change has made it more difficult to assess future water availability and demand.

Within the BINGO project, 20 different hydro models have been applied in order to evaluate the impact of climate and socio-economic change on 14 different water systems in 6 countries for the next 10 to 85 years. These different models were chosen based on their suitability to represent/predict the relevant processes for typical water problems in Europe.

Based on the model results and in cooperation with BINGO WP4 and WP5 potential risks and measures were discussed in communities of practices.

The guideline presented in this report is part of the BINGO exploitation strategy and is designed to help stakeholders by informing about the BINGO approach and to serve as a modular blueprint.

2. METHODOLOGY

Water stakeholders need hydro models to predict the future quantitate and qualitative state of their natural resources in order to plan and manage water related assets and to develop business plans. Within BINGO a procedure was developed which enabled the assessment of future water states for many different water bodies at different sites and for different objectives. The following methods have been developed/applied at the BINGO sites, all in cooperation with local stakeholders:

Cyprus:

- Flood extent modelling
- Catchment modelling
- Drought analysis
- Forest water processes

Germany:

- Reservoir modelling
- Catchment modelling
- Urban runoff modelling

Netherlands:

- Groundwater modelling
- Evapotranspiration analysis
- Vegetation analysis

Norway:

- CSO modelling
- Urban runoff modelling
- Reservoir modelling

Portugal:

- Groundwater modelling
- Salinity modelling
- Ocean level modelling
- Catchment modelling

Spain:

- CSO modelling
- Urban runoff modelling
- Ocean bathing water quality modelling
- Cost functions analysis

The lessons learned of BINGO for selecting, setting up, calibrating and validating a model, driving it with adequate climate and socio-economic change data, and finally to assess the expected impacts (i.e. model results) will be described in Chapter 3.

The resources needed to follow the BINGO approach strongly depend on the type of water problem, choice of hydro model, computing power as well as background and training of staff.

The advantages and disadvantages of applying hydro models by stakeholders can be summarized as:

+ Understanding of processes that drive local water resources

+ Defining and ranking of local water problems

+ Increasing technical competence

+ Learning about future changes in climate and state of water resources

+ Assessing the impact of future land and water use changes on water resources

+ Decision support system to derive risks and measures (what-if modelling scenarios)

+ Set-up model framework for other applications

- New hardware and software might be necessary

- Hiring or training of staff

- Data post-processing, modelling, data post-processing is time consuming

- Model results can be inconclusive (model failure, spread and uncertainty)

- Not all extremes can be predicted by models

3. GUIDELINES

Within this chapter all steps necessary to follow the BINGO approach on modelling of hydro systems will be described in details. The approach has been divided in ten consecutive steps, which are listed below:

- Analysis of the water system and/or water problems
- Selection of applicable model
- Model set-up
- Model calibration and validation
- Selection of climate scenarios
- Modelling the impact of climate change
- Selection of socio-economic scenarios
- Modelling the impact of socio-economic change
- Combined modelling of climate and socio-economic impacts
- Assessment of risks and measures

Analysis of the water system

The first step focusses on the assessment of the local water system(s), which should investigate especially those water quantity and quality parameters that are of concern. Typically, water managers and other stakeholders become aware of a problem, if water amounts, e.g. not enough water for public supply/irrigation during droughts or combined sewer overflows (CSOs) during floods, and/or water quality, e.g. pollution of groundwater aquifers, are outside an accepted range. As socio-economic and environmental impacts are often the results of periods with long lasting water problems, it is recommended to anticipate those future impacts as early as possible in order to mitigate them by selected measures. This can be achieved by analysing the past and current state of the water system. Generally, it is recommended to gather as much data as possible in order to understand the development and trends of the local water resources system, for example river runoff, groundwater levels, soil moisture, evapotranspiration, precipitation, air temperature, land-use, water use, geological and soil maps, snow cover, etc. In order to evaluate spatio-temporal trends, statistical time series analysis can be employed and its results visualised by graphs, e.g. development of groundwater levels since 1970, and/or maps, e.g. changes in soil moisture. A detailed overview of the analysis of the various BINGO water systems can be found in "D3.1 Characterization of the catchments and the water systems". An example for long-term trends in groundwater levels is provided in Figure 1 for the Dutch research site Veluwe.

