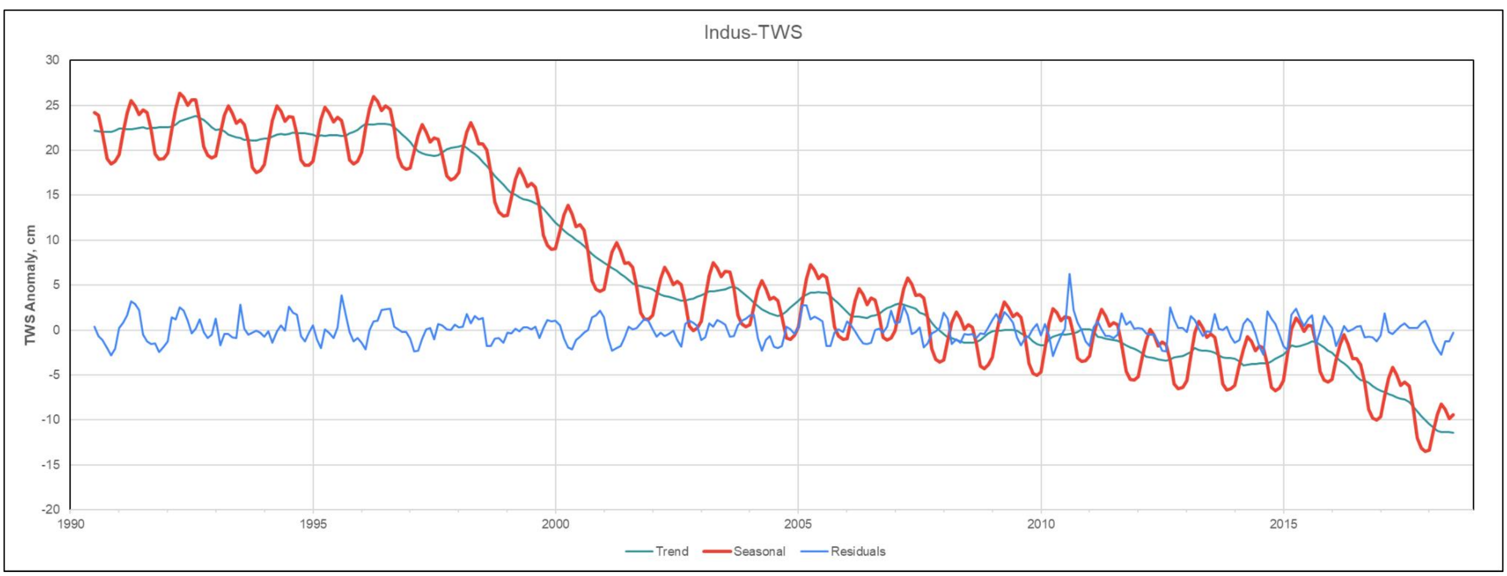
Supplementary Materials

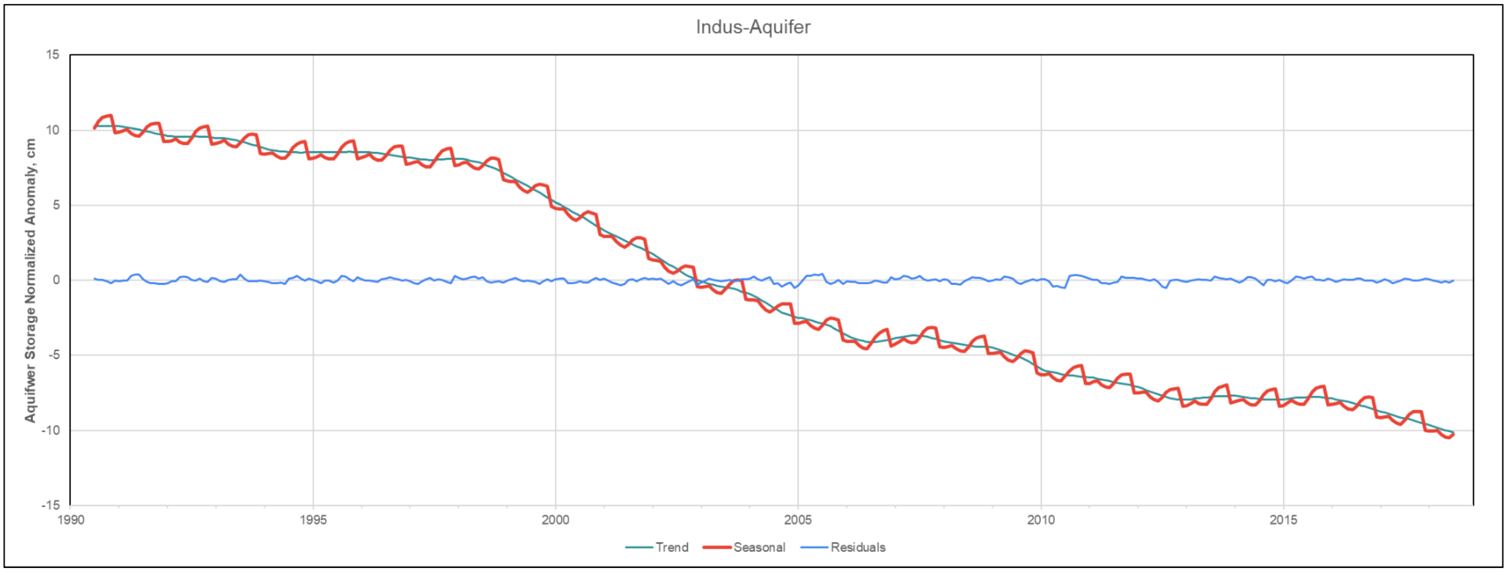
Content of the Supplementary Material:

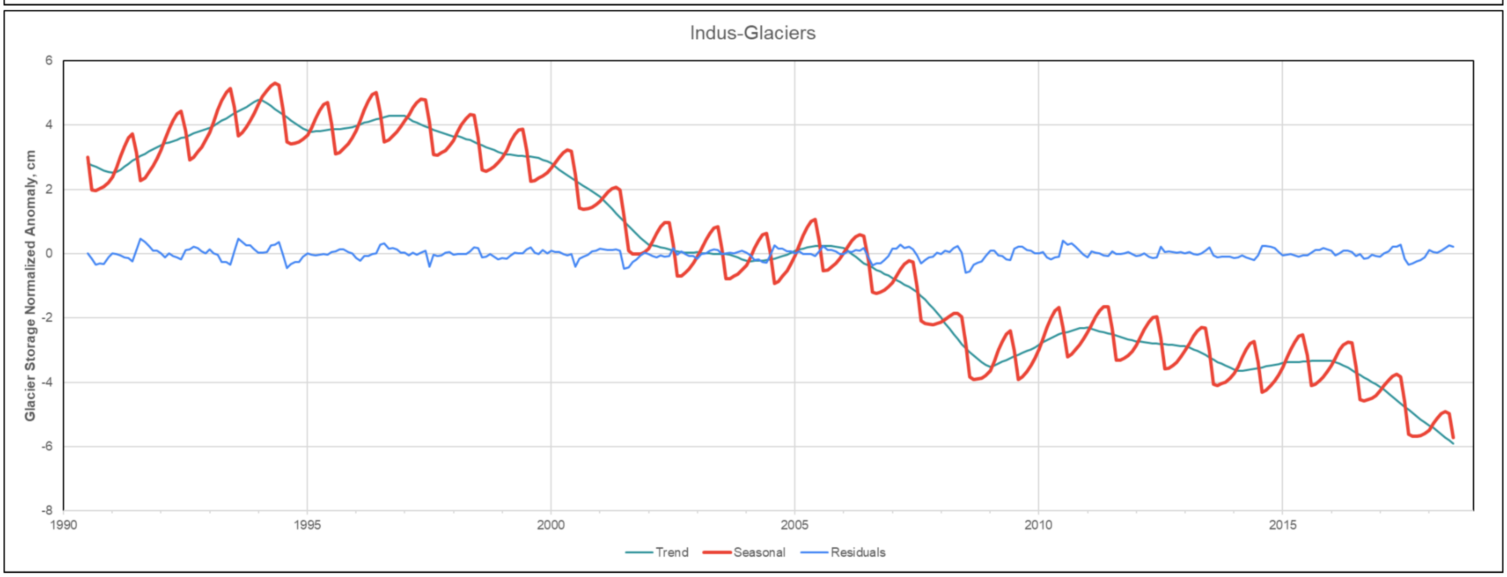
1. Figures of Total Water Storage (TWS) and its components by classical time series decomposition -
    a. All three time series decomposition signals: trend, seasonal, and residual **(Figures S1-S3**).
    b. Approximation of seasonal signals by the sinusoidal function fit (**Figure S4**).
2. Figures of Total Water Storage (TWS) and its components by Singular Spectral Analysis (SSA) time series decomposition -
    a. TWS and its components SSA time series decomposition results and **Figures S5-S7.**
    b. Evaluation of TWS long term trend (**Figure S8**) and Seasonal variability (**Figure S9**) contributions from TWS components.
3. Additional figures (**Figure S10**).
4. Streamflow validation.
5. Comparison of modeled and observed groundwater and aquifer storage.
6. Spreadsheet of the data and calculations. Most of figures below and in the main text of the paper are also available in their original format in this spreadsheet file.

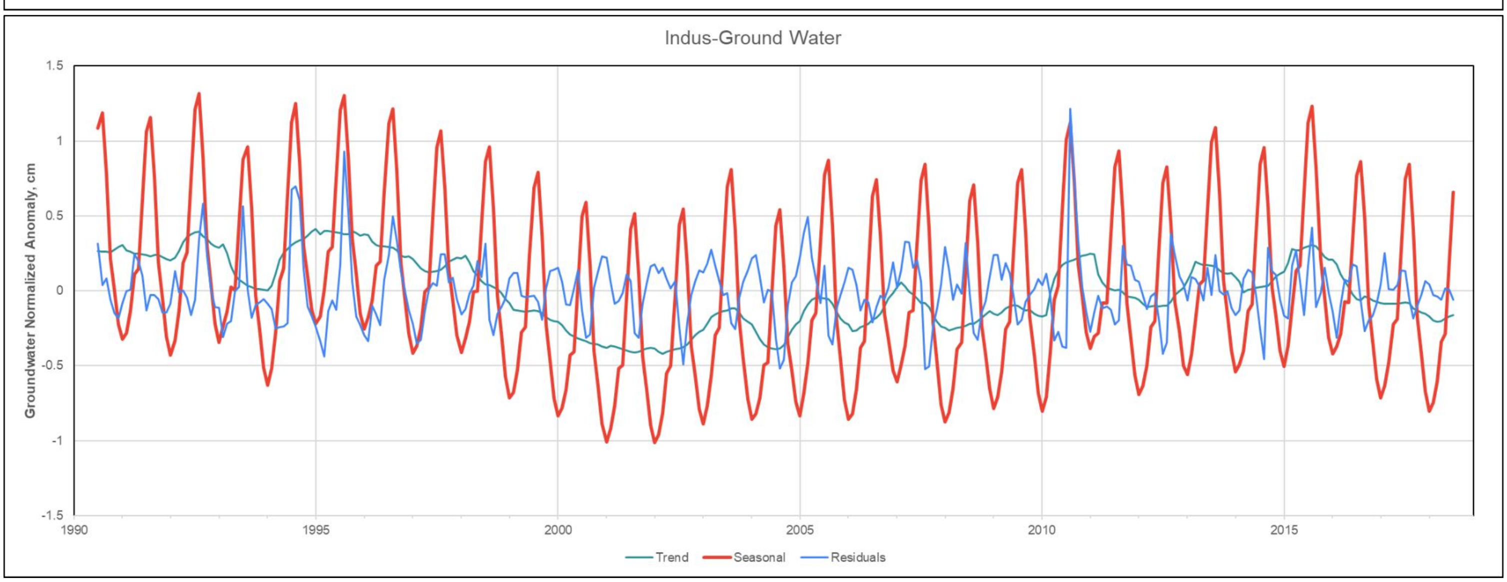
S1. Figures of Total Water Storage (TWS) and its components by Classical time series (TS) decomposition

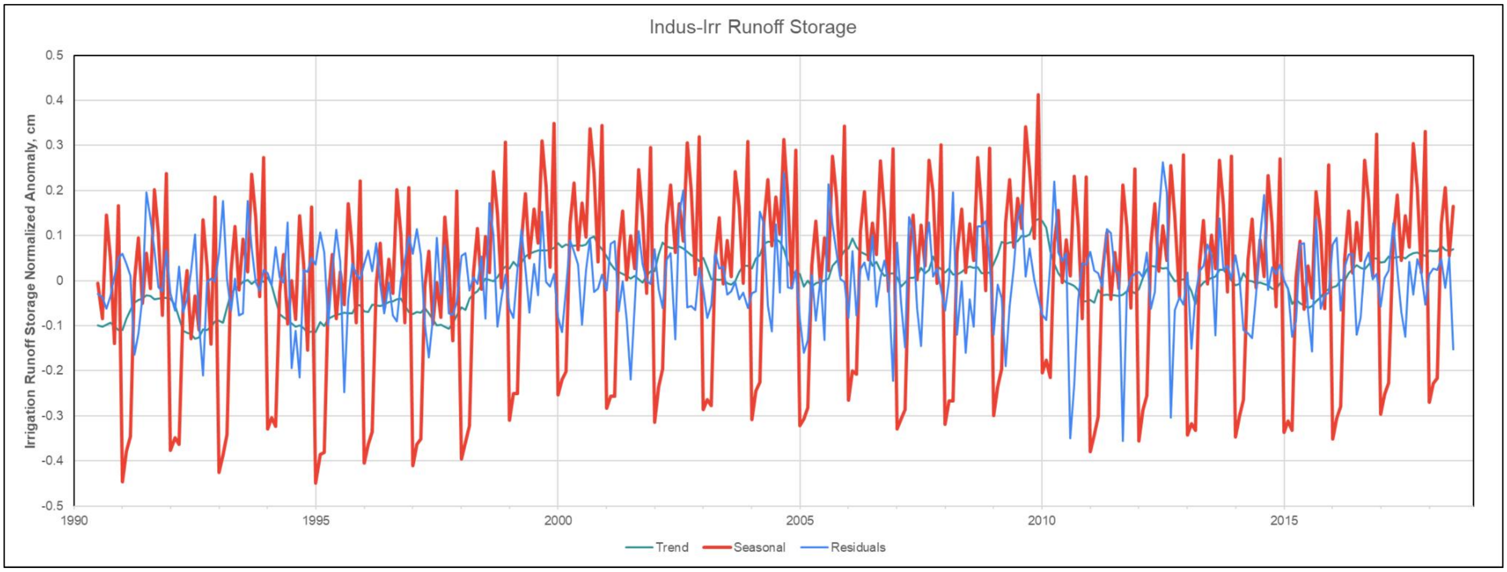
a. Graphs of TS decomposition signals are given in the **Figures S1, S2**, and **S3** for Indus, Ganges and Brahmaputra basins respectively. Each figure has panels for TWS and its 9 components described in **Table 1** of the manuscript.

