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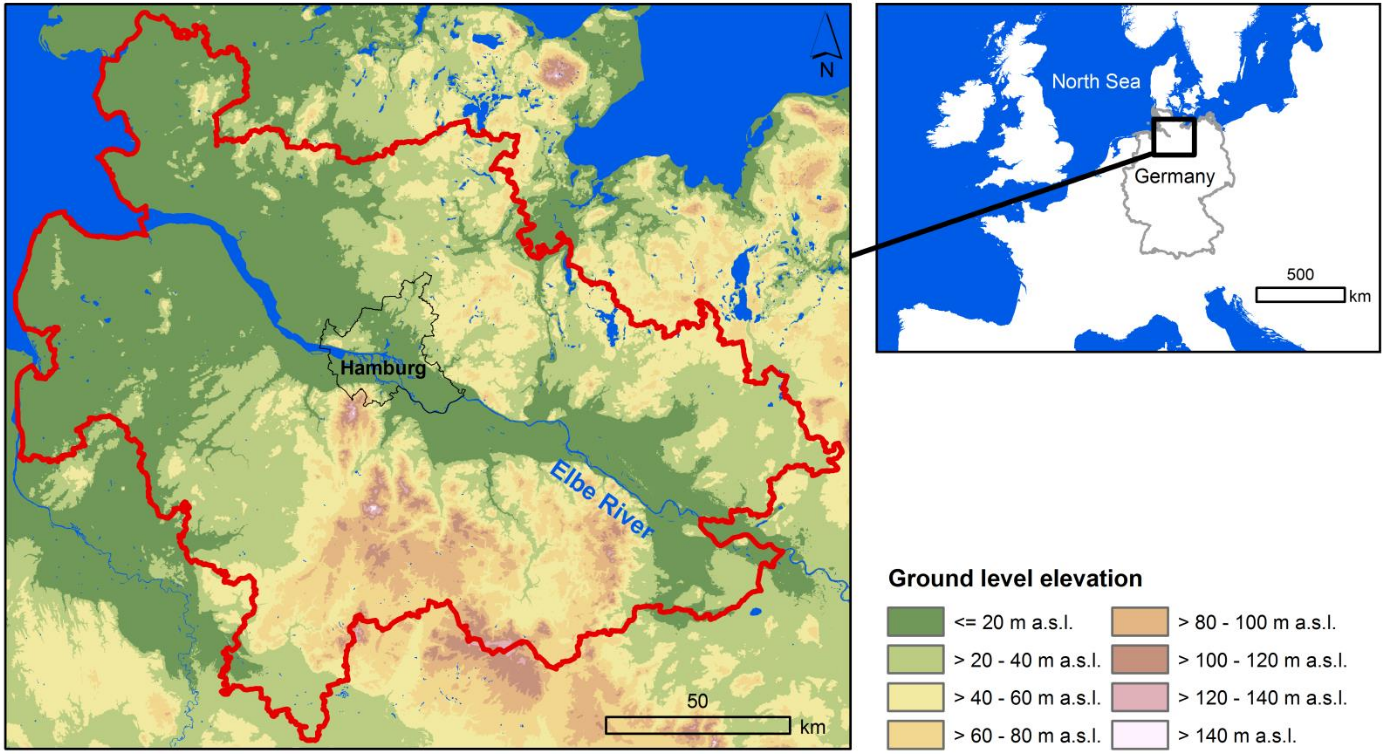
Impact of climate change on irrigation needs and groundwater resources in the metropolitan area of Hamburg (Germany)

Frank Herrmann, Ralf Kunkel, Harry Vereecken, Frank Wendland

Metropolitan area of Hamburg (MAH)



- **Area:** 22,400 km², i.e. 2.24 million 100 m grid cells.
- **Hydrogeological setting:** The region is part of the pore aquifer systems of the Central European Pleistocene lowland, which is composed of glacial sand and gravel sediments, displaying a thickness of 50 – 100 m on average.
- **Population:** 5 million (city-state of Hamburg 1.7 million).

Metropolitan area of Hamburg (MAH)

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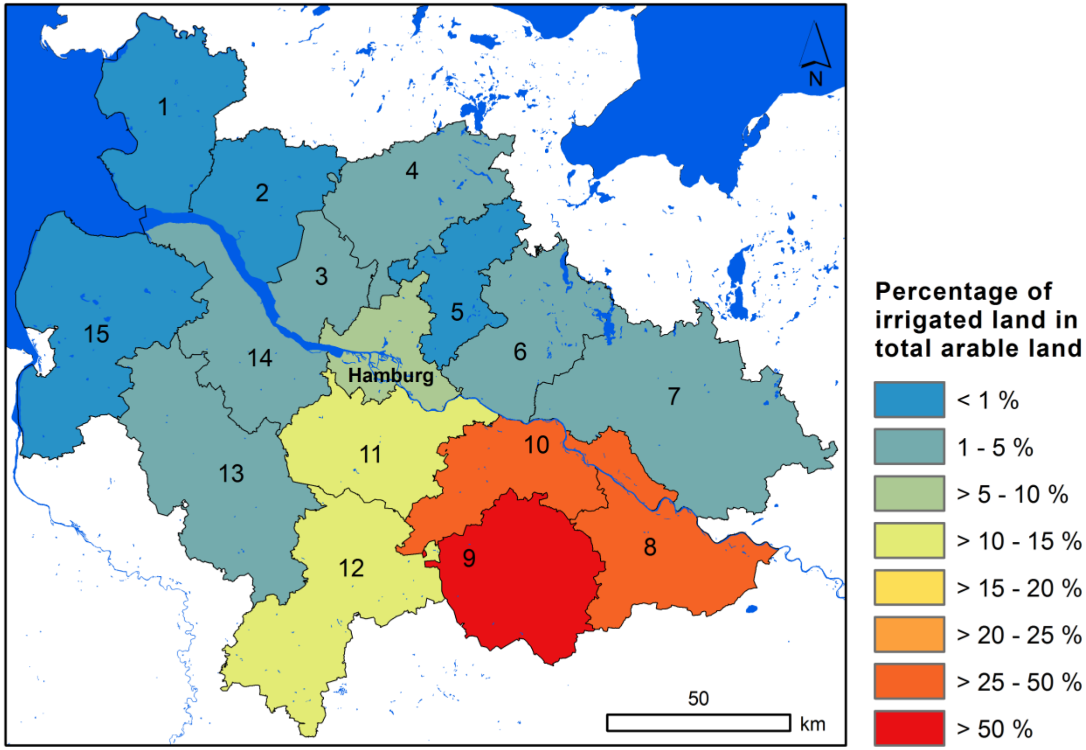

