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Groundwater trends in the Brahmani-Baitarni River Basin, India

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March 2017

Australian Government
Department of Foreign Affairs and Trade

Australian Aid

Citation

Schmid W, Pollino C, Merrin L, Stratford D (2017) Groundwater Trends in the Brahmani-Baitarni River Basin, India. Sustainable Development Investment Portfolio (SDIP) project. CSIRO, Australia.

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Important disclaimer

This report designed and implemented by CSIRO contributes to the South Asia Sustainable Development Investment Portfolio and is supported by the Australian Government.

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Acknowledgements

We would like to acknowledge the support of the Government of Australia in financing this study. We would like to thank the Government of India in their support throughout the project. This has been in provision of data and expertise, hosting the project team on field visits, and provision of guidance throughout the project. We would particularly like to thank and acknowledge the contributions of Dr A Singh, Mr RK Jain, Dr RN Sankhua, Mr R Srivastava, Mr NK Sharma, Mr S Bisht and Miss D Shikha.

We would like to thank the States of Jharkhand, Odisha and Chhattisgarh for their participation in the study, including the provision of data and engaging in project activities.

We would like to acknowledge the Non-Government Organisation Pradan for giving us insights into the lives of people in the basin. This experience opened our eyes to the challenges faced by basin farming communities. We also extend our thanks to Vaibhav Chaturvedi from the Council for Energy, Environmental and Water for support with eliciting scenarios used in the model analysis.

We would also like to thank Geoff Hodgson, CSIRO for his valuable review.

We hope that the results of this study are used to improve the livelihoods of the people of the Brahmani-Baitarni Basin.

1 Introduction

1.1 Background

This technical report on groundwater trends in the Brahmani-Baitarni Basin (Figure 1) is a product of the 'Water Resources Management: Capacity Building in the Brahmani-Baitarni' project (referred to herein as the Brahmani-Baitarni project), which was funded by the Government of Australia and supported by the Government of India. The project ran from July 2013 to June 2016, and was part of Phase 1 of the 'Sustainable Development Investment Portfolio', an Australian government initiative with the goal of increasing water, food and energy security in South Asia. This work was undertaken in the context of a Memorandum of Understanding (MoU) on water resources management between the Government of Australia and the Government of India, established in 2009 and renewed in 2014.

Several reports have been authored for the Brahmani-Baitarni project. Synthesis (Pollino et al. 2016a) and technical (Pollino et al. 2016b) reports overview the model outcomes of the river system model for the Brahmani sub-basin (Figure 1). A separate technical project report has also been prepared for agricultural productivity across the basin (Mainuddin et al. 2016). The report described herein presents the groundwater-related work undertaken for this project, which consists of a short review of selected groundwater models in India and a larger component on statistical trend analysis of groundwater levels in the basin.

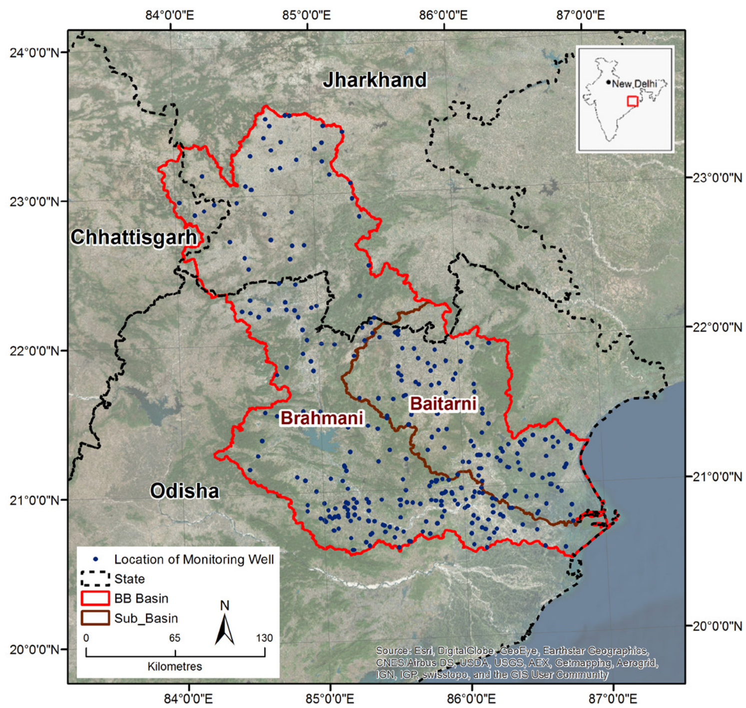


Figure 1: Location of the Brahmani-Baitarni Basin and groundwater monitoring wells

1.2 Groundwater in the Basin

In the Brahmani-Baitarni (BB) basin, groundwater is one of the water resources that makes up the basin water balance, which is represented in models, and is an important consideration in basin planning and basin management. The primary goal of the groundwater analyses in the BB project was to get a better understanding of the groundwater resource, focusing on its availability and change over time. In parts of the basin, groundwater use may exceed the sustainable yield (Alley and Leake 2004; Kalf and Woolley 2005), but in others it may remain be far below sustainable extraction limits. Therefore, for the purposes of this project, the primary objective was to evaluate spatially discretised trends of this ever-changing resource.

As stated above the Governments of India and Australia signed an MoU with a focus on Water Resource Management. This emphasises the relevance of groundwater in water resource planning, and the need to consider this in basin planning. The MoU stipulates "Partners will work to enhance cooperation on water resources development and management through policy and technical experiences. These experiences will focus on the development and management of water resources of both surface and groundwater, and particularly river basin management and impact of climate variability and change."

Consistent with the MoU's particular focus on river basin management, the BB project includes a modelling component for a river system model (Pollino et al. 2016). However, this model is limited in that it does not explicitly simulate surface water / groundwater interactions or groundwater-depletion induced stream capture, both of which impact on the surface-water balance. The explicit inclusion of groundwater into the river system model and the building of a stand-alone groundwater model was infeasible within the project timeframe due to limitations of available data.

The BB groundwater-related work did include a component on (a) the understanding of selected pre-existing groundwater models and (b) on trend analysis of groundwater levels in the basin. The former consisted of reviews of previous groundwater modelling studies in India and their potential relevance or applicability to the basin. The latter contained a statistical trend analysis of individual wells and of averages over districts using the Mann-Kendall technique. Its purpose was to distinguish spatially between command areas affected by rising or falling trends indicating either water logging or groundwater depletion. The trend analysis also included a graphical inspection of smoothed hydrographs using the LOWESS method. Trends of smoothed hydrographs can reveal "genuine" groundwater trends not heavily influenced by climate or Irrigation for pre-monsoon water levels or an increase or decrease in recharge for differences between pre- and post-monsoon water levels.

Using the LOWESS method and linear regression, correlative studies between smoothed observed or modelled rainfall and smoothed groundwater time series were conducted. Smoothing both rainfall and depth-to-water is appropriate as both rainfall and depth-to-water data suffer from outliers and data gaps. These studies are based on three representative areas of declining water levels, rising water levels outside command areas, and rising water levels inside command areas and select wells in those areas. Aside from water levels of particular seasons, pre/post-monsoon water-level depth-to-water differences (of the same year and per-monsoon lagged by 1 year) have been included into this correlation analysis. This can give evidence of the contribution or the lack of monsoon rainfalls to recharge as well as the reduction of such correlation by recharge from surface-water irrigation or groundwater pumping.

The results of the groundwater-level trend analysis have to be viewed in an integrated context by allowing for a better understanding of links between surface and groundwater and the complexity of surface water / groundwater interaction in the BB basin. This will aid in the incorporation of the surface-groundwater interactions into the river system model, should this be required in the future. For instance, the knowledge of temporal and spatial differences in groundwater-level trends potentially will allow for correlating groundwater depletion evident from the groundwater trend analysis and surface-water losses resulting from calibrating the river system model. In addition, regions with trends of groundwater depletion may coincide with areas of surface-water irrigation deficit or ecologic assets. That is, while at this point the BB project's focus was on river system modelling, the groundwater-level trend analysis is indeed part of an integrated hydrologic framework of groundwater, surface water, agriculture, and ecology.

2 Previous investigations

2.1 Existing groundwater models in India potentially relevant for the Brahmani-Baitarni Basin

The static, non-replenishable fresh groundwater resources of the BB basin rank 9th among all river basins in India (CGWB 1999) with 43.4 km^3 and the replenishable groundwater resources of the BB basin are estimated to be 4.05 km^3/year (Kumar et al. 2005). Yet, no basin-wide groundwater model has been undertaken to help manage the sustainable use of groundwater tapping the dynamic resources and to simulate adverse effects of groundwater overdraft on static resources and on river streamflow capture.

2.1.1 Quick review of four groundwater modelling studies in India potentially relevant for the Brahmani-Baitarni Basin

In lieu of any groundwater model within the BB basin, four pre-existing groundwater-modelling studies from India were reviewed. The studies were reviewed with the objective to identify the relevance or applicability of the methodology used for a potential future groundwater model in the BB basin:

- Massuel, S, George, BA, Venot, JP, Bharati, L, Acharya, S (2013) Improving assessment of groundwater-resource sustainability with deterministic modelling: a case study of the semi-arid Musi sub-basin, South India. Hydrogeology Journal, 21(7), 1567-1580.
- Rao, SVN, Radhakrishna, I, Joshi, N, Sharma, A, Shekhar, S (2010) A Study of saline freshwater interface phenomena in the Mahanadi Delta region: Orissa, India. Proceedings of National conference on sustainable water resources management and impact of climate change, BITS-Pilani, Hyderabad, pp452-468, March 5-6, 2010 http://www.indiawaterportal.org/sites/indiawaterportal.org/files/Rao_et%20al%20India.pdf
- Rejani, R, Jha, MK, Panda, SN, Mull, R (2003) Hydrologic and hydrogeologic analyses in a coastal groundwater basin, Orissa, India. Applied engineering in agriculture. Vol. 19(2): 177–186
- Rejani, R, Jha, MK, Panda, SN (2009) Simulation-optimization modelling for sustainable groundwater management in a coastal basin of Orissa, India. Water resources management, 23(2), 235-263.

Three of these studies were carried out in the neighbouring Balasore coastal groundwater basin and the Mahanadi delta region. Among those, two are groundwater models in MODFLOW (Harbaugh et al. 2000) in the Balasore region and in FEFLOW (Diersch 2006) in the Mahanadi delta. Another study in the Balasore region is at best a regression analysis of rainfall, river stage, and corresponding groundwater level, but not a distributed, numerical model. While the two MODFLOW and FEFLOW groundwater models are typical for coastal aquifers neighbouring the BB basin, they are only distantly related to the issues specific to the BB, as the basin only includes a short stretch of coastal areas. A forth model discussed here was applied to the Musi River Basin, which is quite distant from the BB Basin and located in a different climate zone. However, it might provide techniques useful to a potential groundwater model for the BB Basin, as sustainable groundwater irrigation is a main topic in both basins.

In summary, since three studies are related to coastal aquifers, they are not of prime interest in the BB basin, and one study is quite distant from the basin. The four studies were reviewed based on their technical value and potential applicability to the BB basin.

The following contains a bulleted listing of the main characteristics of each study, which could be of advantage or potential use for the BB basin, and some issues or disadvantages of adopting some techniques for the BB basin project. Note that the project did not enter into any groundwater modelling. Hence, the outcomes of these four quick-reviews may only benefit future phases of the BB project should groundwater modelling be undertaken.

Balasore coastal groundwater basin:

Rejani et al. (2009) MODFLOW response linked to optimization model

Main Characteristics and potential use for BB: Focus is on sustainable irrigated agriculture

- Integrated Simulation-Optimization Model based on MODFLOW → development of response matrix using
  - Hydraulic management model for optimal pumpage subject to drawdown, water demand, and recharge constraints and
  - Crop model for optimal cropping pattern subject to water and land availability constraints integrated with groundwater flow simulation.
- Optimal pumpage and optimal cropping patterns (for normal, wet, and dry years) suggested to be adopted by farmers in order to increase net annual returns;
- Control of seawater intrusion by improving groundwater levels; and
- Sensitivity to crop prices, land availability, cost of cultivation, and water availability.

Issues:

- It would be difficult to convince farmers by rather inflexible optimization scenarios with "optimal solutions."
- Balasore neighbours Baitarni, but is outside BB basin.
- The Modflow flow model was just 2-dimensional, i.e., insufficient to answer 3-D regional development scenarios.

Rejani et al. (2003) Hydrology/Hydrogeology study with GW/SW-correlation analysis

Main characteristics and potential use for BB: Correlation analysis techniques between groundwater level and rainfall or river stage; Hydrostratigraphy for BB delta region.

- Regression analysis of rainfall, river stage, and corresponding groundwater level:
  - Correlation expected, as river seepage and rainfall are major sources of recharge.
- Stratigraphic analysis
  - 3 confined aquifers
  - Contamination of second aquifer by seawater intrusion.

Issues:

- Basin scale estimates and not a distributed parameter model
- Balasore neighbours Baitarani, but is outside BB basin
- Conclusions are only "urgent measures" to ensure sustainable groundwater resources, such as a proposal for rainwater harvesting and reduced pumping. However, those are not dynamically linked outcomes from scenarios.

Mahanadi delta region:

Rao et al. (2010) FEFLOW model

Main characteristics and potential use for BB basin: Hydrostratigraphy for BB delta region

- FEFLOW model with solute migration scenarios that are subject to increasing pumping rates under steady state conditions.
- 2 groups of aquifer systems:
  a. South western delta region: unconfined to semi-confined freshwater underlain by brackish/saline system;
  b. Northeastern delta region: deep freshwater overlain by brackish/saline system.
- Results show that freshwater system 1 is more prone to saline mixing than system 2. System 2 can handle relatively higher pumpage without affecting water quality.

Issues:

- Time-invariant constant head boundaries at rivers and at the coast should be conceptualized as variable stage river boundary and general head coastal boundary conditions.
- Mahanadi delta neighbours Brahmani, but is outside BB Basin.

Musi River Basin:

Massuel et al. (2013) MODFLOW linked to water allocation model

Main characteristics and potential use for BB basin: Focus on sustainable irrigated agriculture

- Water allocation planning to prevent aquifer overexploitation;
- Integration of groundwater-resources assessment with MODFLOW into water allocation plans and strategies using REALM;
- Deficit in groundwater storage / water table decline;
- Comparison scenarios between renewable recharge and sustainable versus actual levels of irrigation pumping;
- Integration with water-allocation modelling framework:
  – Demand reduction through changes in cropping pattern (e.g., rainfed crops).

Issues:

- The Musi river is a tributary to Krishna River in the Krishna Basin distant from BB basin.
- The Musi river basin is in a semi-arid climate zone, while BB basin is in the humid tropics.

2.1.2 Review result

For a potential future groundwater model in the BB Basin, technically, some of the approach used in the MODFLOW model of the Musi River basin would be best suited among the four reviewed studies. The Musi River study contains scenario analyses of human activity dominated by irrigated agriculture, as is the case for the BB Basin. Model scenarios of how a changing cropping pattern relates to sustainable levels of irrigation and counteracts groundwater overdraft could be more convincing to the public than optimization scenarios as used in the integrated MODFLOW-Optimization model in the Balasore basin. A dynamic linkage between a water allocation model and MODFLOW as used in the Musi River study will allow additional impacts of operational decisions on the river system, from which irrigators divert. In the case of the Musi River basin model, MODFLOW was linked to a REALM water allocation model (Perera et al. 2005). In the

SDIP BB basin project, a river system model was constructed using eWater SOURCE (Carr and Podger 2012; Welsh et al. 2012). Although there are significant differences between the Musi River basin water allocation model and the BB basin river system model, it might be worth analysing whether linkage techniques between the MODFLOW and REALM models could also be applied to a linkage between MODFLOW and SOURCE.

The integrated simulation-optimization model in the Balasore basin is based on response functions/matrices (and connected optimization models for optimal pumping and cropping) that are rather inflexible suggestions to farmers. However, modification of constraints, such as crop price, land availability, cost of cultivation and water availability allows scenarios of the optimization to changes in those parameters. Yet, this may not address questions of individual farms or irrigation districts, whatever level the water accounting is on, on a spatial scale. In addition, this study's groundwater model is only 2-dimensional, which limits the ability to answer regional development scenarios.

The FEFLOW study in the Mahanadi delta region focuses on seawater intrusion, which is not applicable to the BB basin, as it does not contain extended coastal aquifers. However, even if the BB basin's short stretch of coast were to be simulated in a groundwater model, the technique the authors used is compromised because the model's coastal boundary was not extended offshore and did not simulate the equivalent freshwater heads. As the Mahanadi delta model's focus is on coastal seawater intrusion this is less relevant to this study. Naturally, a constant head at the coast will zero out any solute plumes near the coast and leads to mass accumulation near or around the cones of depression of the pumping wells. In conclusion, I think neither the topic nor the quality of the technique used in the Mahanadi delta study should be adopted for a potential groundwater model in the BB basin.