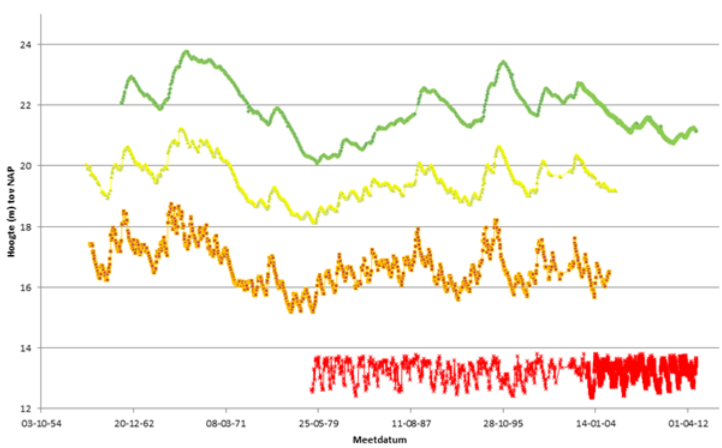


Figure 1

Measured groundwater heads form centre to the edge of the Veluwe, Netherlands

Selection of applicable model

Based on the analysis of the water system a suitable and applicable hydro model should be selected as a plethora of models is available. However, most of the available models are restricted to only represent specific processes of the hydrological cycle, such as groundwater models. Also, the more physical processes are integrated in the model the more input data, such as climate data and soil moisture levels, are needed. Here, surface water model types mostly vary from lumped (e.g. aggregated) to semi-distributed (e.g. hydrological-response units) to fully distributed models (gridded). Therefore, not only the type of water problem but also the data availability should determine the selection of a suitable model. In addition, depending on available funding, it can be differentiated between commercial (e.g. https://www.mikepoweredbydhi.com/products) and open-source models (e.g. https://www.hec.usace.army.mil/software/hec-hms or https://swat.tamu.edu/). Commercial models often include technical support. Table 1 provides an overview of some of the models applied in BINGO.

Table 1:

Overview of some of the models applied in BINGO

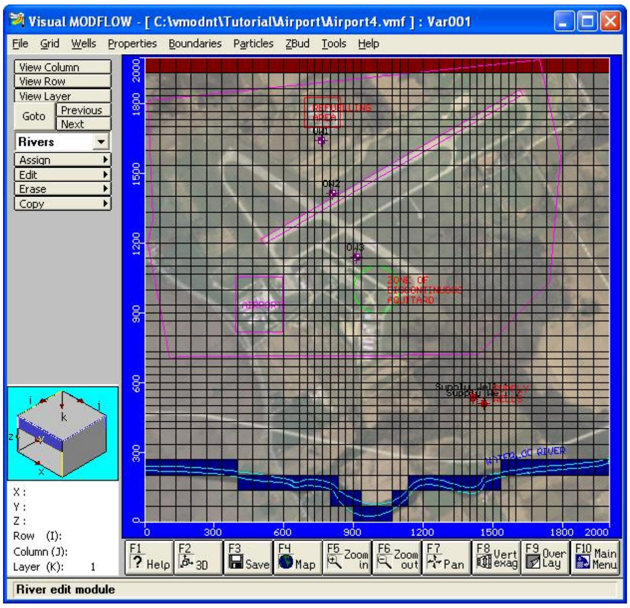
Model name	Site	Site type	Scope	Institution	Field Experiments
WRF-Hydro (or ParFlow)	Troodos Mountains, Cyprus	Multiple catchments	Surface/groundwater	CYI	Quantification of groundwater recharge from streams and quantification of evapotranspiration of trees and understory
HEC-HMS, HEC-RAS	Troodos Mountains, Cyprus	Multiple catchments	Floods	CYI	
Water Balance Model	Troodos Mountains, Cyprus	Plot	Trees	CYI	
AZURE (distributed MODFLOW)	Veluwe, Netherlands	Aquifer	Groundwater	KWR	Measurements of actual evapotranspiration in different vegetation types (e.g. heathlands, grass-lands, mosses and lichens, bare soil) with the aid of mini-lysimeters that are combined with a thermal camera to extrapolate the measurements to an undisturbed area of ca. 200 m²
SWAP (1D),	Veluwe, Netherlands	Plot	ETA/ETP	KWR	
Menyanthes (1D)	Veluwe, Netherlands	Plot	ETA/ETP	KWR	
HBV	Bergen, Norway	Multiple catchments	Surface water	NTNU	Flow measurements to calibrate hydrological model
nMag	Bergen, Norway	Reservoir	Reservoir Management	NTNU	CSO modelling
MOUSE/MIKE Urban	Badalona, Spain	Urban	Urban sewage/flood	Aqualogy	Collecting field data on: new sewer structures, sewer inlets, mapping land

