Meteorological Input Variables in Meso- and Macroscale Hydrological Modelling

W. Lahmer[1], B. Klöcking[1] and B. Pfützner[2]

[1] Potsdam Institute for Climate Impact Research (PIK), Telegrafenberg, D-14412 Potsdam, Germany

[2] Bureau for Applied Hydrology (BAH), Wollankstr. 117, D-13187 Berlin, Germany

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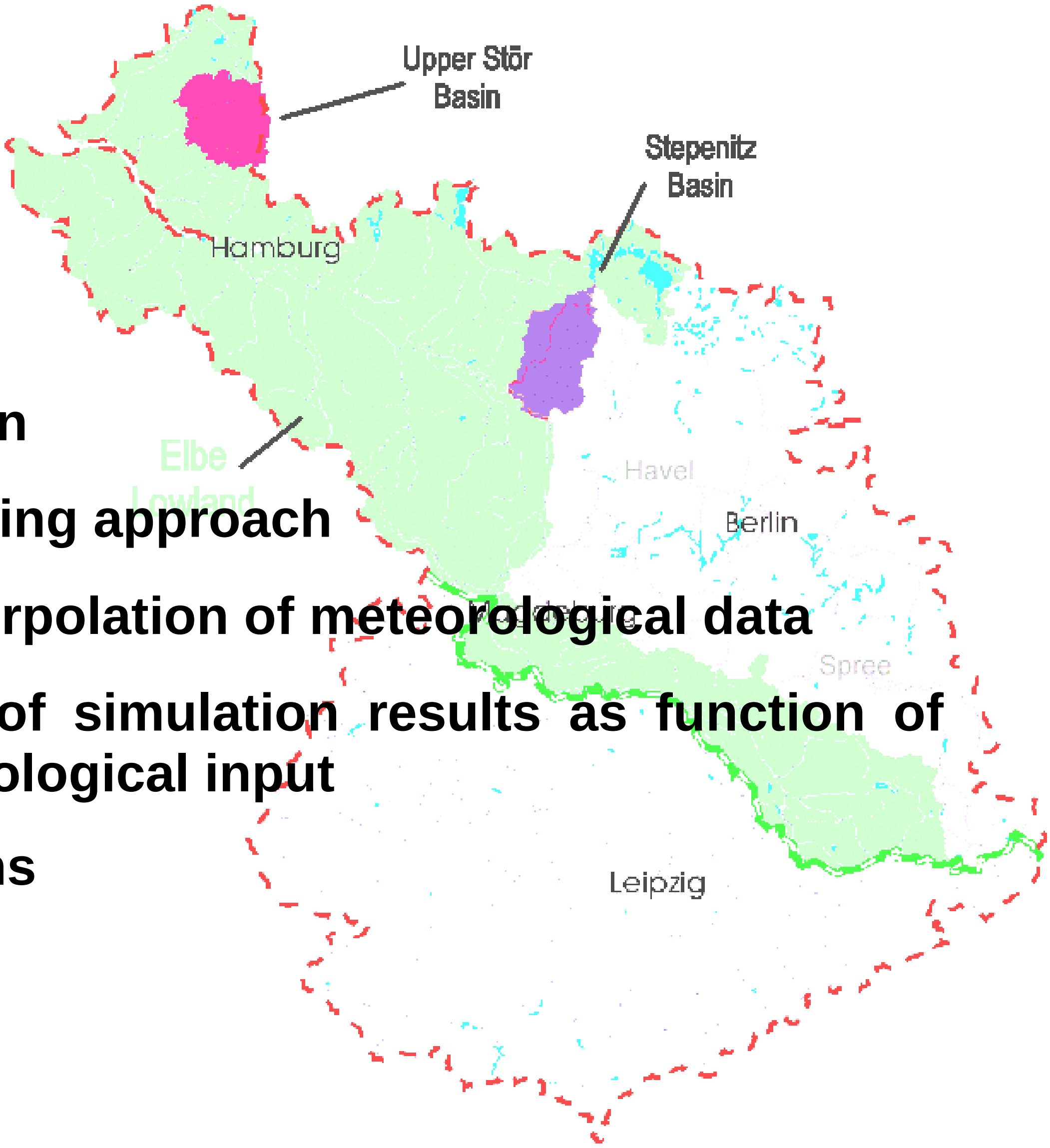


- **Introduction**
- **The modelling approach**
- **Spatial interpolation of meteorological data**
- **Reliability of simulation results as function of the meteorological input**
- **Conclusions**

INTRODUCTION

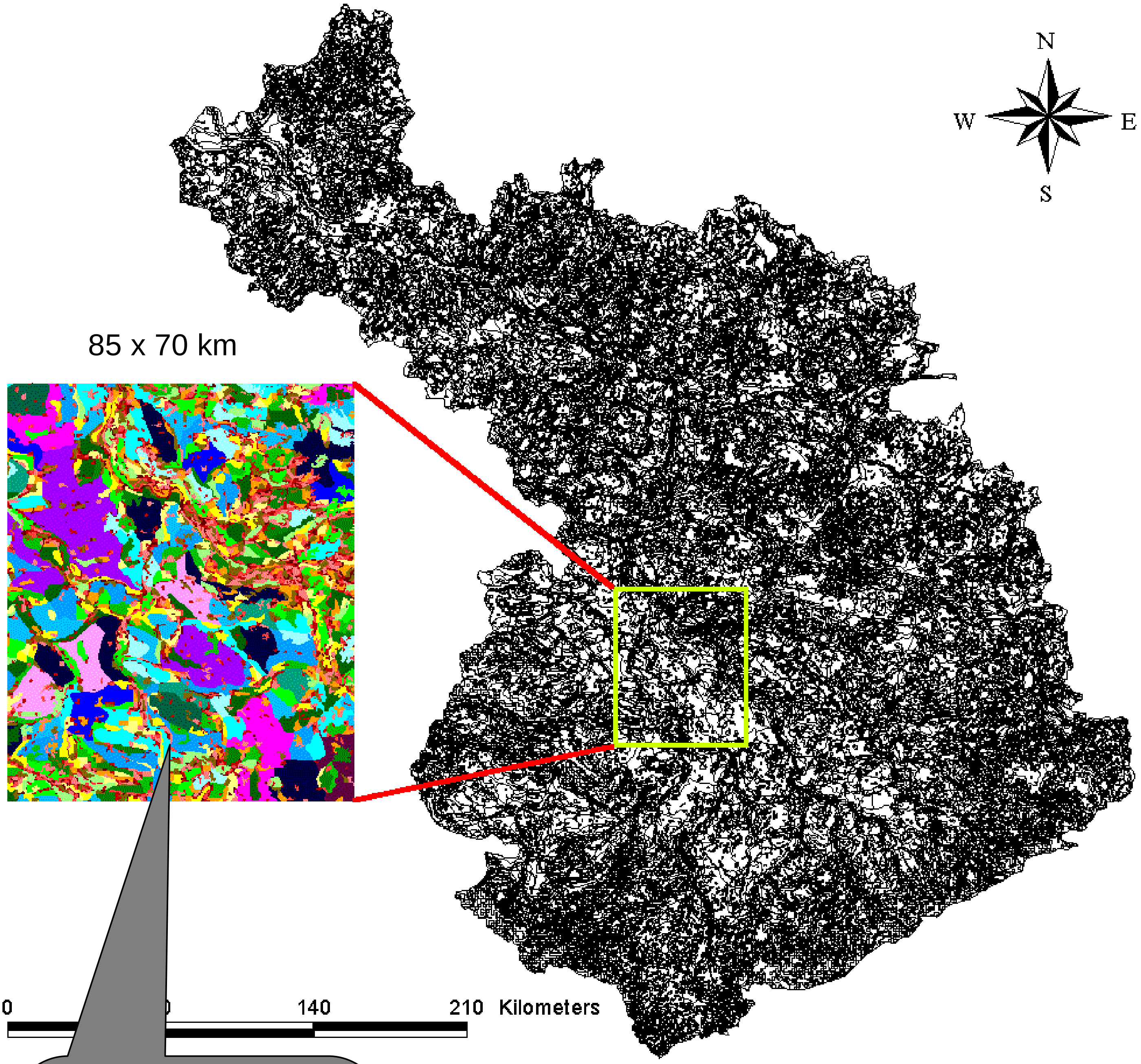
- The study of **human impacts on the hydrological cycle** plays a growing role in today's hydrological research.
- In order to forecast the effects of climate and/or landuse changes, **appropriate models** and high resolution data at various spatial and temporal scales are necessary.
- The availability of high resolution **hydrometeorological data** is especially important, since only then the driving forces of hydrological processes can be appropriately taken into account in simulation calculations at the meso- and macro-scale.
- Studies performed in the **Elbe basin and some of its sub-basins** demonstrate that the spatial **interpolation** of climatic input variables plays a key role in large scale hydrological modelling (i.e. for the calculation of various **water balance components**).
- The present study
    - ➢ illustrates **problems resulting from the availability and accuracy** of temporal data and their spatial interpolation on various scales, which is important in the modelling of large scale river basins
    - ➢ quantifies some **uncertainties in the results of model applications**.

THE MODELLING APPROACH

- The large scale application of **fully distributed physically based hydrological models** is constrained by the availability of required input data. In addition, their use at the regional level is often of limited value.
- Therefore, **simplified (conceptional) models** with physically meaningful parameters are needed which can be applied at different scales.
- Such models must be able to use directly the information provided by digital maps (**GIS coupling**) and to handle different temporal and spatial discretization levels.
- The modelling approach used in the present study is based on variable spatial disaggregation and aggregation techniques and consequently uses the GIS-based derivation of model parameters from generally available spatial data.
- A key element of the approach is the modelling system **ARC/EGMO**. Basic characteristics are the

  - ❖ distinction of **two domains of hydrological processes** (vertical and lateral fluxes), where different disaggregation, aggregation, and scaling techniques can be applied
  - ❖ **spatial disaggregation** of the study region in homogeneous sub-areas (‘*Elementary Units’, Hydrological Response Units-HRUs*)
  - ❖ **spatial aggregation** of these sub-areas to larger spatial units (*hydrotopes, hydrotope classes*) to simplify large scale modelling and to reduce computing time (‘fractional area concept’, important regionalization method)
  - ❖ representation of the ‘intra patch’ areal parameter variability of aggreated spatial units by areal **distribution functions.**

Map of elementary units for the Elbe river basin



Polygons are best suited to represent the mosaic structure of real landscapes.

