

Quantifying groundwater recovery after drought: a comparative modelling study in the Emilia-Romagna multi-layered aquifer system



1. INTRODUCTION

- Extreme hydroclimatic events are increasingly challenging groundwater security.
- The recovery dynamics of aquifer systems after prolonged drought events remain poorly quantified.

How do climatic stressors and anthropogenic pressures shape groundwater head decline and post-drought rebound?

OBJECTIVES:

- Quantify the **recovery time** after a drought as a function of its **duration** and **intensity**.
- Estimate the **relative contribution** of **abstraction** changes to driving **groundwater decline** and **recovery**.
- Assess the **sensitivity** of **recovery times** to different **input variables**.
- Assess the extent to which **machine learning** methods can **replicate physics-based** models under **unseen future scenarios**.

5. CLIMATE AND PUMPING SCENARIOS

SCENARIO (2019-2050)	PRECIPITATION	GROUNDWATER ABSTRACTION	DURATION
A1	Reduced	Reference	1 year
A3	Reduced	Reference	3 years
A5	Reduced	Reference	5 years
B1	Reduced	Null	1 year
B3	Reduced	Null	3 years
B5	Reduced	Null	5 years
C1	Reduced	-40%	1 year
C3	Reduced	-40%	3 years
C5	Reduced	-40%	5 years
D1	Reduced	-20%	1 year
D3	Reduced	-20%	3 years
D5	Reduced	-20%	5 years
E1	Reduced	+20%	1 year
E3	Reduced	+20%	3 years
E5	Reduced	+20%	5 years
F1	Reduced	+40%	1 year
F3	Reduced	+40%	3 years
F5	Reduced	+40%	5 years
G1	Null	Reference	1 year
G2	Null	Reference	3 years
G5	Null	Reference	5 years

Month	Precipitation rate reduction (%)	Month	Precipitation rate reduction (%)
Jan.	16.3	Jul.	12.8
Feb.	12.4	Aug.	23.5
Mar.	17.1	Sep.	15.1
Apr.	20.5	Oct.	12.7
May	11.8	Nov.	14.0
Jun.	11.4	Dec.	21.0

- Imposition of a **set of drought conditions** characterized by **reductions in precipitation** and **varied groundwater abstractions**.
- Evaluation of **aquifer system's behaviour** under **combined climatic** and **anthropogenic forcings**.
- Reference scenario (R):** **time dependent** input parameters are **constant** at the **seasonal scale**, and equal to their **average** over **2014-2018**.

6. RECOVERY TIME

- For each well, for each scenario X, the groundwater head (*gwh*) is considered recovered in the first month in which:

$$\frac{|gwh_X(t) - gwh_R(t)|}{|gwh_R(t)|} \leq \epsilon$$

gwh simulated in scenario X at time t
gwh simulated in scenario R at time t

This condition must be satisfied for **k** (3, 6, 9, 12) consecutive months.

$$\epsilon = \min(\epsilon_{rel}, \epsilon_{stag}, \epsilon_{var})$$

$\epsilon_{rel} = p \cdot \text{mean_pre}$
 AVERAGE WELL VALUE
 mean_pre = average gwh before the drought
 p = 0.05

$\epsilon_{stag} = q \cdot \text{amp}$
 SEASONAL VARIABILITY
 amp = $\max_{\text{month}} - \min_{\text{month}}$
 q = 0.1

$\epsilon_{var} = S \cdot \text{std_ref}$
 NATURAL VARIABILITY
 std_ref over 12 months before the drought
 S = 0.5

- Then, the **aquifer system recovery time (RTs)** is computed as:

$$RT_s = \bar{T} \cdot \left[1 + \alpha \frac{N_{nr}}{N_{tot}} \right]$$

\bar{T} Average recovery time for the wells that recover
 N_{nr} Number of wells that do not recover
 N_{tot} Total number of wells
 α 2

For each well not recovering, \bar{T} increases by 5%.