Lastly, the hydrology/hydrogeology study in the Balasore coastal groundwater basin provides only basin scale, but not distributed, estimates and conclusions that are rather speculative then dynamically linked outcomes from scenarios. However, correlation analysis techniques between groundwater level and rainfall or river stage as well as hydrostratigraphy for BB delta region might provide some benefit, should those topics be undertaken in the BB basin.

2.1.3 Consideration of groundwater modelling in the Brahmani-Baitarni Basin

This brief review of existing groundwater models provides a starting point for a groundwater model in the future. Only the Musi River study was found to provide MODFLOW / water allocation model linkages and scenario analyses of human activity within settings of irrigated agriculture, which could be of benefit to a BB groundwater model.

In lieu of building a groundwater model, a comprehensive groundwater-level trend analysis was undertaken, which can be used to reveal correlations between groundwater depletion evident from the groundwater trend analysis and surface-water losses resulting from the river system model. In that sense, the objective of a better understanding of surface water / groundwater interaction can be met without a groundwater model.

2.2 Previous research on groundwater-level trend analysis

Several tools are available for groundwater-level trend analysis. This includes tools that have an emphasis on analysing seasonality rather than trend and ARMA models or Fourier Series that are capable of detecting the presence of dominant frequencies, such as annual or biannual cycles. Such methods are best used after first removing an underlying trend, which is often determined by simple parametric tests, such as linear regression.

Similarly, seasonal-trend decomposition, e.g., based on LOESS, aims at removing trends from seasonality if a time series are dominated by it (Cleveland 1979; Cleveland and Devlin 1988). The LOESS technique performs a regression on points in a moving range around an X value while weighting the values within this range according to their distance from this X value. The more points are included into the range, the lesser the seasonality and the smoother the result, i.e., the clearer the trend. However, for trend analyses, where seasonality is either ignored or assumed not to be present, removal of seasonality is redundant. A method addressing this type of groundwater-level trend analysis is the Mann-Kendall method (Gilbert 1987). Advantages of using this test are that it does not require the data to be normally distributed (non-parametric test) and has a low sensitivity to breaks in time series.

Groundwater-level trend analyses have been carried out in proximity to the BB Basin in Asian mega-deltas, where groundwater levels in shallow aquifers are often characterized by strong seasonal variations associated with monsoon rainfall. Shamsudduha et al. (2009a) applied a nonparametric seasonal-trend decomposition procedure based on LOESS (STL) (Cleveland et al. 1990) to resolve trend and seasonal components in weekly groundwater levels in the Ganges-Brahmaputra-Meghna (GBM) Delta in Bangladesh. The study reveals that seasonality dominates the observed variance in groundwater levels. However, the authors also demonstrated a link between groundwater abstraction and trends in groundwater levels and, hence, the unsustainability of groundwater irrigation. However, the authors appreciated reviewer suggestions (Shamsudduha et al. 2009b) to also assess relationships between rainfall, groundwater abstraction and sea-level rise on groundwater levels using the HARTT method (Hydrograph Analysis-Rainfall and Time Trend) (Ferdowsian and Pannell (2001; 2009), which is one of several temporal trend analysis methods.

Similar to the GBM delta, the BB basin also is dominated by monsoon seasonality. However, unlike in the GBM Delta, analysis of seasonality in the BB basin is neither an objective nor an option as at most four groundwater level measurements are available for any year (irrigation, pre-monsoon, monsoon, and post-monsoon). Furthermore, the monsoon and irrigation seasons are often compromised by skipped monitoring or, in the case of the monsoon season, by unpredictable rain and pumping effects. To study cross-correlations (Lee et al., 2006) between monsoon rainfall and groundwater levels, higher frequency observations of both parameters are necessary. Such data are not available in the BB Basin.

The objective of this report is to evaluate trends of two “reliable” seasons (pre- and post-monsoon) with good data record and without unpredictable events, but not the study of seasonality. The primary objective is the analysis of non-seasonal trends within long-term pre- or post-monsoon records. A secondary objective is the removal of long-term multi-annual seasonality or fluctuation by smoothing pre- and post-monsoon hydrographs using the LOESS or LOWESS method. Looking at the difference between smoothed pre- and post-monsoon trends helps the visual detection of trends of recharge and potential changes to those trends (e.g., by lack of monsoonal rainfall or by irrigation recharge).

Panda et al. (2007) carried out a comprehensive analysis of groundwater level trends of the state of Odisha using the non-parametric Mann-Kendall statistical procedure to understand the forcing mechanisms of climate in conjunction with the anthropogenic pressure on groundwater levels. The study analysed pre and post-monsoon groundwater level records of 1002 monitoring stations from 1994 to 2003. Results show that drawdowns due to dry years, high temperatures, and anthropogenic pressure have not recovered through the recharge in wet years. The authors also analysed individual groundwater level trends related to different rock formations (unconsolidated, semi-consolidated, and consolidated). While the consolidated rock formation covering 80% or the study area experienced a significant decline irrespective of season, the semi- and unconsolidated formations experienced a decline in the pre-monsoon season only.

The Panda et al. study covers the state of Odisha’s share of the BB basins drainage area (57%)(Figure 1). However, this study is based on a different and much wider geographical extent than the BB basin. Therefore, a BB basin specific groundwater trend analysis was necessary, for which we adopted the Mann-

Kendall procedure. In addition, our study's spatial focus is slightly different in that the Panda results relate to example monitoring wells or the entire state while our study looks at trends of wells and by district to check the effect of increasing or decreasing trends on irrigation areas, such as command areas. We did not pursue an investigation of groundwater level trends specific to separate hydrogeological formations due to a lack of hydrogeology data. In the Panda paper, monitoring wells were mapped to geological formations based on "broad settings defined by the Central Ground Water Board of India" but not to the lithology of geological formations, which wells are screened over. Given the lack of lithology data, we consider the approach of associating wells with surface outcrops of geological formations to be highly uncertain.

3 Trend analysis of groundwater levels in the Brahmani-Baitarni Basin

The statistical trend analysis of groundwater levels in the BB basin made use of 16102 records of four measurements for any year (irrigation, pre-monsoon, monsoon, and post-monsoon) of 363 individual wells and of averages over 17 districts from 1995 to 2012. These records were obtained “as-is” from a geodatabase, which CSIRO received from the Central Water Commission in May 2014 (CGWB 2014).

No additional information was available to the authors regarding the monitoring network, data quality, frequency of observations, land use, cropping patterns or seasons, and hydrogeology of the BB basin. That is, the trend analysis described herein is indeed purely statistical. More information on limitations can found in section 4.

3.1 Objectives

At most, only four measurements for groundwater area available in any year (irrigation, pre-monsoon, monsoon, and post-monsoon), limiting any seasonality analysis. The objective of this project was to evaluate the trends of the two “reliable” seasons (pre- and post-monsoon) with a good data record and without unpredictable events from rainfall and pumping.

The analysis focusses on investigating non-seasonal trends of long-term pre- or post-monsoon records using the non-parametric Mann-Kendall technique. The purpose of the trend analysis was to distinguish spatially between regions or command areas affected by rising or falling trends indicating either shallow groundwater (or even water logging) or groundwater depletion. Therefore, rising or falling trends were investigated in clusters of individual wells or of averages over districts. Average trends of groundwater levels in different hydrogeological formations were not analysed, as the procedure of matching well locations with geological formations is uncertain.

A secondary objective is the removal of long-term multi-annual seasonality or fluctuation by smoothing pre- and post-monsoon hydrographs using the LOESS or LOWESS method. Trends of smoothed hydrographs can reveal (a) long-term groundwater trends not heavily influenced by short-term climate or irrigation for pre-monsoon water levels or (b) trends in recharge for differences between pre- and post-monsoon water levels and potential changes to those recharge trends (e.g., by lack of monsoonal rainfall or by irrigation recharge). A correlative analysis between rainfall and depth-to-groundwater trends has been conducted to better understand whether the lack of monsoonal rainfall or rather irrigation recharge are factors that influence the pre/post-monsoon difference trends.

A tertiary objective for future phases of this project would be to help calibrate surface-water losses resulting from the river system model by a correlation between groundwater depletion and stream seepage. In addition, regions dominated by trends of falling groundwater levels may directly or indirectly coincide with areas of highly stressed aquifers. A direct connection is evident between falling groundwater levels and aquifer overexploitation by irrigation pumping, i.e., unsustainable groundwater irrigation. An indirect relation between dropping water levels and unsustainable irrigation is given, where irrigation demand is in excess of surface-water supply. i.e., groundwater supplementation can be inferred. Similarly, regions with significant changes to the composition of ecologic assets may follow either falling or rising water levels.

3.2 Methods

3.2.1 Trend analysis: Mann-Kendall statistics

The Mann-Kendall (MK) method is a non-parametric statistical trend analysis (Gilbert 1987). It does not assume a statistical distribution of the data or sampling intervals. This is important for the BB basin dataset as measurements were at semi-regular intervals. In addition, the test ranks individual data points independent of their overall magnitude. Therefore, the measurement errors (outliers) do not need corrections.

An existing software tool is available to perform trend analysis. The Monitoring and Remediation Optimization System (MAROS) (Aziz et al. 2003; AFCEC 2004) is technically robust, but according to Connor et al. (2012), these tools require more significant time investment and a larger quantity of monitoring data than is practical at many sites. The GSI Mann-Kendall Toolkit (Connor et al. 2012) or MAKESENS (Salmi et al. 2002) are examples of tools that are free and easy to use, but the underlying code or macros is protected and not available in the public domain. To overcome this, we programmed parameters in Microsoft Excel and Visual Basic (based on the MK-methodology as described in Aziz et al., 2003):

Test Statistic (S): S expresses a general trend versus time. The sign of S expresses if observations obtained later tend to be larger (positive S) or smaller (negative S) than observations made earlier:

- negative S value = decreasing trend
- positive S value = increasing trend

The MK test statistic S for any time series is defined as the sum of all signs of differences between observations X of sequential sampling events (1, 2, ... , n) within the time series, which, in the case of this BB basin trend analysis, were depth to water (DTW) at a monitoring well or DTW-averages over a district:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(X_j - X_i\right) \quad \forall\, 1 \le i < j \le n, \ \text{ where } \ sgn(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \qquad (1)$$

The differences are assessed in a matrix between the time series events in row and column headers as +1 if a next event is larger or -1 if smaller than a previous event. Figure 2 shows an example for DTW averages for the district of Anugul, for the month of April (i.e., pre-monsoon), and for years 1995 to 2012. The signs (in green cells in Figure 2) are then summed up to derive the S-value for time series. In the example, the result is +49, which indicates an increasing trend.

Z-statistic: The z-value expresses a significance of trend. If the null hypothesis is true assuming no trend, then S is approximately normally distributed with mean = 0 and variance = n (n-1)(2n+5)/18 (assuming no ties). Ties are not very likely for DTW measurements of individual wells given double-digit decimals and highly unlikely for DTW-averages. The z-value becomes:

$$z = \frac{|S| - 1}{\sqrt{\sigma}} \qquad (2)$$

Confidence Factor (CF): CF is equal to the normal cumulative distribution function of z and expresses the confidence in the trend result. We used Excel's NORMSDIST(z) function, the standard normal cumulative distribution function, which returns the probability that the observed value of a standard normal random variable will be less than or equal to z. The distribution has a mean of 0 and a standard deviation of 1:

	5.52	5.98	6.22	5.63	6.72	6.16	6.60	6.33	6.45	6.92	6.09	6.52	6.43	6.17	7.01	6.34	7.06	6.13
5.52		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
5.98			1	-1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.22				-1	1	-1	1	1	1	1	-1	1	1	-1	1	1	1	-1
5.63					1	1	1	1	1	1	1	1	1	1	1	1	1	1
6.72						-1	-1	-1	-1	1	-1	-1	-1	-1	1	-1	1	-1
6.16							1	1	1	1	-1	1	1	1	1	1	1	-1
6.60								-1	-1	1	-1	-1	-1	-1	1	-1	1	-1
6.33									1	1	-1	1	1	-1	1	1	1	-1
6.45										1	-1	1	-1	-1	1	-1	1	-1
6.92											-1	-1	-1	-1	1	-1	1	-1
6.09												1	1	1	1	1	1	1
6.52													-1	-1	1	-1	1	-1
6.43														-1	1	-1	1	-1
6.17															1	1	1	-1
7.01																-1	1	-1
6.34																	1	-1
7.06																		-1
6.13																		

Figure 2: Computation of Mann-Kendall test statistic S for a time series for DTW averages for the district of Anugul

$$f(z) = \int_{-\infty}^{z} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}} \tag{3}$$

- CF ≥ 95 % - Strongly Increasing/Decreasing
- CF ≥ 90 % - Probably Increasing/Decreasing
- CF < 90 % - No Trend or Stable

Coefficient of Variation (COV): informs if data are scattered or non-variable. The COV is given by the fraction between the sample standard deviation and the sample mean.

- No Significant Trend (COV ≥ 1) (data trend versus time highly scattered)
- Stable (limited change in data versus time)

A combination of S, CF, and COV leads to the following **Classification** (Aziz et al. 2003), which combines a Trend (increasing/decreasing/stable/no trend) and a Qualifier (strongly, probably):

- Strongly Increasing (S > 0 & CF > 95%)
- Probably Increasing (S > 0 & 95% ≥ CF ≥ 90%)
- Stable (S ≤ 0 & CF < 90% & COV < 1)
- Probably Decreasing (S < 0 & 95% ≥ CF ≥ 90%)
- Strongly Decreasing (S < 0 & CF > 95%)
- No Trend (S > 0 & CF < 90 %; OR S ≤ 0 & CF < 90% & COV ≥ 1)
- No Data; Insufficient Record

The results of the Excel procedure were verified by copying and pasting 7 hydrographs of average depth to water time series for seven districts into the GSI Mann-Kendall Tool. The MK analysis was carried out with DTW data. That is, the trend classification for groundwater heads is reverse. That is, “Decrease” means a decrease in depth to water, i.e., an increase in groundwater heads. In addition, MK trends were also analysed for differences between pre- and post-monsoon DTW data, which can be a proxy for recharge.

3.2.2 Smoothed depth-to-water and rainfall time series: LOWESS method

Using the MK analysis, particular DTW time series are known to be increasing or decreasing trend. However, the MK analysis does not provide information on the linearity of this trend. The LOESS or LOWESS or "Locally Weighted Scatter-plot Smooth" method's aim is the detection of non-linear patterns in long-term, for instance multi-annual, trends that cannot be described with linear trend analyses (Cleveland 1979; Cleveland and Devlin 1988).

Depending on the number of points included in a range of a moving regression around an X value, the smoothing is lesser or higher degree. Values in the moving range are weighted according to their distance from this X value. The advantage of LOWESS over the Moving average technique is that the smoothed graph has no phase shift and does not lag behind the trend. In addition, it is insensitive to outlier data.

While short frequency seasonality is removed from the trend by just a minimum number within a moving regression (e.g., five), higher frequency seasonality is eliminated by a higher number up to the maximum number being equal to the sample size. Normally, this would allow removing intra-annual cycles with the least number of points, but in this specific case of pre-monsoon DTW series (or series of differences between pre- and post-monsoon DTW data), year-on-year data already lack any intra-annual seasonality. For the BB basin DTW data, the objective is the removal of long-term multi-annual seasonality or fluctuation.

LOWESS-smoothed hydrographs allow the visualization of groundwater trends for pre-monsoon water levels, which implicitly are not heavily influenced by seasonal climate or irrigation. That is, any non-linearities of the smoothed graphs that deviate from an overall linear increasing or decreasing trend may be linked to multi-annual, prolonged impacts of changes in climate or irrigation. Trends of differences between pre- and post-monsoon water levels indicate trends in recharge. Any non-linearities within the difference between the smoothed pre- and post-monsoon hydrographs can reveal potential changes to the recharge rends (e.g., by lack of monsoonal rainfall or by irrigation recharge).

LOWESS curves for each season of each chosen monitoring well were calculated with an array function called "public function LOESS" available in the public domain (Peltier 2009). The function was modified to accommodate the averaging of data preceding and following a year with a data gap.

The LOWESS method can smooth time series of annual or maximum precipitation to study potential correlations with smoothed DTW series of all four seasons and with smoothed series of differences between pre- and post-monsoon DTW. Smoothening both rainfall and DTW series is consistent in that it eliminates outliers or short-term natural variability of both data sets and, hence, increase the change to detect potential correlations between rainfall and long-term trends or fluctuations of DTW for particular seasons. Potential correlations between smoothed rainfall and smoothed DTW are analysed in section 3.3.4.