The zoomed sub-area demonstrates the various *size* and *shape* of these modelling units, which is especially important in simulating land-use changes, as such changes may be restricted to rather small and widely distributed parts of the study region.

Map of **64.550 elementary units** deduced for the Elbe river basin by a Geographic Information System (GIS) from the available digital maps (*land use, vegetation cover, soil characteristics, topography, ground water level, river net, sub-basins etc*.) in the pre-processing stage

SPATIAL INTERPOLATION OF METEOROLOGICAL INPUT VARIABLES

- The development of spatially distributed, large-scale hydrological models has enlarged their data needs.
- Shortcomings are still obvious both
  - ❖ for **spatial data** (which often provide an insufficient resolution) and
  - ❖ for **time series data** needed to provide the necessary meteorological input and to validate the model results.
- The spatial distribution of meteorological input variables has an important influence on the calculated **water balance components**.
- In order to include realistic distributions of these variables in the simulation calculations, an **appropriate interpolation method** must be used.
- Since the interpolation is performed for every time step of the simulation period, the method must be **fast**.

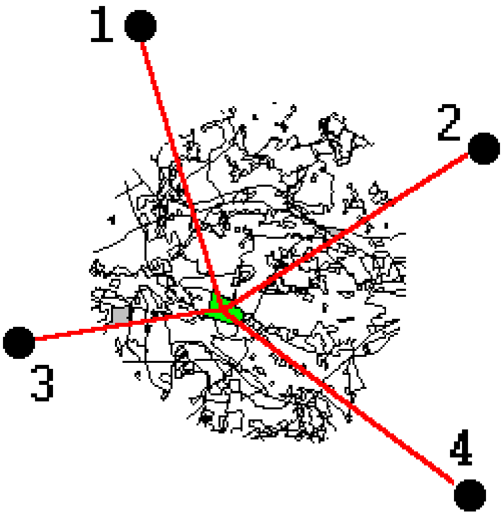
The analyses presented here, in general include information from all meteorological stations available in the study region.

- However, due to **missing values** or **too short observation periods**, many stations had to be excluded from the simulation calculations.
- In addition, the calculation of **potential evaporation** according to more sophisticated approaches is not possible, since there is only a small number of climate stations providing all specific parameters for longer time periods.

The interpolation method

- The standard interpolation method used in the present study (‘**extended quadrant method**’) has turned out to be the most effective approach in interpolating meteorological point data for every time step (one day) of the simulation period.

- It is characterized by
  - the *selection of relevant stations* by the quadrant method
  - an *inverse distance interpol*ation of the respective variables
  - the *inclusion of other dependencies* (elevation, exposition or slope) based on mean annual values.



Schematic representation of the interpolation method used in the simulation calculations

- The interpolation can be performed on the basis of elementary units, hydrotopes, sub-basins or the whole basin.

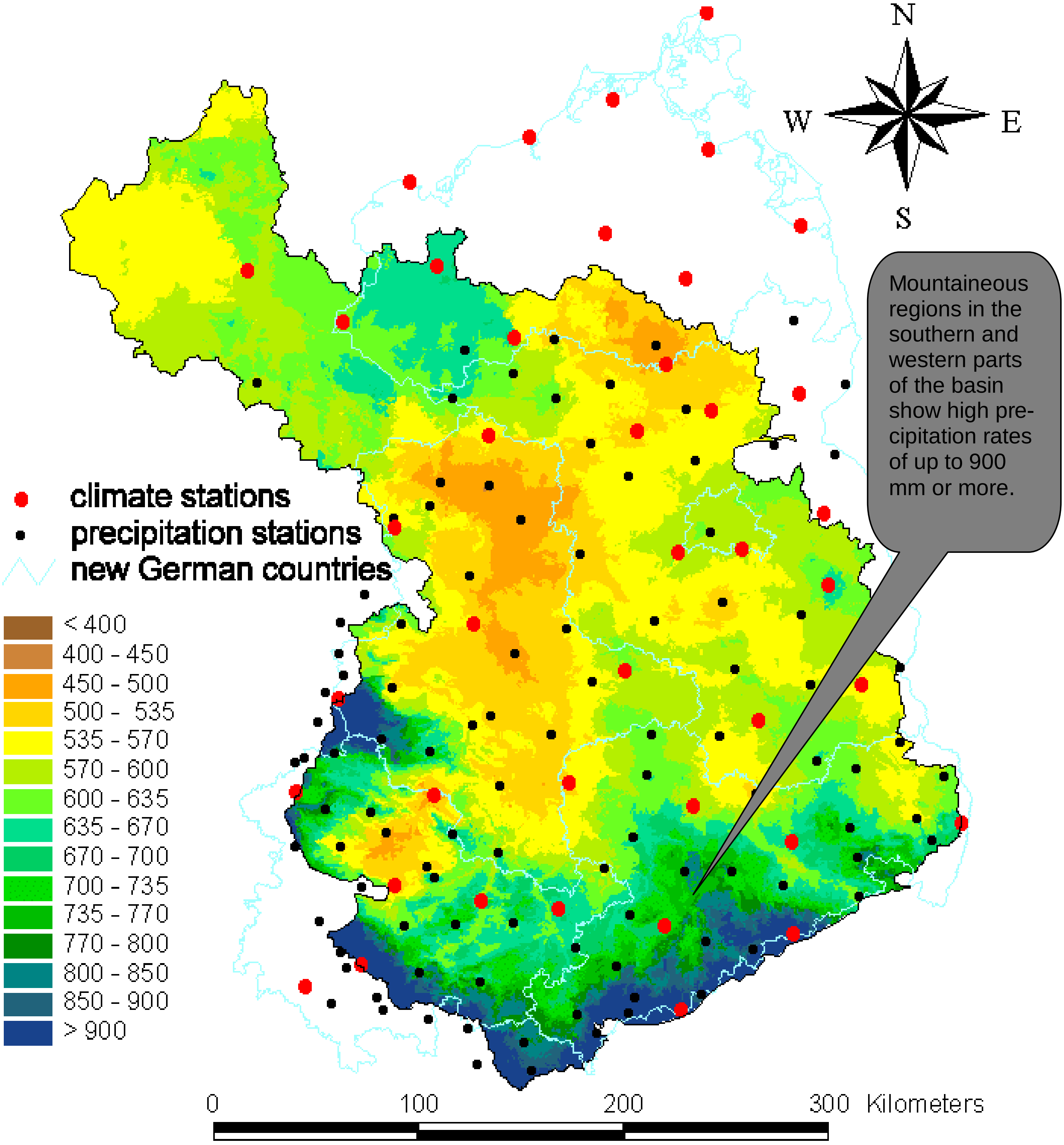
- For the water balance calculations
  - ➢ **33** climate and **107** precipitation stations (Elbe basin)
  - ➢ **9** climate and **24** precipitation stations (Stepenitz)

  were used for the spatial interpolation of

precipitation
mean temperature
relative humidity
sunshine duration

} for the calculation of potential evaporation according Turc/Ivanov

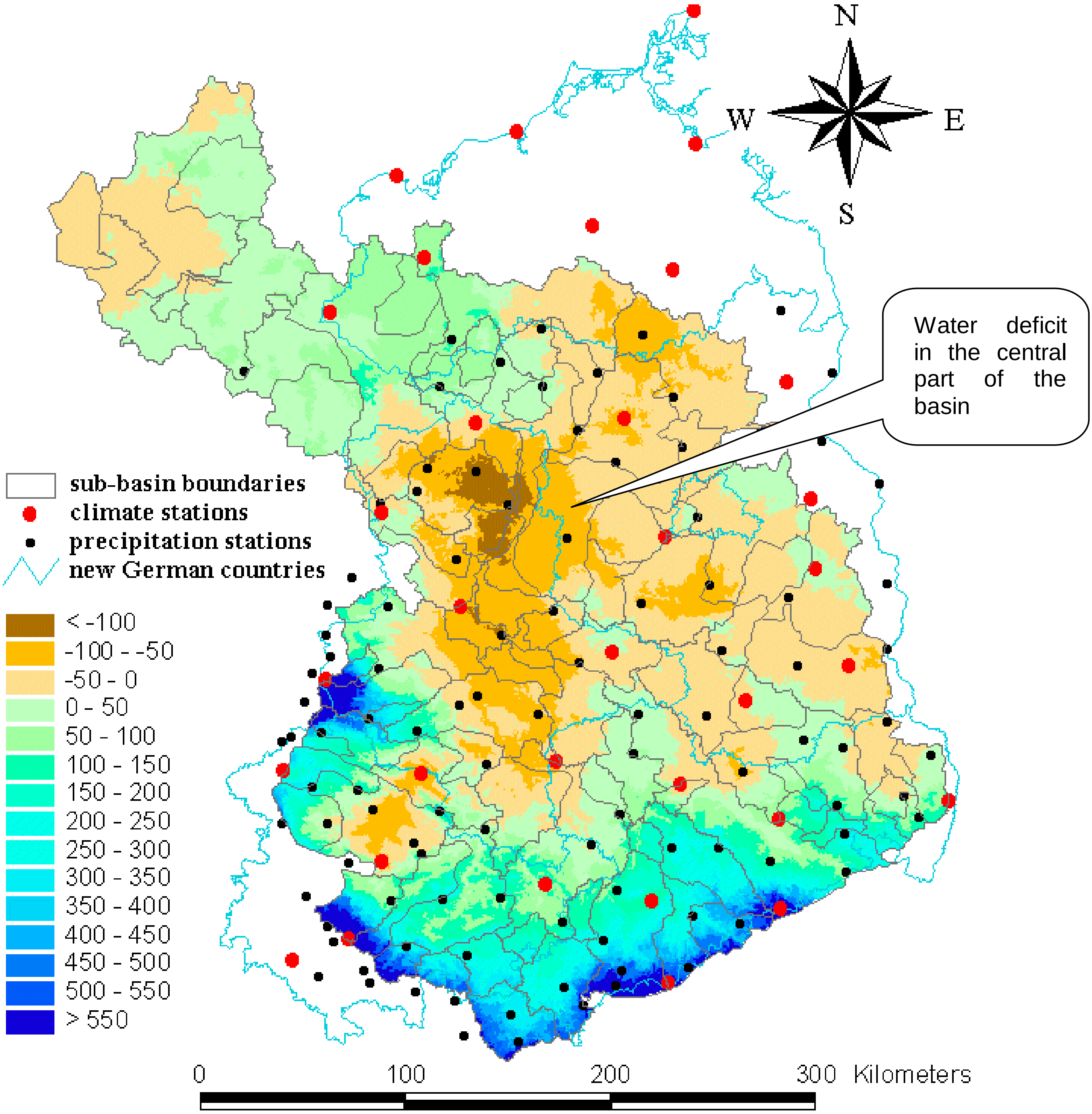
Spatial distribution of precipitation



Mountaineous regions in the southern and western parts of the basin show high precipitation rates of up to 900 mm or more.