Rural districts:
1 Dithmarschen
2 Steinburg
3 Pinneberg
4 Segeberg
5 Stormarn
6 Herzogtum Lauenburg
7 Ludwigslust
8 Lüchow-Dannenberg
9 Uelzen
10 Lüneburg
11 Harburg
12 Soltau-Fallingbostel
13 Rotenburg (Wümme)
14 Stade
15 Cuxhaven

- **Administrative structure:** City-state of Hamburg and 15 rural districts located in 3 adjacent German Federal States.
- **Agriculture:** Important economic factor in the rural areas.
- **Usage conflicts concerning groundwater**:
  - Public water suppliers.
  - Increasing irrigated agriculture in the southeastern.

Climate change in the MAH

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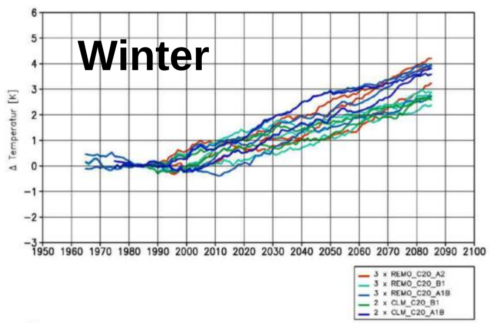
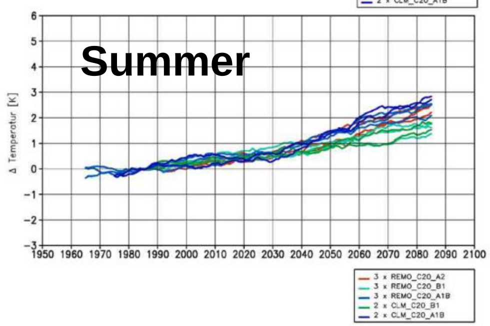
- **Analysis of the long-term data showed that the climate has already changed (Schlünzen et al., 2010):**
  - Annual precipitation significantly increased ~1.3 mm/a (1948-2007), however decrease during vegetation period.
  - Average temperatures significantly increased by 0.6 K/decade (1978-2007) with largest increases in fall.

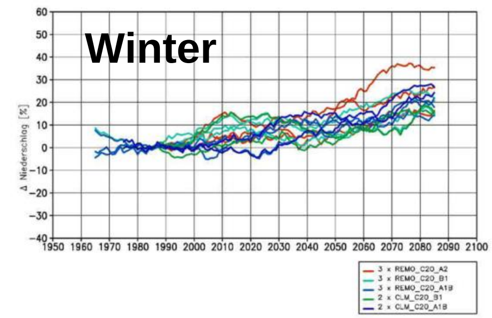
- **Projected climate change until 2100 (Jacob et al., 2012):**

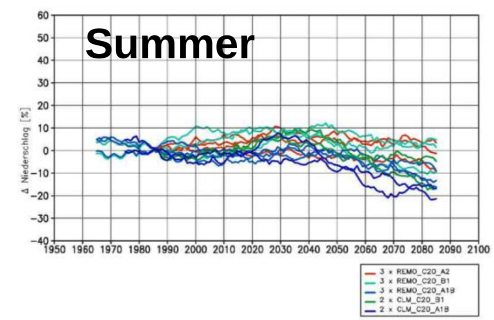
Temperature change in K





Precipitation change in %





Jacob, D., Bülow, K., Kotova, L., Moseley, C., Petersen, J., Rechid, D., 2012. Regionale Klimaprojektionen für Europa und Deutschland: Ensemble-Simulationen für die Klimafolgenforschung, CSC Report 6, Climate Service Center, Germany.

Schlünzen, K.H., Hoffmann, P., Rosenhagen, G., Riecke, W., 2010. Long-term changes and regional differences in temperature and precipitation in the metropolitan area of Hamburg. International Journal of Climatology, 30(8): 1121-1136. DOI: 10.1002/joc.1968

Objectives of the study

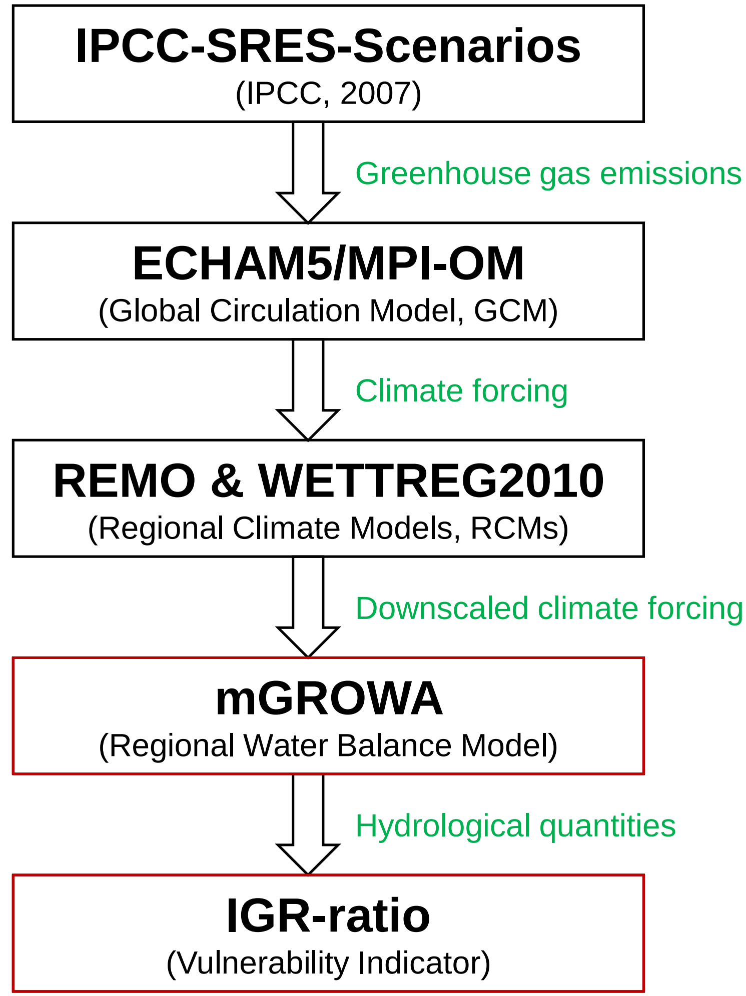
- Simulations for the observed reference period 1971-2000 using mGROWA:
  - Groundwater recharge
  - Irrigation need of typical field crops