Generally, a correlation between DTW of pre-monsoon seasons and the subsequent monsoon seasons rainfall is not sensible. However, the LOWESS smoothing of pre-monsoon DTW series and rainfall does take into account multiple points in the moving regression around the measurement. That is, a particular year's smoothed value of an April DTW includes also several future measurements within the span of points in the moving regression. Hence, any effect of monsoon rainfall on following year's (or years') DTW measurement (potentially through delayed recharge) is already reflected in current year's smoothed DTW value. However, smoothing one-year lagged irrigation or pre-monsoon seasons' DTW will most likely improve the correlation with previous year's monsoon fall and the detection of delayed recharge.

3.3 Results

The Mann-Kendall trend analysis made use of 16102 DTW records of 363 monitoring wells over 17 districts from 1995 to 2012. The frequency of monitoring was, at most, four measurements for any year and hence did not permit any inter-annual seasonality analysis or estimates of the magnitude of water-level change on an annual basis as minima and maxima were not captured (see section 4 'Limitations'). The MK trend analysis was used to distinguish spatially between regions or command areas affected by non-seasonal, long-term, rising or falling DTW trends indicating either shallow water levels or groundwater depletion. Rising or falling trends were investigated in form of averages over districts or clusters of individual wells. Trends of smoothed long-term hydrographs of particular seasons distinguished two groups of wells, which either represent areas with rising pre-monsoon water levels and decreasing trends of pre/post-monsoon differences or areas with declining pre-monsoon water levels and increasing trends of pre/post-monsoon differences. Finally, we tested smoothed long-term groundwater trends of particular areas with rising or falling trends for their correlation with rainfall.

3.3.1 Observations on Mann-Kendall trend maps of DTW averages over districts

For Pre-Monsoon DTW trends (Figure 3, left), strongly increasing DTW trends, i.e., strong trends of declining groundwater heads, were found for the districts of Anugul, Kendrapara, and Mayurbhanj. Bhadrak and Jajapur showed weaker increasing DTW trends. Strongly decreasing DTW trends, i.e., strong trends of rising groundwater heads were detected for just the district of Baleshwar. Many districts reveal no significant trend. The northern half of the basin had insufficient record for a trend analysis to be carried out.

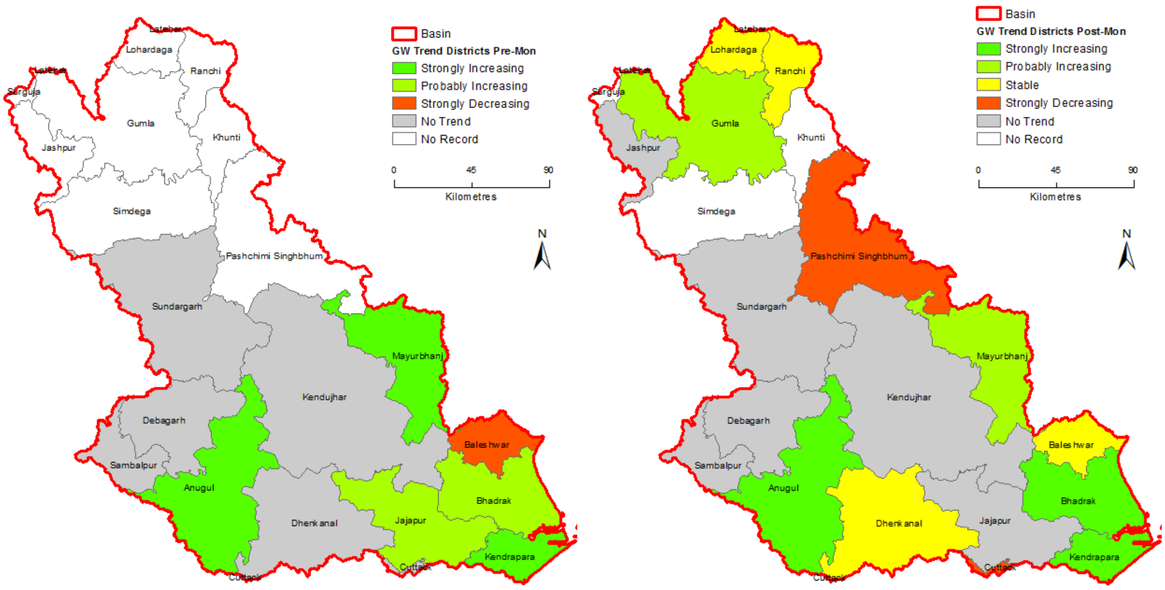


Figure 3: MK-Trends of pre- (left) and post-monsoon (right) of pre-monsoon DTW-averages over Districts

For Post-Monsoon DTW trends (Figure 3, right), strongly increasing DTW trends, i.e., strong trends of declining groundwater heads, were again found for the two districts of Anugul and Kendrapara, which also showed the same strong trends for pre-monsoon data. Bhadrak also demonstrates a strong post-monsoon trend of declining groundwater levels, but only showed a weak pre-monsoon trend. Conversely, Majurbhanj shows a weaker post-monsoon trend of declining groundwater levels while exhibiting a strong pre-monsoon trend. Strongly decreasing DTW trends, i.e., strong trends of rising groundwater heads were detected for the district of Pashchimi Singhbhum and for a small section of Cuttack in the south of the basin. Opposite to the pre-monsoon trends of the northern districts, many more districts reveal at least a probable trend or stability for post-monsoon DTW data. Several districts across the entire BB Basin have insufficient record for a post-monsoon DTW trend analysis.

A synopsis of all districts ranked and grouped by more or less significant trends is given in Table 1. Among the 17 districts that lie partially or fully within the BB basin, only Anugul and Kendrapara reveal an overall strong trend of declining groundwater levels (with 96 to 99.8 % confidence). Levels of Mayurbhanj and Bhadrak are either strongly (CF = 99.7; 98.6 %) or probably (CF = 93.1; 92.5 %) declining in one or the other season. Even weaker trends of dropping groundwater levels are found for Jajapur and Gumla (with 90.1 and 90.4 % confidence). However, among the six districts that show a declining trend, Kendrapara relies only on one or two observation wells for any year and Gumla has no observations for pre-monsoon DTW averages at all (Table 1). That is, the smaller the number of observation wells, the more uncertain the resulting MK-trend becomes regardless of whether the trend is with strong or probable confidence.

Conversely, *strong trends of groundwater level rise* are only found for either pre-monsoon levels of Baleshwar (with 98.8 % confidence) or post-monsoon levels of Pashchimi Singhbhum and Cuttack (CF = 97.6; 96.8 %). However, the latter two have only one to three observations wells for any one year and Cuttack barely touches the basin in the south. That is, trends of rising post-monsoon groundwater levels are highly uncertain for these two districts and statements about any trends are very vague.

Excluding trends based on very few observations or low confidence, a qualitative assessment of the overall groundwater level situation may conclude: With strong or probable confidence, five districts in the BB basin suffer from various degrees of declining groundwater levels (Anugul, Mayurbhanj, Bhadrak, Jajapur, and Gumla). Only one districts experiences rising pre-monsoon water levels (Baleshwar), but post-monsoon levels remain stable.

Table 1: Ranked groundwater level tends of districts within the BB Basin (CF = confidence factor)

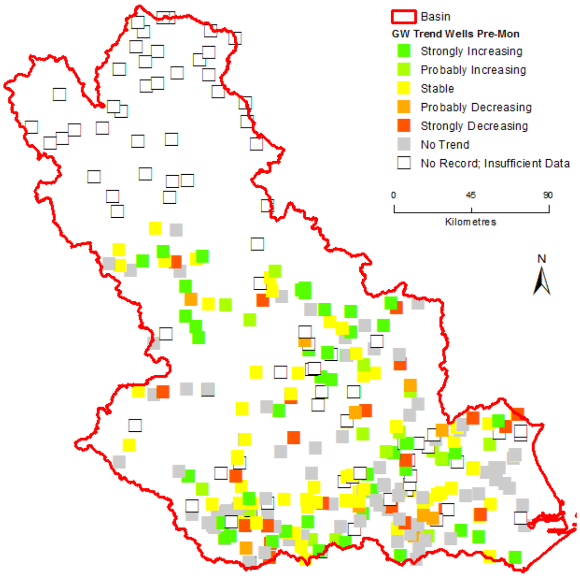
District	Min obs/year pre-mons	Max obs/year pre-mons	Min obs/year post-mons	Max obs/year post-mons	CF pre-mon [%]	CF post mon [%]	DTW trend Pre-Monsoon	DTW trend Post-Monsoon	Overall Groundwater Level Trend (reverse of DTW)
Anugul	20	36	22	30	96.5	96.0	Strongly Increasing	Strongly Increasing	Strongly declining trend of both pre- and post-monsoon levels
Kendrapara	1	2	1	2	98.8	99.8	Strongly Increasing	Strongly Increasing	
Mayurbhanj	9	14	11	13	99.7	93.1	Strongly Increasing	Probably Increasing	Strongly to probably declining trend of pre- and post-monsoon levels
Bhadrak	10	21	7	20	92.5	98.6	Probably Increasing	Strongly Increasing	
Jajapur	23	38	20	43	90.1	85.0	Probably Increasing	No Trend	Probable declining trend in either pre- or post-monsoon levels
Gumla	N/A	N/A	4	20	N/A	90.4	No Data	Probably Increasing	
Baleshwar	5	9	4	10	98.8	51.8	Strongly Decreasing	Stable	Strongly rising trend of pre-monsoon levels
Cuttack	1	1	1	1	68.9	97.6	No Trend	Strongly Decreasing	Strongly rising trend of post-monsoon levels
Pashchimi Singhbhum	N/A	N/A	1	3	N/A	96.8	No Data	Strongly Decreasing	
Dhenkanal	20	39	29	39	72.8	65.7	No Trend	Stable	Stable, no trend, or no data
Lohardaga	N/A	N/A	3	7	N/A	55.4	No Data	Stable	
Ranchi	N/A	N/A	3	8	N/A	51.8	No Data	Stable	
Debagarh	2	5	2	4	83.8	88.8	No Trend	No Trend	
Kendujhar	40	64	39	63	72.8	62.4	No Trend	No Trend	
Sambalpur	2	2	1	2	50.0	53.9	No Trend	No Trend	
Sundargarh	13	21	17	21	50.0	80.4	No Trend	No Trend	
Jashpur	N/A	N/A	2	4	N/A	65.7	No Data	No Trend	

3.3.2 Observations on Mann-Kendall trend maps of DTW data of individual wells

The two most frequent trend categories for both pre- and post-monsoon DTW trends of individual wells are ‘no trend’ and ‘stability.’ The third most frequent category are wells with strongly increasing DTW trends, i.e., strong trends of declining groundwater heads, which prevail over wells showing strongly decreasing, probably increasing, and probably decreasing DTW trends. When ignoring ‘no and stable trends’ and when comparing only wells with increasing versus decreasing trend basin wide (Table 2), then increasing DTW trends prevail over decreasing trends (68 vs. 33 for pre-monsoon DTW; 45 vs. 14 for post-monsoon DTW). This is evidence that for the BB basin as a whole, groundwater depletion prevails over rising groundwater levels. Yet, a suggestion that strong trends of declining groundwater levels prevail in the BB Basin in general cannot be made as indeed the prevailing trends are ‘no or stable trends.’ In addition, there is also no apparent pattern in the spatial distribution or clustering of the different trend categories in the pre- and post-monsoon trends of individual monitoring wells (Figure 4).

Table 2: Count of observation wells per trend categories for pre-, post-, and pre-minus-post-monsoon DTW trends

	DTW trend pre-monsoon	**DTW trend post-monsoon**	**DTW trend of difference pre/post monsoon**
Strongly Increasing	49	29	14
Probably Increasing	19	16	13
Stable	71	91	76
Probably Decreasing	11	4	7
Strongly Decreasing	22	10	16
No Trend	89	131	102
No Record, Insufficient Data	101	81	136
Total Increasing	68	45	27
Total Decreasing	33	14	23
Increasing versus Decreasing	68 >> 33 BB basin as a whole dominated by declining water levels	45 >> 14 BB basin as a whole dominated by declining water levels	27 > 23 BB basin not dominated by increasing or decreasing trends



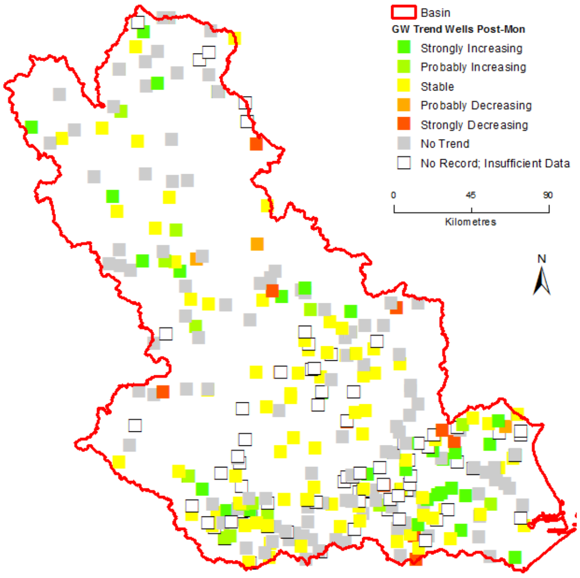


Figure 4: MK-Trends of pre- (left) and post-monsoon (right) DTW data of individual wells

Trends of differences between pre- and post-monsoon DTW data are also dominated basin-wide by no trend or stability. However, as opposed to pre- and post-monsoon trends, the difference-trends do indicate spatial clusters of increasing or decreasing trends (see ovals in Figure 5).

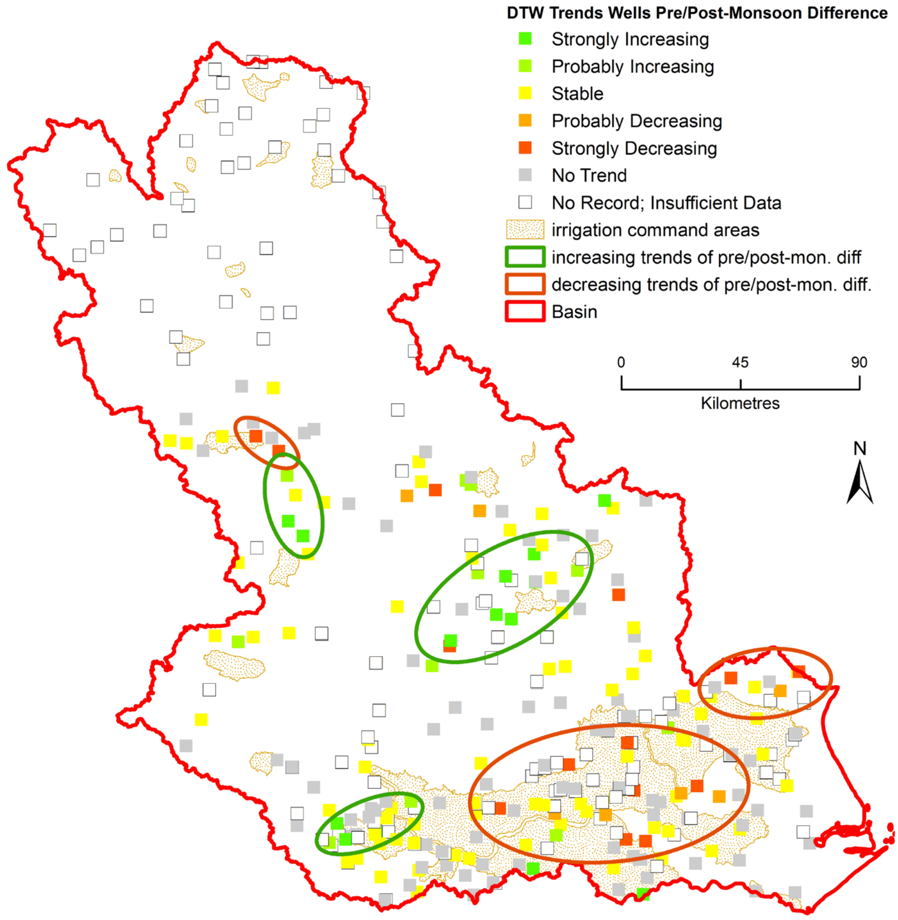


Figure 5: MK-Trends of differences between pre- and post-monsoon DTW data of individual wells

Generally, the increasing/decreasing differences between pre- and post-monsoon DTW data can be attributed to:

- Rising/declining pre-monsoon levels following increasing/decreasing irrigation recharge from inefficient losses in excess of crop water demand during the irrigation season, prior to the pre-monsoon season; or
- Rising/declining post-monsoon levels following increasing/decreasing rainfall recharge due to an abundance/lack of rainfall during the monsoon season, prior to the post-monsoon season.

Clusters of strongly decreasing difference-trends (ORANGE clusters in Figure 5) are concentrated in large command areas in the south of the basin near the delta, e.g., in the areas of the Dhenkanal, Jajapur, and Bhadrak districts. Surface-water irrigation is dominant in these large irrigation districts. Hence, such "narrowing between pre- and post-monsoon levels" could indeed be a result of rising pre-monsoon water levels (and even water logging) following increased recharge from surface-water irrigation. However, without correlation with rainfall trends, the question cannot be answered whether this phenomenon is indeed caused by elevated pre-monsoon water levels following irrigation or rather by dropping post-monsoon water levels due to lack of monsoonal rainfall. Correlation between select wells and either observed or modelled rainfall is discussed in section 3.3.4.