Mean annual **precipitation** [mm] in the **Elbe river basin** (~96.500 km²) for the period 1983-1987, calculated from 33 climate and 107 precipitation stations on the basis of 64.550 elementary units.

Spatial distribution of the climatic water balance

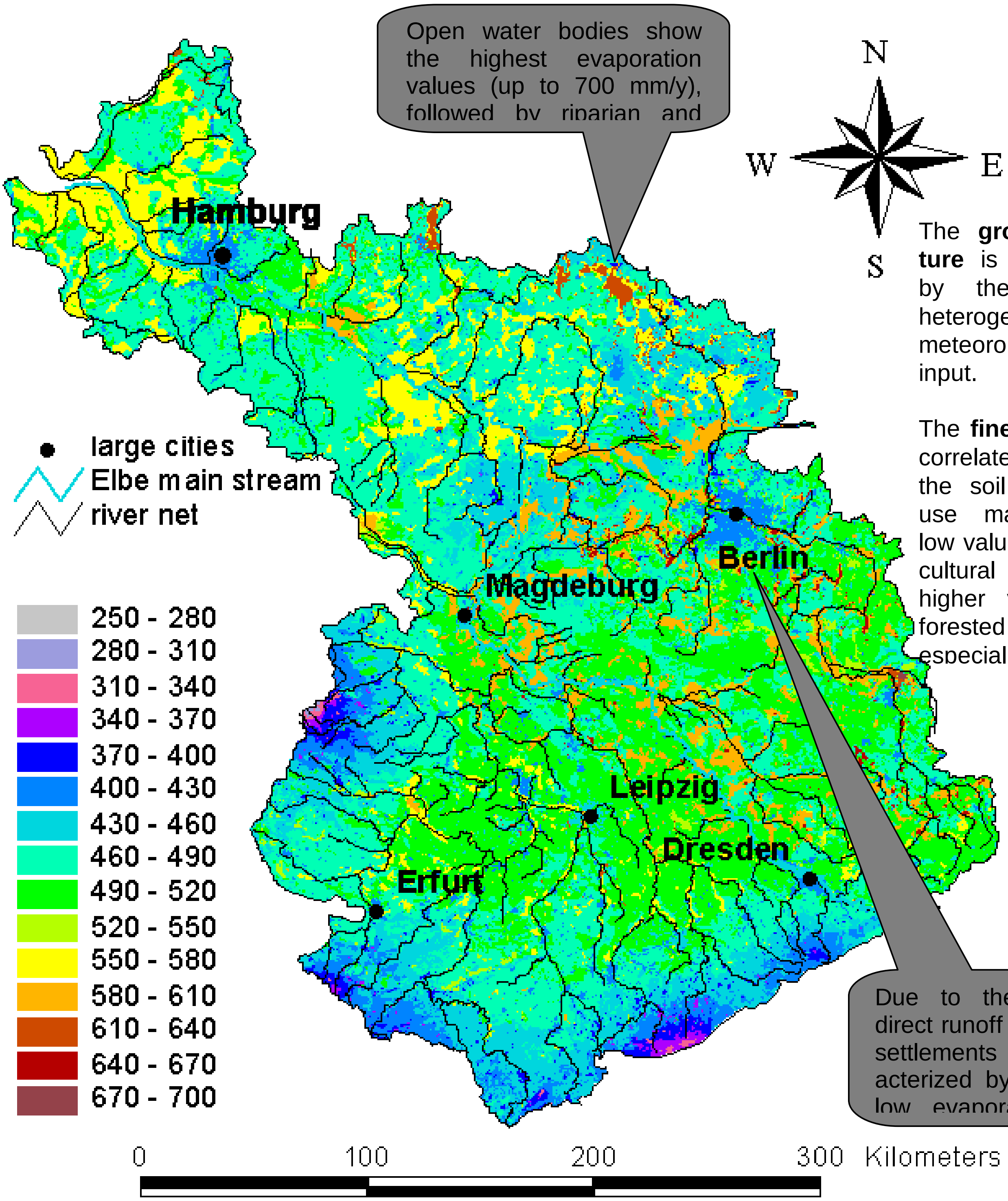


Water deficit in the central part of the basin

Mean annual **climatic water balance** [mm] in the Elbe river basin (~96.500 km²) for the period 1983-1987, calculated from 33 climate and 107 precipitation stations on the basis of 64.550 elementary units.

The spatially distributed maps of meteorological input variables emphasize the **importance of a high density meteorological network** in case of large heterogeneities of these variables, in order to calculate realistic distributions of water balance terms.

Spatial distribution of evapotranspiration



Open water bodies show the highest evaporation values (up to 700 mm/y), followed by riparian and

The **gross structure** is dominated by the strongly heterogeneous meteorological input.

The **fine structure** correlates well with the soil and land use map, giving low values for agricultural areas and higher values for forested areas and especially wet-

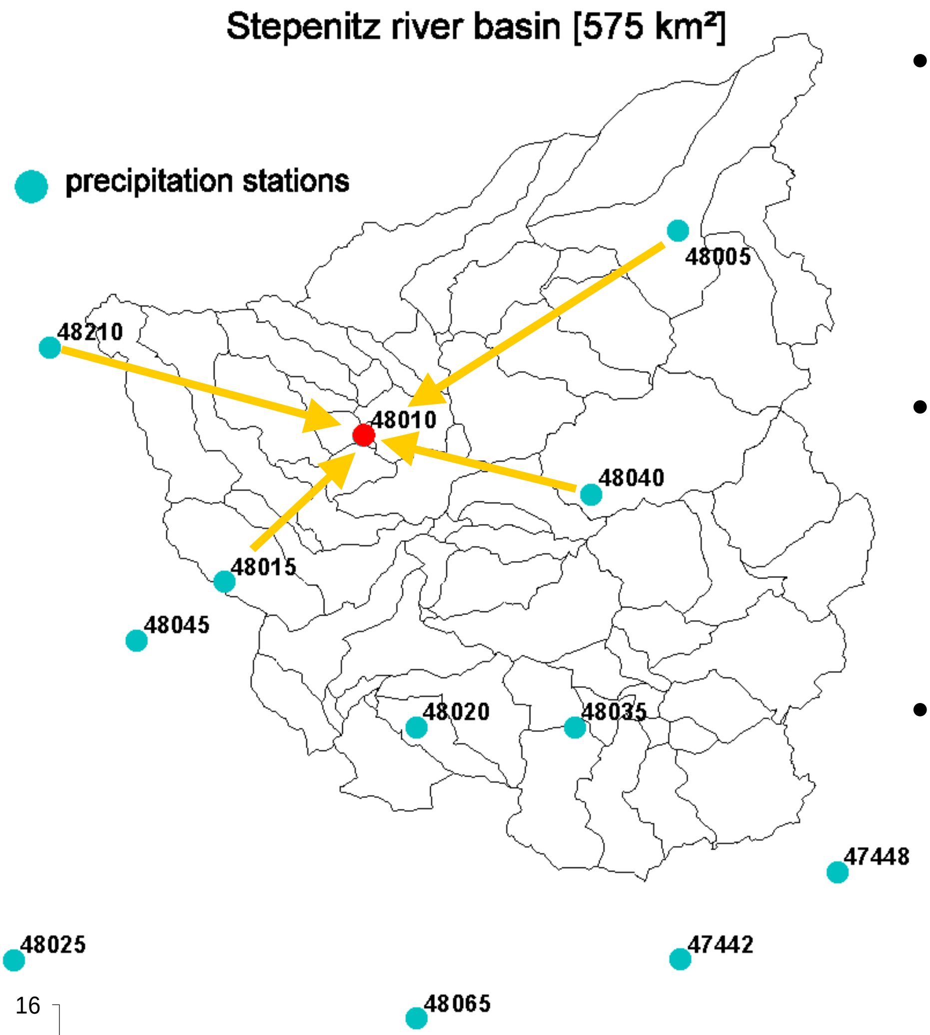
Due to their higher direct runoff formation, settlements are characterized by relatively low evaporation val-

*Mean annual **evapotranspiration** [mm] in the **Elbe river basin** for the period 1983-1987, calculated on the basis of 64.550 elementary units.*

RELIABILITY OF SIMULATION RESULTS AS FUNCTION OF THE METEOROLOGICAL INPUT

- The quality of calculated **water balance terms** (evaporation, percolation, surface runoff formation) and the simulated **basin discharge** depends both
  - on the basic spatial maps and
  - on the meteorological input.
- **Quality losses** of the meteorological input influencing the model results may be (among others) due to
  - **(1)** **gaps in the time series** for various input parameters,
  - **(2)** the used **interpolation method,**
  - **(3)** **uncertainties of measured parameters**, and
  - **(4)** a too low **station density**.
- In general, for hydrological calculations the hydrometeorological time series data should be available for a period of at least some years.
- This is especially true for **climate or land use change impact studies** where time periods of 50 to 100 years are studied and the conditions of the present state must be simulated as reliably as possible in order to forcast the hydrological effects of human influences.