2. MODELING APPROACHES

RANDOM FOREST ALGORITHM (RF)

- Comparison of **groundwater heads** simulated by **two modeling approaches**.
- Both models are **calibrated** over the years **2010-2018**, using **groundwater head observations** from the regional monitoring network (127 wells in the study area, each providing 2 measurements per year).

NUMERICAL GROUNDWATER FLOW MODEL (MF)

- MODFLOW 6** and **ModelMuse**
- Based on a previous application of MODFLOW to the whole Emilia-Romagna region by the Regional Agency for Environmental Protection (ARPAE).
- Spatial resolution:** 1 km (horizontal), 35 layers of variable thickness.

TYPE/GROUP	VARIABLES
Hydrogeology	Vertical and horizontal hydraulic conductivity, specific storage, specific yield
Topography	DEM
Water	Vertical and horizontal distance to the nearest water body
Climatic	Precipitation (6 months cumulation), average temperature, potential evapotranspiration (6 months cumulation)
Land cover	Land use coefficient (0-1)
Coordinates	X utm, Y utm
	Groundwater abstraction (5-10 years cumulation)
	Time

3. STUDY AREA

- Portion of **Emilia-Romagna** region (Italy). **7000 km²** east of the river Secchia.
- Large **agricultural plain**. The subsurface consists of **multiple aquifers** in fluvial sediment deposits underlain by marine sediment.
- Aquifer Group A** and **Aquifer Group B** are simulated.