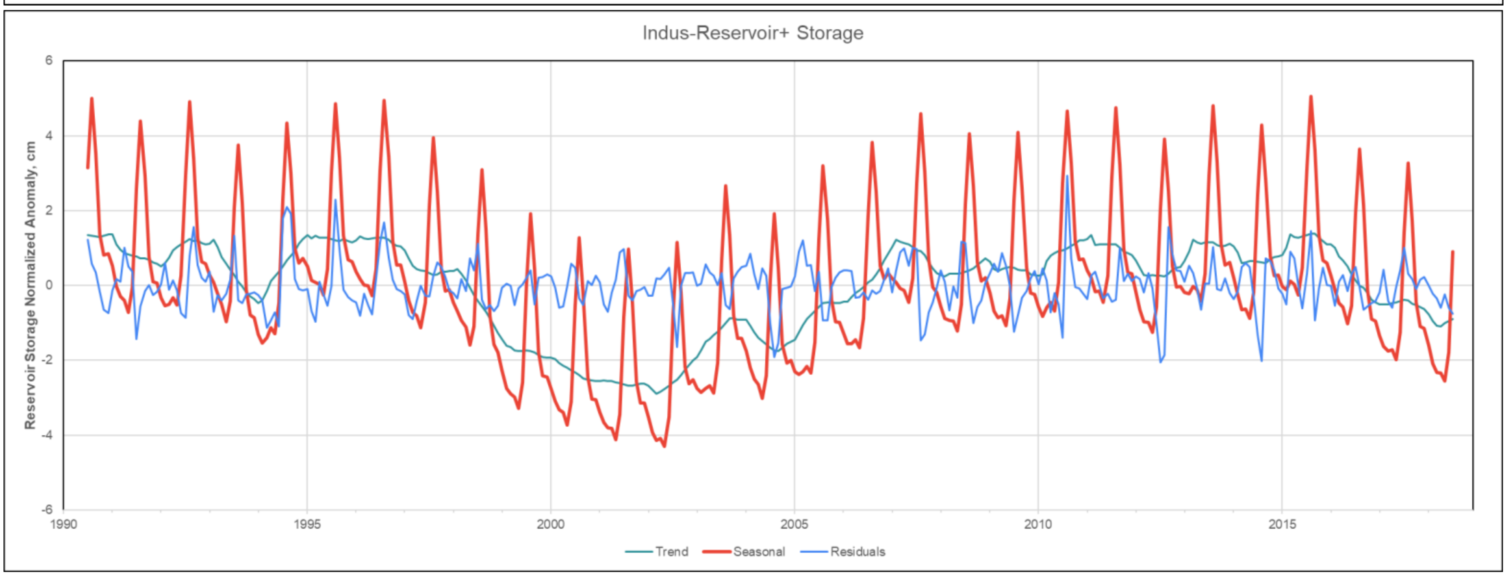


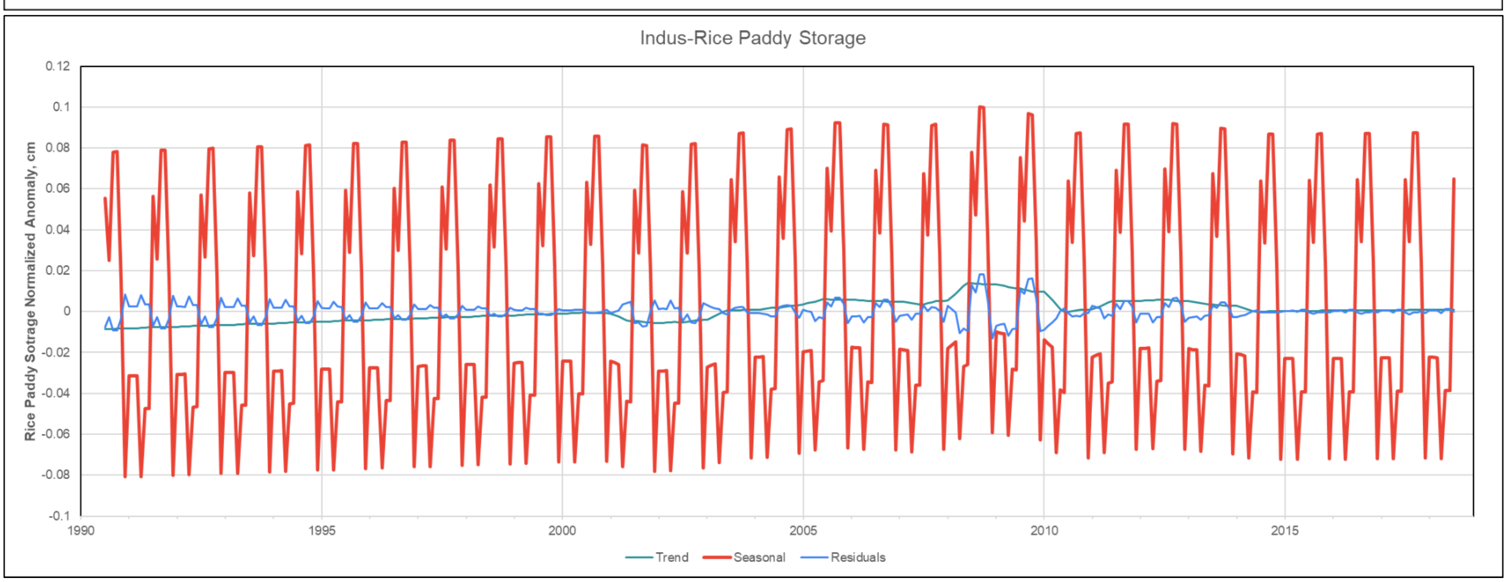

Indus-Aquifer
Aquifwer Storage Normalized Anomaly, cm
15
10
5
0
-5
-10
-15
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

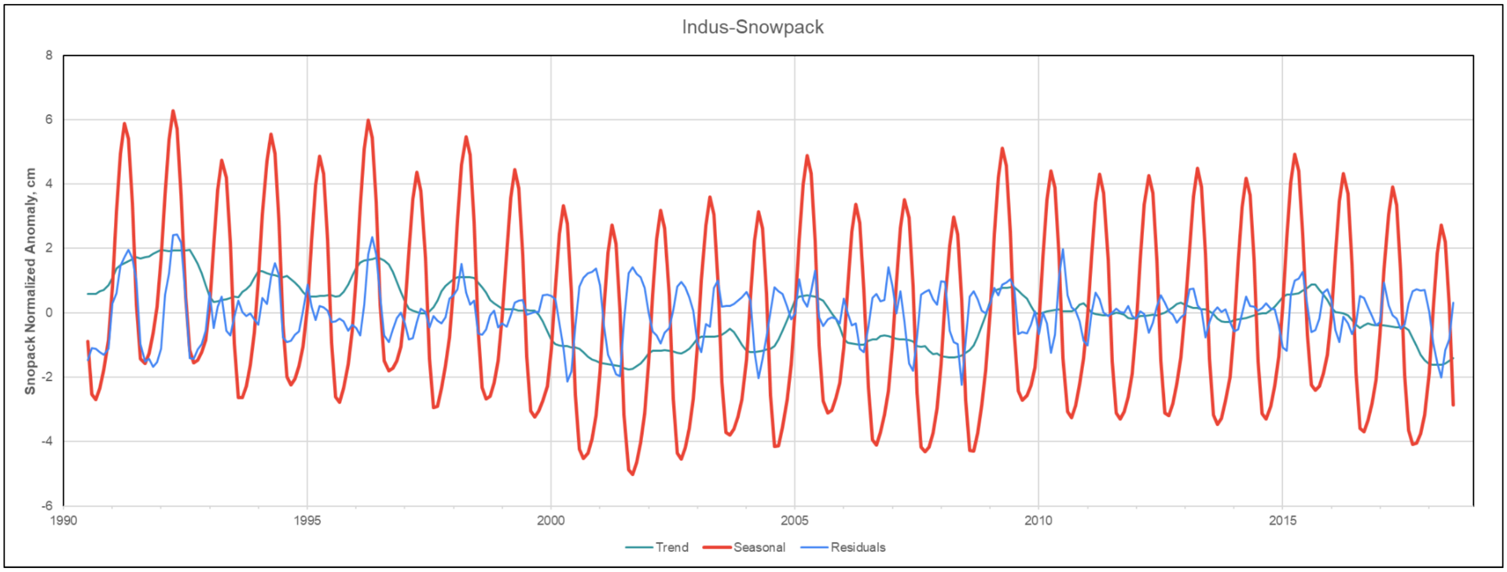

Indus-Glaciers
Glacier Storage Normalized Anomaly, cm
6
4
2
0
-2
-4
-6
-8
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

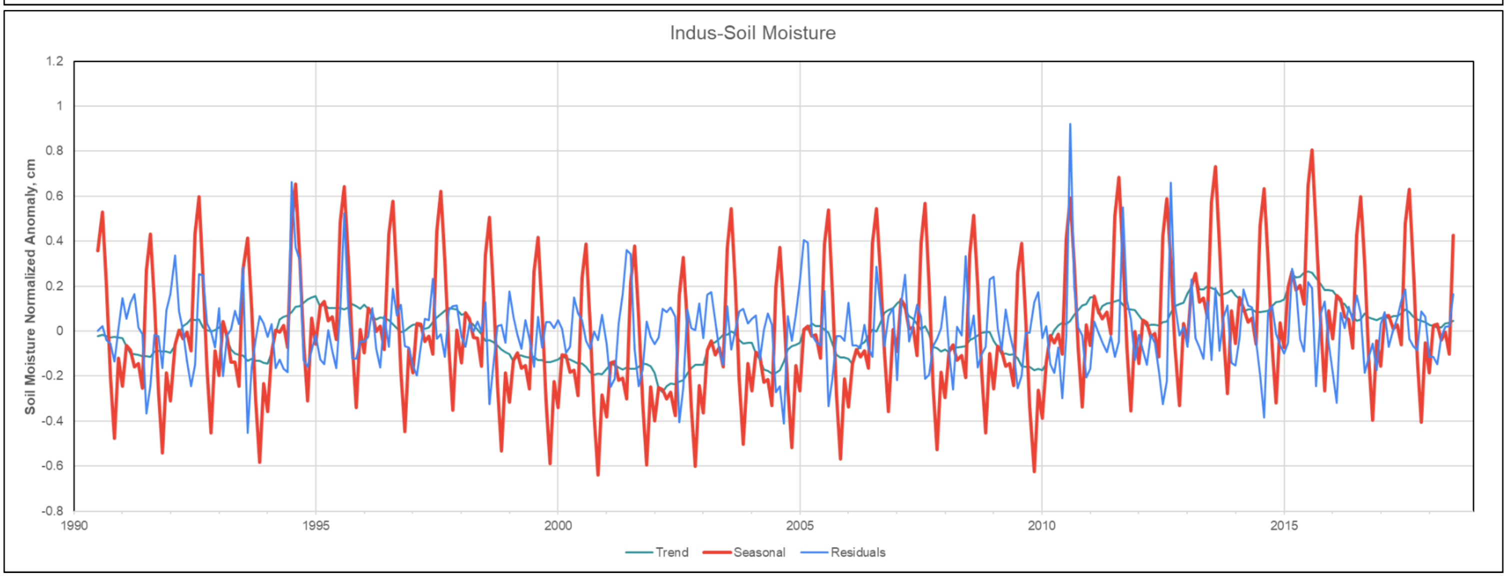

Indus-Ground Water
Groundwater Normalized Anomaly, cm
1.5
1
0.5
0
-0.5
-1
-1.5
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Indus-Irr Runoff Storage
Irrigation Runoff Storage Normalized Anomaly, cm
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Indus-Reservoir+ Storage
Reservoir Storage Normalized Anomaly, cm
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Indus-Rice Paddy Storage
Rice Paddy Sotrage Normalized Anomaly, cm
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Indus-Snowpack
Snopack Normalized Anomaly, cm
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Indus-Soil Moisture
Soil Moisture Normalized Anomaly, cm
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