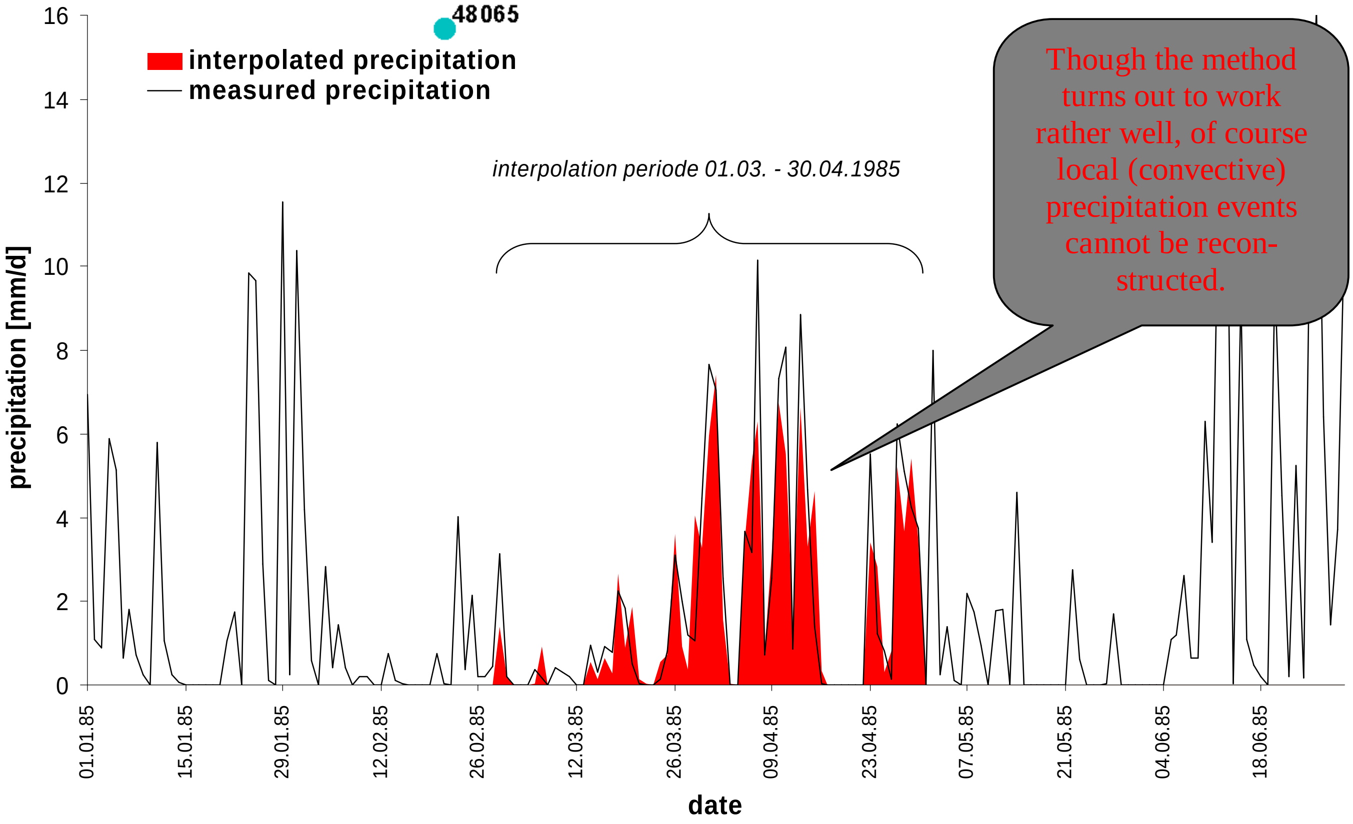
Completion of time series



- In order to include as much information as possible in the simulation calculations, also time series were used which do not provide the necessary parameters for the *whole* simulation period.

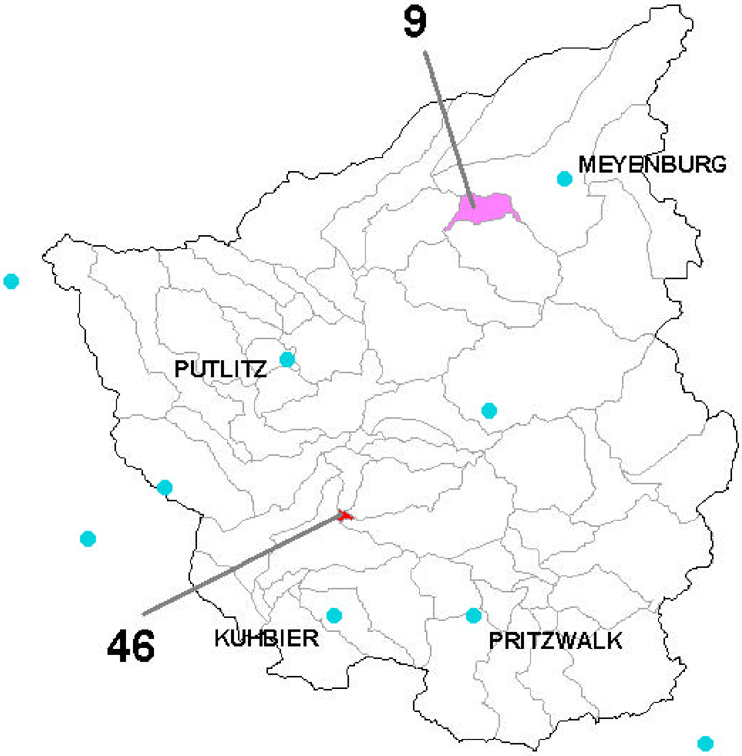
- For one of the 24 precipitation stations (Putlitz) used in the simulation runs data for two months (March/April 1985) are replaced by ‚missing data‘.

- These data are interpolated from those of the neighbouring stations by the ‚quadrant interpolation method‘.



Though the method turns out to work rather well, of course local (convective) precipitation events cannot be reconstructed.

Comparison of different interpolation methods



Comparison of interpolated precipitation for **2 sub-basins** in the Stepenitz river basin

(a) for the **total simulation period 1981 - 1994**
(b) for an **extreme precipitation event on 12.06.1993**

APPLIED METHODS

- **quadrant method**
- **N=x: nearest neigbours**, x = 1...6 (N=1 corresponds to the Thiessen method)
- 2 variations of **Ordinary Kriging**

Ordinary Kriging

- Daily off-line interpolation for the whole German part of the Elbe basin based on ~1500 precipitation stations and a 1 x 1 km grid basis.
- For every grid the next 24 neighbouring stations were used for interpolation.

(1) *without station specific correction (‚uncorrected Kriging‘)*

➢ values were used in the simulation runs by applying a constant correction factor of 1.15 (rain) and 1.30 (snow)

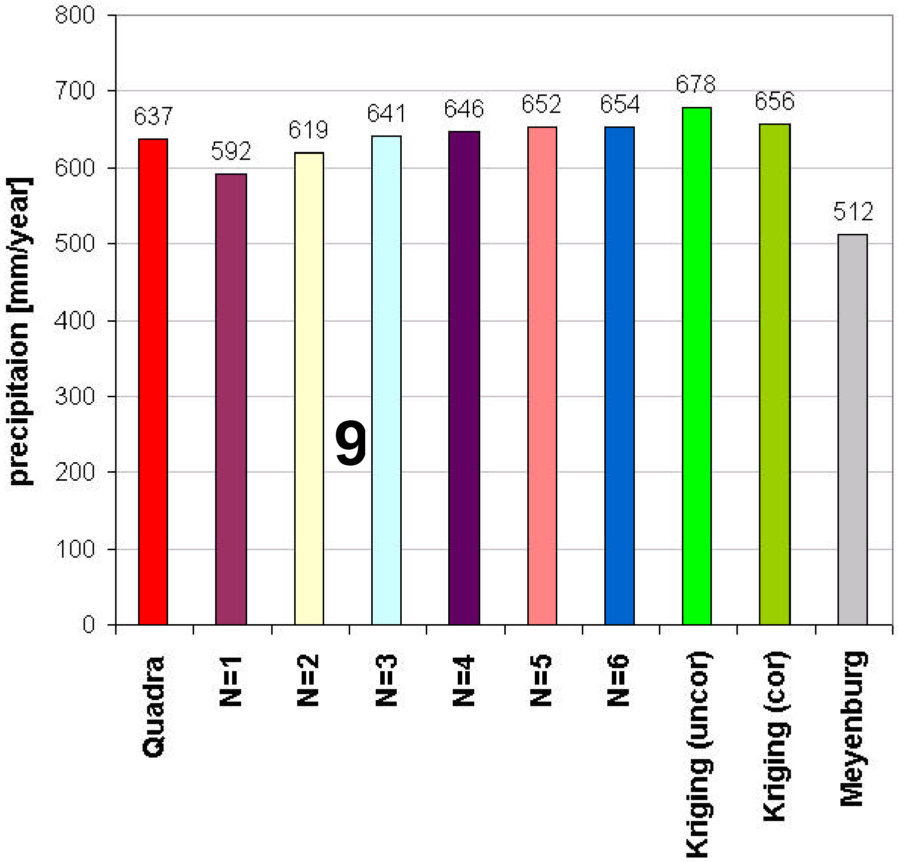
(2) *with station specific correction (‚corrected Kriging‘)*

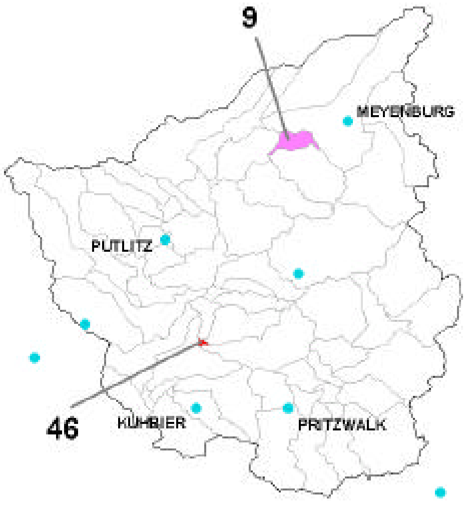
- the interpolation uses correction factors given by Richter for 4 precipitation types: rain in summer/winter, mixed, snow
- the exposition of all stations was taken as 'medium'

➢ values were directly used in the simulation runs (without any further correction).

Possible improvements for the Kriging method:
(1) Instead of generating the variogramm for the whole Elbe, the interpolation could be restricted to the region of interest.
(2) Instead of using a time-constant variogramm, it could be calculated for smaller time periods or even on a daily basis (time consuming!)