- Development of a quantitative indicator to assess climate change impacts on the vulnerability of groundwater resources towards overexploitation by agricultural irrigation:
  - Ratio of irrigation to groundwater recharge (**IGR-ratio**)

- Delineation of **at risk areas** based on the **spatial IGR-ratio distribution** (status quo).

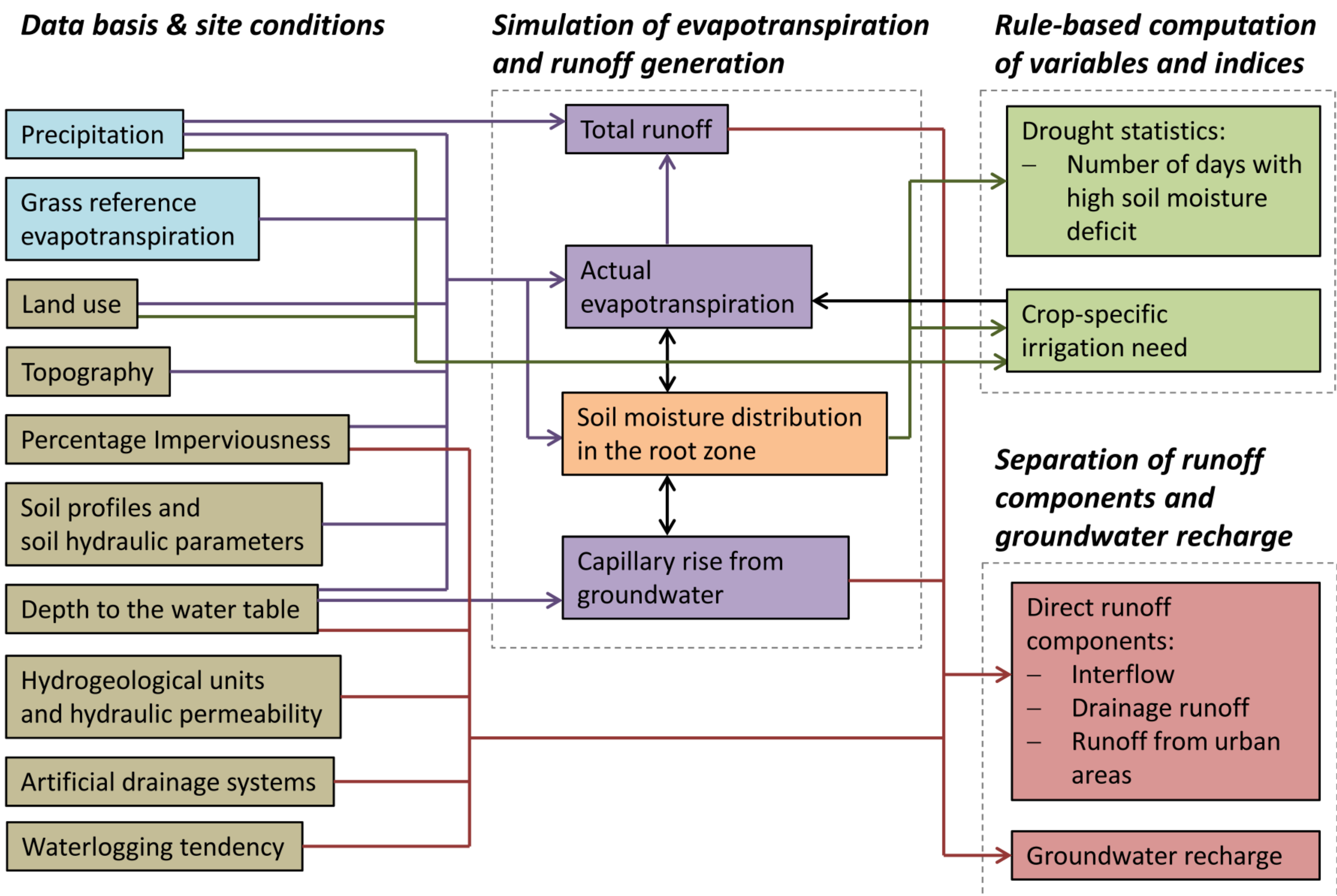
- **Projection of the IGR-ratios** (climate model ensemble as climate input).

Established model chain (Ensemble)