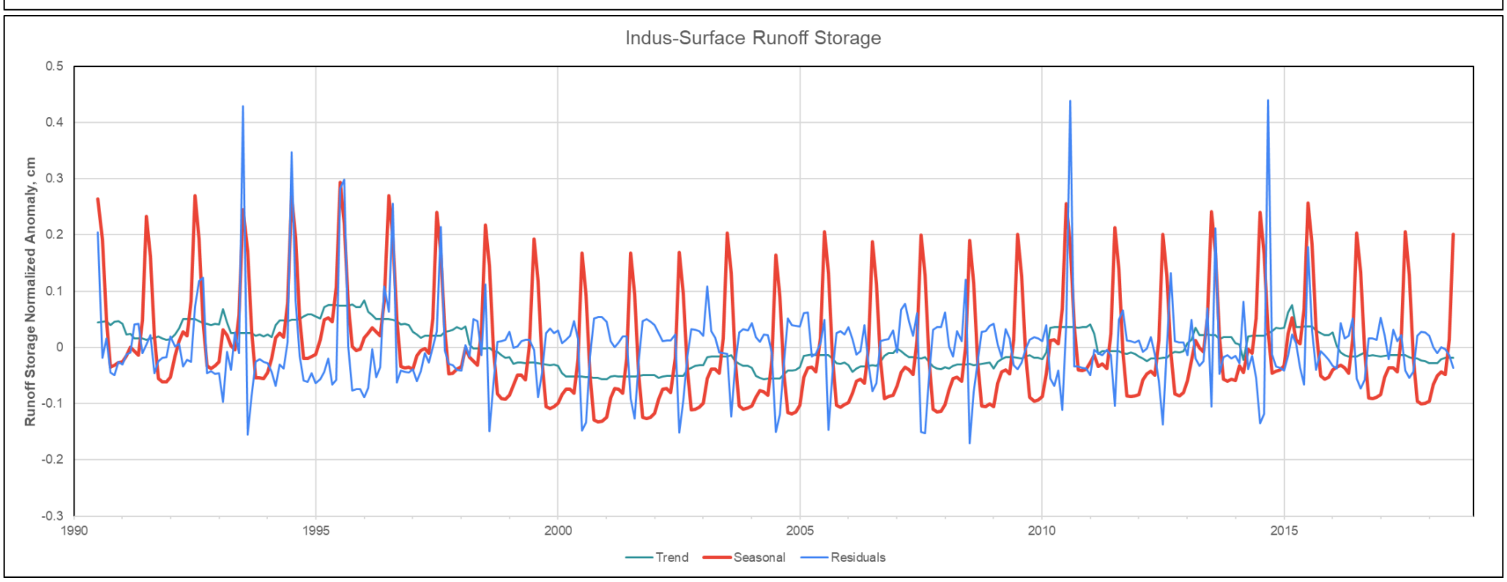
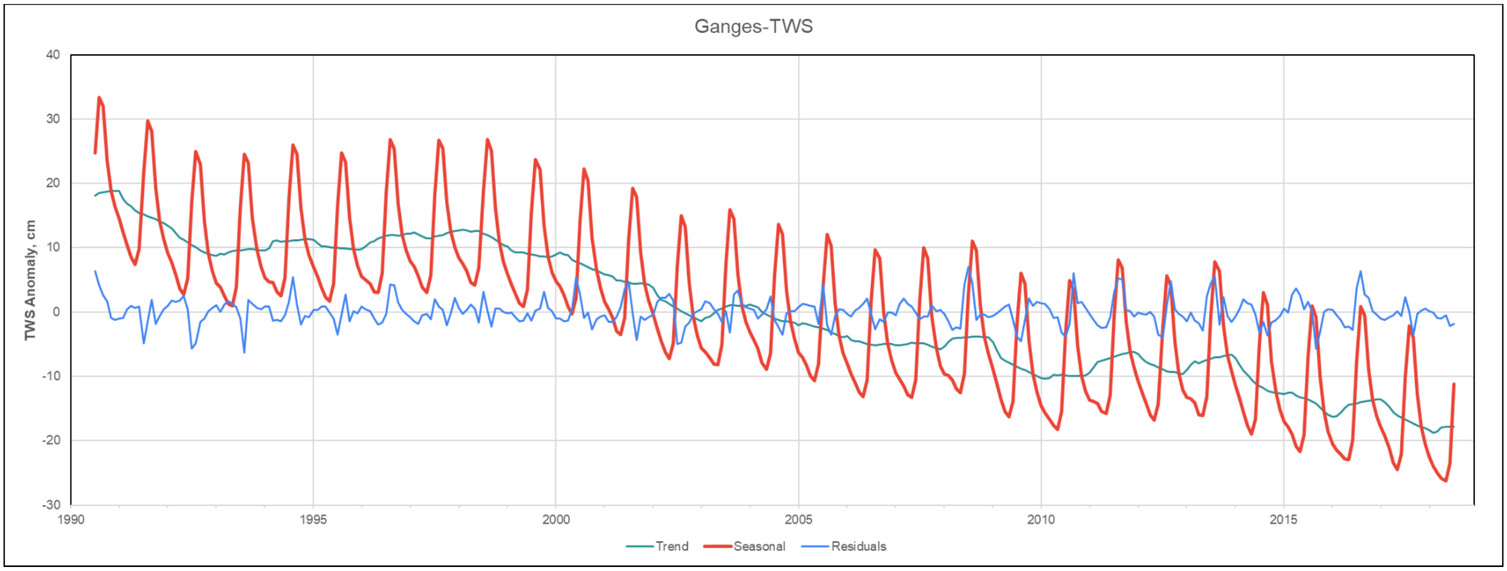
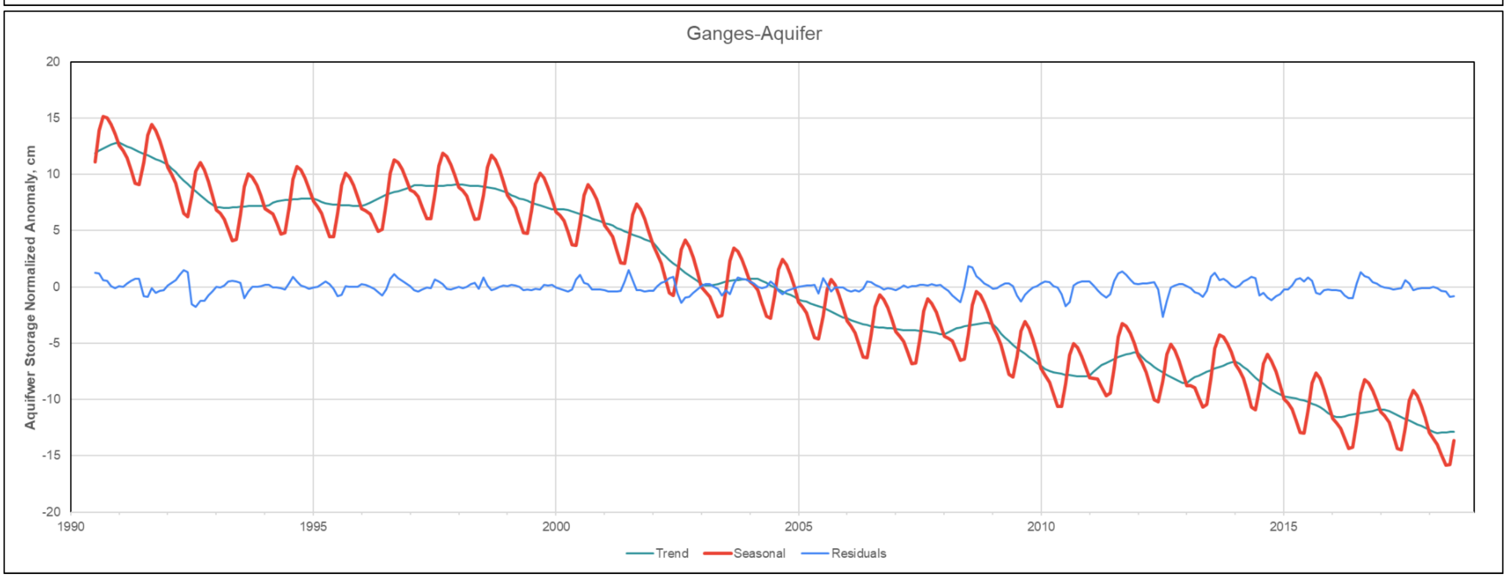
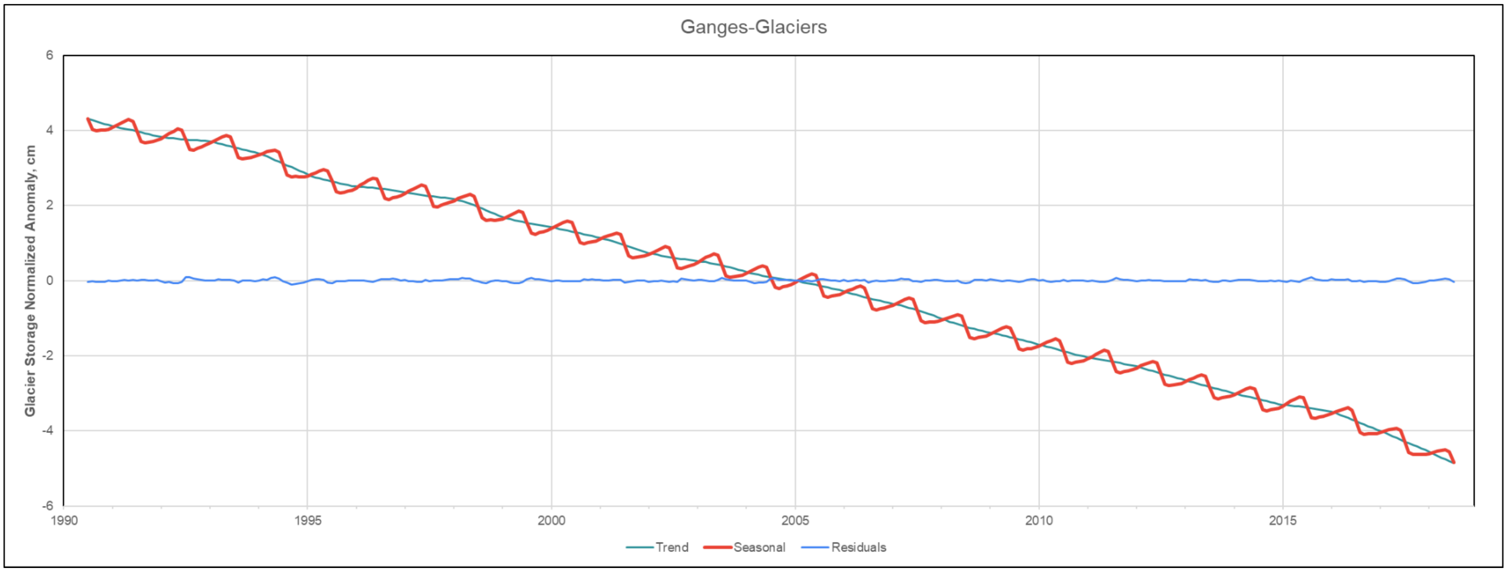
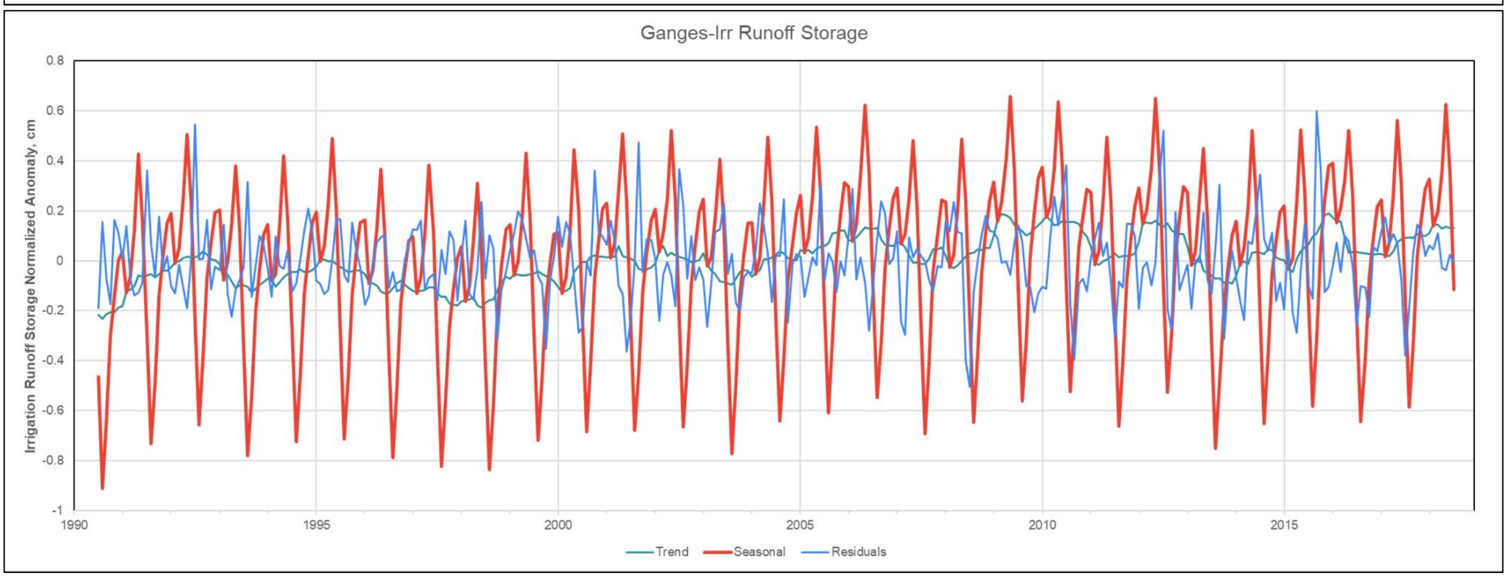