Mean annual sums (period 1981-1994) of interpolated precipitation for sub-basins 9 and 46 of the Stepenitz river basin

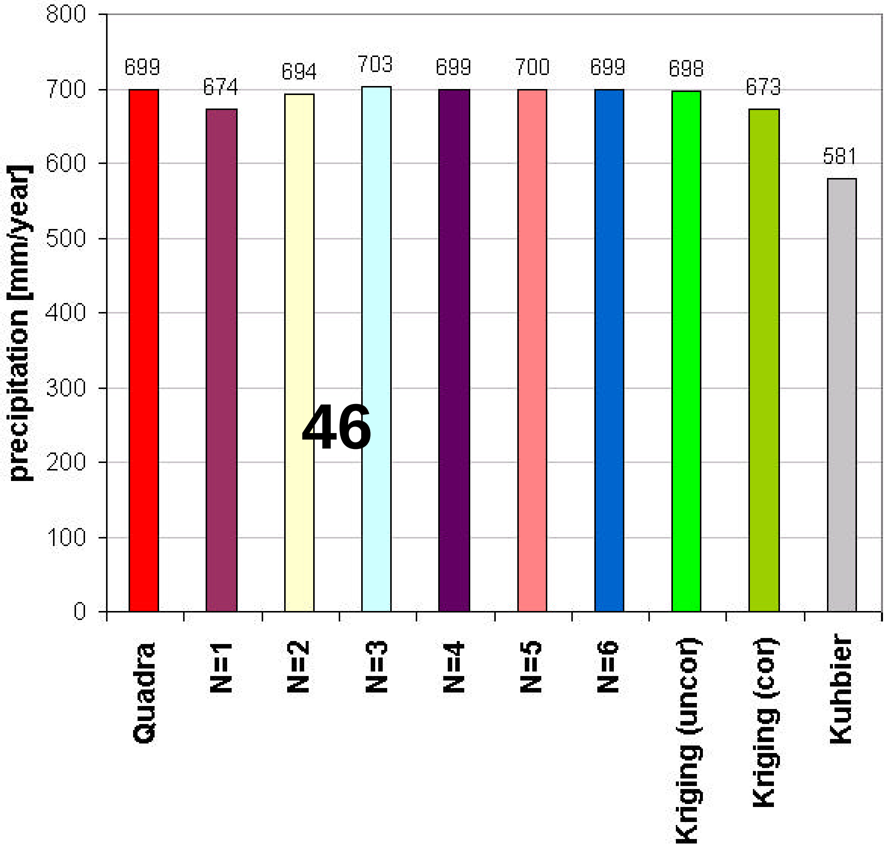




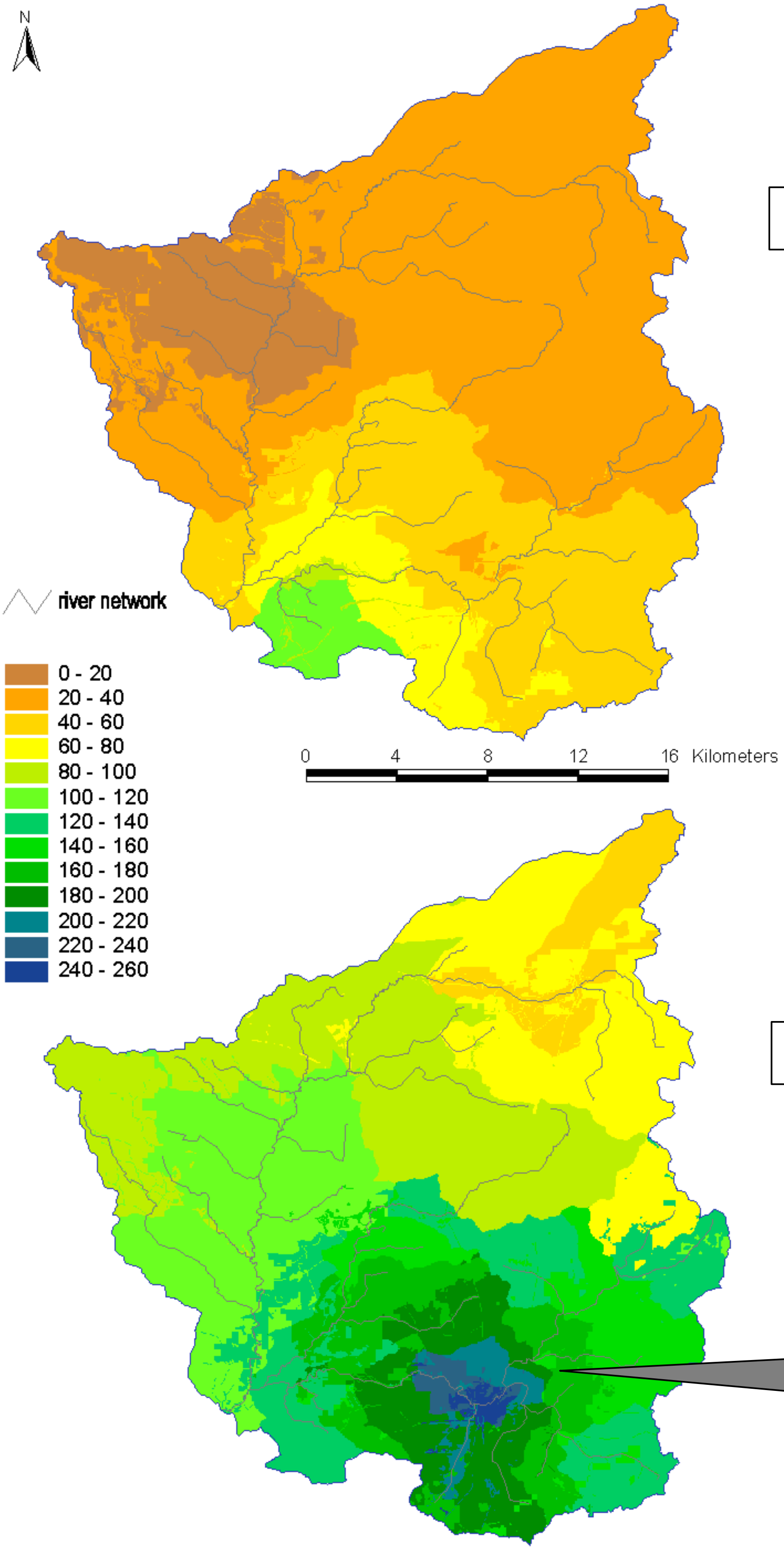
- For **long time periods** the differences between the interpolation methods are comparatively small.

- The differences are more pronounced for **sub-basin 9**, because

- it is considerably larger than sub-basin 46
- the station density is lower in the northern part of the basin.



Spatial distribution of precipitation in the Stepenitz river basin



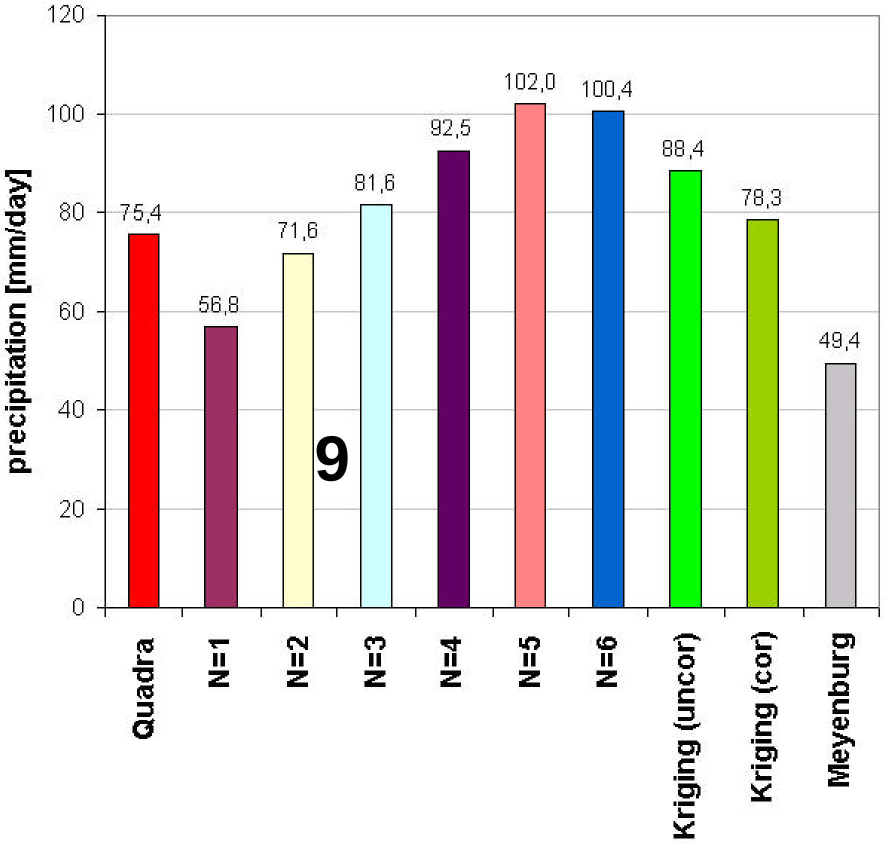
11.06.1993

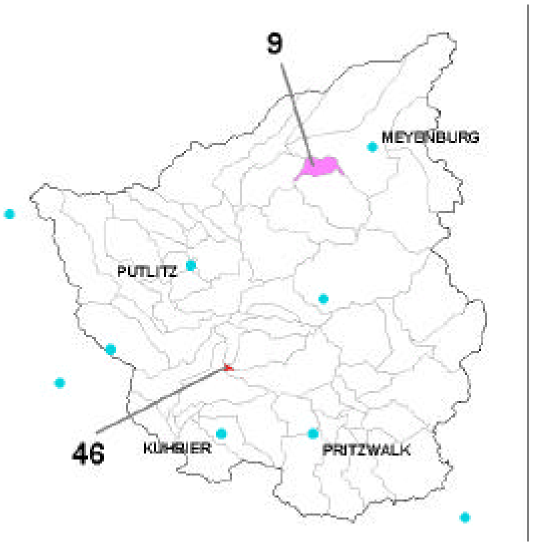
Spatial distribution of ***pre-cipitation*** *[mm] in the* ***Stepenitz river basin*** *for an* ***extreme precipitation event*** *on 12th June 1993 (calculated from* 9 climate and 24 precipitation sta*tions on the basis of 557 hydrotopes in 64 sub-basins).*