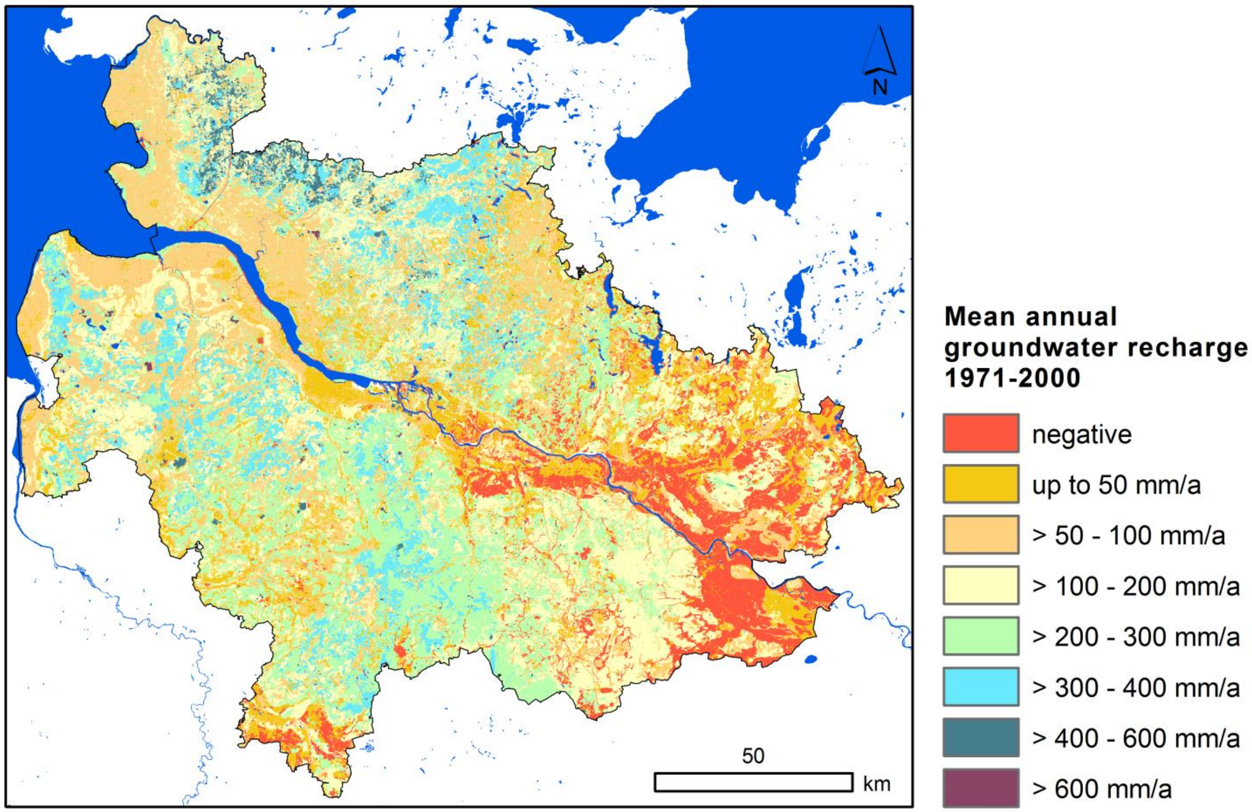
IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)], IPCC, Geneva, Switzerland.

Data basis and general modelling scheme of the mGROWA model (Herrmann et al. 2015)



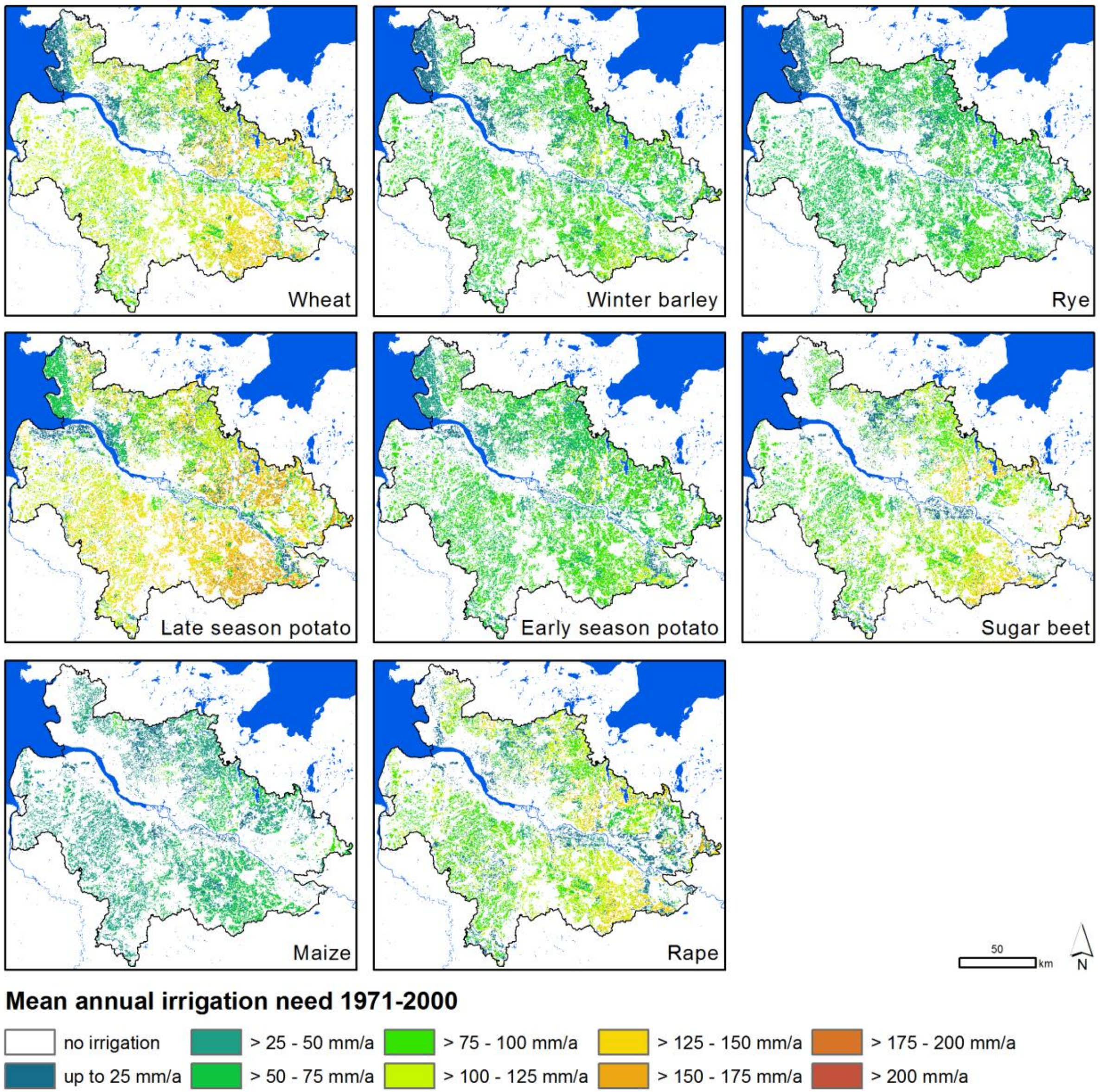
Herrmann, F., Keller, L., Kunkel, R., Vereecken, H., Wendland, F., 2015. Determination of spatially differentiated water balance components including groundwater recharge on the Federal State level – A case study using the mGROWA model in North Rhine-Westphalia (Germany). Journal of Hydrology: Regional Studies, 4: 294-312. DOI: 10.1016/j.ejrh.2015.06.018

