ARTIFICIAL GROUNDWATER RECHARGE FOR ADAPTING TO DROUGHT RISK IN LARGE AGRICULTURAL AREAS

Ilaria Delfini*[1], Andrea Chahoud[2], Alberto Montanari[1], Daniel Zamrsky[3]
[1]Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), Alma Mater Studiorum - Università di Bologna, Italy (*ilaria.delfini2@unibo.it)
[2]ARPAE Emilia-Romagna, Bologna, Italy
[3]Utrecht University, The Netherlands

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1. INTRODUCTION

Artificial groundwater recharge is a promising **adaptation** measure to face the increasing **drought** risk on freshwater availability. Its efficiency strongly depends on the **climatic and hydrogeological conditions** of the area of interest. In particular the structure of the **underlying aquifer** plays a key role. In fact, many open questions remain about the effectiveness of recharge for **multi-layer aquifers**, due to the complexity of their hydrogeological behaviour.

In this study we perform a series of **simulations** aimed at assessing the **effectiveness** of **winter/spring artificial groundwater recharge** on a portion of alluvial fans in the Emilia-Romagna region (Italy).

2. METHODOLOGY

A **numerical groundwater flow model** has been developed in **MODFLOW 6**. This model is based on a previous application of MODFLOW to the whole Emilia-Romagna area by the Regional Agency for Environmental Protection (**ARPAE**).

MODFLOW is a modular finite-difference flow model used to simulate the 3D **movement** of groundwater through **porous media**. In this case MODFLOW has been run by means of an open graphical user interface, i.e. **ModelMuse**. It allows the user to locate the spatial input for the models by drawing points, lines or polygons on top, front and side views of the domain. These objects can be **3-dimensional**, and are independent of the spatial and temporal discretization of the model. The simulation period is broken down into **stress periods**, that are time intervals over which the model input is constant.

After the **calibration** of the model, simulations are generated for different recharge conditions. In particular, we assume to **increase** the **recharge** in January, February, and March by **20%**, homogeneously in space over the study area. This is aimed to simulate a spatially distributed artificial recharge which may be provided by winter **irrigation**.

3. STUDY AREA

The study area is a portion of the **Emilia-Romagna** region (Italy), which spans for approximately **7000 km²** east of the River Secchia.
Considering the available data, the simulation period is set to range **from 2002 to 2018**. This multi-year simulation period allows to represent seasonal variations of hydrometeorology.
Cells are **1000x1000 m²**, and the system is subdivided into **35 layers** of variable thickness.

Figure 3.1. Emilia-Romagna Region, Italy.