			management		use and pollution sources, CSO points, measurements of bacterial pollution in sewers and beaches
SELFE/ECO-SELFE	Targus River, Portugal	Transition surface waters	Estuary	LNEC	
BALSEQ-MOD	Targus River, Portugal	ETA/ETP, GW-recharge	Groundwater	LNEC	
FeFlow	Targus River, Portugal	Aquifer	Groundwater	LNEC	
HEC-HMS, HEC-RAS	Targus River, Portugal	Catchment	Floods	LNEC	
RTD Drought	Targus River, Portugal	Catchment	Droughts	LNEC	
HEQ-5Q	Targus River, Portugal	Catchment	Risk management	LNEC	
IRAS	Targus River, Portugal	Catchment	Risk management	LNEC	
NASIM	Wupper River, Germany	Catchment	Surface water quantity/quality	WV (IWW)	Measurements of soil water content related to flood generation at two representative sites in the basin.
TalSIM	Wupper River, Germany	Reservoir	Reservoir Management	WV (IWW)	
SWAT	Dhünn River, Germnay	Catchment	Surface water processes	IWW	

Model set-up

Once a model has been selected, it needs to be installed and set-up. Many models are not available for all computer operating systems and might need an emulator. Furthermore, some models are implemented in frameworks with other software, such as Geographical Information Systems (e.g. ArcGIS or QGis), which need to be installed as well. These models mostly provide graphic user interfaces (GUI), as shown exemplarily in Figure 2, whereas other models are operated by scripts or command lines.

Once the model is installed its input data needs to be pre-processed. Primarily, the data can be selected by the defined input parameters of the model. Usually, dynamic variables, such as climate or water fluxes, need time series data, whereas rather static variables, such as soil or geological maps, are fixed. Depending on the spatial and temporal resolution of the model, the amounts of data needed can be large, which makes it difficult to format them manually. Instead, software tools, such as R (https://www.r-project.org/) can be used to automatize re-formatting of input data. Once



the pre-processing of the input data is completed, the first model test run can be started.

As the pre-processing of model input data often relies of multiple data sources from different disciplines, e.g. water use data from irrigation, household and industry departments, this step can be used to integrate other local water related stakeholders right from the beginning of the model study.

Figure 2:

Example of a graphic user interface of a hydro model (here: Visual MODFLOW; http://enacademic.com/dic.nsf/enwiki/1676168)

Model calibration and validation

Once the test run of the model has been completed successfully, the model needs to be calibrated and validated. Many models provide large degrees of freedom based on the number of parameters and often integrated semi-empirical process descriptions. Therefore, the most reliable combination of parameter set-ups within the chosen parameter range needs to be derived. This is usually achieved by calibrating/fitting the model to observed data, e.g. river runoff as shown in Figure 3, which is an example from the German BINGO research site. Mostly, single criteria calibration, i.e. time series of one observed parameter, and less often multi criteria calibration, i.e. time series of two or more observed parameters) is used. For some models automatic calibration tools[1] can be applied, which facilitates the often time consuming calibration procedure.

[1] e.g. https://swat.tamu.edu/software/swat-cup/

The goal of calibration is a good fit between modelled and observed data, often expressed as statistical functions of goodness of fit, such Kling-Gupta Efficiency, Nash-Sutcliffe-Efficiency, determination coefficient, volume errors, etc. Usually, the longer part of the observed data is being used for the model calibration (e.g. 1970-2000), whereas the remaining data is used to validate the model (e.g. 2000-2015). Once the calibration is sufficient, the model is validated, which means its performance for a non-calibrated part of the observed data is evaluated. If the validation goodness of fit is similar to the calibration, it can be assumed that the model is suitable to also produce reliable results for future predictions.

The calibration and validation of the models applied in BINGO is described in detail in "D3.3. Calibrated water resources models for past conditions".