Clusters of strongly increasing difference-trends (GREEN clusters in Figure 5) are found mostly further north outside irrigation command areas, e.g., in the areas of the Kendujhar and Sundargarh districts. Contrary to above, this may be a result either (a) of a combination of decreased recharge from irrigation and groundwater pumping in excess of recharge prior to the pre-monsoon season or (b) of increased recharge during the monsoon season. Under the assumption that irrigation in regions outside the command areas is not prevalent, the influence of irrigation recharge would be less likely than of increased monsoonal recharge. However, smaller irrigation projects located outside the command areas may indeed rely more on groundwater use, which, if exceeding recharge, may indeed lead to a further drop of pre-monsoon groundwater levels.

3.3.3 Smoothed Depth-to-Water curves using LOWESS

Monitoring wells were only selected for the LOWESS analysis for trends with a high degree of confidence (CF ≥ 95 %) in both pre-monsoon trend DTW data and trend in differences between pre- and post-monsoon DTW data:

- Pre-monsoon DTW strongly increasing/decreasing AND
- Pre-minus-post-monsoon DTW-differences strongly increasing/decreasing.

Table 3: Selection of monitoring wells for LOWESS analysis (*bold & italic* –further inspection and discussion)

WLCODE	DISTRICT	DTW Trend Pre-Monsoon	DTW Trend Pre-minus Post-Monsoon	CF pre-monsoon [%]	CF pre-minus post-monsoon [%]
W09014	Anugul	Strongly Increasing	Strongly Increasing	95.9	95.4
W09021	***Anugul***	***Strongly Increasing***	***Strongly Increasing***	100.0	96.9
W09286	Dhenkanal	Strongly Increasing	Strongly Increasing	97.8	98.3
W09301	***Dhenkanal***	***Strongly Decreasing***	***Strongly Decreasing***	99.8	97.6
W09472	***Jajapur***	***Strongly Decreasing***	***Strongly Decreasing***	96.8	97.2
W09589	Kendujhar	Strongly Decreasing	Strongly Decreasing	99.4	96.9
W09596	Kendujhar	Strongly Decreasing	Strongly Decreasing	96.5	95.2

WLCODE	DISTRICT	DTW Trend Pre-Monsoon	DTW Trend Pre-minus Post-Monsoon	CF pre-monsoon [%]	CF pre-minus post-monsoon [%]
W09621	***Kendujhar***	***Strongly Increasing***	***Strongly Increasing***	99.9	99.4
W09622	Kendujhar	Strongly Increasing	Strongly Increasing	98.6	95.2
W09628	***Kendujhar***	***Strongly Increasing***	***Strongly Increasing***	97.4	99.2
W09761	Mayurbhanj	Strongly Increasing	Strongly Increasing	100.0	99.7
W09797	Mayurbhanj	Strongly Decreasing	Strongly Decreasing	99.0	96.4
W10012	Sundargarh	Strongly Increasing	Strongly Increasing	96.8	97.0
W10013	Sundargarh	Strongly Increasing	Strongly Increasing	98.5	98.8

Among the monitoring wells in Table 3, only five were chosen as representative examples for further inspection and discussion (bold & italic). Among those, two are located in areas with strongly decreasing trend and three in areas with strongly increasing trend of pre-monsoon DTW and of difference-trends between pre- and post-monsoon DTW (Figure 6). Note, that a biased pre-selection of wells near rivers to study the impact of surface water / groundwater interaction on groundwater trends was not possible, because only a high number of wells with strong trends (unlike in the present case) would allow such a selection.

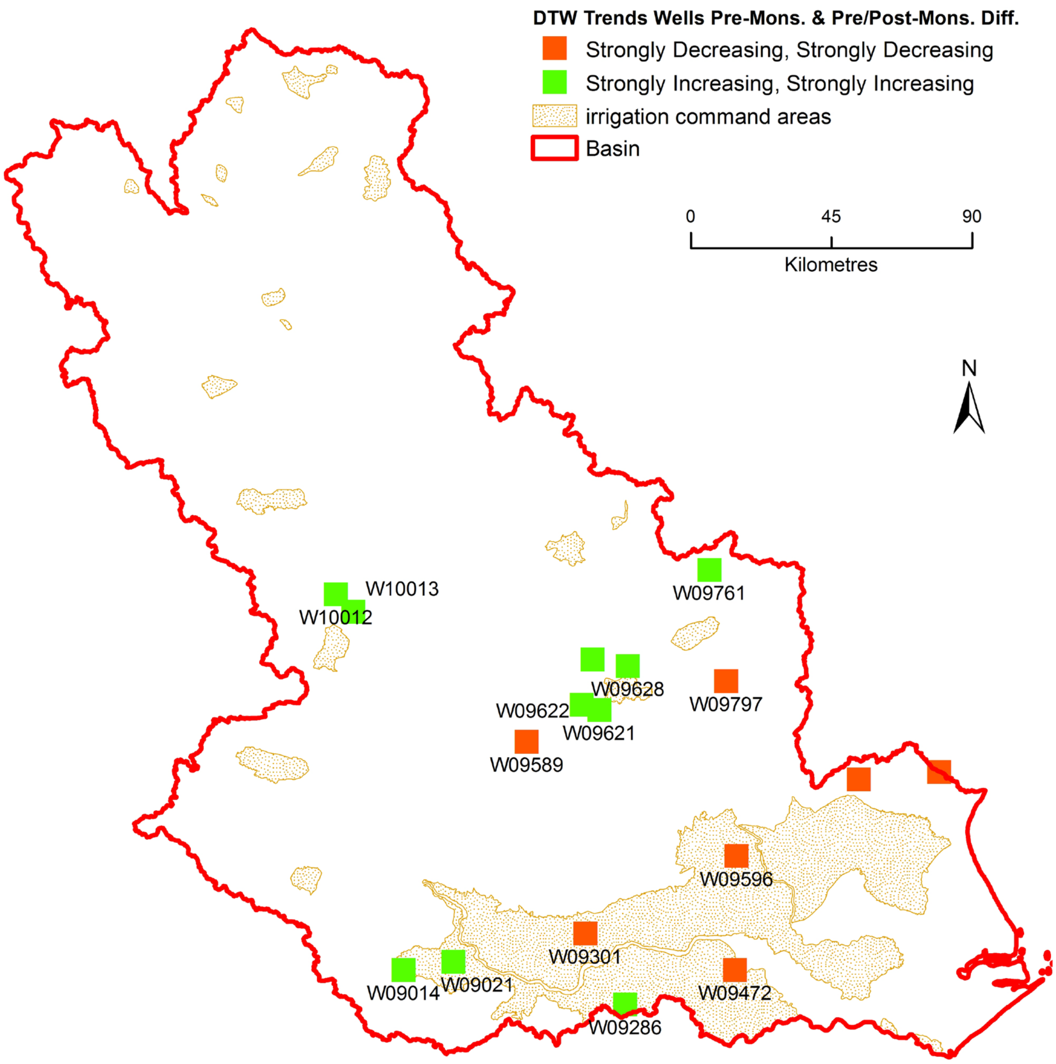


Figure 6: Location of monitoring wells selected for LOWESS analysis (selection criteria: Pre-monsoon DTW and Pre-minus-Post-monsoon differences strongly increasing/decreasing)

The example in Figure 7 demonstrates that without the LOWESS smoothing (upper left), it would be difficult to clearly visualize the trend of each season's hydrograph as well as to identify the trend of the difference between the pre- and post-monsoon seasons (red arrow; upper right). The latter benefits from a higher degree of smoothing by including more points into the moving regression.

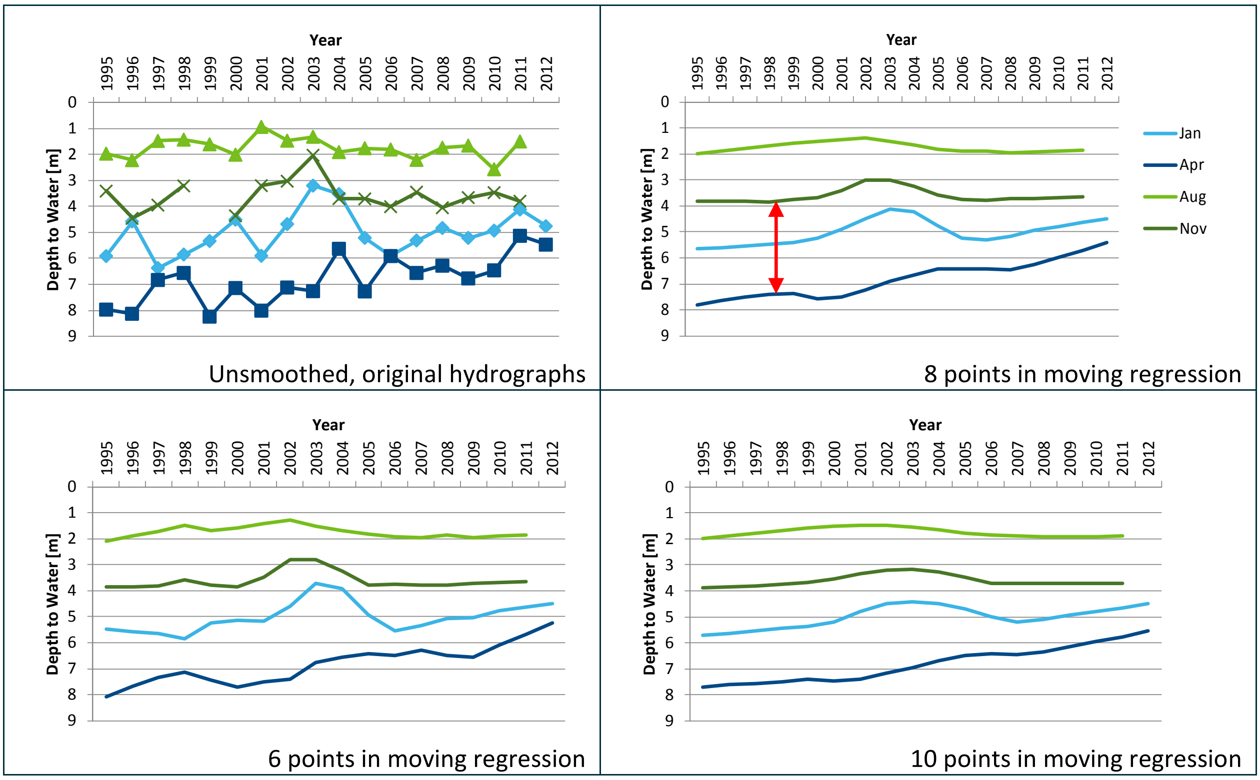


Figure 7: Example of LOWESS smoothing (Well W09301 in Dhenkanal District; Jan = Irrigation Season, Apr = Pre-Monsoon Season, Aug = Monsoon Season, Nov = Post-Monsoon Season)

Rising trend of pre-monsoon water levels & decreasing trend of pre/post-monsoon differences

Two monitoring wells (W09301, W09472) located in areas with strongly decreasing trends of pre-monsoon DTW, i.e., rising water levels, and strong decreasing difference-trends between pre- and post-monsoon DTW (Figure 6) were chosen to illustrate those trends after LOWESS smoothing (Figure 8). The inference of dominant factors, which are likely responsible for those trends, may seem obvious yet is to some degree speculative.

For monitoring well W09301, pre-monsoon water levels (Apr; dark blue) are strongly (CF=99.8%) and steadily rising while post-monsoon levels (Nov; dark green) are stable, this is likely due to controlled drainage. This illustrates how a well that lies in areas that are heavily irrigated by surface-water is affected by recharge from irrigation. Once recharge from monsoonal rainfall adds to the irrigation recharge, one would assume that this would ultimately lead to water logging conditions. However, the post-monsoon levels are kept stable, which most likely is the result of controlled drainage pumping, which prevents water levels from reaching the surface.

For monitoring well W09472, post-monsoon water levels seem to be temporarily influenced by monsoon rainfall or the lack of it. For instance, after 2008, a sharp decline of monsoonal and post-monsoon water levels is recorded (Aug: light green & Nov; dark green). Conversely, pre-monsoon groundwater heads kept rising after 2008 and do NOT follow the declining trend of post monsoonal heads. One possible conclusion could be that irrigation recharge is still responsible for rising pre-monsoon heads but that evapotranspiration in excess of sparse monsoonal rainfall leads to a depletion of monsoonal and post-monsoonal water levels.

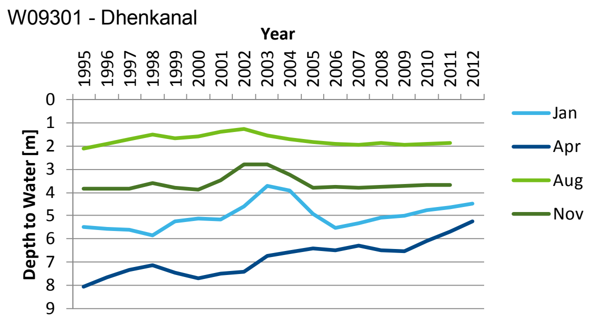
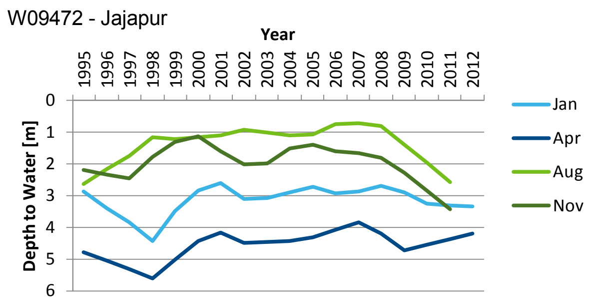
Well ID / Likely dominant factor for trends	**Pre-Mons. Water Level (strong trend; CF ≥ 95 %)**	**Post-Mons. Water Level (probable trend; CF < 95%)**	**Trend of Difference (strong trend; CF ≥ 95 %)**	**LOWESS-smoothed seasonal hydrographs in areas with rising pre-monsoon water levels**
W09301 / Recharge from SW-Irrigation; GW pumping likely for drainage control	Rising	Stable; Likely to be controlled by drainage?	Decreasing	
W09472 / Recharge from SW Irrigation & Monsoon; Absence of GW pumping	Rising	No clear trend, but likely climate influenced ?	Decreasing	

Figure 8: LOWESS smoothing of wells W09301 and W09472 showing a rising trend of pre-monsoon groundwater levels and decreasing recharge

The understanding gained from visualizing wells in areas with rising pre-monsoon water levels and decreasing trends of pre/post-monsoon differences may be summarized as follows (note that post-monsoon trends are of lower confidence and, hence, are not discussed):

- Rising pre-monsoon water levels are:
  - likely a result of recharge from irrigation rather than rainfall;
  - insensitive to the decreasing difference between pre- and post-monsoon that can be attributed to reduced recharge from monsoon rainfall.
- Decreasing differences between pre- and post-monsoon water levels are likely due to:
  - rising pre-monsoon water levels as a result of irrigation recharge;
  - stable post-monsoon water levels controlled by drainage pumping;
  - declining post-monsoon water levels as a result of a reduced recharge from monsoonal rainfall (e.g., following a drought).

Declining trend of pre-monsoon water levels & increasing trend of pre/post-monsoon differences

Three monitoring wells (W09628, W09621, and W09021) located in areas with strongly increasing trends of pre-monsoon DTW, i.e., declining water table, and strongly increasing difference-trends between pre- and post-monsoon DTW (Figure 6) were chosen to illustrate those trends after LOWESS smoothing (Figure 9).