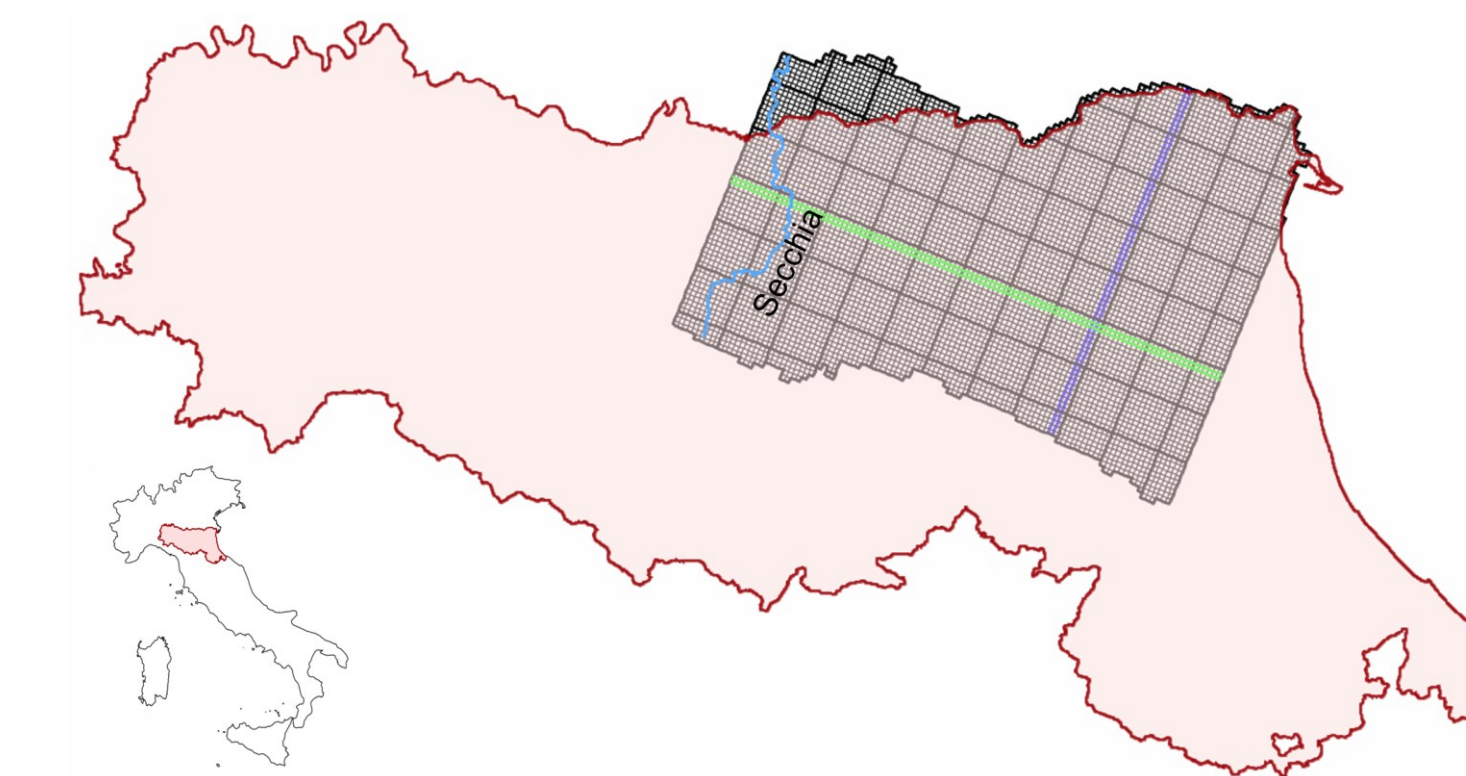


Figure 3.3. Simulated area compared to the whole territory of the Emilia-Romagna Region.

4. MONITORING WELLS

- Monitoring wells close to the rivers and the boundary cells (less than 2 MODFLOW cells, ~2.8 km) are **discarded**.
- 40 monitoring wells** considered in the analysis.