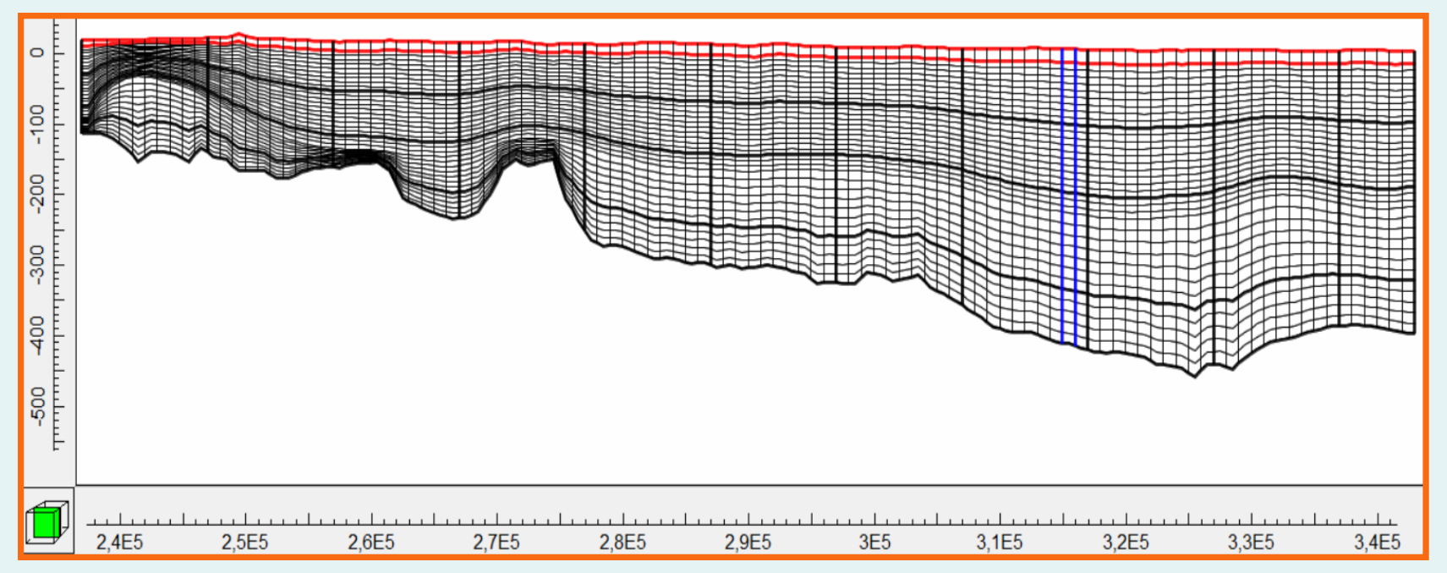


Figure 3.2. Subdivision into layers; vertical representation of the green section in *Figure 2*.

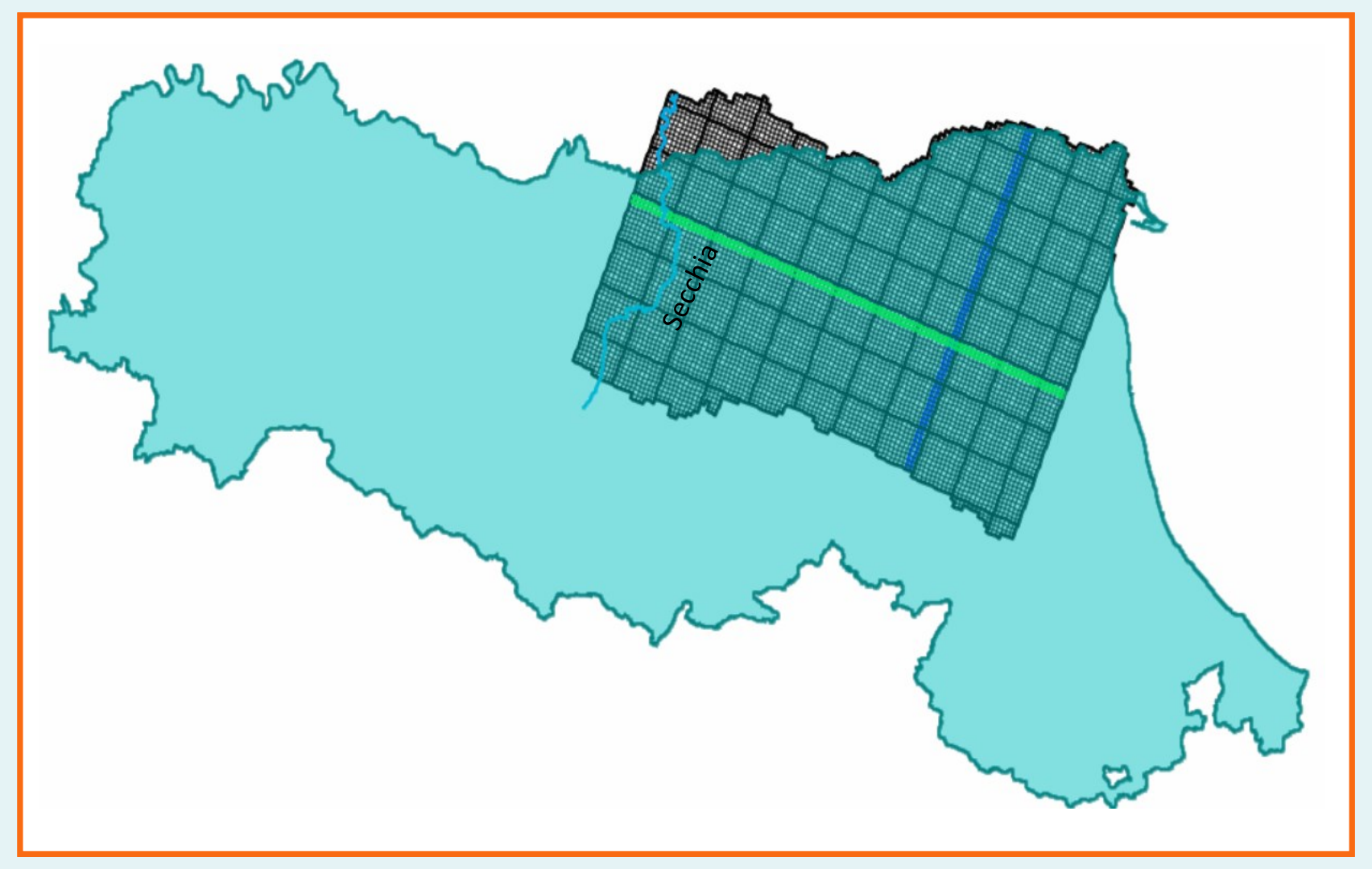


Figure 3.3. Simulated area compared to the whole territory of the Emilia-Romagna Region.