Indus-Surface Runoff Storage
Runoff Storage Normalized Anomaly, cm
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

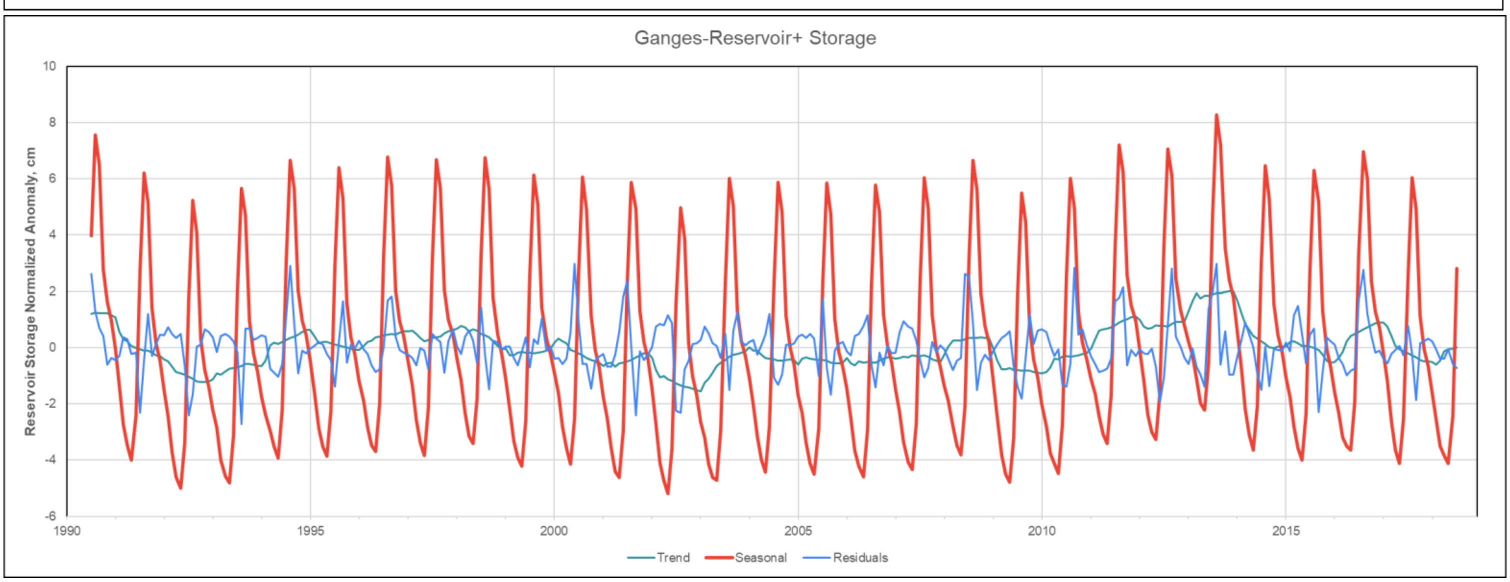
Figure S1. Classical time series decomposition for TWS and its components for the Indus basin.

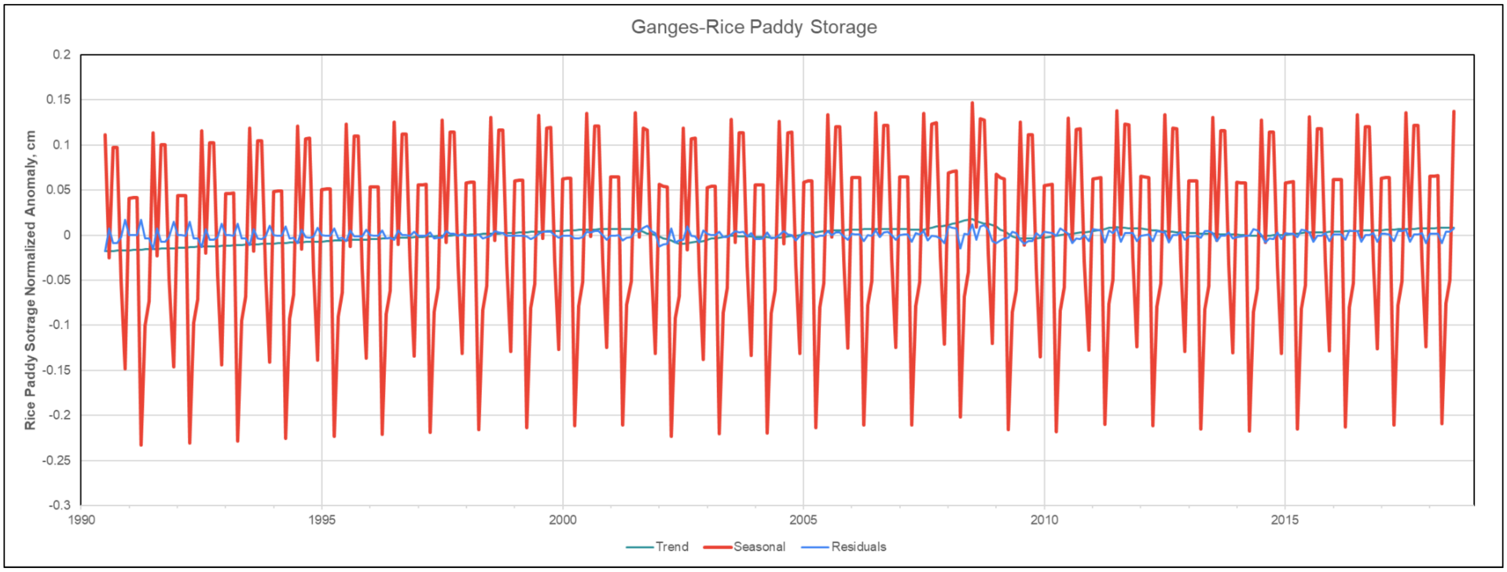


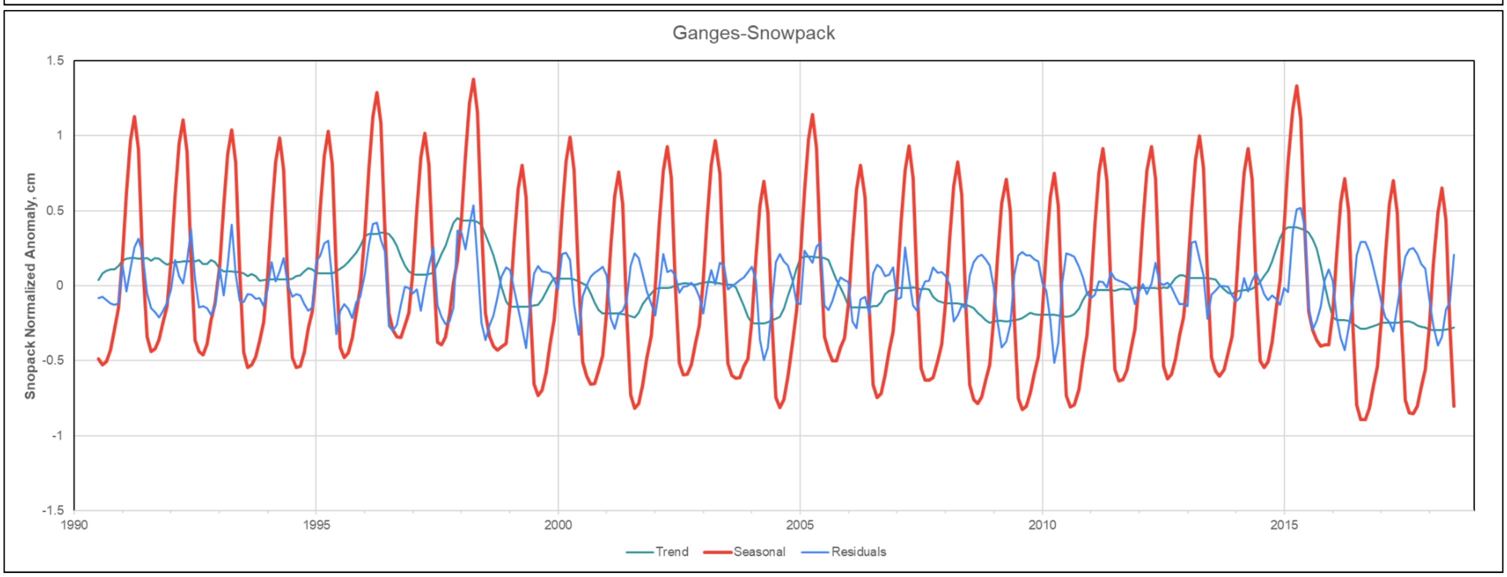


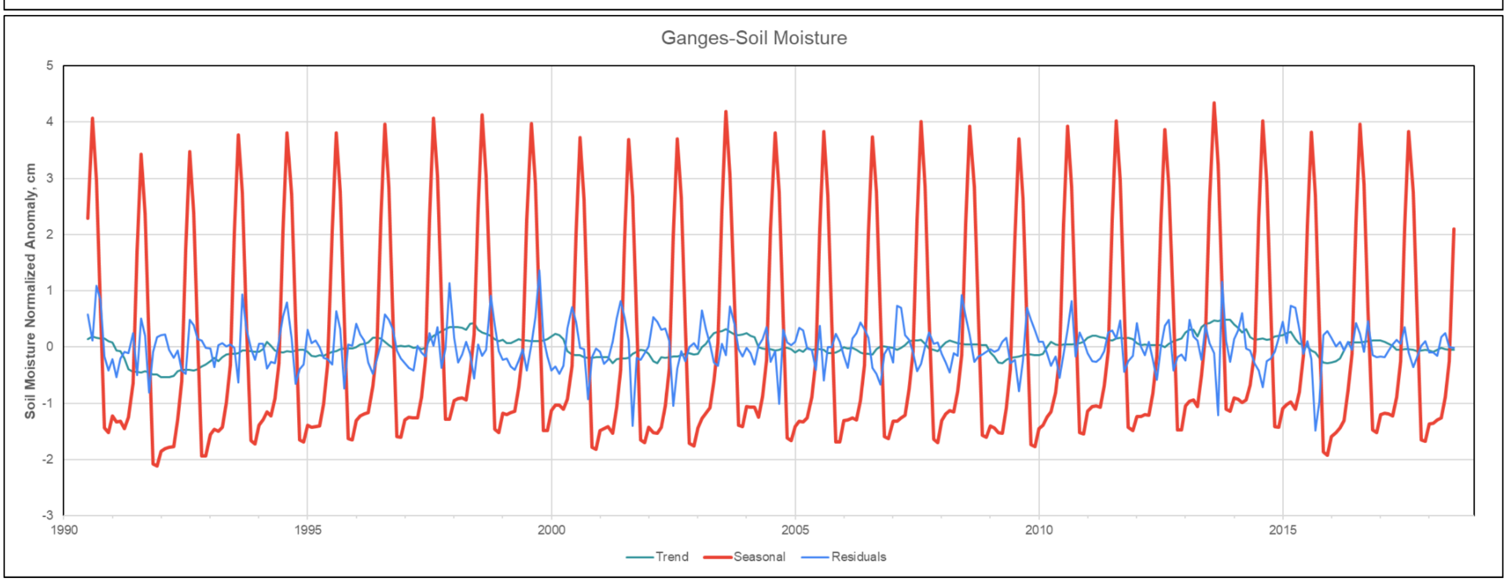

Ganges-Glaciers
Glacier Storage Normalized Anomaly, cm
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Ganges-Irr Runoff Storage
Irrigation Runoff Storage Normalized Anomaly, cm
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Ganges-Reservoir+ Storage
Reservoir Storage Normalized Anomaly, cm
10
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Ganges-Rice Paddy Storage
Rice Paddy Sotrage Normalized Anomaly, cm
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Ganges-Snowpack
Snopack Normalized Anomaly, cm
1.5
1
0.5
0
-0.5
-1
-1.5
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Ganges-Soil Moisture
Soil Moisture Normalized Anomaly, cm
5
4
3
2
1
0
-1
-2
-3
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