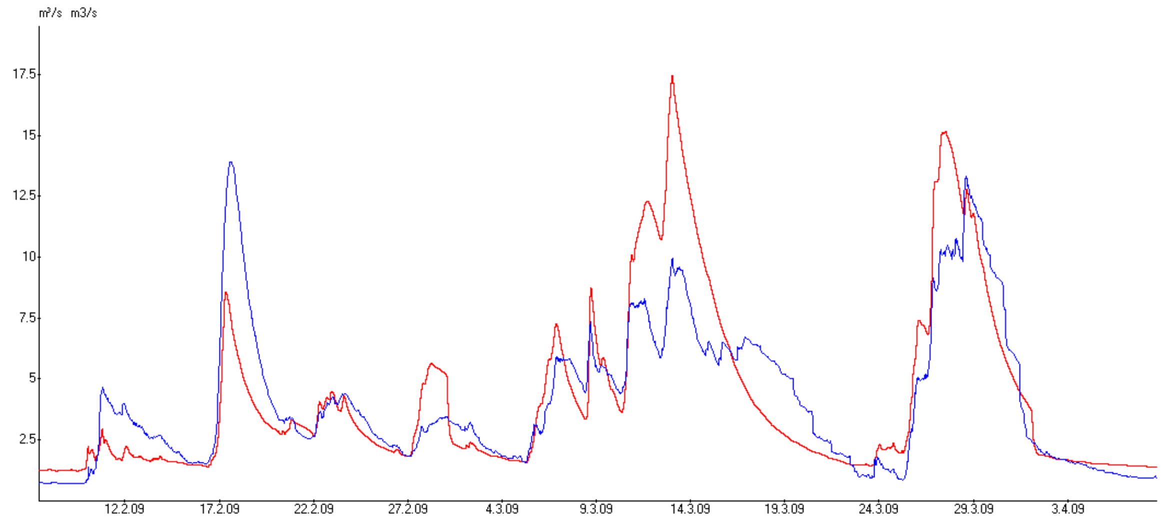


Figure 3:

Lower Große Dhünn (Germany) – observed and simulated discharge at Hummelsheim hydrometric station (blue: observed; red: simulated)

Selection of climate scenarios

As the model is able to realistically represent the water fluxes of the past and present, and thus the natural processes that drive them, it can be used to predict changes in the future water system. Depending on the scope of the predictions, different climate data sets can be applied as model input. An overview of data sets from weather predictions to long-term climate change projections is provided in Figure 4.

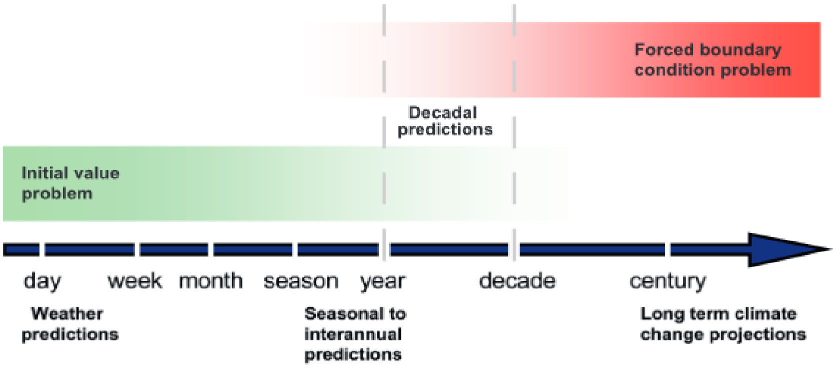


Figure 4:

Overview of data sets from weather predictions to long-term climate change projections (IPCC 2018)

For operational management, e.g. flood forecasts, near real time weather forecasts can be applied, which are often available from national weather services. Next, there are seasonal forecasts for the next few months, which for example can be used for agricultural purposes or reservoir management. This forecast data set is available at ECMWF (https://www.ecmwf.int/en/forecasts/datasets) or sometimes at national weather services as well. Then, there are decadal predictions, which have been used in BINGO (see D2.2 “Data downscaled to 12km/daily, Europe, for the period 2015-2024”). They provide climate predictions for the next ten years and can thus be of interest, if it is important for water managers to anticipate changes in the water system in the short to mid-term range. Finally, the longest data set for climate scenarios are the IPCC-RCP (Representative Concentration Pathways) scenarios, for which five scenarios (RCP 2.0 to 8.5) from 2006 to 2100 have been developed. The concentration pathways are usually used as input for regional (RCM) and global (GCM) climate models, which output can be used as climate input for the hydro models. It is recommended to use the output of an ensemble of climate models to take their uncertainty into account.

Modelling the impact of climate change

Once the climate data has been selected and re-formatted as input for the hydro model, it can be applied to model future states of the water system. Generally, there are three most often used approaches. First, conducting transient model runs, which means to run the model for an often long time period, which can include past, present and future data, e.g. a daily/monthly model run from 1970 to 2030. Second, the delta change approach, where a specific period (e.g. 2071-2100) is compared to past conditions (e.g. 1981-2010). Here, it is important to choose two periods that have the same temporal range. Third, future extremal episodes can be selected if for example droughts and floods are of interest, see D2.3 "Definition of extremal circulation patterns, present climate" for details). An example for impact modelling by using decadal predictions is provided in Figure 5 for a groundwater aquifer in Portugal. Details for the results of climate change impacts on all BINGO sites are described in D3.4 "Model results for water and land use scenarios completed and analysed".