FUTURE WORK

- Improve the model **calibration**, considering that the output is very sensitive to the distribution of **extraction rates**.
- Run additional simulations considering more specific **climate scenarios**.
- Better assess the **local effects** of **groundwater pumping** in the study region.
- Consider several scenarios of future **climate** and water pumping, to get an insight of the **combined effects** of changes in **natural** and **artificial stresses** on aquifers.

References

Pistocchi, A., **Bouraoui**, F., & **Bittelli**, M. (2008). *A simplified parameterization of the monthly topsoil water budget*. Water Resources Research, 44(12).

Yates, D., & **Strzepek**, K. M. (1994). *Potential evapotranspiration methods and their impact on the assessment of river basin runoff under climate change*.

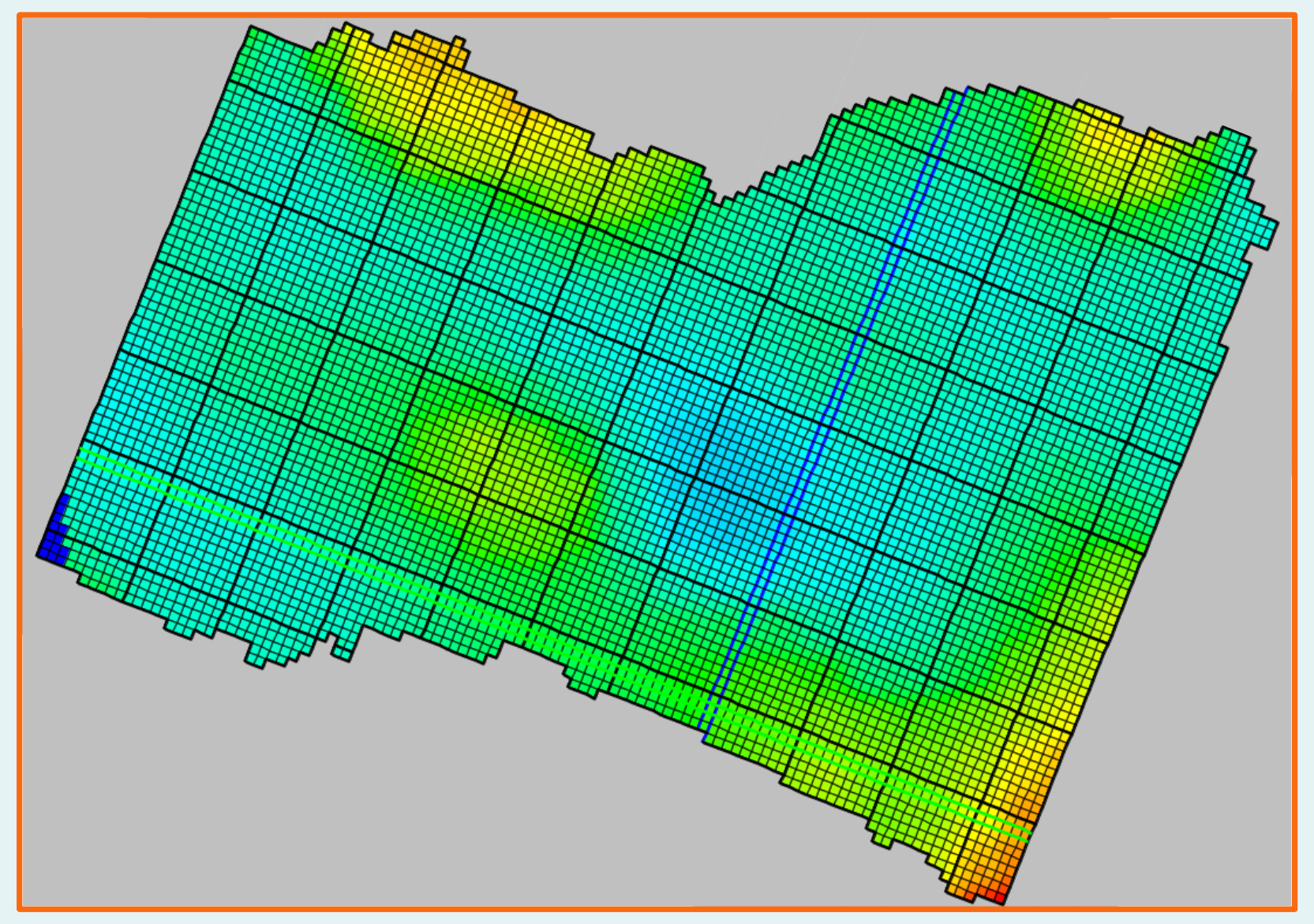
4. DATA

Data are mainly available from:

A. a **Modflow application** to the whole groundwater flow system of **Emilia-Romagna** by **ARPAE** (the regional agency for environmental protection), which can provide data related to:
    - the **geometry** and the **hydrogeologic properties** of the aquifers (vertical and horizontal hydraulic conductivity, starting head, specific storage, specific yield);
    - **extraction rates** of the wells present in the study area;

B. freely accessible datasets on the **Emilia-Romagna Region** and **ARPAE websites**, such as:
    - **rainfall** at several raingauges
    - **water stage** in the main rivers.

Figure 4.1.