Mean long-term annual groundwater recharge simulated with mGROWA for the reference period (1971-2000) based on observed climate data



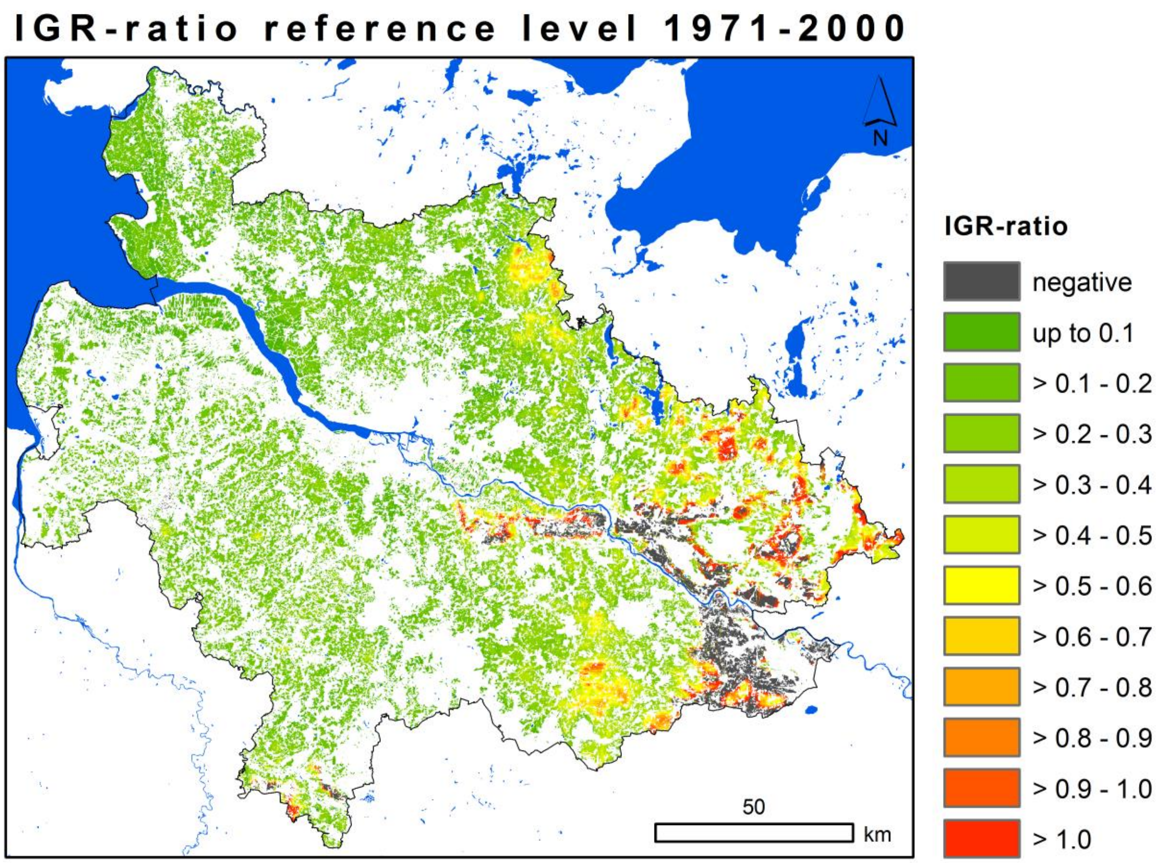
- Regional gradient of groundwater recharge from the coastal area to eastern parts caused by decreasing precipitation and increasing continentality of the climate.

Mean long-term annual irrigation need of 8 field crops simulated with mGROWA for the reference period (1971-2000) based on observed climate data.



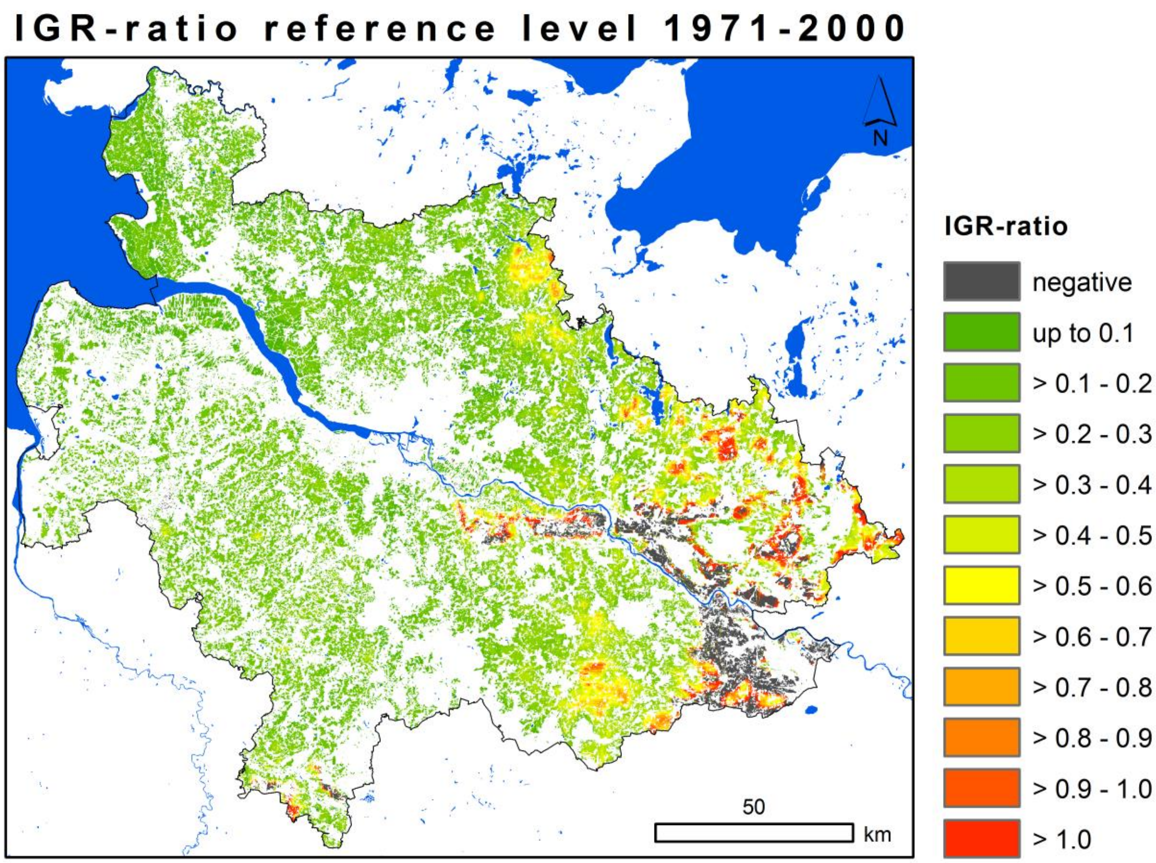
- Regional gradients of precipitation and continentality lead to significant irrigation needs in the southeastern of the MAH.