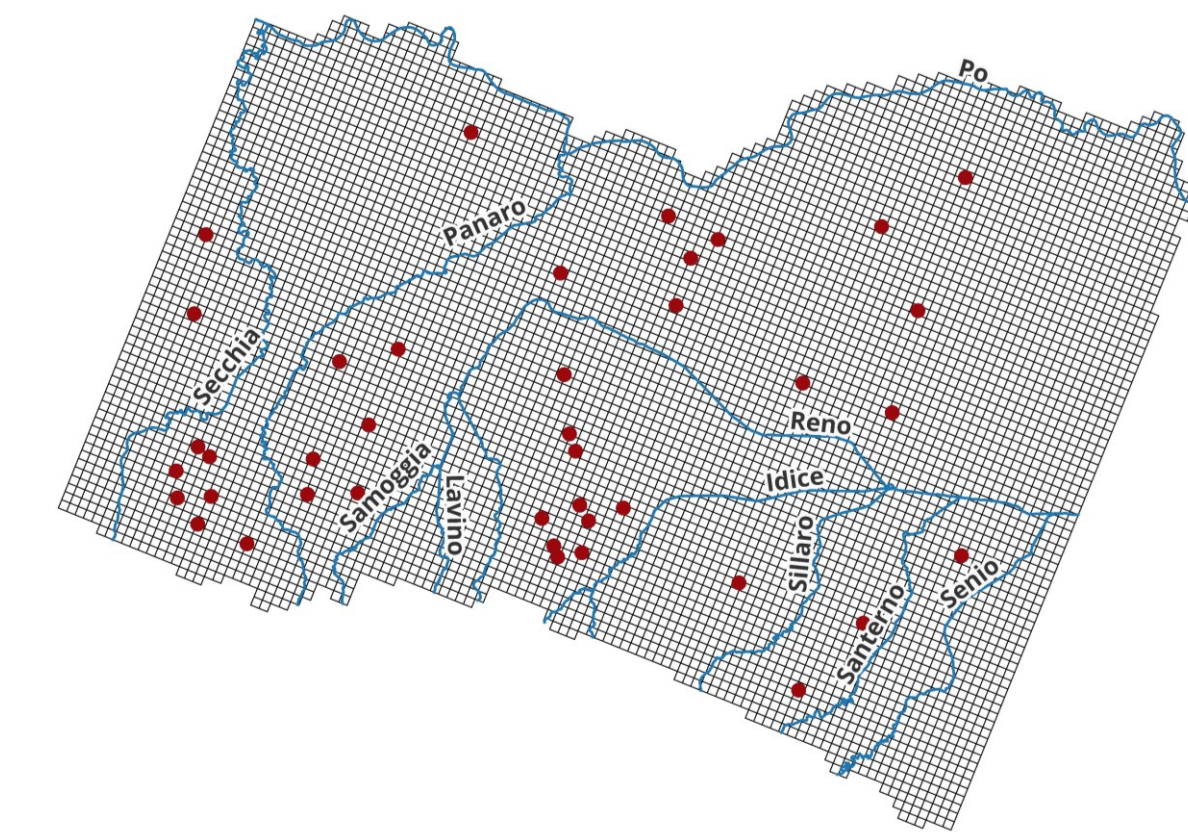


Figure 4.1. Monitoring wells considered in the analysis.