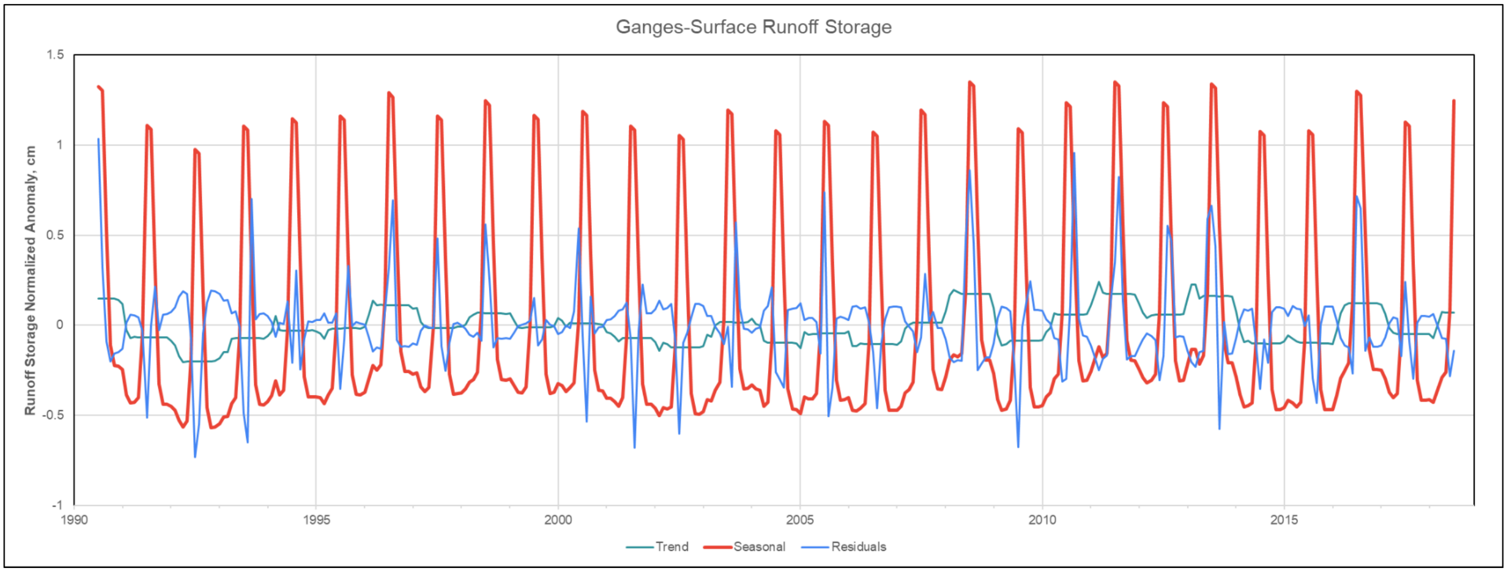
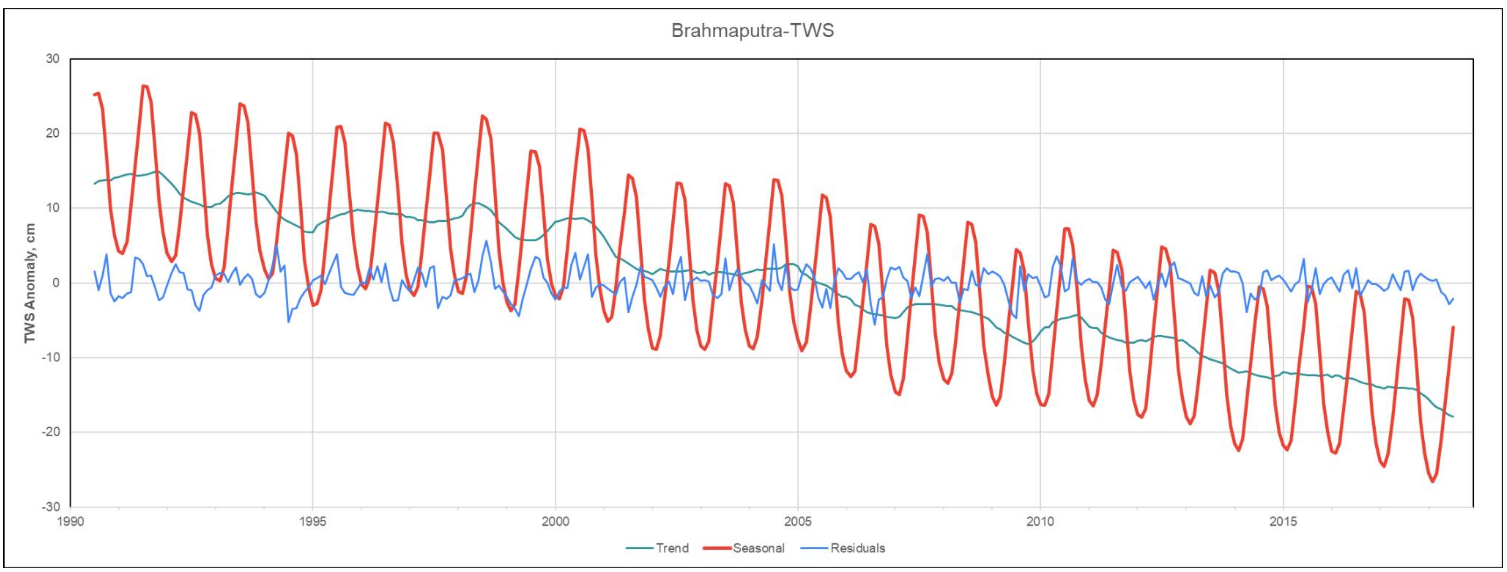
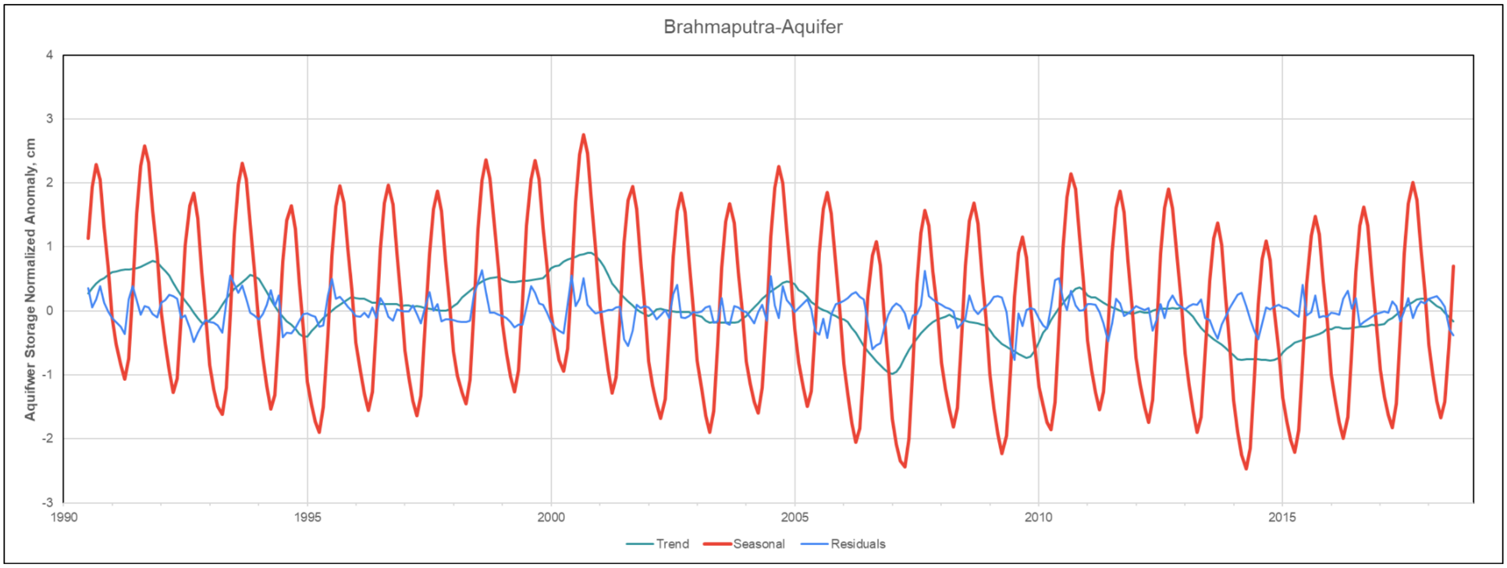
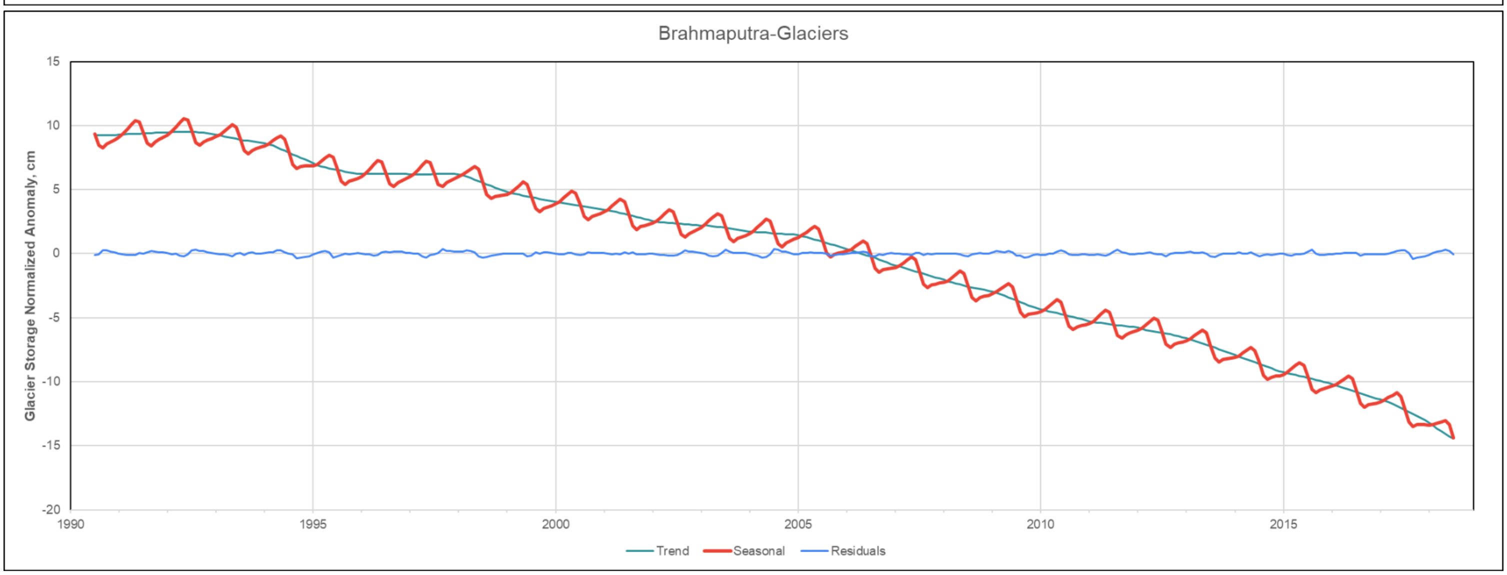
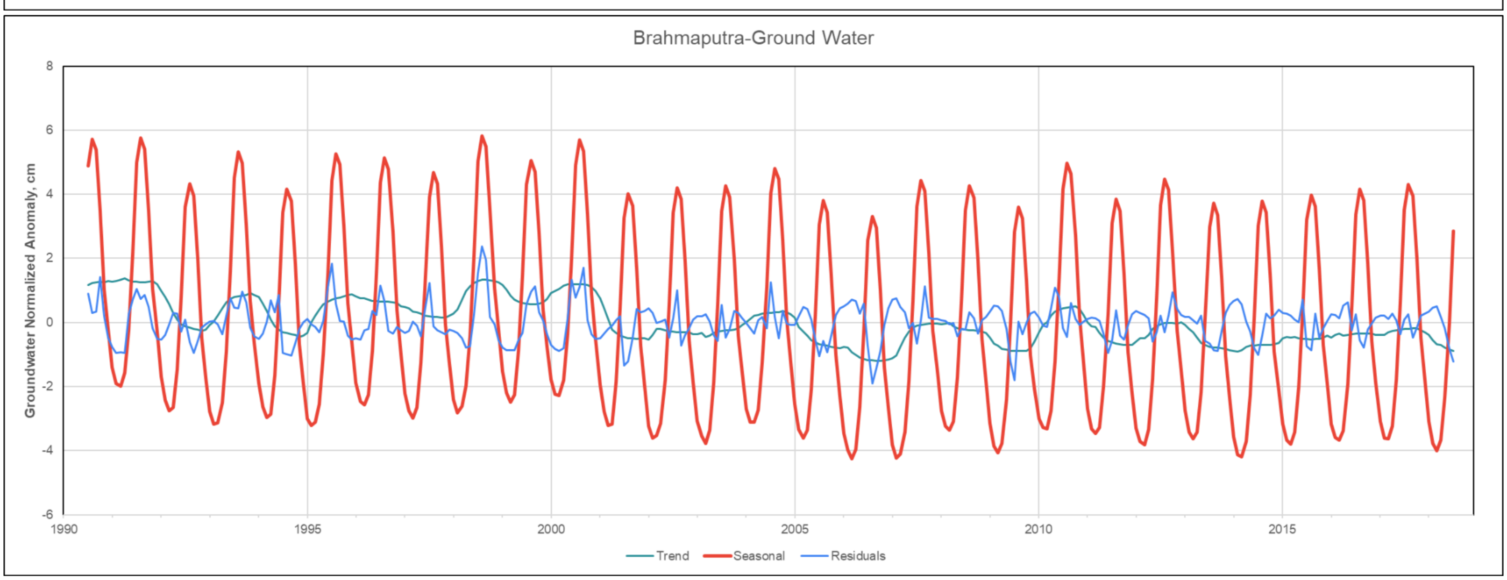


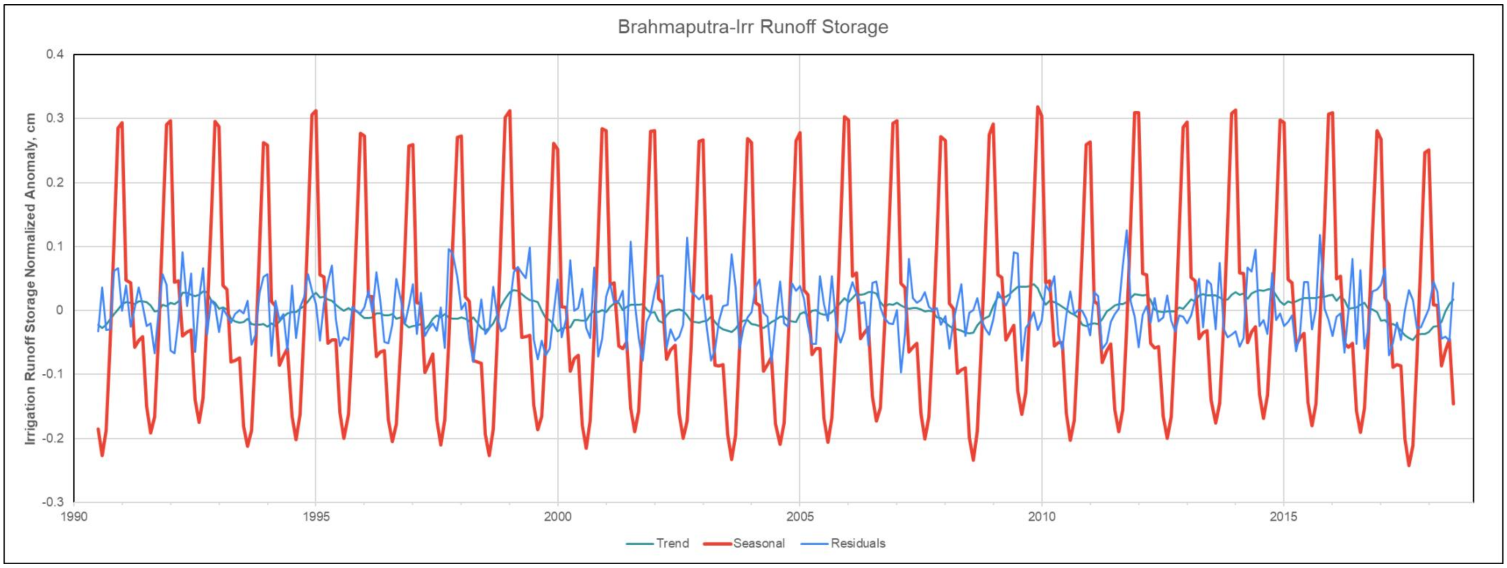
Figure S2. Classical time series decomposition for TWS and its components for the Ganges basin.