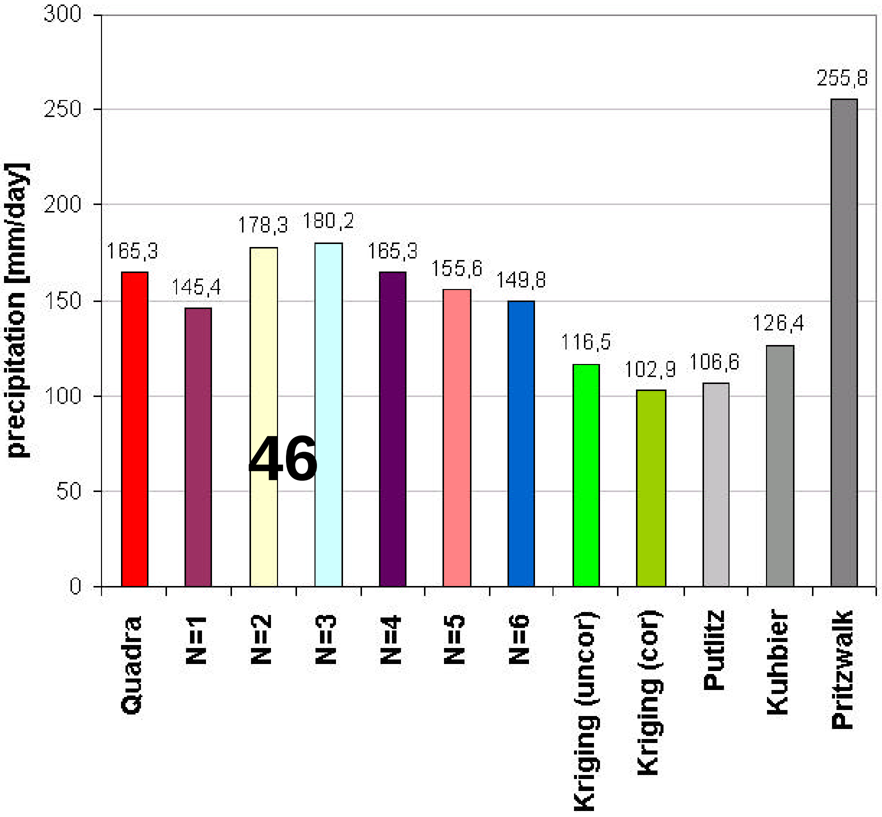
12.06.1993

Strongly localized event of up to 255 mm/day

Interpolated precipitation for the extreme event on 12.06.1993 for the sub-basins 9 and 46 of the Stepenitz river basin



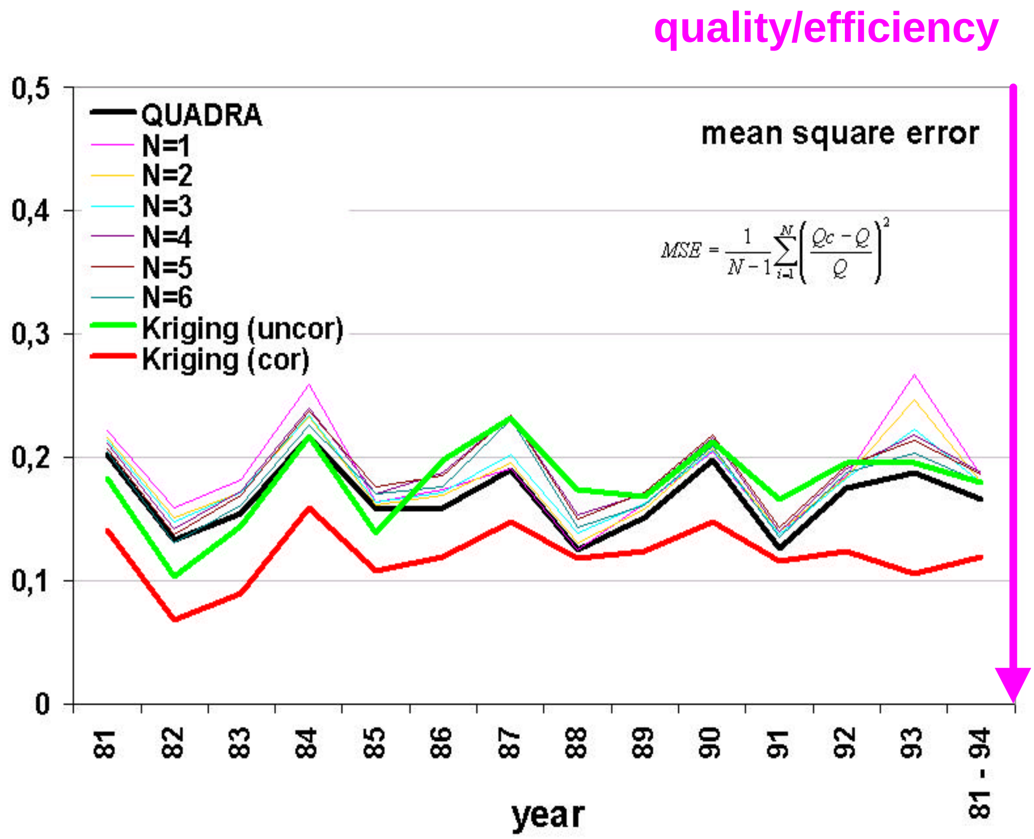




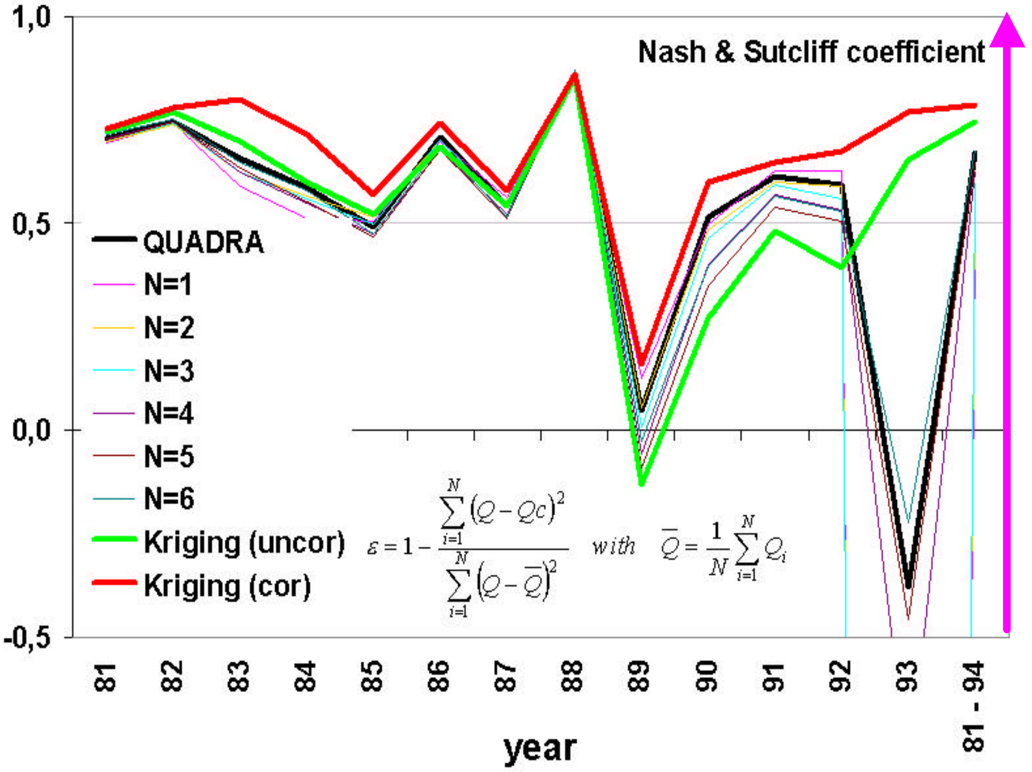
For **short time periods** the differences between the interpolation methods can be rather pronounced.

- They are especially high for **sub-basin 9**, because due to the low station density more and more stations in the south (where the event is concentrated) are included for the N=x interpolation.
- In case of **sub-basin 46,** the differences are smaller.
- The interpolated values decrease with increasing number of stations, due to the inclusion of stations in the north.
- **Conclusion**: In order to model such *convective events*, a higher station density and data of higher temporal resolution are needed.

Influence of the interpolation method on the basin discharge



$$MSE = \frac{1}{N-1}\sum_{i=1}^{N}\left(\frac{Qc-Q}{Q}\right)^2$$



$$\varepsilon = 1 - \frac{\sum_{i=1}^{N}(Q-Qc)^2}{\sum_{i=1}^{N}(Q-\overline{Q})^2} \quad with \quad \overline{Q} = \frac{1}{N}\sum_{i=1}^{N} Q_i$$

How does the interpolation method influence the simulated basin discharge?