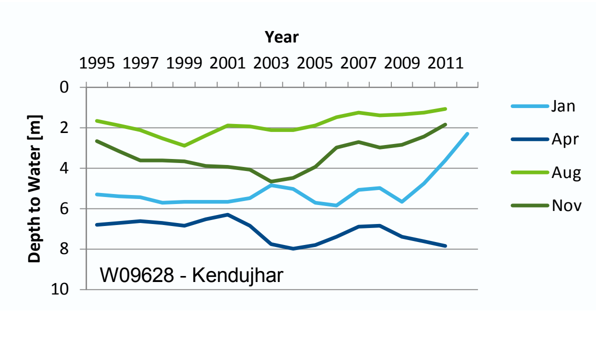
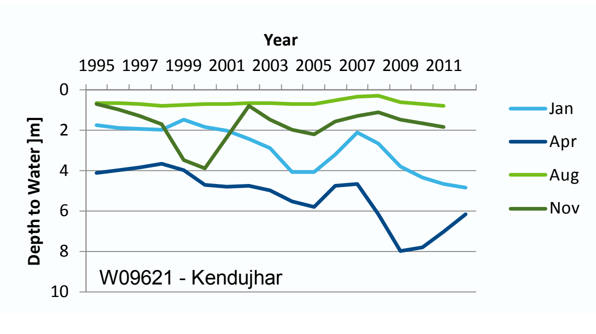
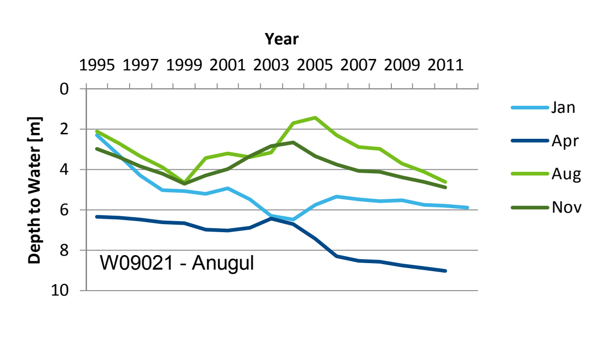
Well ID / Likely dominant factor for trends	**Pre-Mons. Water Level** (strong trend; CF ≥ 95 %)	**Post-Mons. Water Level** (probable trend; CF < 95%)	**Trend of Difference** (strong trend; CF ≥ 95 %)	**LOWESS-smoothed seasonal hydrographs in areas with declining pre-monsoon water levels**
W09628 / Increasing recharge from SW irrigation and monsoon; Declining pre-mons. levels: GW pumping	Declining	Rising; Influenced initially by monsoon and later on by irrigation	Increasing	
W09621 / Increasing recharge from SW Irrigation; Declining pre-mons. levels: GW pumping	Declining	Stable (since 2002); Likely to be controlled by drainage?	Increasing	
W09021 / Increasing, but variable recharge from monsoon rainfall; Declining pre-mons. levels: GW pumping	Declining	Probably Declining, but likely climate Influenced?	Increasing	

Figure 9: LOWESS smoothing of wells W09628 and W09621, and W09021 showing a declining trend of pre-monsoon groundwater levels and increasing recharge

For monitoring well W09628, pre-monsoon water levels (Apr; dark blue) are declining (CF = 97.4%), yet post-monsoon levels (Nov; dark green) are rising and seem to follow initially monsoonal levels (Aug; light green), but after 2009 also irrigation season levels (Jan; light blue). That is, this well recorded an overall increasing pre/post-monsoon difference both due to increasing recharge from irrigation and rainfall.

For monitoring well W09621, pre-monsoon water levels (Apr; dark blue) are declining as in well W09628, yet the trend is more significant (CF=99.9%). Monsoonal and post-monsoon levels (Nov; dark green) are not rising as in well W09628 and are stable after 2002. A likely cause for the stable water levels could be control by drainage pumping. Increasing pre/post-monsoon differences indicate increasing recharge, which, however, maybe unrelated to climate but a result of irrigation. Indeed, pre-monsoon water levels (Apr; dark blue) follow irrigation season levels (Jan; light blue) closely.

For monitoring well W09021, pre-monsoon water levels (Apr; dark blue) are also sharply declining (CF=100%). Post-monsoon levels (Nov; dark green) are probably declining, but rather variable following the monsoonal levels (Aug; light green). However, after 2004, a drop in pre-monsoon levels follows the declining trend of post-monsoonal heads probably because of a lack of monsoonal rainfall. The overall decreasing trend may also be a result of groundwater pumping.

The understanding gained from visualizing wells in areas with declining pre-monsoon water levels and increasing trends of pre/post-monsoon differences may be summarized as follows (note that post-monsoon trends are of lower confidence and, hence, are not discussed):

- declining pre-monsoon water levels are:
  - probably dominated by groundwater pumping (that is, the effect of pumping is greater than either rainfall or irrigation recharge);
  - insensitive to the increasing difference between pre- and post monsoon that can be attributed to increased recharge from monsoon rainfall.
- Increasing differences between pre- and post-monsoon water levels are likely due to:
  - falling pre-monsoon water levels as a result of groundwater pumping;
  - stable post-monsoon water levels controlled by drainage pumping;
  - rising and dropping post-monsoon water levels as a result of a fluctuating recharge from variable monsoonal rainfall.

3.3.4 Correlation between smoothed rainfall and smoothed depth-to-water

For analysing a potential correlation between rainfall and depth-to-water, only monitoring wells were selected that have strong pre-monsoon and strong pre-minus-post monsoon trends in three different areas (Figure 10):

- Area 1: Area of declining water level trends (Figure 11) north of major canal command areas (wells: W09590, W09621, W09622, W09628, W09630, W10073) near rainfall station 42891;
- Area 2: Area of rising water level trends (Figure 12), but outside command areas located at the eastern Baitarni catchment boundary (wells: W09087, W09120) near station 42895;
- Area 3: Areas of rising water level trends (Figure 13) in surface-water dominated command areas in the South (wells: W09301, W09472, W09596) near station 42970.

For all three areas, correlations were calculated between annual sums and maxima of *modelled* precipitation of IMD4 grid cells coinciding with selected monitoring wells and the DTW of these wells from:

- January (irrigation), April (pre-monsoon), August (monsoon), November (post-monsoon),
- Minimum DTW, and Maximum DTW,
- next year’s January, and next year’s April,
- differences between April and November and between November and next year’s April

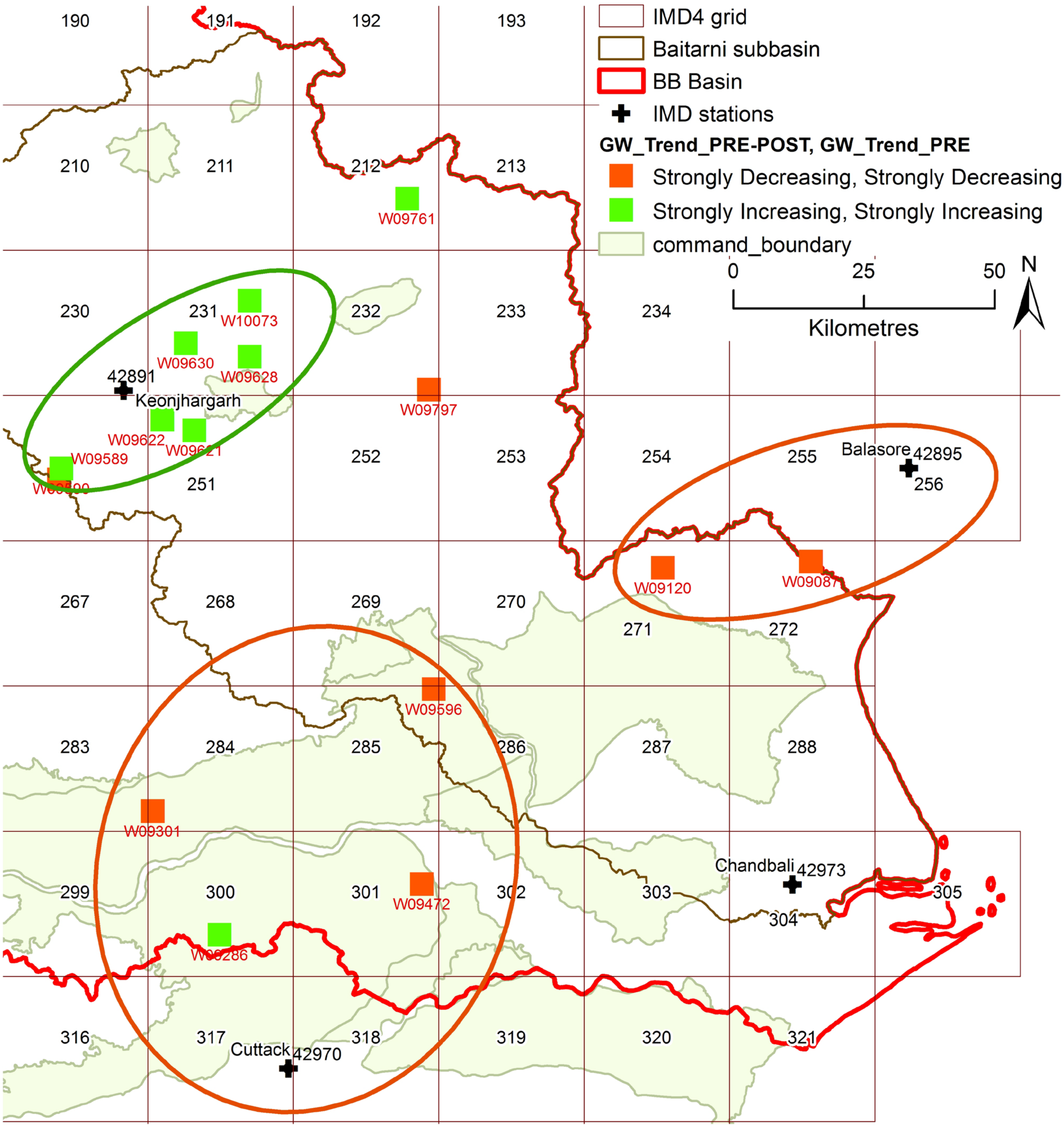


Figure 10: Location of monitoring wells selected for correlation between rainfall and depth-to-water

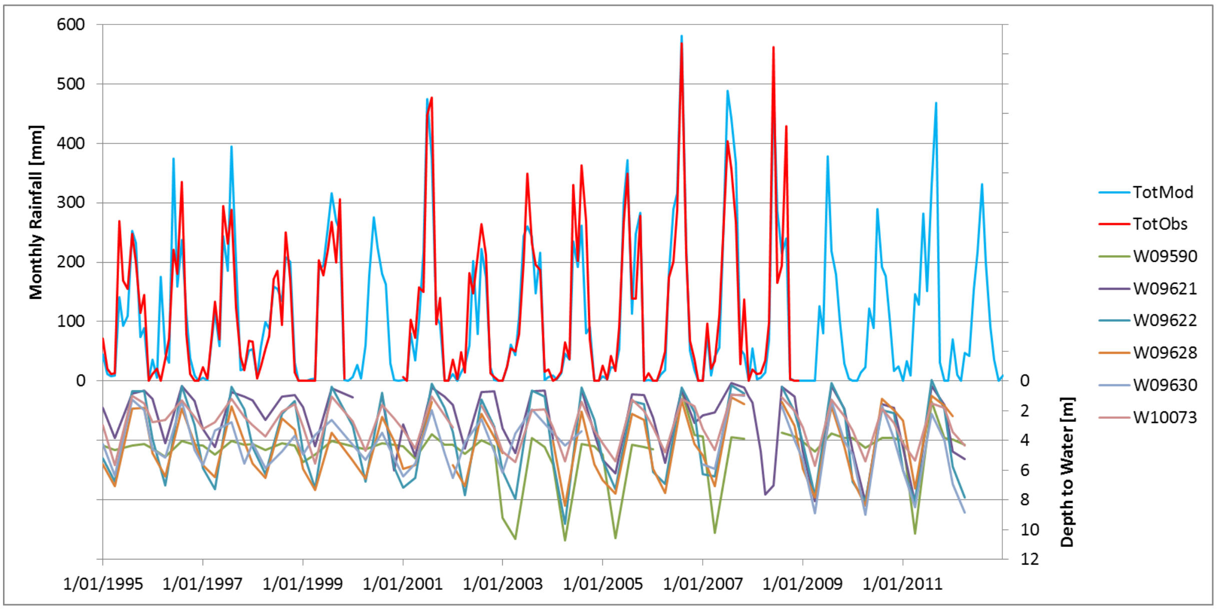


Figure 11: Time series of observed and modelled monthly rainfall and depth to groundwater for Area 1

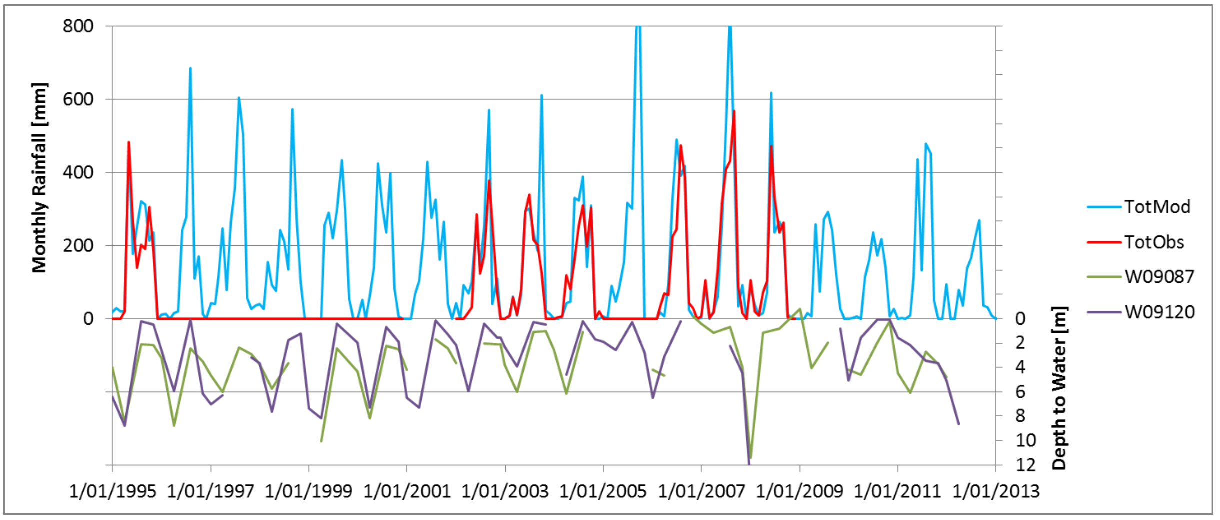


Figure 12: Time series of observed and modelled monthly rainfall and depth to groundwater for Area 2

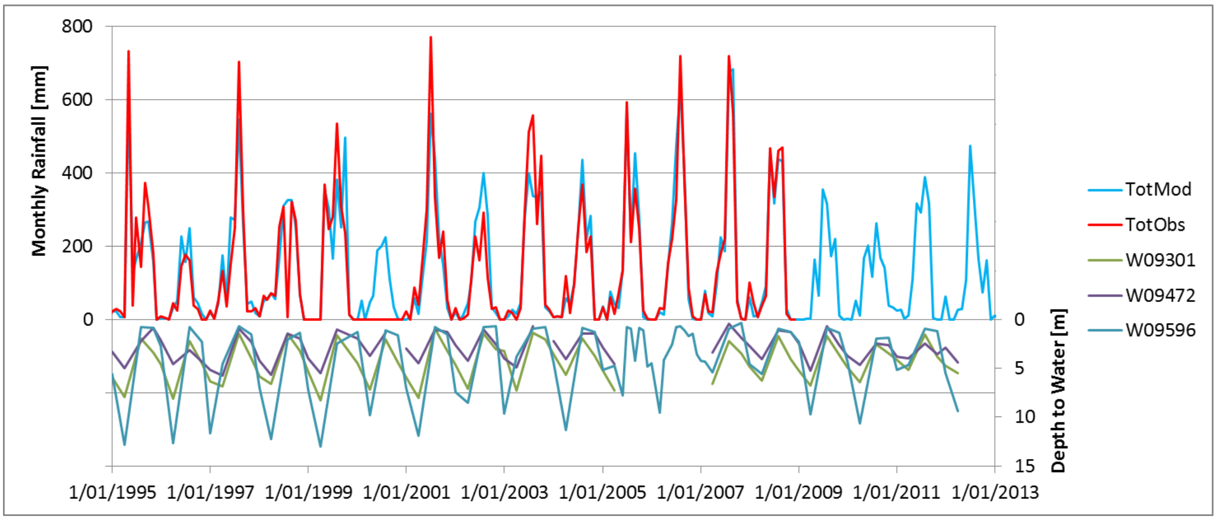
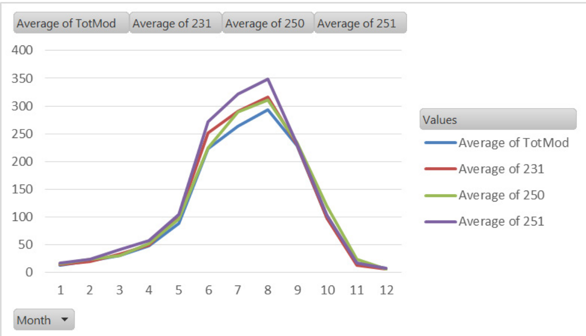
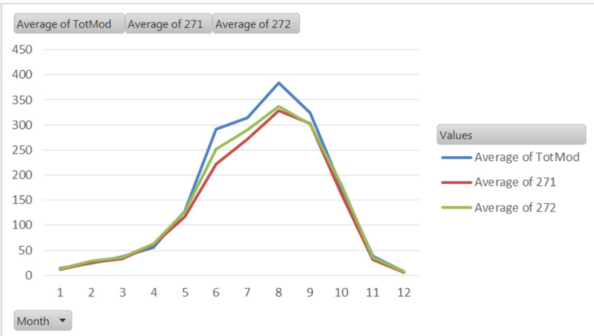


Figure 13: Time series of observed and modelled monthly rainfall and depth to groundwater for Area 3

Only in Area 1, correlations were also calculated for *observed* precipitation of station 42891, because four out of six wells are located in close proximity. It is unclear whether correlations between DTW and modelled rainfall of IMD grid cells that wells coincide with yield better R^2-coefficients than correlations between DTW of and nearby observed rainfall. In some cases, wells might be closer to the station than to IMD grid points, which rainfall was modelled at. Even where wells may be closer to one or the other, observed data may have data gaps and quality issues. Furthermore, modelled data for particular grid points may not be representative of actual values. For wells in Areas 2 and 3, the rainfall stations were too far away to draw any meaningful correlations. Modelled rainfall was also used because the rainfall observations were only available from around 1970 until 2008, while IMD4-modelled rainfall was obtained from 1901 through 2013. The correlations relate to the period of DTW measurements from 1995 through 2012.