Areal recharge values at the end of the simulation period (31st December 2018).



RECHARGE (mm/day)			
🟦	0	🟩	$1.58 \cdot 10^{-1}$
🟦	$3.16 \cdot 10^{-2}$	🟩	$1.89 \cdot 10^{-1}$
🟦	$6.32 \cdot 10^{-2}$	🟨	$2.21 \cdot 10^{-1}$
🟩	$9.50 \cdot 10^{-2}$	🟧	$2.52 \cdot 10^{-1}$
🟩	$1.26 \cdot 10^{-1}$	🟥	$2.84 \cdot 10^{-1}$

Recharge estimation

One of the main elements of the groundwater system water balance is the **areal recharge** contribution, due to **rainfall** and **infiltration**. It is the result of the interaction between several complex phenomena, but as a first **approximation** it can be simplified as the difference between **precipitation** (*P*) and **actual evapotranspiration** (*ETa*).

Both of these terms were computed first at a daily time scale over the simulation period, and then averaged at the **three-monthly scale** required by the model. Data derive from a freely accessible dataset by ARPAE.

In particular, according to *Pistocchi, Bouraoui, & Bittelli (2008)*, *ETa* has been defined by the **Turc's formula** as:

$$ET_a = \frac{P}{\left[\alpha + \left(\frac{P}{ET_p}\right)^{\beta}\right]^{1/\beta}}$$

Where α = 1, β = 1.5, and *Etp* is the potential evapotranspiration.

In turn, **potential evapotranspiration** has been computed by the **Hargreaves' formula** as:

$$ET_p = 0.0022 \cdot R_A \cdot {\delta_T}^{0.5} \cdot (T + 17.8)$$

where:

- R_A is the mean extra-terrestrial radiation, which is a function of latitude;
- δ_T is the difference between the maximum and the minimum temperature;
- T is the mean air temperature.