6. RESULTS

INFLUENCE OF DROUGHT DURATION

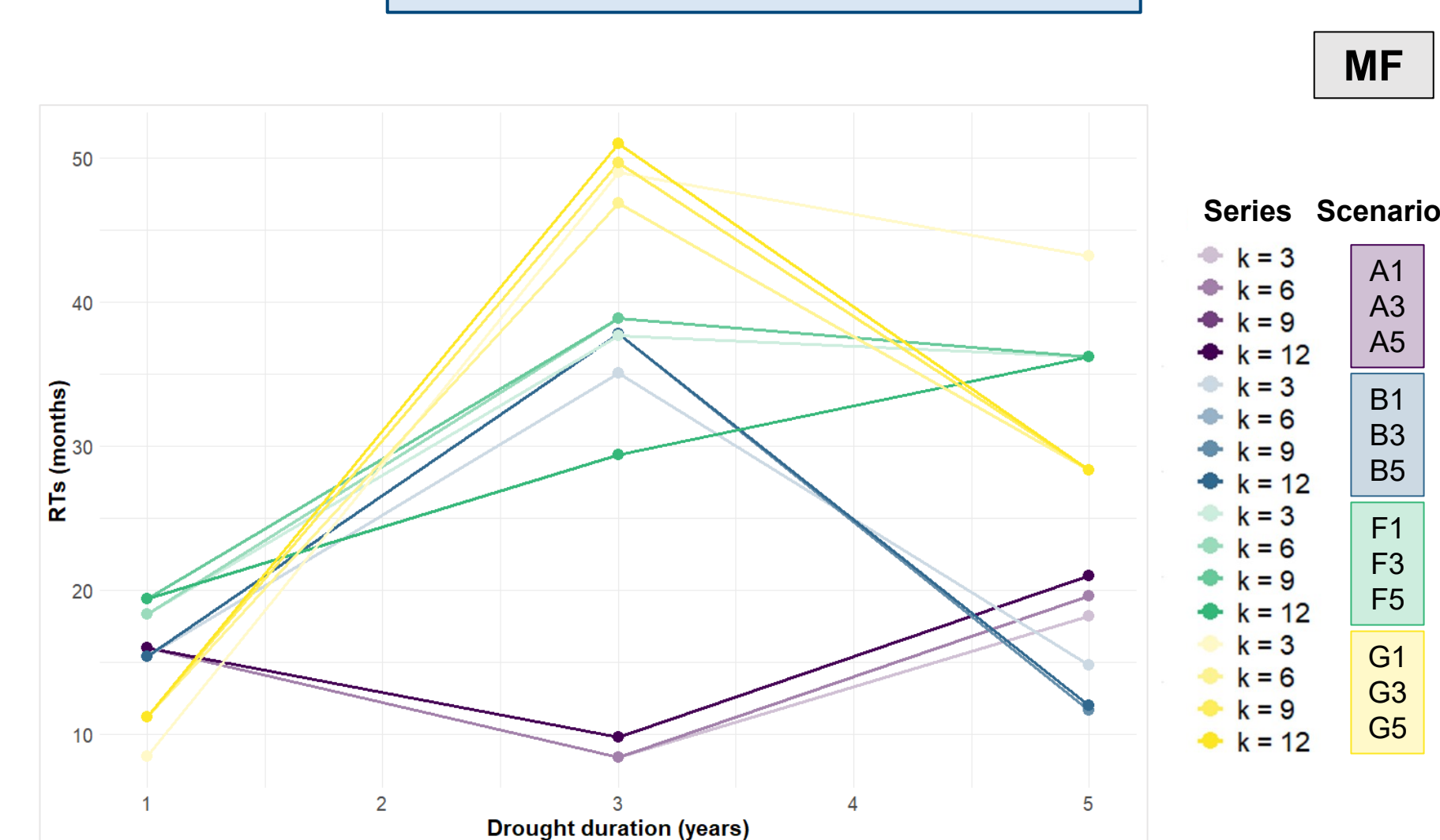


Figure 6.1. MF. Representation of RTs as a function of drought duration, considering different scenarios.

k	RTs (months)											
	A1	A3	A5	B1	B3	B5	F1	F3	F5	G1	G3	G5
3	3.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	1.0	3.0	3.0	3.0
6	4.0	1.0	1.0	4.0	1.0	1.0	4.0	1.0	1.0	3.0	3.0	3.0
9	5.0	1.0	1.0	5.0	1.0	1.0	5.0	1.0	1.0	4.0	4.0	4.0
12	5.0	1.0	1.0	5.0	1.0	1.0	5.0	1.0	1.0	2.3	2.3	2.3

Table 6.1. RF. RTs values for different drought durations and groundwater pumping variations.

- MF: 3-year droughts** usually produce the **longest RTs**.
- RF** usually simulates **higher RTs** for **1-year droughts**.
- RF:** when there is **no precipitation** (scenarios G1, G2, G5), **RTs do not depend** on drought duration.
- RF** simulates **much shorter RTs** than MF.
- RF:** results do **not appear to be sensitive** to variations in input data.
- For **1-year droughts**, **RTs vary less** than for longer droughts.
- There is generally **no strong influence** of **k** values.