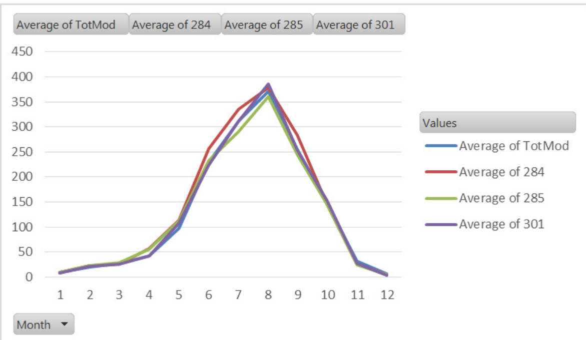


Figure 14: average monthly precipitation for IMD4-modelled rainfall in grid cells coinciding with wells in Areas 1, 2, and 3 around stations 42891, 42895, and 42970 (a - top left, b - top right, c - bottom left)

Correlations are expected to be similar for August DTW versus rainfall and minimum DTW versus rainfall, for April DTW versus rainfall and maximum DTW, as well as for any season's DTW versus annual sums of rainfall and any season's DTW versus maxima of rainfall. This rests on the assumption that commonly DTW reach minima during the peak monsoon season, i.e., in August, and maxima during the pre-monsoon season, i.e., in April. Similarly, if the bulk of rainfall occurs in August and is narrowly and normally distributed around August (see Figure 14c), correlations with DTW will be similar for annual sums and maxima of precipitation.

Correlation between smoothed rainfall and declining water levels

Area 1 is located in the northern part of the Baitarni Subbasin in an area of declining water level trends north of major canal command areas. Correlations were calculated between four wells near the Keonjhargarh rainfall station 42891 (W09622 - 9km; W09630 - 14km; W09621 - 15km; W09628 - 23km) and observed rainfall. In addition, correlations were analysed between the DTW of these wells and two additional wells further from the station (W09590 and W10073) and modelled IMD4 rainfall of each IMD4 grid cell coinciding with the location of each respective well. W09590 is located in mountainous terrain and W09621 is 1.5 km from a storage also in a hilly area. All wells are situated outside, but differently far from, the nearby Kanjhari command area. While the four wells grouped around the rainfall station are between 2.5 and 7.7 km from the command area, W10073 and W09590 are quite distant from the command areas (13 and 28 km).

In general, correlations between maximum precipitation (MaxP) and DTW are much better than between annual precipitation sums (SumP) and DTW, because the variance of average monthly rainfall around the month of August is wide or skewed towards June and July (Figure 14a).

Table 4: Correlation between annual sums of rainfall (a: top) or maxima of monthly rainfall (b: middle) and DTW (Jan, Jan/nxtyr, Apr, Apr/nxtyr, Aug, Nov) or DTW-differences (Apr-Nov; Apr/nxtyr-Nov); average DTW and average of DTW-differences for area 1 (c: bottom)

(numbers in blue = IMD4 grid cell; R2 = correlation coefficient; Sl. = Slope)

	W09621-Obs		W09622-Obs		W09628-Obs		W09630-Obs		R^2-avg	W09590-250		W09621-251		W09622-251		W09628-231		W09630-231		W10073-231		R^2-avg
Sum Precip vs.	R2	Sl.	R2	Sl.	R2	Sl.	R2	Sl.		R2	Sl.	R2	Sl.	R2	Sl.	R2	Sl.	R2	Sl.	R2	Sl.	
Jan	0.06	+	0.08	+	0.00	-	0.01	+	0.04	0.25	-	0.02	-	0.05	+	0.01	+	0.03	-	0.00	-	0.06
Jan/nxtyr	0.11	+	0.03	+	0.02	-	0.09	+	0.06	0.50	-	0.25	-	0.12	-	0.16	+	0.11	-	0.16	-	0.22
Apr	0.45	+	0.00	+	0.00	+	0.03	+	0.12	0.18	+	0.14	-	0.20	-	0.03	-	0.24	-	0.00	-	0.13
Apr/nxtyr	0.55	+	0.07	+	0.00	+	0.35	+	0.24	0.00	-	0.07	-	0.39	-	0.10	-	0.13	-	0.00	+	0.12
Aug	0.54	-	0.36	-	0.28	-	0.20	-	0.34	0.53	-	0.17	-	0.02	-	0.00	+	0.04	-	0.31	-	0.18
Nov	0.06	+	0.00	+	0.07	-	0.12	-	0.06	0.56	-	0.00	-	0.07	-	0.03	+	0.30	-	0.21	-	0.19
Apr-Nov	0.14	+	0.00	+	0.17	+	0.22	+	0.13	0.29	+	0.19	-	0.03	-	0.04	-	0.06	-	0.04	+	0.11
Apr/nxtyr-Nov	0.19	+	0.01	+	0.05	+	0.40	+	0.16	0.00	+	0.04	-	0.05	-	0.01	-	0.03	-	0.04	+	0.03
Max	0.72		0.01		0.08		0.08		0.22	0.05		0.12		0.25		0.00		0.44		0.00		0.14
Min	0.32		0.26		0.27		0.11		0.24	0.70		0.00		0.00		0.00		0.01		0.08		0.13
Max Precip vs.																						
Jan	0.11	+	0.12	+	0.03	-	0.00	+	0.07	0.23	-	0.00	+	0.04	+	0.07	+	0.02	-	0.16	-	0.09
Jan/nxtyr	0.18	+	0.04	+	0.02	-	0.03	+	0.07	0.43	-	0.00	-	0.01	-	0.05	+	0.00	-	0.09	-	0.10
Apr	0.53	+	0.02	+	0.02	+	0.04	+	0.15	0.18	+	0.00	+	0.01	-	0.18	-	0.01	-	0.03	-	0.07
Apr/nxtyr	0.63	+	0.09	+	0.03	+	0.41	+	0.29	0.01	+	0.06	+	0.02	-	0.05	-	0.00	+	0.05	-	0.03
Aug	0.70	-	0.39	-	0.45	-	0.31	-	0.46	0.65	-	0.65	-	0.31	-	0.22	-	0.46	-	0.64	-	0.49
Nov	0.01	+	0.02	-	0.11	-	0.20	-	0.08	0.72	-	0.03	-	0.16	-	0.04	-	0.04	-	0.33	-	0.22
Apr-Nov	0.26	+	0.04	+	0.28	+	0.31	+	0.22	0.35	+	0.00	+	0.05	+	0.00	+	0.01	+	0.04	+	0.07
Apr/nxtyr-Nov	0.37	+	0.06	+	0.12	+	0.56	+	0.28	0.03	+	0.11	+	0.04	+	0.02	+	0.03	+	0.02	-	0.04
Max	0.71		0.02		0.12		0.09		0.24	0.05		0.00		0.02		0.05		0.08		0.04		0.04
Min	0.46		0.30		0.44		0.19		0.35	0.76		0.09		0.07		0.36		0.43		0.28		0.33
Average DTW																						
Jan	2.88		5.17		5.12		5.10			4.68		2.88		5.17		5.12		5.10		3.30		
Apr	5.26		7.42		7.12		5.57			6.62		5.26		7.42		7.12		5.57		4.78		
Aug	0.64		0.69		1.84		2.15			3.60		0.64		0.69		1.84		2.15		1.37		
Nov	1.69		2.12		3.39		3.27			4.14		1.69		2.12		3.39		3.27		2.16		
Avg of smoothed DTW diff between Apr & Nov																						
Apr-Nov	3.90		5.17		3.75		1.88			2.66		3.90		5.17		3.75		1.88		2.64		
Apr/nxtyr-Nov	3.52		5.29		3.05		1.77			2.65		3.52		5.29		3.05		1.77		2.52		

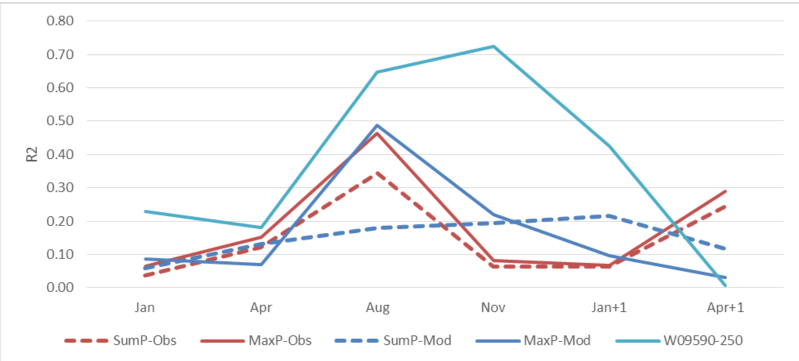


Figure 15: Average correlation coefficients for each season for Area 1

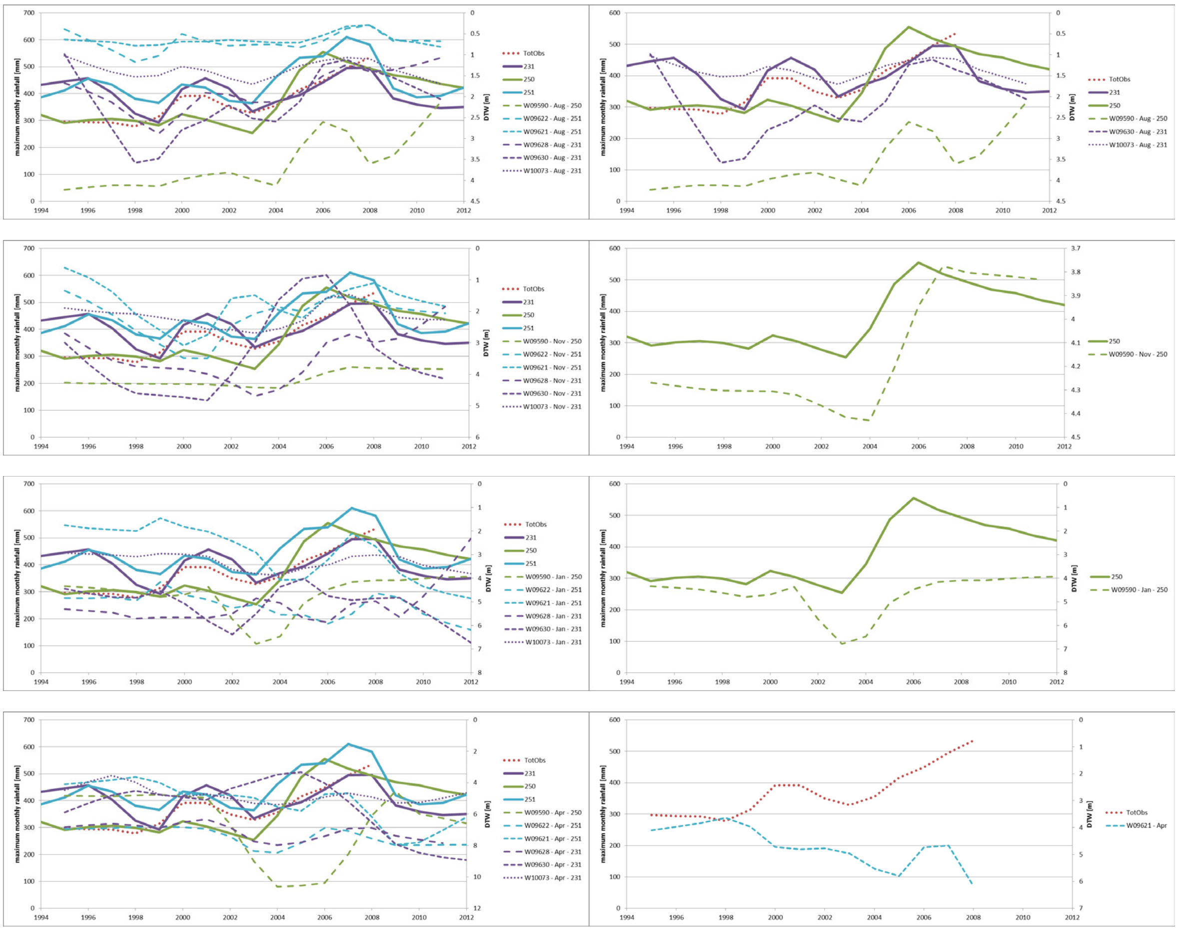


Figure 16: Smoothed maximum monthly rainfall and DTW of wells in Area 1 for August (a), November (b), January (c), April (d) (left: all wells; right: wells with good correlation)

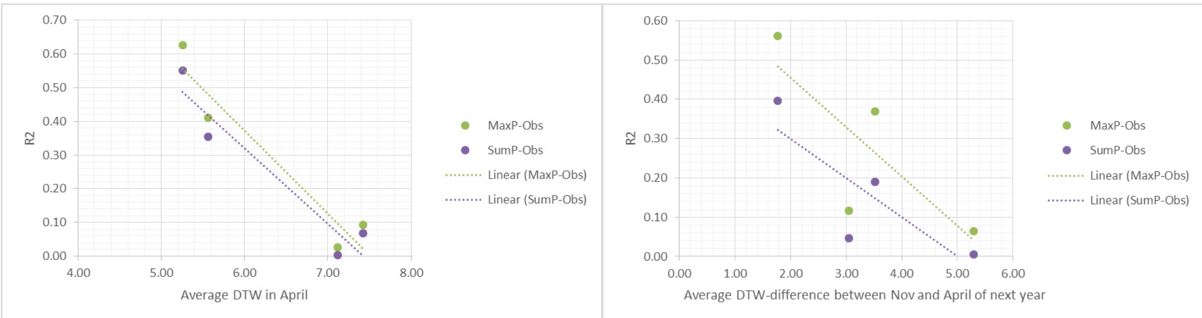


Figure 17: Relationship between rainfall-DTW correlation and Average DTW (a: left) and between rainfall-DTW-difference correlation and Average DTW-difference (b: next year) (right) for Area 1

August

The best overall correlation between observed rainfall of station 42891 or modelled IMD4-rainfall and depth to water was achieved either for MaxP and Aug DTW or MaxP and Min DTW (R2-average: 0.49 & 0.33)(Figure 15). Best correlations were achieved for wells W09590, W09630, and W10073 (Figure 16a). However, for some wells (W09622 & W09628), there is no significant correlation with modelled rainfall, but instead with observed rainfall. For W09628, Aug or Min DTW correlate well with the observed rainfall of the nearby station (0.45 & 0.44).

April same year and next year

The second best correlation was found between SumP or MaxP of observed rainfall and pre-monsoon DTW of the next year (R2-average: 0.24 & 0.29)(Figure 15), with the best correlation for the shallowest wells

W09621 and W09630 (R2: 0.55 & 0.63; 0.35 & 0.41)(Figure 16d). However, this correlation is associated with a positive slope between rainfall and DTW, i.e., the higher monsoon rainfall, the deeper the DTW in April or April of next year.

Notice that W09621 is not in an agricultural area indicating that the shallow water level is related to an absence of groundwater pumping. For Area 1, a general rule appears to be that the deeper the water level in April of next year (probably as a result of GW pumping), the lesser is the correlation between rainfall and pre-monsoon DTW of next year (Figure 17a).

November to January

Conversely, the deeper the water level during post-monsoon (Nov), the higher the correlation between rainfall and DTW, especially in W09590 (R2: 0.72 & 0.56), where, even after the monsoon, the DTW is still >4m (Table 4c), i.e., recharge from monsoon is delayed. Even for January of next year, the correlation with MaxP or SumP is still at 0.43 & 0.50. W09590 is an outlier compared to the rest of the wells in Area 1 in that it is in mountainous terrain and most likely rainfed with no groundwater irrigation. That is, in the absence of groundwater pumping, November and January DTW are more likely to be still influenced by monsoon rainfall.