IGR-ratio in the reference period 1971-2000 calculated based on observed climate values (status quo)



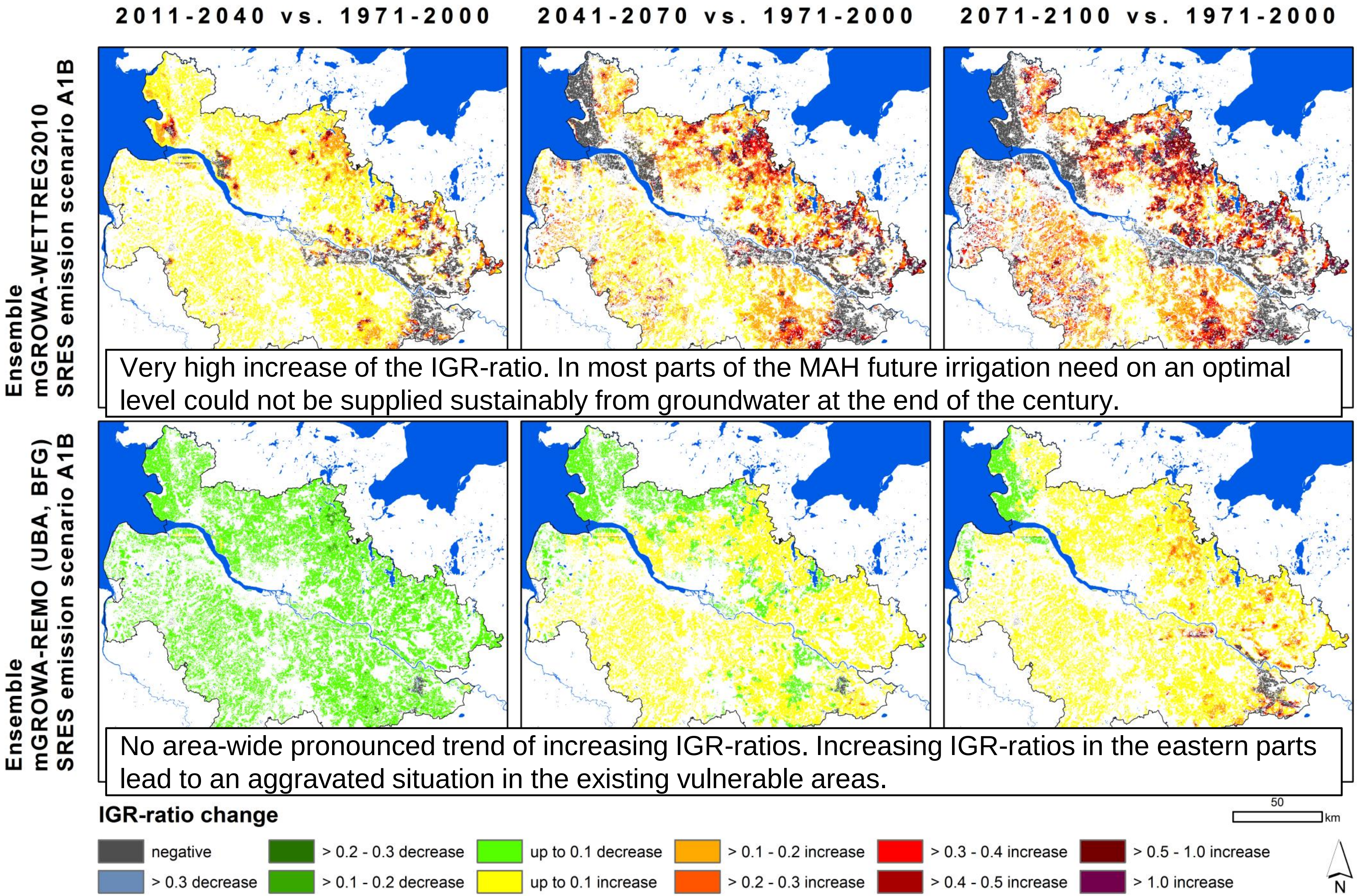
- Very sharp delineation of areas with high IGR-ratios.
- IGR-ratios tend to increase towards the eastern parts of the MAH due to an increasing irrigation need and decreasing groundwater recharge rates.
- Large areas with high irrigation need and low groundwater recharge in the surrounding groundwater-contributing-areas become visible as vulnerable areas.

IGR-ratio in the reference period 1971-2000 calculated based on observed climate values (status quo)



- The delineated vulnerable areas coincide with the regions for which high irrigation quantities from groundwater resources have been documented at present.
- Additionally, the IGR-ratio depicts the areas in which irrigation is currently still negligible, but in which the introduction of irrigation into agricultural practice would lead to an immediate overexploitation of the sustainably available groundwater budget.