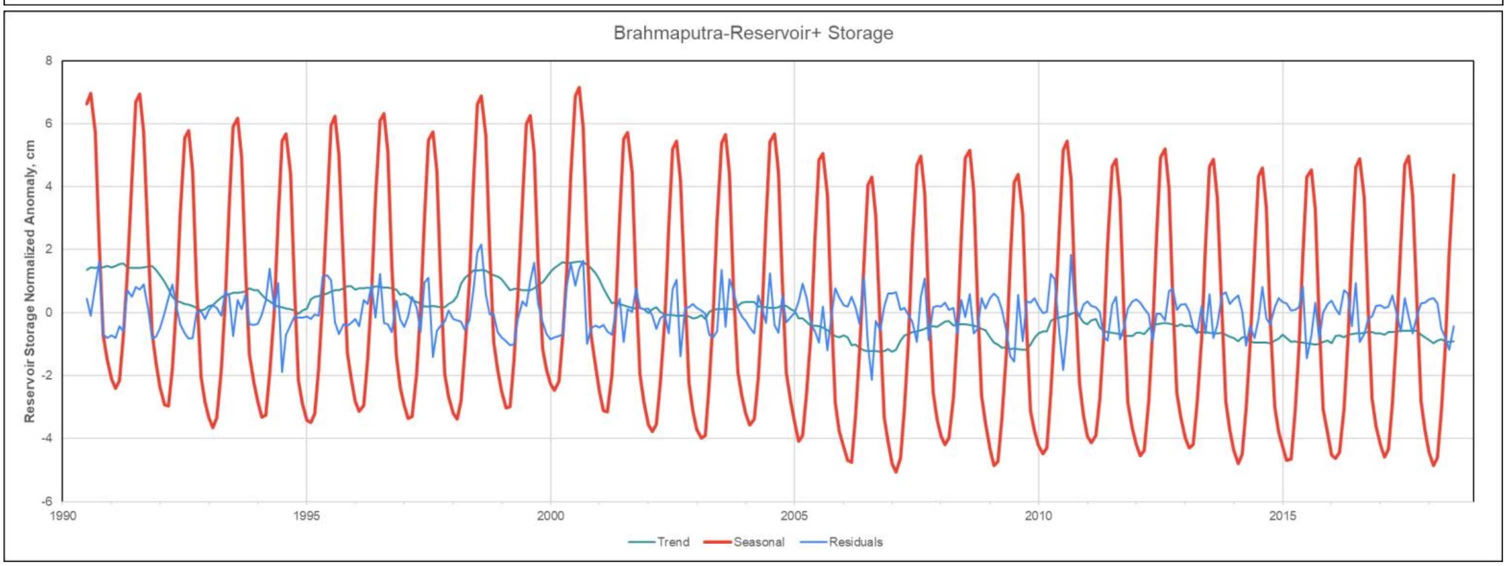


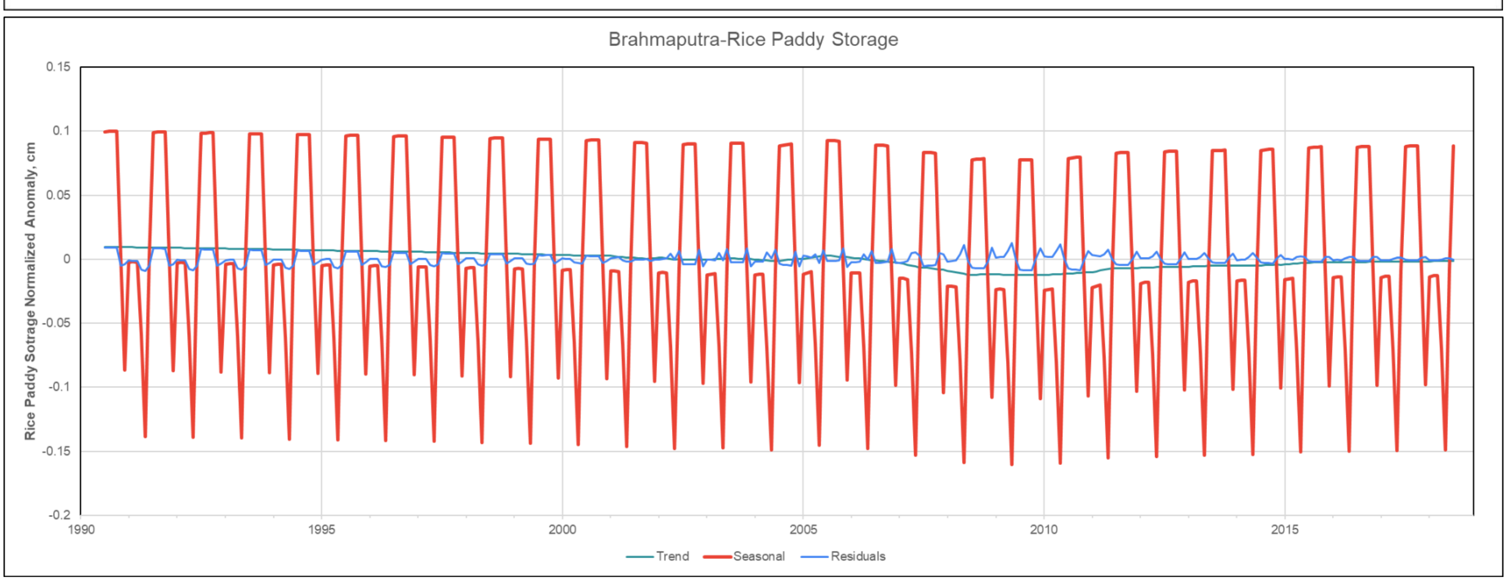

Brahmaputra-Aquifer
Aquifwer Storage Normalized Anomaly, cm
4
3
2
1
0
-1
-2
-3
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

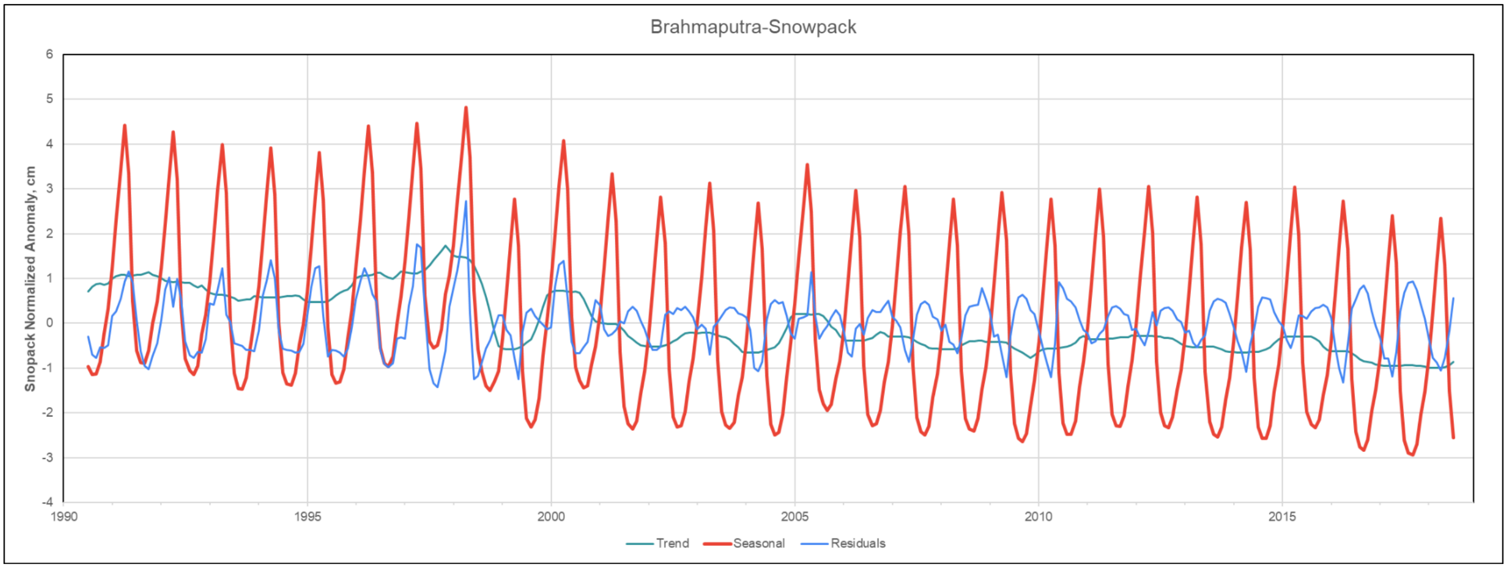

Brahmaputra-Glaciers
Glacier Storage Normalized Anomaly, cm
15
10
5
0
-5
-10
-15
-20
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals

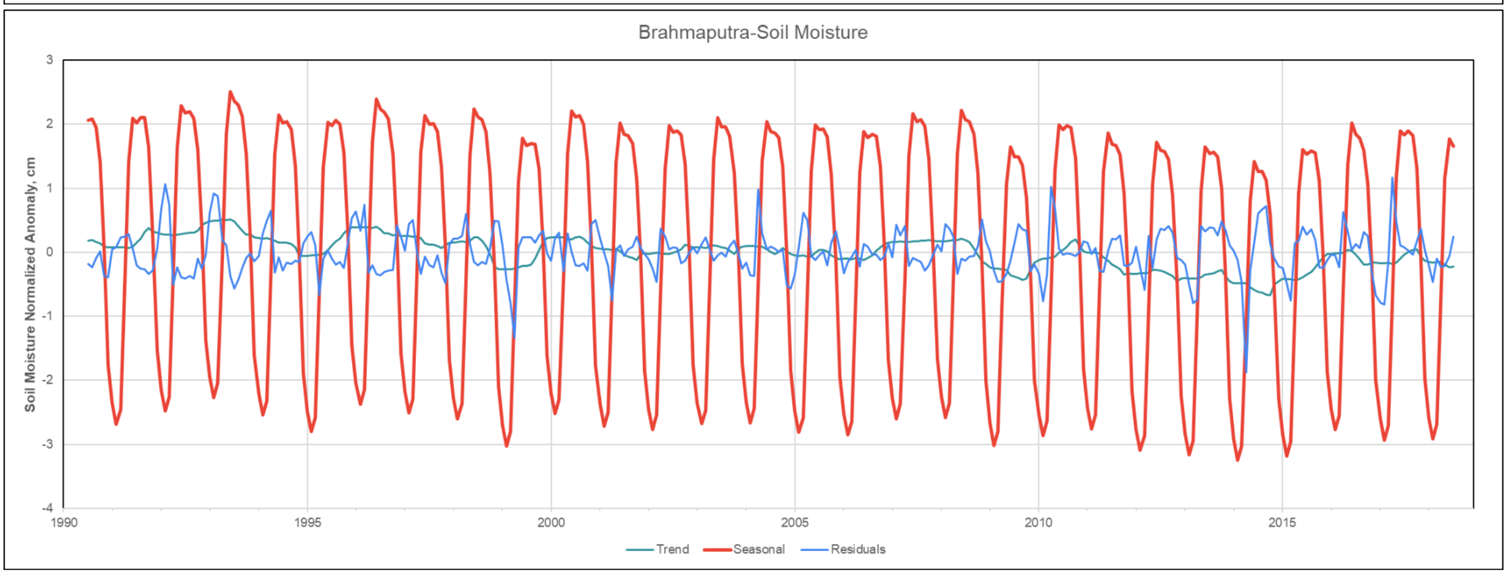

Brahmaputra-Ground Water
Groundwater Normalized Anomaly, cm
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Brahmaputra-Irr Runoff Storage
Irrigation Runoff Storage Normalized Anomaly, cm
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Brahmaputra-Reservoir+ Storage
Reservoir Storage Normalized Anomaly, cm
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Brahmaputra-Rice Paddy Storage
Rice Paddy Sotrage Normalized Anomaly, cm
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1990
1995
2000
2005
2010
2015
Trend
Seasonal
Residuals


Brahmaputra-Snowpack
Snopack Normalized Anomaly, cm
Trend
Seasonal
Residuals


Brahmaputra-Soil Moisture
Soil Moisture Normalized Anomaly, cm
Trend
Seasonal
Residuals