Difference between April (of the same and next year) and November DTW

The smaller the difference, the better the correlation with rainfall (e.g., Apr/nxtyr-Nov of W09630 with 0.56 & 0.40 for MaxP or SumP). For W09630, Apr/nxtyr-Nov correlates better with rainfall than Apr-Nov, which indicates that there is only minor distortion of the correlation by any potential depletion from groundwater pumping, which occurs during the irrigation season between Nov and next year's April. Conversely, wells with significant drawdown prior to the pre-monsoon season (i.e., between Nov and April next year) show a bigger DTW-difference (e.g., wells W09621, W09622, and W09628), and, hence, no correlation with rainfall since the Pre-Post difference cannot only be attributed to rainfall (Figure 17b).

Summary

Water levels wells of Area 1 correlate well with rainfall during monsoon and somewhat well with DTW during pre-monsoon (of next year), although the latter correlation is reduced in wells with deeper average water levels. This area is located north of the major surface-water irrigation command areas and even outside of smaller nearby command area. In that respect, it is quite likely that the only source of irrigation is groundwater pumping. Therefore, the trend of a gradual widening between November and April DTW (see section 3.3.3) may indeed be more related to groundwater pumping rather than to increased recharge from monsoon rainfall. For the latter to be the dominant factor, November DTW should have shown significant correlation with rainfall, which is the case only for one out of six wells.

Correlation between smoothed rainfall and rising water levels outside command areas

Area 2 is an area of rising water level trends of wells located between the Salandi command area and the Balasore rainfall station 42895 along the eastern Baitarni sub-catchment boundary (wells: W09087, W09120). Correlations of DTW of those two wells with observed rainfall of station 42895 were disregarded (station is too distant: W09087 - 25km, W09120 - 48km) and limited to modelled rainfall for the IMD4 grid cell, which the station falls in.

One would expect that W09087, which is only 13 km from coast, might be influenced by coastal boundary effects buffering any correlation with rainfall and/or by depletion of the Balasore coastal aquifer.

In general, correlations between maximum precipitation (MaxP) and DTW are much better than between annual precipitation sums (SumP) and DTW, because the variance of average monthly rainfall around the month of August is wide (Figure 14b).

August and Min DTW

There is no significant correlation between rainfall and DTW in August or Min DTW except for W09120 between MaxP and Min DTW (R2: 0.47), but not Aug DTW, meaning the Min DTW and Aug DTW do not always occur at the same time. For W09120, sometimes the minimum DTW occurs in November, which influences the good correlation of MaxP with Nov DTW.

		W09087-272		W09120-271		
Sum Precip vs.		R2	Slope	R2	Slope	R^2-avg
	Jan	0.24	-	0.34	+	0.29
	Jan/nxtyr	0.12	-	0.33	+	0.23
	Apr	0.02	+	0.08	-	0.05
	Apr/nxtyr	0.02	+	0.04	-	0.03
	Aug	0.08	-	0.00	-	0.04
	Nov	0.02	-	0.35	+	0.18
	Apr-Nov	0.01	+	0.02	-	0.01
	Apr/nxtyr-Nov	0.02	+	0.11	-	0.06
	Max	0.20		0.02		0.11
	Min	0.21		0.02		0.12
Max Precip vs.						
	Jan	0.14	-	0.75	+	0.44
	Jan/nxtyr	0.04	-	0.73	+	0.38
	Apr	0.10	-	0.55	-	0.33
	Apr/nxtyr	0.08	-	0.38	-	0.23
	Aug	0.26	-	0.21	+	0.23
	Nov	0.06	-	0.52	+	0.29
	Apr-Nov	0.09	-	0.50	-	0.30
	Apr/nxtyr-Nov	0.01	-	0.46	-	0.23
	Max	0.05		0.00		0.03
	Min	0.37		0.47		0.42
Average DTW						
	Jan	3.93		5.32		
	Apr	5.67		5.04		
	Aug	1.79		0.80		
	Nov	2.02		2.21		
Average of smoothed DTW diff between Apr & Nov						
	Apr-Nov	2.79		3.61		
	Apr/nxtyr-Nov	2.33		2.97		

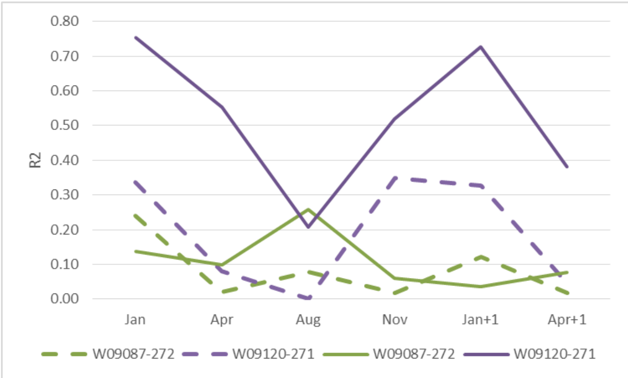


Figure 18: (TOP) Correlation coefficients for each season for wells in Area 2

Table 5: (LEFT) Correlation (R2) between annual sums of rainfall (a: top) or maxima of monthly rainfall (b: middle) and DTW (Jan, Jan/nxtyr, Apr, Apr/nxtyr, Aug, Nov) or DTW-differences (Apr-Nov; Apr/nxtyr-Nov); average DTW and average of DTW-differences for Area 2 (c: bottom)

Post-Monsoon to Pre-Monsoon (Nov - Jan - April)

Opposite to wells near the Keonjhargarh rainfall station 42891 with nearly no correlation between annual sums or maxima of rainfall and pre-monsoon DTW, here, W09120 shows a significant correlation between rainfall and WLs from Post-Monsoon to next year's Pre-monsoon (0.52; 0.73; 0.38) (Table 5 and Figure 18). Note that the LOWESS method does include future observations into the moving regression and reduces the effect of a phase shift. Hence, correlations between rainfall and same year January or April DTW are also meaningful (R2: 0.75 & 0.55). It is not clear why the correlation is better without the one-year lag, when one would expect the opposite. The good correlation between rainfall and post- to pre-monsoon DTW of well W09120 indicates that it is significantly influenced by recharge from delayed monsoon recharge.

Notable, the maximum R2 of 0.73 or 0.75 for next year's or same year's January is achieved through a correlation between DTW and rainfall with positive slope, that is, the higher the rainfall, the deeper the water level (Figure 19c). This suggests that the good correlation with monsoon rainfall is not considerably diminished by potential recharge from irrigation.

Generally, one would expect pre-monsoon water levels to follow the previous year's monsoon rainfall as long as they are not depleted by groundwater pumping or raised by surface-water irrigation recharge. This is reflected in the moderate correlation between DTW of well W09120 and MaxP of cell 271 of April and April of next year (R2 = 0.55 & 0.38). Yet, a recent water level decline after 2010-2011 dampens this correlation (Figure 19). In well W09087, April water levels decline sharply already after 2008 (Figure 19), which has an impact on any potential correlation of rainfall with April DTW. That is, the absence of any correlation for W09087 indicates that groundwater pumping is a factor. A steep decline from average January DTW to average April DTW (from 3.9 to 5.7 m) corroborates this inference.

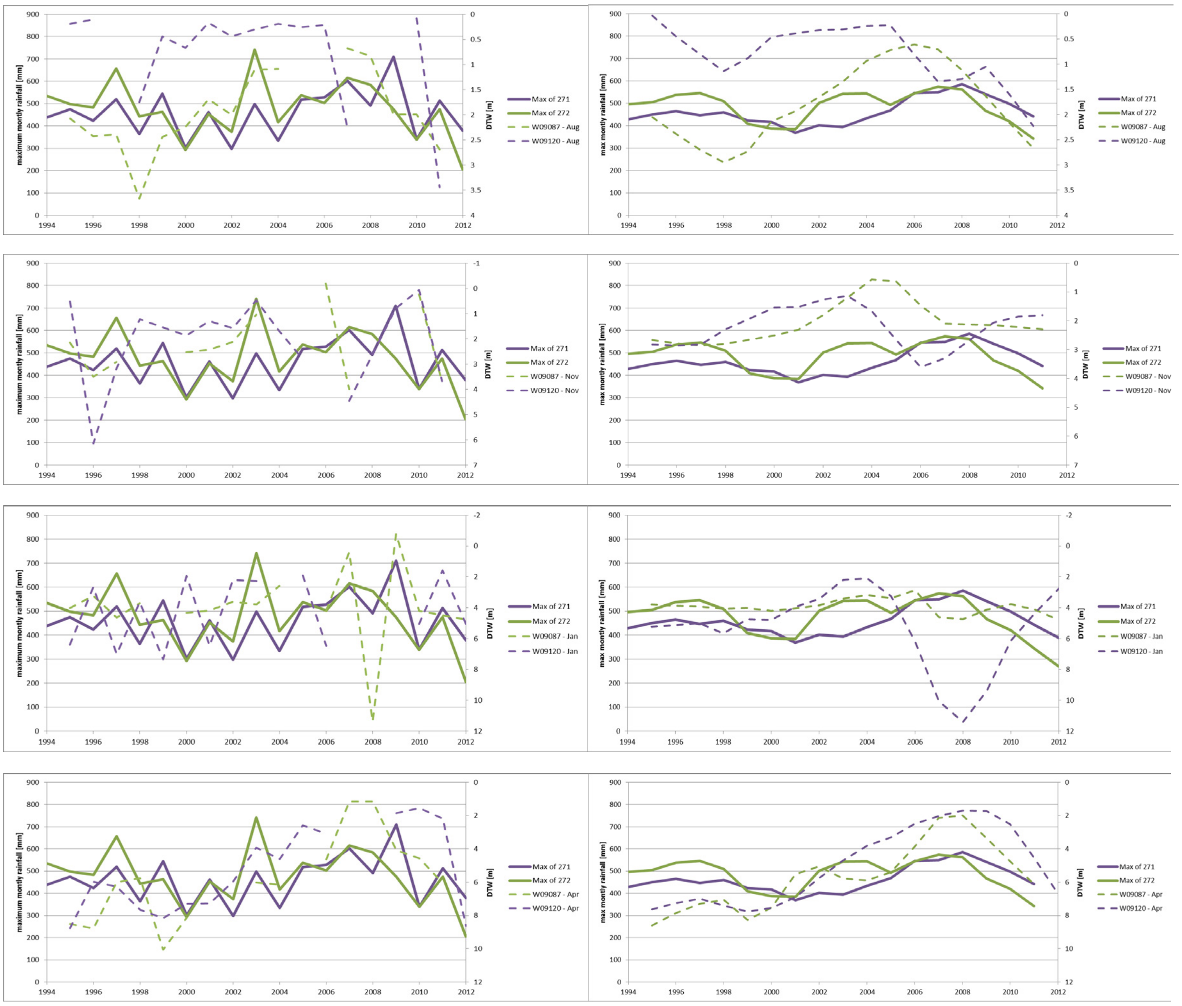


Figure 19: Un-smoothed and smoothed maximum monthly rainfall for IMD4 grid cells (271, 272) and DTW of wells W09087 and W09120 for August (a), November (b), January (c), and April (d).

Difference between April (of the same and next year) and November DTW

Correlation between modelled rainfall and DTW-difference does not exist for W09087 (R2 of 0.01), but is quite good for W09120 (R2: 0.50 & 0.46). This supports again the above stated inference that the difference is related to delayed recharge from monsoon rainfall.

Summary

Even though the investigated wells are located outside surface-water dominated canal command, they are within close proximity. The two wells show a mixed picture of good correlations between rainfall and DTW in January indicating delayed monsoon recharge (W09120) or lack of any correlation for DTW in April by the potential presence of groundwater pumping (W09087). The latter well is located near the coast and maybe influenced by coastal boundary effects.

Correlation between smoothed rainfall and rising water levels inside command areas

Area 3 is in an area of rising water level trends in surface-water dominated command areas in the South (Rengali and Naraj-Sapuabadjore-Derjan) at a considerable distance to the nearest rainfall station 42970 (Guttack).

Wells in Area 3 (W09301, W09472, W09596) are most likely influenced predominantly by recharge from rainfall and recharge from surface-water irrigation and to a lesser to a lesser degree by supplemental groundwater pumping.

Correlations of DTW of the three wells with observed rainfall of station 42970 were disregarded (station is too distant: W09301 - 55km, W09472 - 42km, W09472 - 77km) and limited to modelled rainfall for the IMD4 grid cell, which the well falls in.

For most seasons, correlations of DTW with SumP are on average slightly less than MaxP (Figure 20), but are comparable following the narrow temporal distribution of rainfall around August (Figure 14c). However, DTW of individual wells correlate very differently with rainfall.

		W09301-284		W09472-301		W09596-285		
Sum Precip vs.		R^2	Slope	R^2	Slope	R^2	Slope	R^2-avg
	Jan	0.05	-	0.05	-	0.12	-	0.07
	Jan/nxtyr	0.09	-	0.33	-	0.46	-	0.29
	Apr	0.53	-	0.24	-	0.14	-	0.30
	Apr/nxtyr	0.37	-	0.30	-	0.04	-	0.24
	Aug	0.01	+	0.60	-	0.11	+	0.24
	Nov	0.01	+	0.34	-	0.08	-	0.14
	Apr-Nov	0.58	-	0.01	+	0.20	-	0.26
	Apr/nxtyr-Nov	0.33	-	0.03	+	0.01	-	0.12
	Max	0.37		0.30		0.32		0.33
	Min	0.26		0.27		0.03		0.18
Max Precip vs.								
	Jan	0.01	-	0.14	-	0.26	-	0.14
	Jan/nxtyr	0.04	-	0.25	-	0.62	-	0.30
	Apr	0.54	-	0.36	-	0.20	-	0.37
	Apr/nxtyr	0.40	-	0.26	-	0.03	-	0.23
	Aug	0.07	+	0.32	-	0.09	+	0.16
	Nov	0.05	+	0.31	-	0.04	-	0.13
	Apr-Nov	0.68	-	0.02	+	0.31	-	0.34
	Apr/nxtyr-Nov	0.42	-	0.02	+	0.01	-	0.15
	Max	0.40		0.26		0.42		0.36
	Min	0.28		0.23		0.09		0.20
Average DTW								
	Jan	5.00		3.14		5.51		
	Apr	6.82		4.56		8.66		
	Aug	1.74		1.38		1.08		
	Nov	3.60		2.05		1.27		
Average of smoothed DTW diff between Apr & Nov								
	Apr-Nov	3.21		2.38		7.17		
	Apr/nxtyr-Nov	3.22		2.49		7.25		

Table 6: Correlation (R2) between annual sums of rainfall (a: top) or maxima of monthly rainfall (b: middle) and DTW (Jan, Jan/nxtyr, Apr, Apr/nxtyr, Aug, Nov) or DTW-differences (Apr-Nov; Apr/nxtyr-Nov); average DTW and average of DTW-differences for Area 3 (c: bottom)

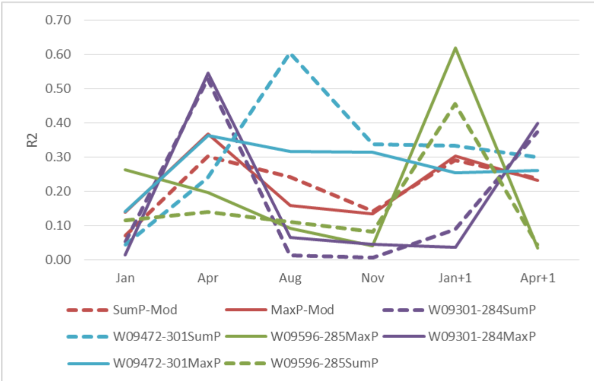


Figure 20: Correlation coefficients (average for SumP and MaxP & individual wells) for each season for Area 3

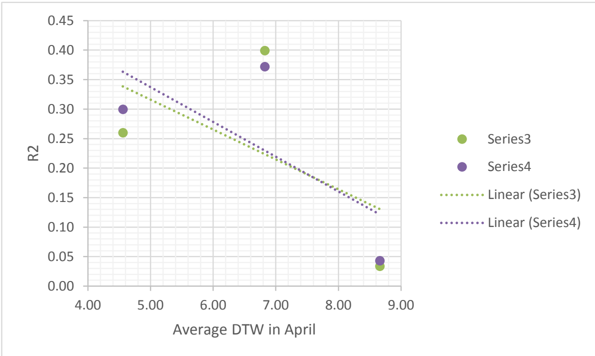


Figure 21: Relationship between rainfall-DTW correlation and average DTW for Area 3