5. CALIBRATION

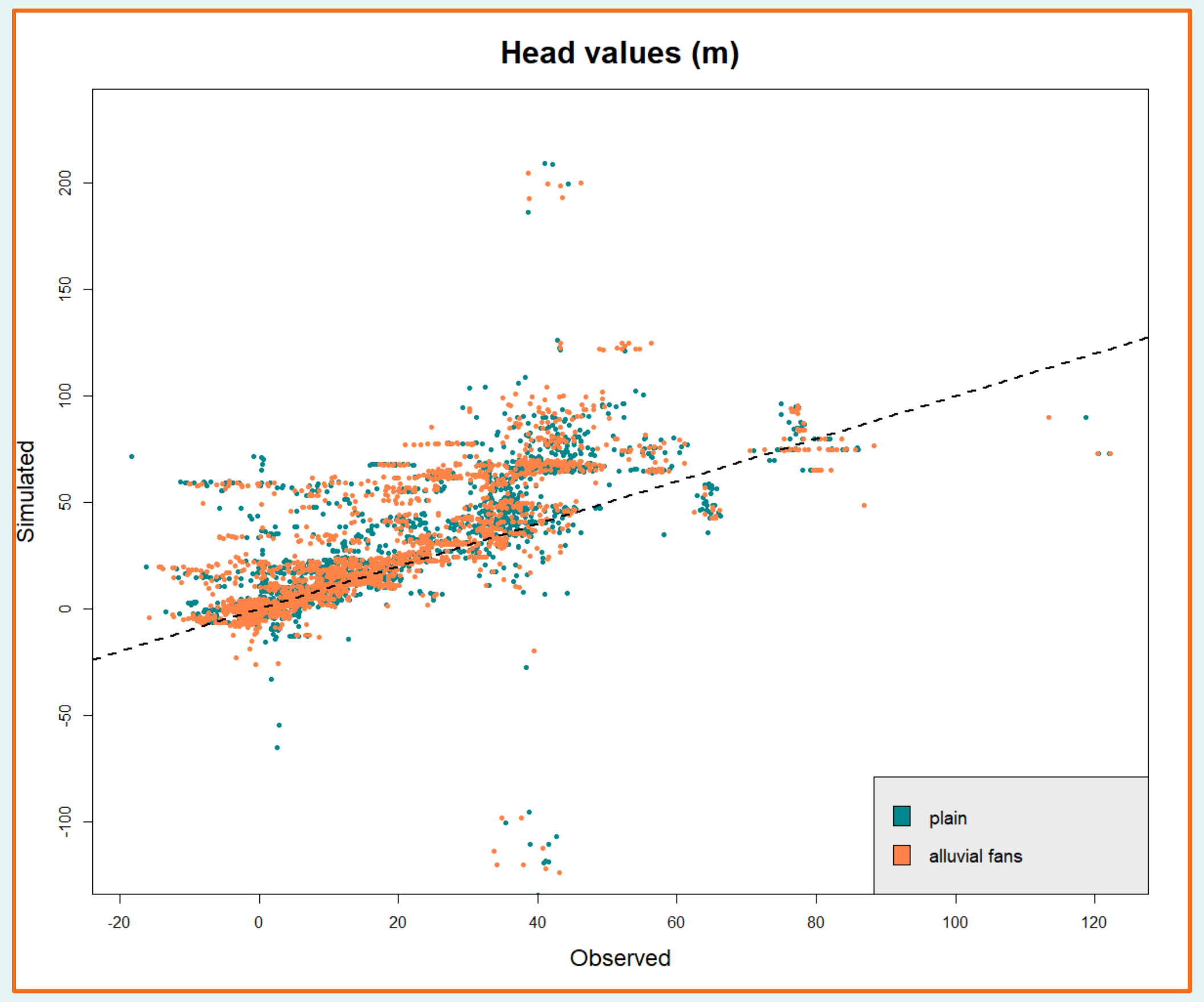


Figure 5.1. Calibration plot.

Calibration has been performed by varying the ***Conductance*** term in both the **rivers** and the **boundary cells**. The conductance is the factor that relates the difference in head to the rate of flow.

The performance of the model has been evaluated by comparing **simulated** and **observed** head values at the same time and location. Observations derive from a dataset freely accessible on the **ARPAE** website; they cover a time span ranging from 2010 to 2018, and are distributed over the whole study area.

In the plot, a distinction has been highlighted between observation points lying in the **alluvial fans** and those in the **Po plain**. The straight, dashed line represents the equality of observed and simulated data, which outlines perfect model performances. In general the model **overestimates** the observed values, therefore **further calibration** attempts would be needed to improve the overall model performance.

6. RESULTS

The effectiveness of the incremented recharge rates in January, February, and March is evaluated by considering the variation in **groundwater head**. The largest increments are located in the northern part of the study area, which corresponds to the **Po plain**.
Figure 6.1 presents on the **comparison** of the values of hydraulic head simulated at the observation points in the Po plain. The X-axis provides the heads simulated in the original configuration, whereas the Y-axis those simulated with the increment in recharge. The straight, dashed line represents the equality of the two series of measures. The majority of points lies either on the line, or on the upper part of the plot, meaning that the **recharge increment** led in general to **equal or higher** hydraulic heads.
Figure 6.2 is a representation of the **hydraulic heads distribution** in both the configurations of recharge in August 2018, which is the last **summer** month in the simulation period.

Figure 6.2. Comparison of the hydraulic head over the study area for (a) standard recharge conditions and (b) incremented recharge rates.