Possible future changes of long-term average IGR-ratios



Very high increase of the IGR-ratio. In most parts of the MAH future irrigation need on an optimal level could not be supplied sustainably from groundwater at the end of the century.

No area-wide pronounced trend of increasing IGR-ratios. Increasing IGR-ratios in the eastern parts lead to an aggravated situation in the existing vulnerable areas.

Conclusions

- The IGR-ratio is suggested as an indicator to assess climate change impacts on the vulnerability of groundwater resources towards overexploitation by agricultural irrigation.
- The IGR-ratio maps are intended to become a part of a decision support system which could be used to allocate water rights for pumping irrigation water out of the aquifers of the MAH.
- The divergent results of the IGR-ratio projections are probably caused by the fundamental conceptual differences of the two RCMs (statistical vs. dynamical downscaling).
- Commonly, such uncertainties regarding the projected bandwidth of an indicator complicate decisions about mitigation and adaptation measures in groundwater management.
- For a future study it is recommended to enhance the employed climate model ensemble, i.e. to use the newly available EURO-CORDEX ensemble (Jacob, 2014).

Jacob, D., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change, 14(2): 563-578. DOI: 10.1007/s10113-013-0499-2

Thanks for your attention !

Publications

Herrmann, F., Kunkel, R., Ostermann, U., Vereecken, H., Wendland, F., 2016. Projected impact of climate change on irrigation needs and groundwater resources in the metropolitan area of Hamburg (Germany). **Environmental Earth Sciences**, 75(14). DOI: 10.1007/s12665-016-5904-y

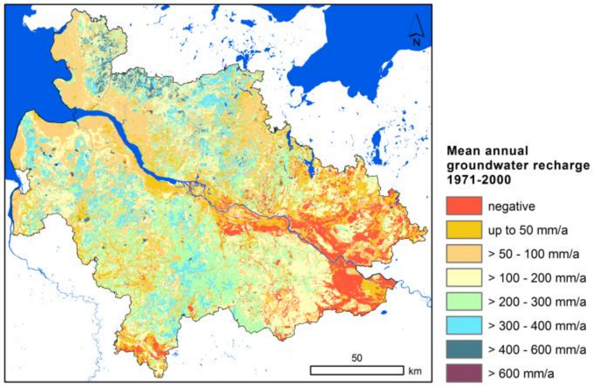
Herrmann, F., Chen, S., Hübsch, L., Engel, N., Kunkel, R., Müller, U., Vereecken, H., Wendland, F., 2014. Auswirkung von möglichen Klimaänderungen auf den Bodenwasserhaushalt und die Grundwasserneubildung in der Metropolregion Hamburg. In: Kaden, S., Dietrich, O., Theobald, S. (Eds.), **Wassermanagement im Klimawandel - Möglichkeiten und Grenzen von Anpassungsmaßnahmen**. oekom Verlag.

Acknowledgements

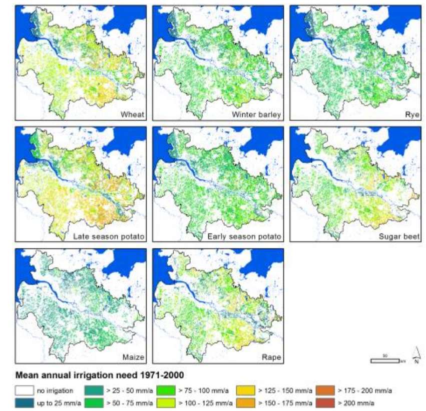
This study has been carried out in the framework of the funding programme KLIMZUG-NORD "Strategies adapted to climate changes concerning the metropolitan area of Hamburg" on behalf of the German Federal Ministry of Education and Research (BMBF).

Available data basis and simulation results

Groundwater recharge



Irrigation need of field crops



Regional statistics of area proportions of field crops

Prozentualer Anteile der Feldfrüchte an der Gesamtackerfläche					
Fruchtart	Cuxhaven	Lüchow-Dannenberg	Lüneburg	Uelzen	...
Weizen	20	10	14	15	...
Wintergerste	4	10	8	10	...
Roggen	4	17	12	7	...
Kartoffel RG 3	1	11	9	18	...
Frühkartoffel RG 1	0	2	2	3	...
Zuckerrübe	0	5	5	14	...
Mais	51	11	13	9	...
Raps	5	9	11	5	...

Regional model of the groundwater surface

Now, we need an approach to calculate the spatial distribution of the IGR-ratio, i.e. our handy indicator to assess the vulnerability of groundwater resources towards overexploitation by agricultural irrigation.

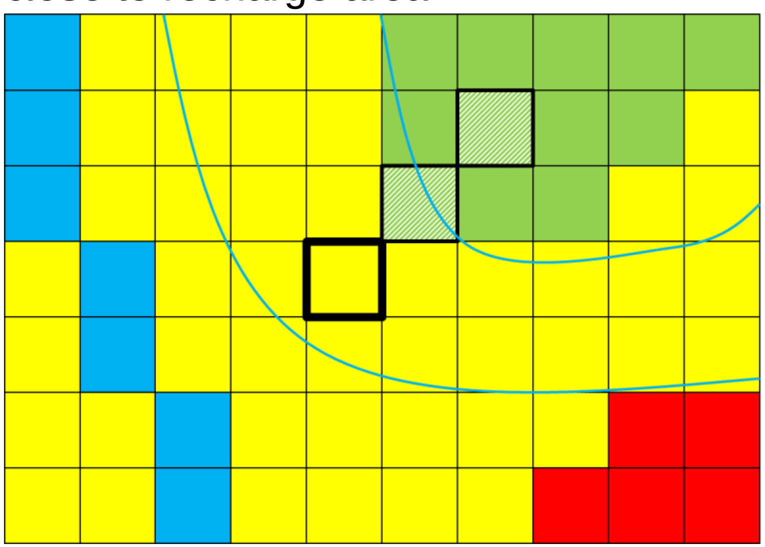
Basics of the IGR-ratio calculation approach

- The calculation is carried out for **grid cell specific hydrogeological reference areas**. General steps:
  - Delineation of the individual sub-surface catchments (ISSC) of all grid cells representing irrigated arable land. An ISSC comprises all grid cells which may contribute groundwater to this particular grid cell.
  - The IGR-ratios are calculated for the ISSCs by using the Eq.:

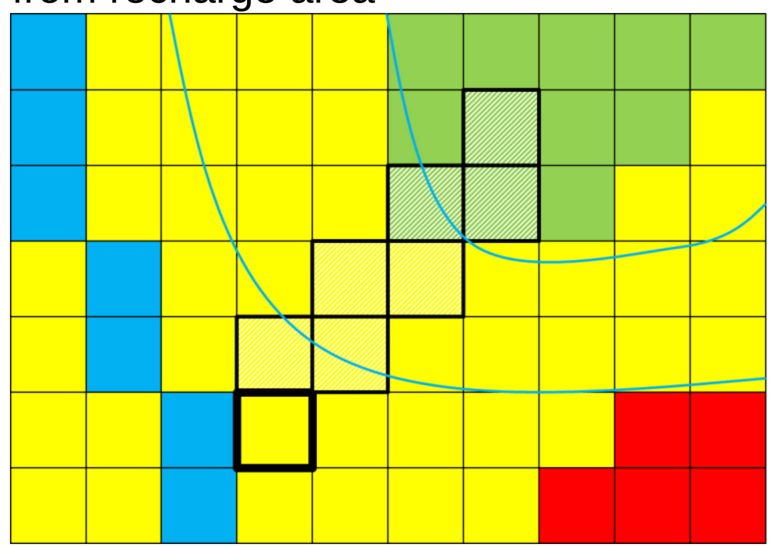
$$IGR = \frac{\sum_{i=1}^{n} irr}{\sum_{j=1}^{m} q_r}$$

irr – mean irrigation need of field crops
qr – groundwater recharge

Example 1: ISSC of grid cell close to recharge area



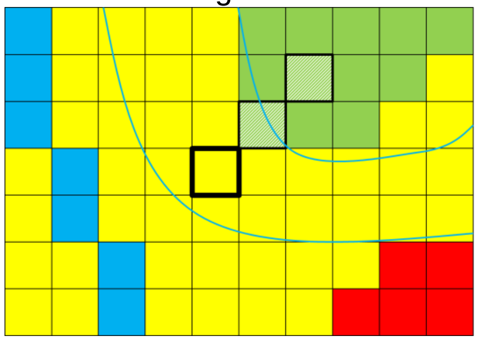
Example 2: ISSC of grid cell far from recharge area



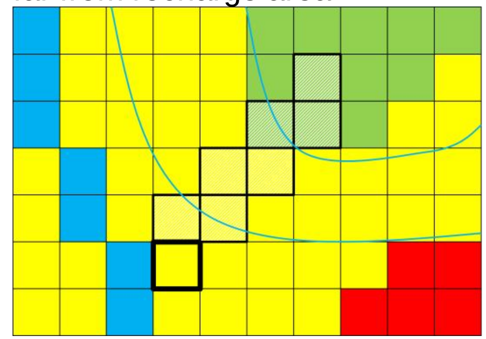
Water Irrigated arable land Forest Village

Results of the IGR-ratio calculation approach

Example 1: ISSC of grid cell close to recharge area



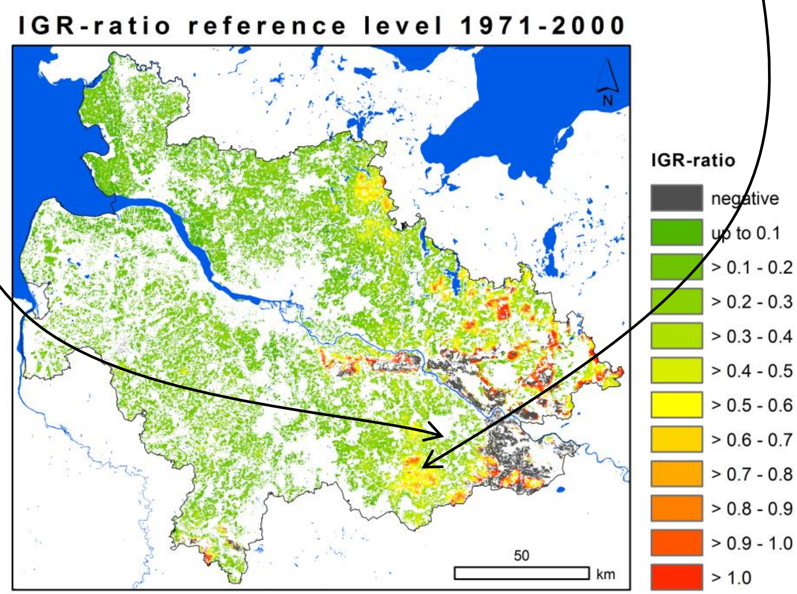
Example 2: ISSC of grid cell far from recharge area



IGR-ratio of example 1 < IGR-ratio of example 2

High frequency of occurrence in green colored areas

IGR-ratio < 0.4



High frequency of occurrence in yellow or red colored areas

IGR-ratio > 0.4

Conclusions

- The IGR-ratio is suggested as an indicator to assess climate change impacts on the vulnerability of groundwater resources towards overexploitation by agricultural irrigation.
- The IGR-ratio maps are intended to become a part of a decision support system which could be used to allocate water rights for pumping irrigation water out of the aquifers of the MAH.
- The divergent results of the IGR-ratio projections are probably caused by the fundamental conceptual differences of the two RCMs (statistical vs. dynamical downscaling).
  - Depending on the projected magnitude of future precipitation and reference evapotranspiration increase during winter, groundwater recharge may possibly increase.
  - In contrast, projected decreasing precipitation and increasing reference evapotranspiration during summer cause correspondingly rising irrigation need of field crops.
- Commonly, such uncertainties regarding the projected bandwidth of an indicator complicate decisions about mitigation and adaptation measures in groundwater management.
- For a future study it is recommended to enhance the employed climate model ensemble, i.e. to use the newly available EURO-CORDEX ensemble (Jacob, 2014).

Jacob, D., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Regional Environmental Change, 14(2): 563-578. DOI: 10.1007/s10113-013-0499-2