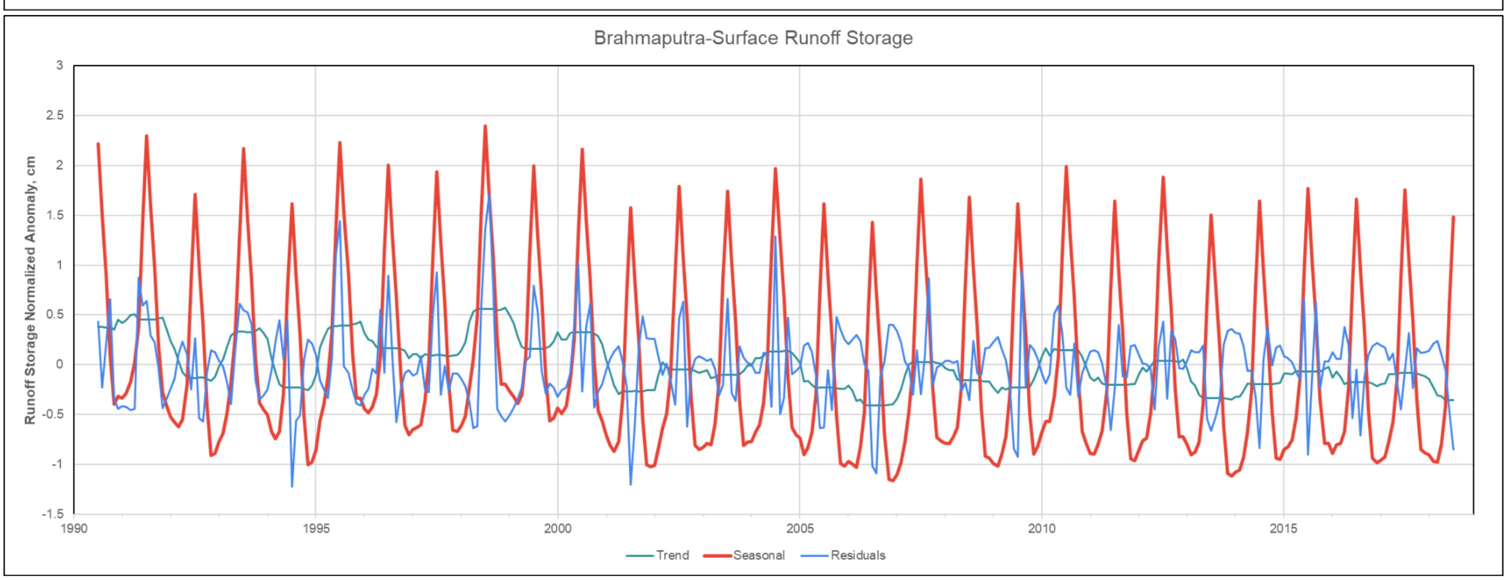
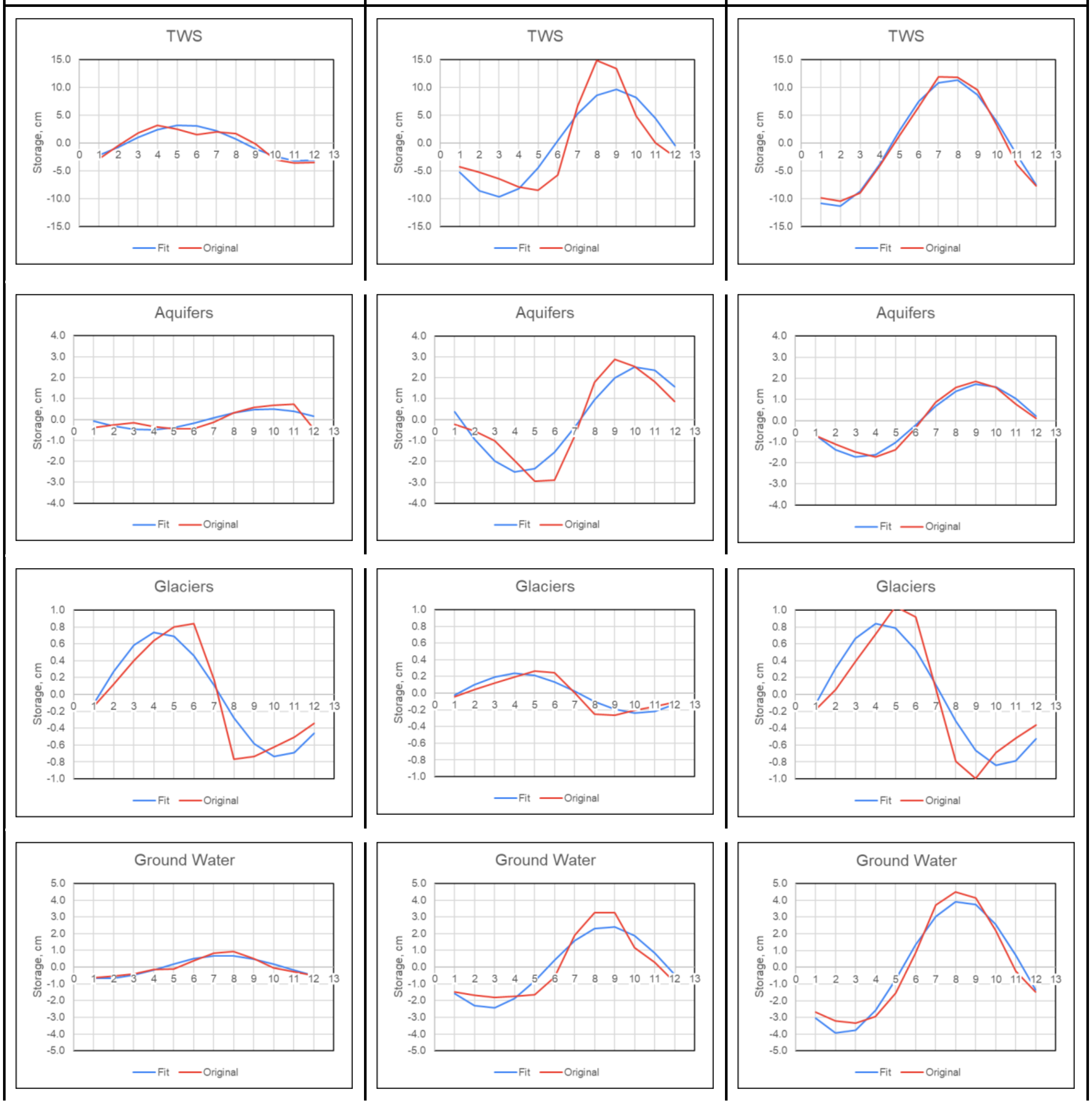
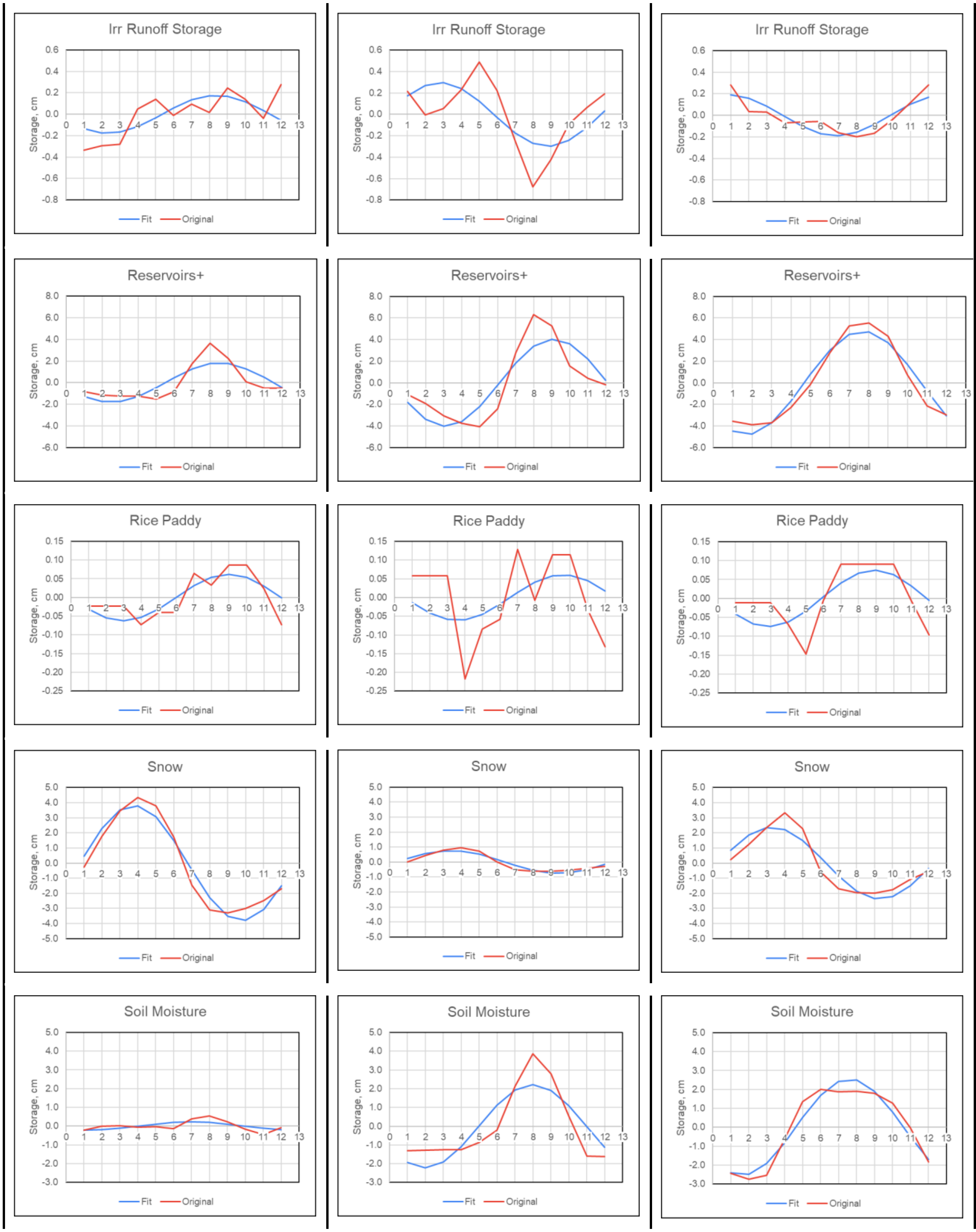

Brahmaputra-Surface Runoff Storage
Runoff Storage Normalized Anomaly, cm
Trend
Seasonal
Residuals

Figure S3. Classical time series decomposition for TWS and its components for the Brahmaputra basin.

b. Graphs of approximation of seasonal signals by the Sinusoidal function fit (**Figure S4**) for Indus, Ganges and Brahmaputra basins. Seasonal signal is a component of Classical TS decomposition applied to TWS and its components/contributors. Summary of the function fit parameters and validation is provided in the **Table 4** of the manuscript.

Indus	Ganges	Brahmaputra





Irr Runoff Storage
Irr Runoff Storage
Irr Runoff Storage
Reservoirs+
Reservoirs+
Reservoirs+
Rice Paddy
Rice Paddy
Rice Paddy
Snow
Snow
Snow
Soil Moisture
Soil Moisture
Soil Moisture
Storage, cm
Fit
Original

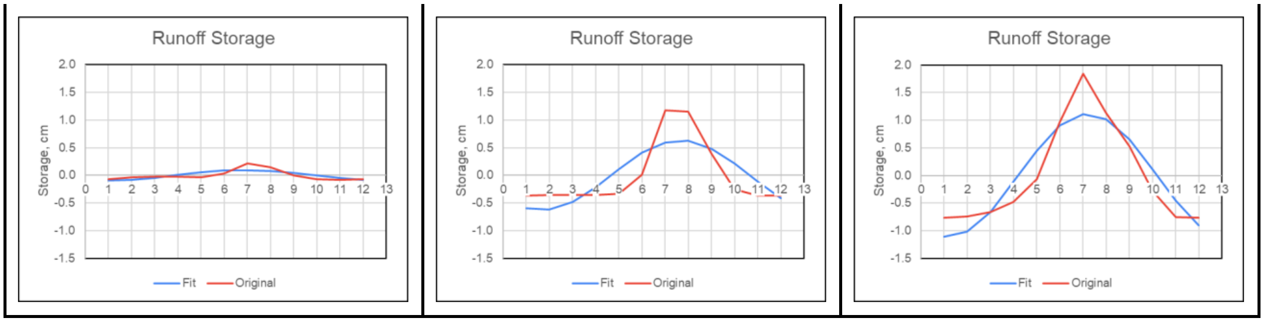
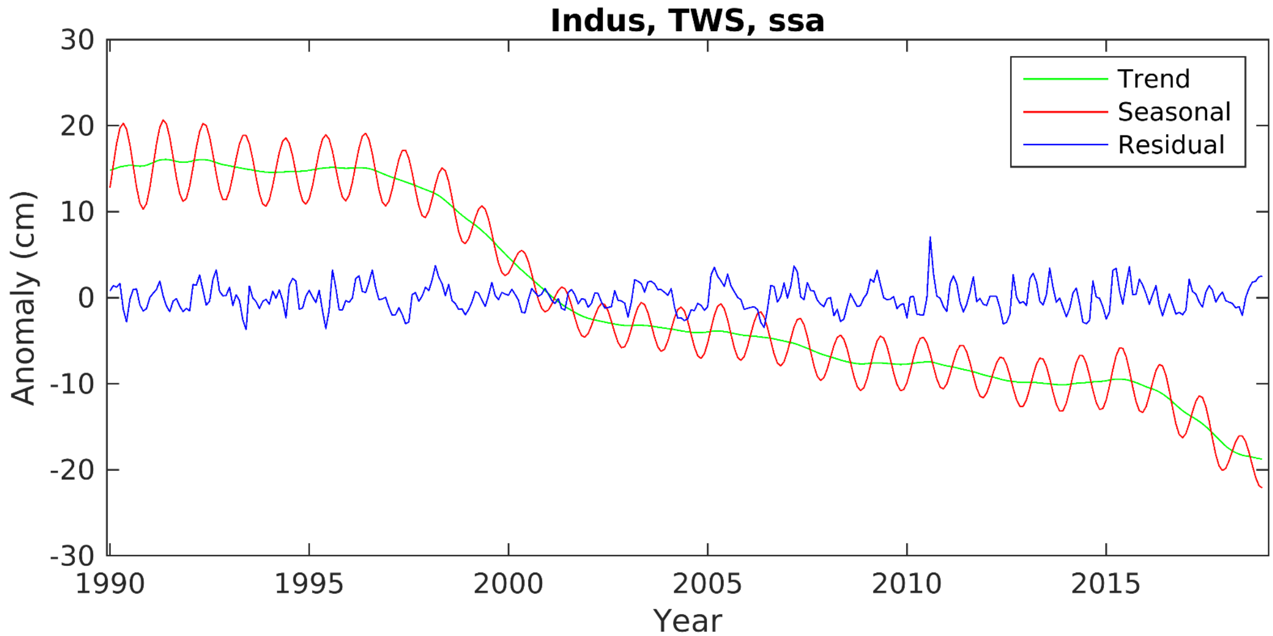


Figure S4. Sinusoidal function fit for the seasonal signal of the classical TS decomposition for TWS and its component storages in Indus, Ganges, and Brahmaputra basins. Note, storage scale on the abscissa axis is purposely fixed for the signal amplitude comparison between the basins.