HEAD (m)	
🟦	-11.00
🟦	-8.11
🟦	-5.22
🟩	-2.33
🟩	0.56
🟩	3.44
🟩	6.33
🟨	9.22
🟧	12.11
🟥	15.00

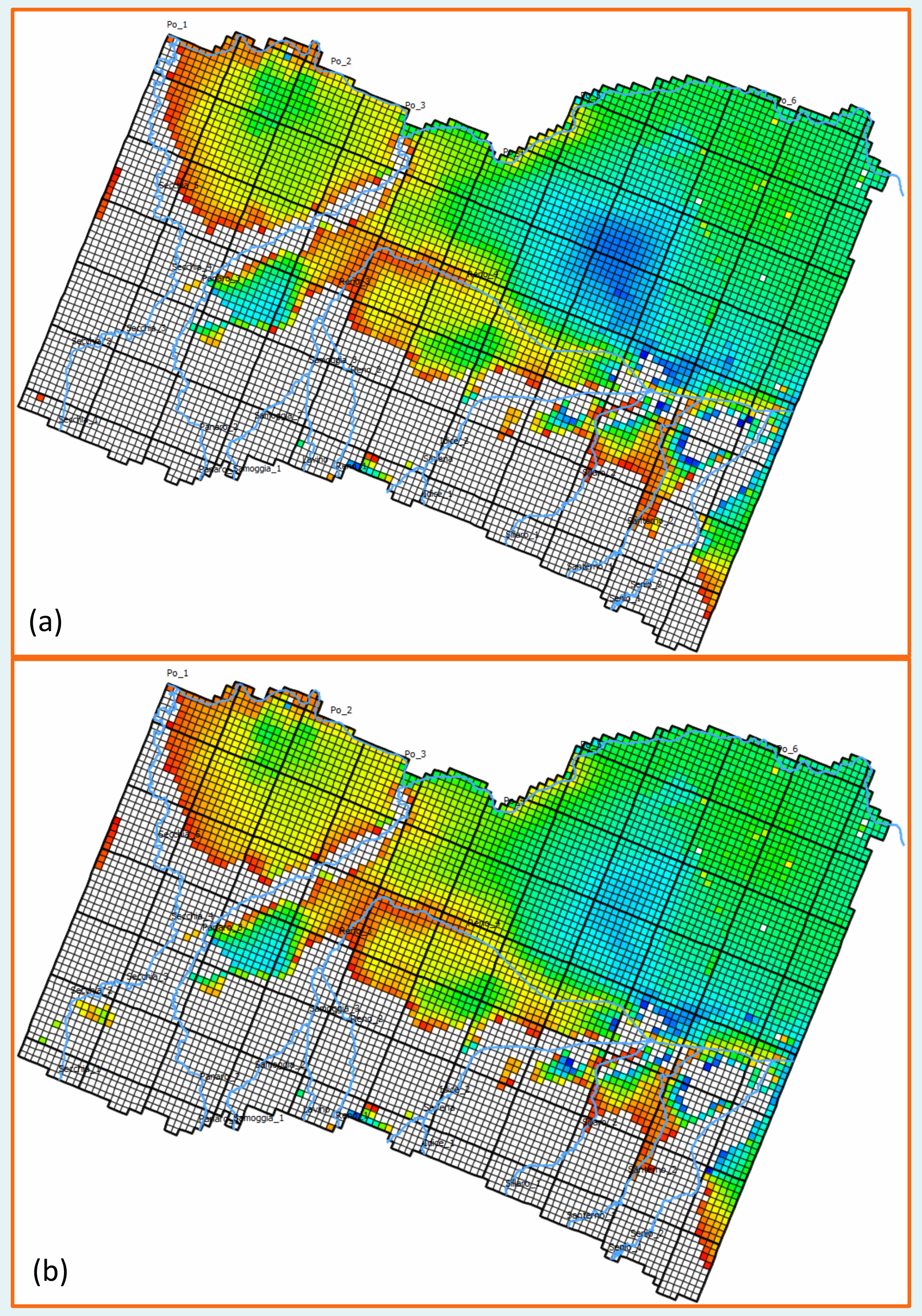


Figure 6.1. Comparison of the hydraulic head at the observation points located in the Po plain, for standard recharge conditions (X-axis) and incremented recharge rates (Y-axis). In the bottom-right corner, a zoom of the same plot.