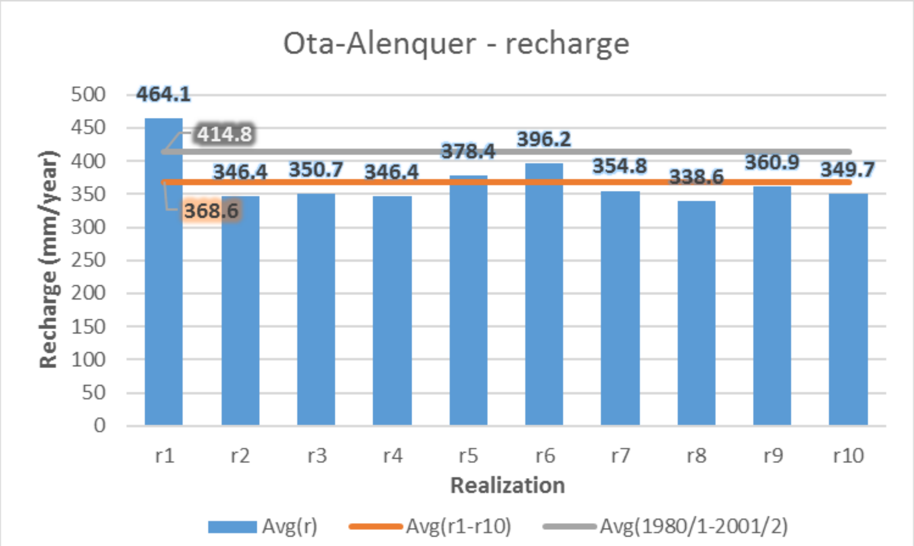


Figure 5

Groundwater recharge in Ota-Alenquer, Portugal – Variability for the ten members of the decadal predictions compared to past conditions.

Selection of socio-economic scenarios

Not only climate change but also socio-economic change can have large impacts on water resources. Therefore, it is recommended to include it any future scenario studies. Within BINGO, two different kinds of parameter sets were considered. First, land-use change (e.g. from forest are to agricultural or urban area) can influence the water cycle, especially evapotranspiration, surface runoff, runoff generation and groundwater recharge. Therefore, in close cooperation with local stakeholders different land-use scenarios were developed tailored to each site. For each five year time step, a new land-use map was produced and used as input for the hydro models. An example for the German research site is provided in Table 2. Second, changes in water use, i.e. for irrigation, domestic and industrial use, also affect water resources. Thus, again in close cooperation with local stakeholders different, realistic spatio-temporal scenarios in water abstractions were quantified. Depending on the model type, these water abstractions can directly be implemented in the model or need to be added in the post-processing of the model results. BINGO additionally used a combined bottom-up (local definition of scenarios with stakeholders) and top-down approach (EU-framework for scenarios *Economy First* and *Sustainability Eventually* from EU-FP6 project SCENES (https://www.peer.eu/projects/peer-flagship-projects/scenes/), which is also described in D3.2 “Future Land and Water Use Scenarios” for all sites.

Table 2

Land-use scenarios Economy First and Sustainability Eventually for the Wupper catchment, Germany

WUPPERTAL LAND USE										
scenario	year	agricultural (total area) [km²]	farmland [km²]	grassland [km²]	forest (total area) [km²]	deciduous forest [km²]	coniferous forest [km²]	mixed forest [km²]	urban + settlement [km²]	Total [km²]
	2000	328,36	116,17	212,19	238,66	95,28	27,14	116,25	246,02	813,04
	2005	319,29	113,03	206,26	243,12	98,70	30,97	113,45	250,63	813,04
	2010	306,67	105,60	201,06	247,85	108,37	41,19	98,28	258,53	813,04
	2015	299,40	100,31	199,09	251,37	112,92	46,63	91,81	262,27	813,04
Economy First	2020	267,47	84,19	183,28	255,96	119,64	54,92	81,40	289,61	813,04
Sustainability Eventually	2020	276,54	86,96	189,59	272,68	115,12	44,44	113,12	263,82	813,04
Economy First	2025	257,84	80,75	177,09	260,24	121,87	60,16	78,21	294,95	813,04
Sustainability Eventually	2025	273,78	86,81	186,97	272,68	119,26	40,30	113,12	266,58	813,04
Economy First	2030	248,21	77,31	170,90	264,53	122,82	65,41	76,30	300,30	813,04
Sustainability Eventually	2030	269,53	86,66	182,87	272,68	122,42	37,13	113,12	270,83	813,04