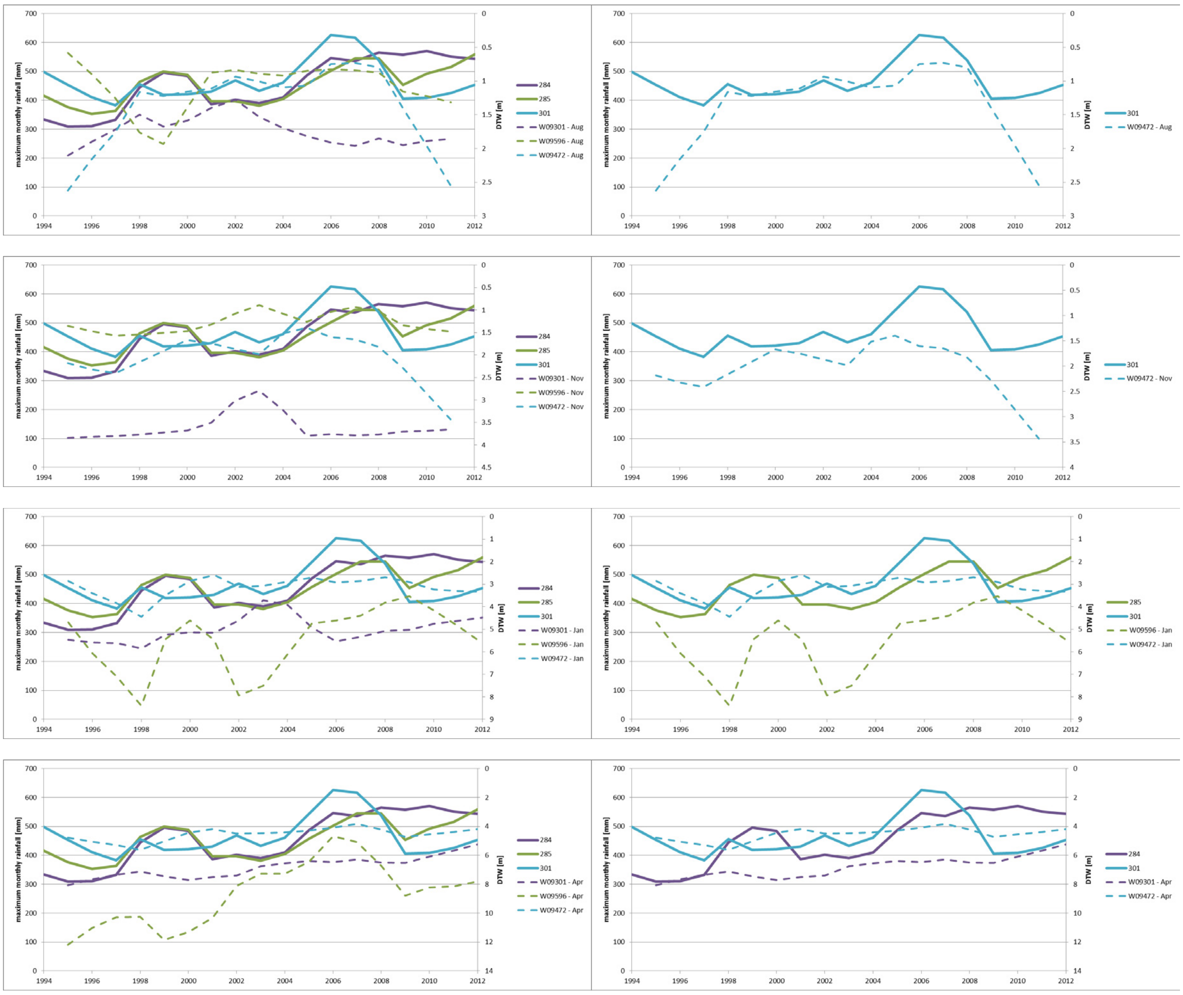


Figure 22: Smoothed maximum monthly rainfall and DTW of wells in Area 3 for August (a), November (b), January (c), April (d) (left: all wells; right: wells with good correlation)

August and Min DTW

There is nearly no correlation between rainfall and DTW in August except for DTW of W09472 with SumP (R2: 0.60). The other two wells show no or minor inverse correlations (positive slope in Table 6), i.e., when monsoon rainfall increases, water levels do not respond or are even slightly dropping. This may have to do with the fact that in surface-water dominated command areas, water levels are shallow and monsoon rainfall runs off. Alternatively, if monsoon rainfall resulted in instant recharge to those shallow water levels, it would be captured by drainage by drains or drainage pumps to prevent water logging.

April and Max DTW

One of three wells (W09301) shows moderate correlation between smoothed DTW of April & April of next year and SumP and MaxP or modelled rainfall in IMD4 grid cell 284 (R2: 0.58 & 0.33 for SumP; 0.68 & 042 for MaxP). This is similar to W09120 near station 42895, which also shows significant correlation between MaxP of cell 271 and April DTW. In both cases, this correlation most likely reflects the absence of groundwater pumping during the irrigation season until April.

IMD4 cell 301 shows a long-term decline of monsoonal rainfall after 2007, yet the water table in W09472 does not drop proportionately. However, the well’s DTW in April or April of next year does correlate modestly with rainfall of cell 301 (R2: 0.24 to 0.36). A possible explanation is that, during times of low monsoon rainfall, recharge from surface-water irrigation replaces the monsoon recharge and keeps the water level from dropping, which affects the correlation in April or April of next year.

Well W09596 shows considerable groundwater depletion in the 1990s and after 2007. Unlike in IMD4 cell 301, the monsoon rainfall of cell 285 that coincides with the location of W09596 does not drop significantly after 2007. A lack of correlation between DTW of April or April of next year and modelled rainfall in cell 285 (R2: 0.04 to 0.03) can be explained by groundwater pumping during certain periods. The groundwater level is relatively deep in this well in April with >8 m for a surface-water dominated command area. Any recharge from monsoon rainfall or surface-water irrigation occurs prior to April or is capture by groundwater pumping. It is noteworthy that the April DTW of each next year does not correlate as well with the previous year's rainfall, meaning, smoothing eradicated some correlation from one year to another.

November to January

There is nearly no correlation for any well between rainfall and DTW during post-monsoon (Nov) seasons. Only one well (W09596) shows a correlation between rainfall and DTW irrigation seasons (Jan) (R2: 0.46 & for Jan; 0.62 for Jan of next year) as a result of delayed recharge. This well's January water levels are comparatively deep with an average January DTW of around 5.5 m.

Difference between April (of the same and next year) and November DTW

In well W09596, the bulk of groundwater pumping seems to occur after January (from February to April) and cause the a big average difference between November and April (> 7m)(Table 6). Theoretically, the gap between November and April water levels could also be caused by raised post-monsoon water levels. Yet the smoothed November DTW series (Figure 22), the water level is relatively well controlled at an average DTW of around 1.3 m. In contrast, the April water level falls sharply after 2007, which indicates that indeed groundwater pumping is responsible for the DTW difference, and, hence, shows only a minor correlation with previous year's rainfall.

While the DTW-difference between April and November of well W09301 correlates well with rainfall, the DTW-difference between April of next year and November does not. This may mean that (a) the same-year April-November difference reveals quick recharge that is not delayed, and (b) that surface-water irrigation between November and April of next year would have distorted any potential correlation.

Summary

Wells in Area 3 show mostly no correlation of rainfall with August DTW, most likely because of rainfall runoff or drainage in areas of shallow water levels.

Short-delay recharge may produce good correlations in the period from post-monsoon to next year's January, but not until next year April. In fact, one well shows a better correlation between the difference between April and November of the same year than November and April of the next year. The former is only possible if recharge is not delayed at all, but relatively instant and completed by November.

Moderate correlations with DTW of April of the same or next year most likely reflects the absence of groundwater pumping during the irrigation season until April. During times of low monsoon rainfall, this correlation may be dampened by recharge from surface-water irrigation replacing the monsoon recharge, which keeps the water level from dropping. If correlations were reduced during times of normal monsoon rainfall, groundwater pumping most certainly would be responsible.

4 Limitations

No information was available to the authors regarding the monitoring network, data quality, frequency of observations, land use, cropping patterns or seasons, and hydrogeology of the BB basin. That is, the trend analysis described herein is indeed purely statistical.

All monitoring data were included in the data analysis regardless of data quality and record length. Firstly, the scope of this project did not include examination for potential errors and clean-up of the used database. Secondly, the used trend analysis methods do not require regular sampling intervals and either rank individual measurements independent of their overall magnitude, i.e., outliers not need to be corrected (Mann-Kendall), or outliers and data gaps are included into a moving regression and smoothed (LOWESS). The frequency of monitoring was generally four measurements for any year and hence did not permit any inter-annual seasonality analysis nor did it allow for an estimate of the magnitude of water-level change on an annual basis as minima and maxima were not captured.

A relation between cropping seasons and water level trends is only meaningful if time series of water levels are temporally distributed across those seasons. This is not the case here as only one single measurement was available per season (irrigation, pre-monsoon, monsoon, and post-monsoon) and, hence, limiting any intra-annual or cropping seasonality seasonality analysis. Therefore, the Mann-Kendall trend analysis focussed on investigating non-seasonal trends of long-term pre- or post-monsoon records.

The spatial distribution of surface outcrops of the geological formations in the BB basin was unknown. If available, it could have been matched with the location of monitoring wells. However, the uncertainty in this approach is high, because it does not capture the correct lithology of screened sections of wells and local patches of unconsolidated alluvium are not resolved in a coarse resolution hydrogeology. We, therefore, refrained from creating a 2D hydrogeology map of the BB basin. Potential correlations between groundwater trends and hydrogeology are only valid if controlled by a clear association between aquifer heads and tapped layers within a 3D hydrogeologic framework. This, however, could not be developed for the BB basin, as the borelog lithology of the used monitoring wells in not known.

Whether groundwater-level trends are spatially correlated to surface water / groundwater interaction along rivers was out of scope for this study. In addition, a biased pre-selection of wells near rivers to study the impact of surface water / groundwater interaction on groundwater trends was not possible, because only a high number of wells with strong trends (unlike in the present case) would allow such a selection. In the future, temporal and spatial differences in groundwater-level trends may allow for correlating groundwater depletion and surface-water losses resulting from calibrating the river system model.

5 Summary, conclusions and outlook

The major component of this project is the development of a river system model of the BB basin for the purposes of water resource planning in the BB Basin and to support collaborative basin planning processes. However, part of the project's original objective was also to get a better understanding of groundwater use and yields as wells on ground-/surface-water interaction, for which a groundwater model could be of benefit.

Rapid reviews of four pre-existing groundwater-modelling studies were carried out as part of this project. Those reviews provided a starting point for which particular techniques of previous studies should be investigated when planning a groundwater model in the future. Among those, only the Musi River study was found to provide MODFLOW / water allocation model linkages and scenario analyses of human activity within settings of irrigated agriculture, some of which could potentially be of benefit to a future BB groundwater model.

In lieu of building a groundwater model, a comprehensive groundwater-level trend analysis was undertaken. This can be used to reveal correlations between groundwater depletion evident from the groundwater trend analysis and surface-water losses resulting from the river system model. In that sense, the objective of a better understanding of surface water / groundwater interaction can still be met, even without a groundwater model.

The trend analysis of pre- and post-monsoon depth-to-water averages over districts indicates that five districts in the BB basin suffer from declining groundwater-level trends with various degrees of confidence (Confidence Factors in % in following sentence). Trends of some districts are strongly *declining both for pre- and post-monsoon* (Anugul: pre: 96.5%, post: 96.0%), *strongly declining or probably declining for either pre- or post-monsoon* (Mayurbhanj: pre: 99.7%, post: 93.1%; Bhadrak: pre: 92.5%, post: 98.6%), or *probably declining in just one or the other season* (Jajapur: pre: 90.1%, post: no trend; Gumla: pre: no data, post: 90.4%). Average levels of Kendrapara also seem to show strongly declining trends, which, however, are based on just one to two observation wells for any year.

Only one district experiences a strong trend of rising pre-monsoon water levels, but post-monsoon levels remain stable (Baleshwar: pre: 98.8%, post: stable). Pashchimi Singhbhum and Cuttack also seem to show strongly rising trends, but, again, are only based on one to three observations wells for any one year. In conclusion, the trend analysis yields answers for around six districts with respect to trends of average groundwater levels. However, among them are many with only *probable* trends and some with *strong* trends yet a high degree of uncertainty based on just a few observations per district. For that reason, a more detailed trend analysis of water levels of individual monitoring wells was conducted.

For pre-monsoon and post-monsoon levels, the number of observation wells in the BB basin with falling groundwater-level trends exceeds the ones with rising trends (68 vs. 33 for pre-monsoon; 45 vs. 14 for post-monsoon). This seems to suggest that groundwater depletion prevails over rising groundwater levels. Yet, the prevailing trend categories are *no trend* or *stable*. In addition, there is no apparent pattern in the spatial distribution of the different trend categories in the pre- and post-monsoon trends of individual monitoring wells. However, trends of differences between pre- and post-monsoon levels do indicate spatial clusters of increasing or decreasing trends.

Clusters of strongly decreasing or increasing difference trends are found, respectively, in surface-water irrigation dominated command areas near the delta (e.g., Dhenkanal, Jajapur, and Bhadrak district) or further north outside irrigation command areas (e.g., in the areas of the Kendujhar and Sundargarh districts). Decreasing differences, i.e., a "narrowing between pre- and post-monsoon levels" could be a result either of (a) rising pre-monsoon water levels following increased recharge from surface-water irrigation, which is common in command areas, or (b) declining post-monsoon levels following decreasing recharge due to a lack of monsoon rainfall. Increasing differences, i.e., a “widening between pre-and post-monsoon levels,” may be a result either (a) of a combination of decreased recharge from irrigation and groundwater pumping in groundwater-irrigated areas or (b) of increased recharge during the monsoon season. Climate factors, such as a lack or abundance of monsoon rainfall, may contribute to the “narrowing” or “widening” of trend differences by virtue of falling or rising post-monsoon levels. However, this contribution cannot be quantified without a systematic correlation with rainfall trends. Such correlation analysis was conducted for select wells in three representative areas, but not systematically across the basin.

LOWESS-smoothed hydrographs of chosen monitoring wells allow the visualization of groundwater trends for pre-monsoon water levels or of trends of differences between pre- and post-monsoon water levels, which indicate trends in recharge. The LOWESS analysis of these hydrographs distinguished two groups of wells, which either represent (i) areas with rising pre-monsoon water levels and decreasing trends of pre/post-monsoon differences or (ii) areas with declining pre-monsoon water levels and increasing trends of pre/post-monsoon differences. Hydrographs of the former group (i) may be explained by rising pre-monsoon levels due to recharge from irrigation and/or monsoon rainfall, but no groundwater pumping. Hydrographs of the latter group (ii) are characterized by declining pre-monsoon levels due to irrigation groundwater pumping and increasing recharge from surface-water irrigation, monsoonal rainfall, or both.

The results of the present groundwater-level trend analysis have to be viewed in an integrated context by allowing for a better understanding of links between surface and groundwater and the complexity of surface water / groundwater interaction in the BB basin. This will aid in the incorporation of the surface-groundwater interactions into the river system model, should this be required in the future. For instance, the knowledge of temporal and spatial differences in groundwater-level trends potentially will allow for correlating groundwater depletion evident from the groundwater trend analysis and surface-water losses resulting from calibrating the river system model (a). In addition, areas of surface-water irrigation deficit (b) or areas of ecologic assets (c) may coincide with regions with trends of groundwater depletion. While topics (a), (b), and (c) are part of this project, correlations between them and groundwater trends were out of scope and budget.

Correlative studies between observed or modelled rainfall trends and groundwater trends have been conducted based on three representative areas and select wells in those areas. Apart from water levels of particular seasons, also pre/post-monsoon water-level differences have been included into this correlation analysis. Pre/post-monsoon differences of the same year can be viewed as a surrogate of recharge from monsoonal rainfall. In contrast, differences between pre-monsoon of next year and post-monsoon of the previous year can reveal information about potential irrigation recharge or groundwater irrigation pumping. Hence, correlations between interpolated rainfall trends and pre/post-monsoon water-level difference trends will give evidence of the contribution or the lack of monsoon rainfalls to recharge as well as the reduction of such correlation by recharge from surface-water irrigation or groundwater pumping.

The three chosen areas are representative of declining water levels, rising water levels outside command areas, and rising water levels inside command areas. In area 1, water levels correlate well with rainfall during monsoon and somewhat during pre-monsoon (of next year), although the latter correlation is reduced in wells with deeper average water levels. This area is located north of the major surface-water irrigation command areas and even outside of smaller nearby command area. In that respect, it is quite likely that the only source of irrigation is groundwater pumping. In area 2, the two selected wells are within close proximity yet outside surface-water dominated canal commands and one well is located near the coast and maybe influenced by coastal boundary effects. Both wells show different correlation patterns, such as good correlation between rainfall and DTW in January indicating delayed monsoon recharge or a lack of any correlation for DTW in April by the potential presence of groundwater pumping. In area 3, wells located within command areas show mostly no correlation of rainfall with August DTW, most likely because of rainfall runoff or drainage in areas of shallow water levels. For some wells, short-delay recharge may produce good correlations in the period from post-monsoon to next year's January. Moderate correlations with DTW of April of the same or next year most likely reflects the absence of groundwater pumping during the irrigation season until April. However, during times of low monsoon rainfall, this correlation may be dampened by recharge from surface-water irrigation. During times of normal monsoon rainfall, groundwater pumping is likely to be the factor for reduced correlations.

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