Annual values of two **efficiency criteria** for the simulation period 1981-1994

In both cases

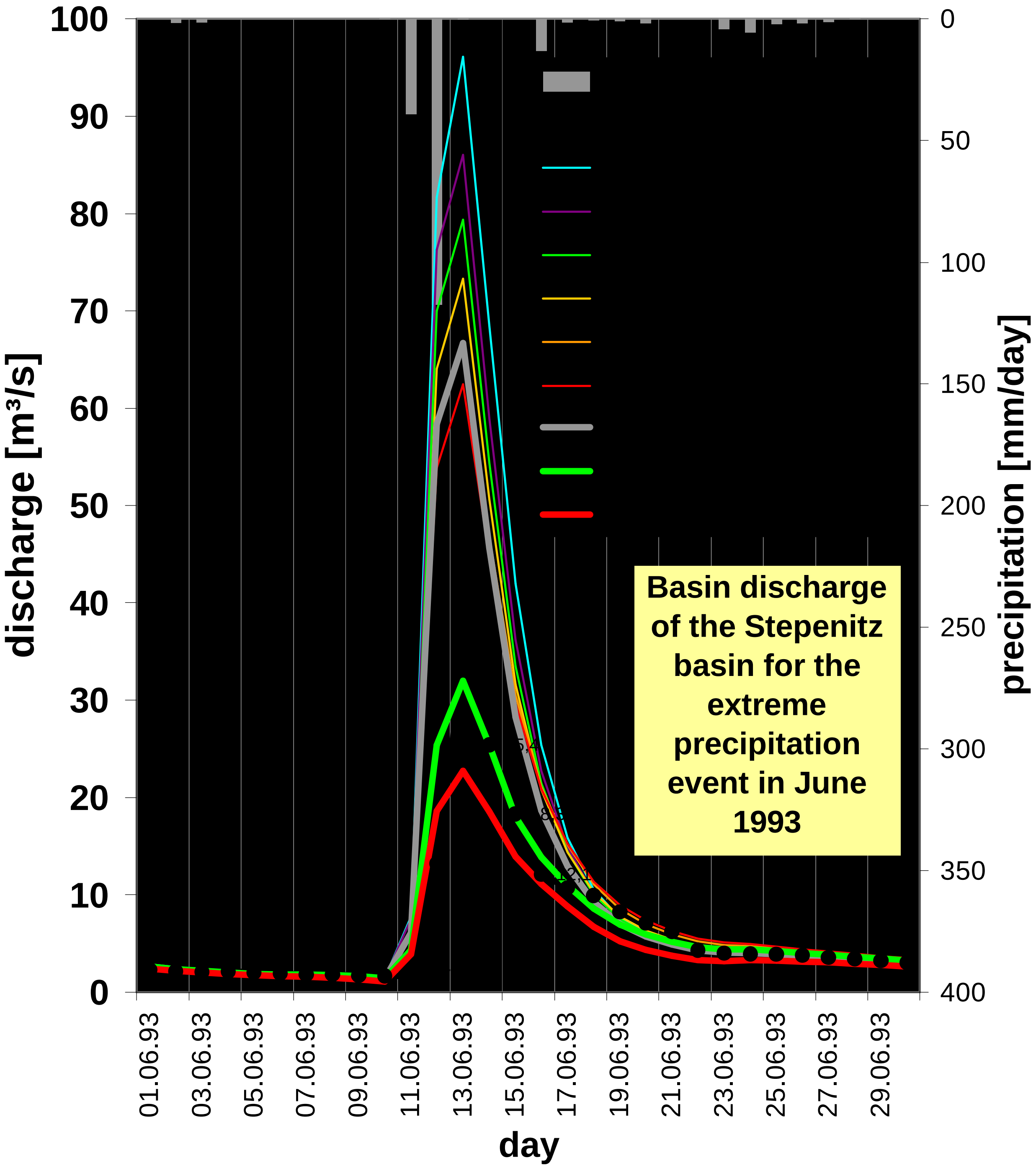
- **corrected Kriging** gives the best approach to measured discharge
- **uncorrected Kriging** is considerably worse
- the default interpolation method (**QUADRA**) gives reasonable quality simulations.

Conclusions

Ordinary Kriging (*with station specific correction*) improves the simulated discharge time series, but in general does not justify the additional effort as compared to the on-line interpolation with the quadrant method.

The results strongly depend on the study region, due to the transformation of the meteorological input by various processes (non-linear).

Simulated basin discharge
for the extreme June 1993 event



- **Ordinary Kriging** gives considerably better results for the extreme precipitation event on 12.06.1993 than all other interpolation methods, which overestimate the discharge at the basin outlet (gauge Wolfshagen).

Influence of station density on the calculated water balance components

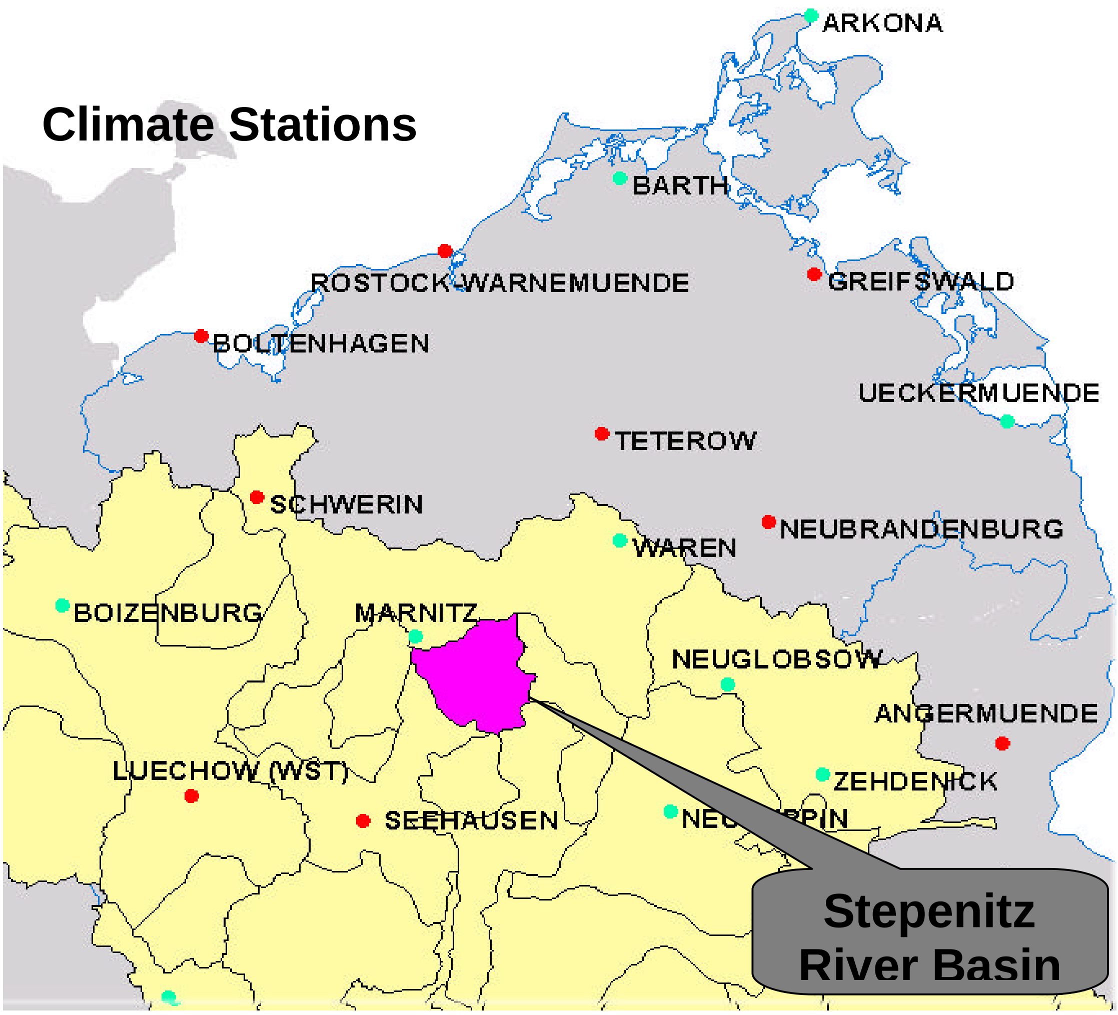
- Meso- and macroscale hydrological modelling can provide reliable results only if the **spatial and temporal resolution of meteorological information** is high enough to represent the meteorological heterogeneities of the basin.
- The reliability of calculated **water balance terms** depends strongly on the station density.
- Especially the number of **precipitation stations** should be rather high to generate realistic interpolation patterns.
- In general, the number of meteorological stations to be included in the simulation runs depends on
  1. the size of the basin,
  2. the basin characteristics (topography, meteorological heterogeneity), and
  3. the specific needs of the used interpolation method.
- For **flatland regions** a rather small number of stations is sufficient to achieve reliable results.
- A higher station density is necessary in **mountainous regions**, where the meteorological heterogeneity is much larger.
- Since the number of climate stations is generally much lower, **additional information** like the station height should be included to derive realistic spatial distributions for mean temperature etc. (especially in basins with pronounced topography).

3 station density scenarios

All of them include 9 selected climate stations which provide all necessary parameters (precipitation, mean air temperature, relative humidity, sunshine duration) for the period 1981-1994.

1. Precipitation measured only at these **9 climate stations**
2. In addition, precipitation measured at **6 precipitation stations in the basin**
3. Precipitation measured at **all 24 precipitation stations** in and around the basin (default)

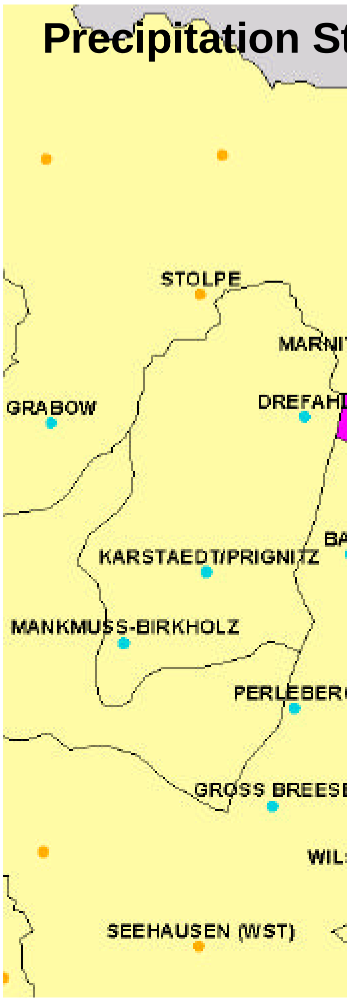
Climate and Precipitation Stations used for the Simula
in the Stepenitz River Basin