INFLUENCE OF DROUGHT INTENSITY

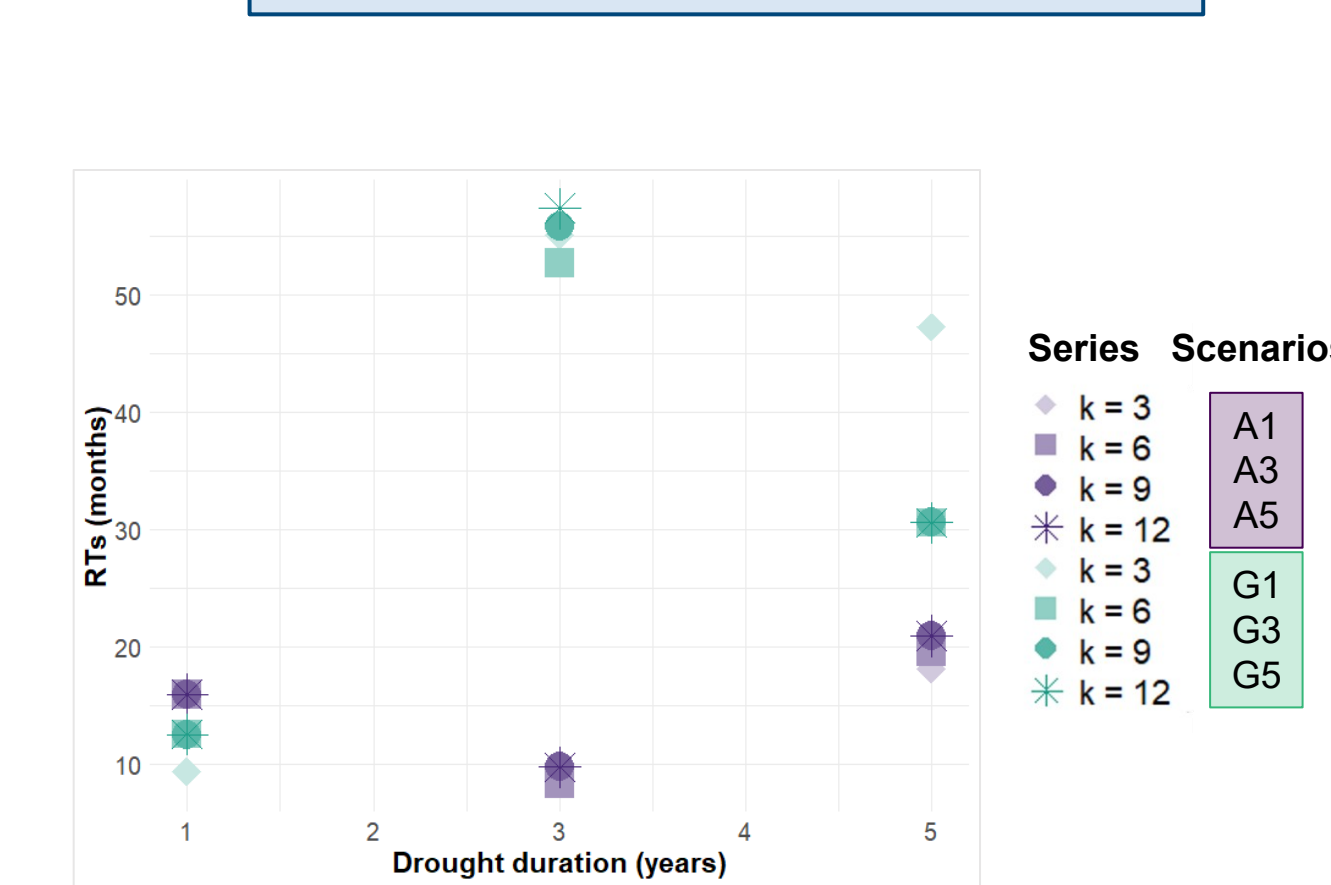


Figure 6.2. MF. Representation of RTs as a function of drought duration, considering different precipitation reduction scenarios.