Note: agricultural (total area) = farmland + grassland

Modelling the impact of socio-economic change

Once the land-use and water use data has been pre-processed, it can be applied in the hydro model. In order to solely asses these socio-economic impacts, climate data from the past and present should be used. Thus, the differences between driving the hydro model with the former and the new land-use / water use data can be evaluated by the differences in water fluxes between the model runs. Details for the results of socio-economic change impacts on all BINGO sites are described in D3.4 “Model results for water and land use scenarios completed and analysed”.

Combined modelling of climate and socio-economic impacts

Once the separate impacts of climate change and socio-economic change have successfully been modelled, they can be combined. It is recommended to combine all potential scenarios with each other. However, depending on the run time of a model, it might not be feasible to conduct that many different model runs, e.g. 3 RCP scenarios from 10 regional climate models (RCM) and 2 socio-economic scenarios equals 60 model runs. Therefore, an ensemble mean/median of the RCM output as well as those RCMs with highest (maximum) und lowest (minimum) impacts can be selected, as they cover the entire range of climate change impacts. This would reduce the number of model runs to 18, given the example above. When analysing the combined modelled impacts, the effects of land-use and water change can be singled out by abstracting the resulting water fluxes from those model runs, where only climate change impacts were modelled (see page 10/11). An example of the combined modelling approach for flood modelling in Cyprus is illustrated in

Table 3. This and the combined results for the other BINGO sites can be found in more detail in in D3.4 “Model results for water and land use scenarios completed and analysed”.

Table 3

Results of combined climate and land-use change impact modelling of floods in Nicosia, Cyprus

Various scenarios		Future Extreme Event	Peak Flow at outlet of the model (m^3/s)	Total Volume of the flood event (Mm^3)	Extent of the flood* (m^2)	Extent of the flood within the Residential Town Planning Zones** (m^2)
Climate change/Land use	**Dam Initial Condition**					
Climate change	Full	2018	91.8	3,457	241,775	28,700
		2022	48.0	3,025	29,600	13,560
		2023	**295.4**	**14,984**	**1,239,865**	**205,160**
Climate + Landuse change (Sustainable)	Full	2018	108.1	3,894	271,747	32,725
		2022	55.8	3,512	45,882	14,856
		2023	**304.2**	**15,700**	**1,282,949**	**220,725**
Climate + Landuse change (Economy)	Full	2018	115.8	4,086	298,185	34,710
		2022	60.1	3,665	73,413	16,500
		2023	**309.6**	**16,070**	**1,287,659**	**230,365**

** The area that extends beyond the river banks*

***These includes residential, industrial and commercial town planning zones (source: Town Planning and Housing Department)*

Assessment of risks and measures

Once the (combined) modelling of impacts on the water system is completed, the results can be post-processed and analysed. These results should be discussed with local stakeholders to check their reliability. Depending on these discussions it might be necessary to modify the scenarios accordingly and to restart the modelling. Based on the final model results, stakeholders and modellers can first derive and define risks (see BINGO deliverables from WP4) and then develop measures to mitigate/avoid those risks (BINGO deliverables from WP5). Some of the measures can already be tested in the hydro models, for example forestation to reduce floods and construction/upgrading of reservoirs/dams for increased water availability and flood reduction. The final goal of the model study should aim at making the local water system more resilient towards impacts of climate and socio-economic change.

4. CONCLUSIONS

The here provided guidelines on modelling the impact of climate change and socio-economic change on multiple water systems follow the approach developed in BINGO. It allows water stakeholders to learn about the steps necessary to choose applicable hydro models and scenarios (climate and socio-economic change) and how to implement them at their site. The guidelines have been generalized, as they cover a wide range of different models and scenarios and should be considered as an overview. Details for different model applications are available through the six deliverables of WP3 and additional deliverables of the other WPs. Additionally, it is important to understand the processes driving the local water systems. Therefore, it is recommended that modellers should have a background in natural sciences in order to follow the physics of a model and to choose the locally relevant and scientifically sound model algorithms. Thereby, the model application can be supported by external researchers, consultants or M.Sc./PhD students.

5. REFERENCES

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