Climate Stations

Stepenitz River Basin

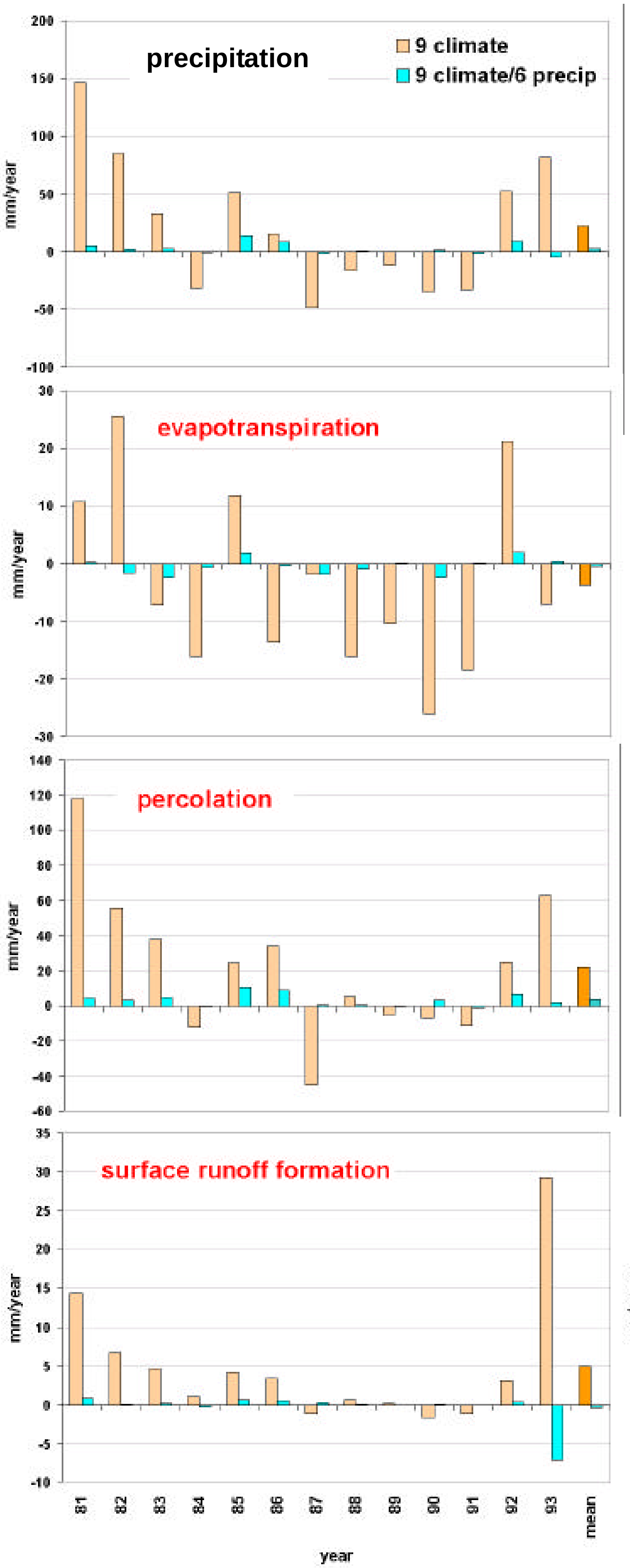
Red: Stations used for the simulation calculations (9)
Green: Stations with time gaps or missing parameters



Precipitation St

Blue: Stations used fo
Orange: Stations with

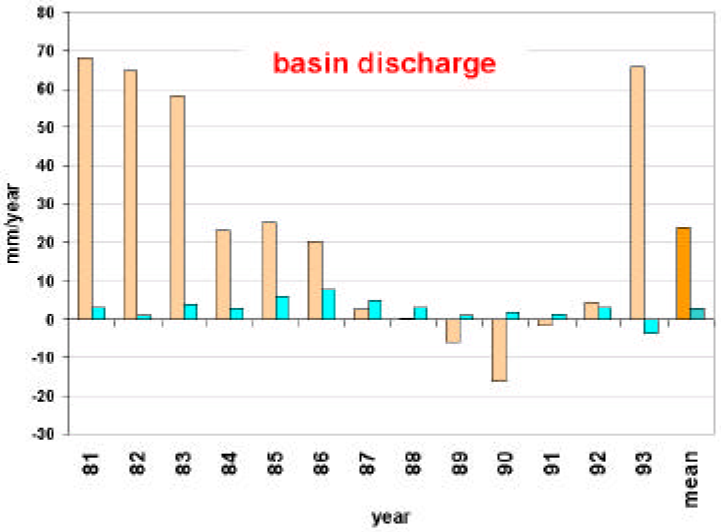
Differences of calculated water balance components for 3 station densities



Differences of annual sums for the period 1981-1993 for the reduced station densities as compared to the default station density (9climate /24 precipitation stations)

- Both precipitation and the water balance terms show large differences, if only 9 climate stations are taken into account.
- The simulation results are much better, if the 6 stations in the basin are taken into account as well.
- The differences are comparatively small for the 81-93 **average values**, vary however considerably for each single year of the simulation period.
- In case of surface runoff formation and basin discharge the differences are extremely high in 1993 (**extreme precipitation event**).

➢ This emphasizes the importance of a high density net of meteorological stations for such convective events in meso-scale hydrological modelling (especially in case of flood modelling and prediction).



Conclusions

- The performed analyses emphasize an **increasing demand for accurate and consistent data** at various spatial and temporal scales, which can be used to study the impacts of **climate and land-use changes** on the hydrological cycle.
- The results obtained in the Elbe river basin and some of its sub-basins provide a better understanding on the **spatial and temporal data** necessary for a physically based, spatially distributed hydrological modelling at different scales.
- The **spatial distribution of climatic input variables** has proven to be a key issue in hydrological modelling at larger scales.

RECOMMENDATIONS FOR FURTHER RESEARCH

- There is a growing need for a **higher density of meteorological stations** which is often too low for large scale studies.
- This is especially true for the **number of climate stations** providing long-term data of at least a few decades, because these data represent the basis for the development of climate change scenarios.
- Therefore, this study strongly supports any effort to establish international co-operation towards the acquisition of reliable and high quality data to face today's challenges of hydrology, like **climate impact research** and **sustainable development studies**.

Propagation of uncertainties

- Among the various meteorological input data **precipitation** is, in general, characterized by the largest uncertainties.

- In order to demonstrate the uncertainty propagation in the modelling results, simulation runs were performed assuming a **general error in precipitation**.

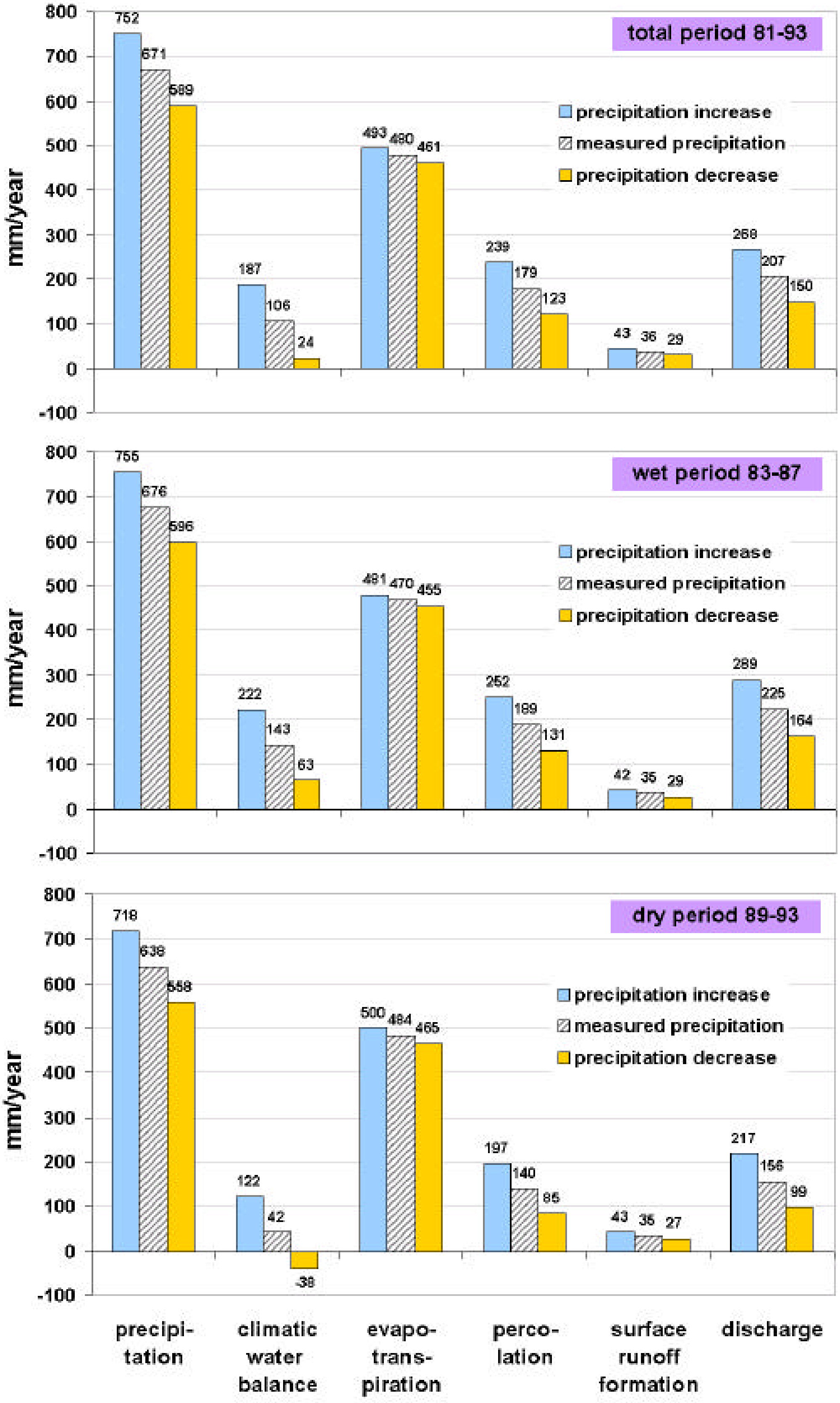
- The effects of an increase or decrease of about **12 %** in precipitation on various water balance components and the basin discharge in the Stepenitz river basin were studied.

- Mean annual values of

  - climatic water balance,
  - evapotranspiration,
  - percolation,
  - surface runoff formation and
  - basin discharge

are calculated for the time periods 1989-1993 (dry), 1983-1987 (wet) and 1981-1993 (total)

Change of various water balance components due to precipitation changes



Climatic water balance: Changes are due to precipitation changes (since pot. evaporation is unchanged). Drastic changes of up to 190%, especially in the dry period 89-93, where decreasing precipitation results in negative values (water deficit).

Evapotranspiration does not change much (less than 4%).

Percolation shows evident changes, especially in the dry period 89-93 (+41%, -39%).

Surface runoff formation changes by about 20%, almost independent for the three evaluation periods.

Basin discharge changes dramatically, especially in the dry period 89-93 (+39%, -37%).

⇨ Errors in the correction of precipitation heavily influence the integrative parameter discharge.