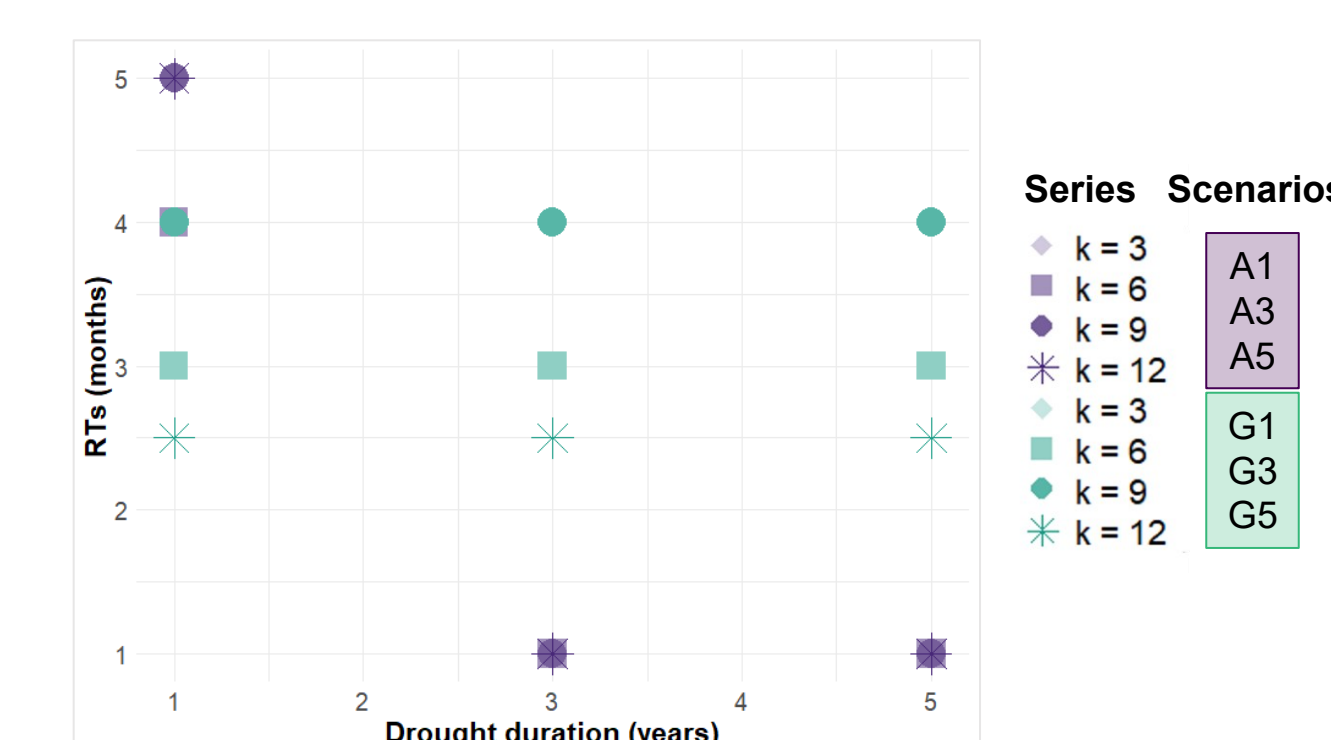


Figure 6.3. RF. Representation of RTs as a function of drought duration, considering different precipitation reduction scenarios.

- RF** simulates **much shorter RTs** than MF.
- For **droughts longer than 1 year**, **higher drought intensity** leads to **higher RTs**.
- In terms of recovery times, **longer, less intense droughts** are **preferable** to shorter, more intense ones.
- The **influence of k** increases with drought intensity.

INFLUENCE OF GROUNDWATER PUMPING

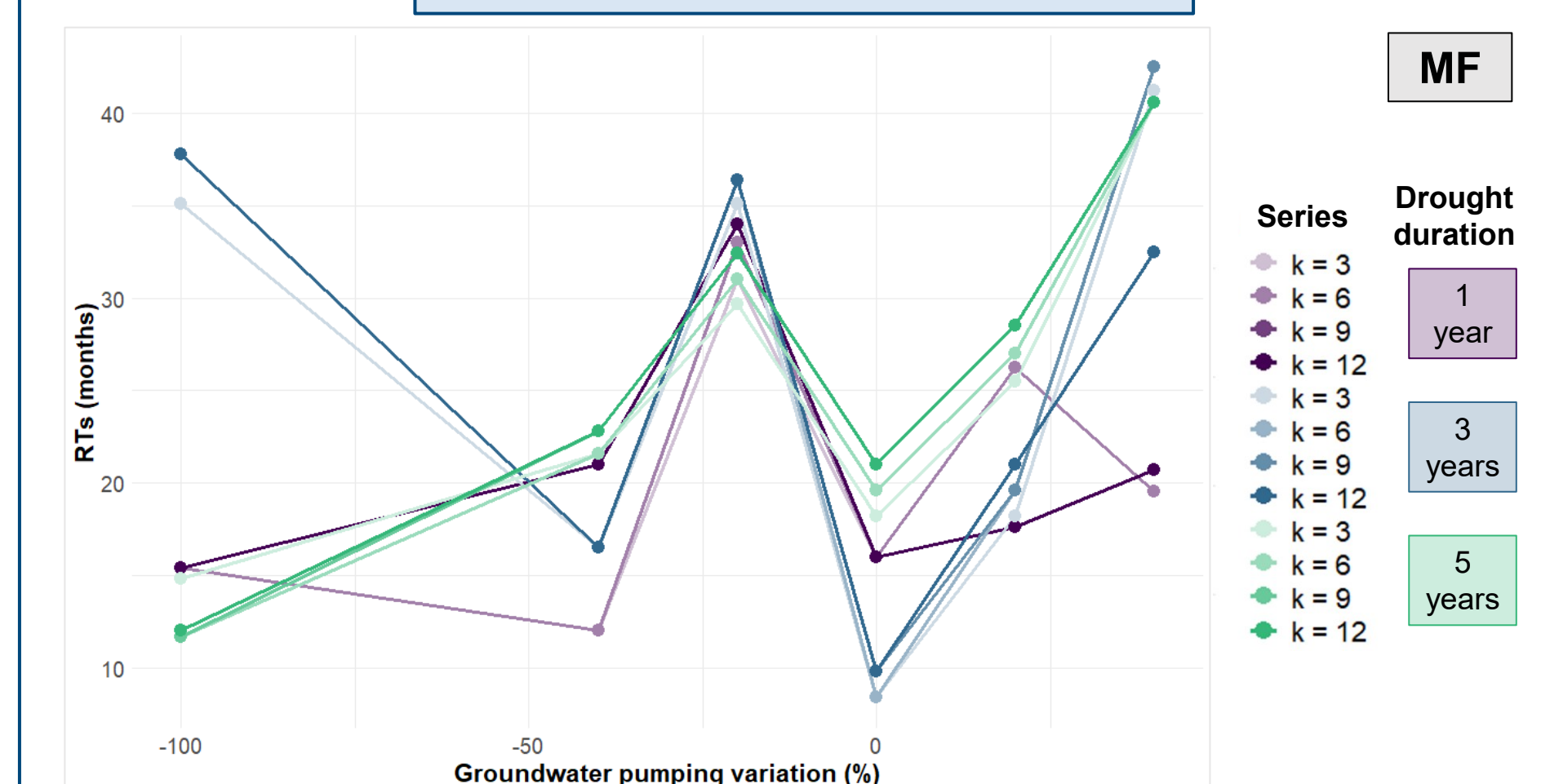


Figure 6.4. MF. Representation of RTs as a function of groundwater abstraction reduction introduced in different scenarios.

k	RTs (months)																	
	Groundwater pumping variation (%)																	
	-100	-40	-20	0	+20	+40	-100	-40	-20	0	+20	+40	-100	-40	-20	0	+20	+40
3	3.0	3.0	3.0	3.0	3.0	3.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
6	4.0	4.0	4.0	4.0	4.0	4.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
9	5.0	5.0	5.0	5.0	5.0	5.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
12	5.0	5.0	5.0	5.0	5.0	5.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	1 YEAR				3 YEARS				5 YEARS									

Table 6.2. RF. RTs values for different drought durations and groundwater pumping variations.

- MF: the pumping regime strongly influences RTs.**
- MF:** for **droughts longer than 1 year**, the **highest RTs** are simulated with a **40% increase** in groundwater pumping; for **1-year droughts**, with a **20% decrease**.
- MF:** even **without pumping**, **RTs remain high** (at least 1 year).
- RF:** results do **not appear to be sensitive** to variations in abstraction.
- RF** simulates **much shorter RTs** than MF.
- RF** simulates **higher RTs** for **1-year droughts**.
- RF:** under the **same pumping** conditions, **RTs remain unchanged**, suggesting a **stronger influence** of precipitation.
- There is generally **no strong influence** of **k** values.

Future work

- Refine the **parameter tuning** in the computation of recovery time.
- Assess the **sensitivity** of the method to different choices of ϵ .
- Improve the **sensitivity** of the **RF** to variations in input data.
- Test **different machine learning techniques**.
- Test the effects of **variations in different variables**.

References

Delfini, I., Chahoud, A., Zamrsky, D., & Montanari, A. (2025). Assessment of climate change impacts on groundwater exploitation sustainability in the Emilia-Romagna region (Italy). *Hydrological Sciences Journal*, 70(12), 2095-2119.

Guo, R., & Montanari, A. (2023). Historical rainfall data in northern Italy predict larger meteorological drought hazard than climate projections. *Hydrology and Earth System Sciences*, 27(15).

Chahoud, A., Patrizi, G., Zaccanti, G., & Gelati, L. Il modello di flusso delle acque sotterranee della Regione Emilia-Romagna. In Farina, M., Marcaccio, M., Zavatti, A. (2014). *Esperienze e prospettive nel monitoraggio delle acque sotterranee. Il contributo dell'Emilia-Romagna*. Pitagora Editrice, Bologna.