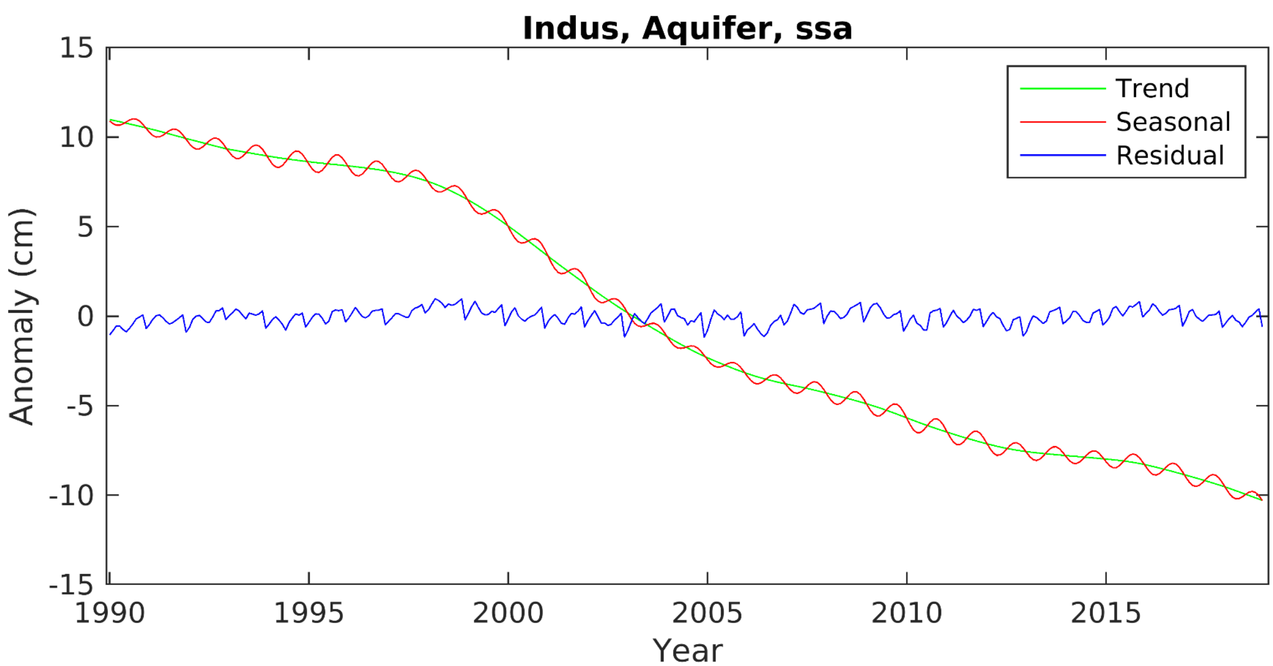
S2. Figures of Total Water Storage (TWS) and its components by Singular Spectral Analysis (SSA) time series decomposition

a. Singular spectral analysis (SSA) decomposition of trend and seasonal signals of total water storage (TWS) for the Indus, Ganges, and Brahmaputra basins (**Figures S5-S7**).

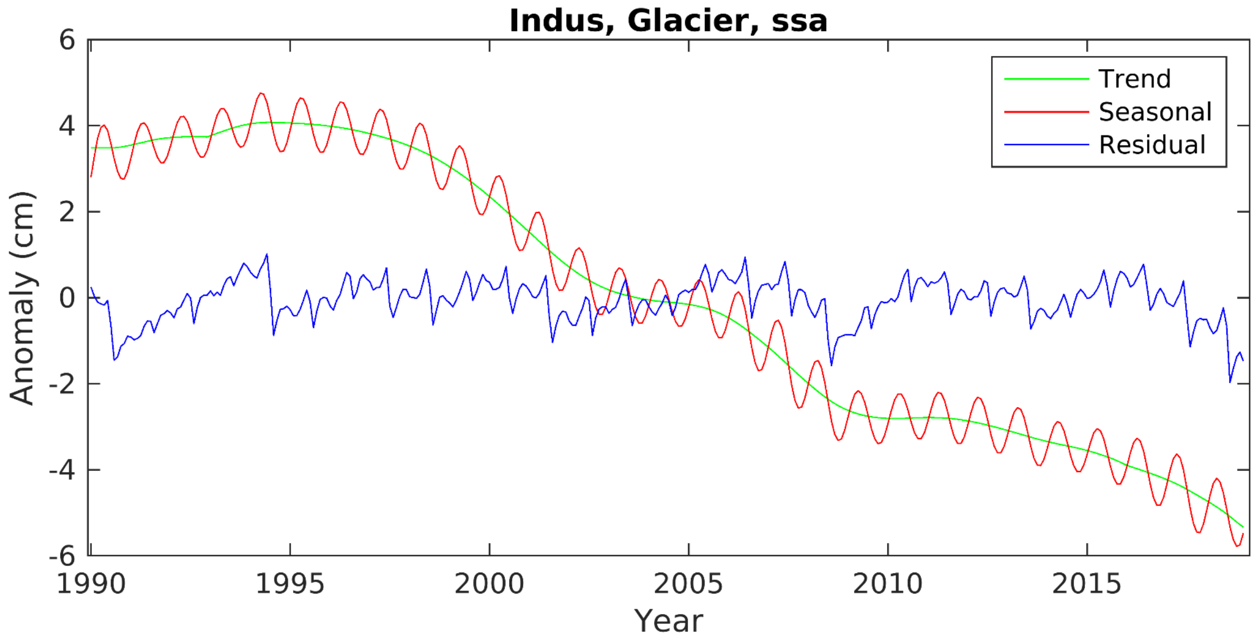
   SSA computed with Matlab function *trenddecomp* on the 348-month (29 years) series starting in January, 1990. Lag parameter for the SSA analysis set to 36 months, and number of desired seasons set to 6. The “seasonal” series most highly correlated with the Classic (constant year-to-year) seasonal series was selected as the final seasonal series. For 28 of the 30 runs (10 WBM variables, 3 basins), the final seasonal series was the most important (highest eigenvalue) in the seasonal matrix returned by *trenddecomp*. For the other two runs, the final seasonal series was the second-most important. Analogous figures for the remaining 29 WBM variables are defined by the title at top of figure. Note that the range of the y-axis varies over figures.

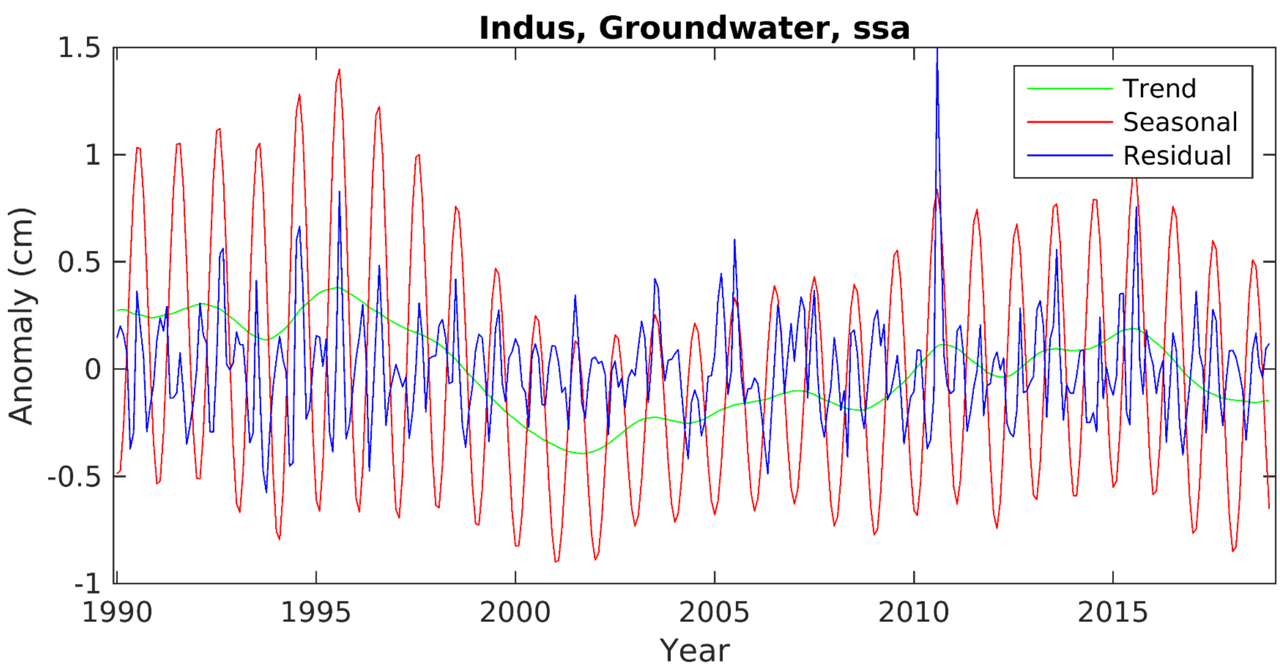


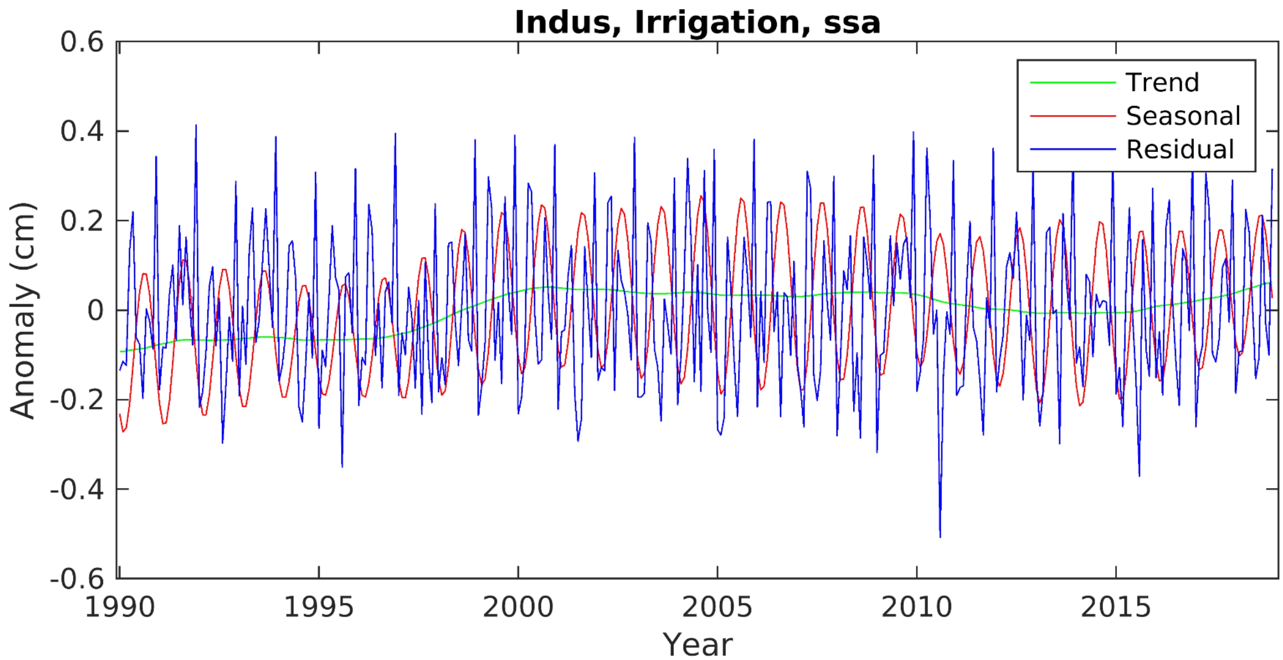
Indus, TWS, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
30
20
10
0
-10
-20
-30
1990
1995
2000
2005
2010
2015

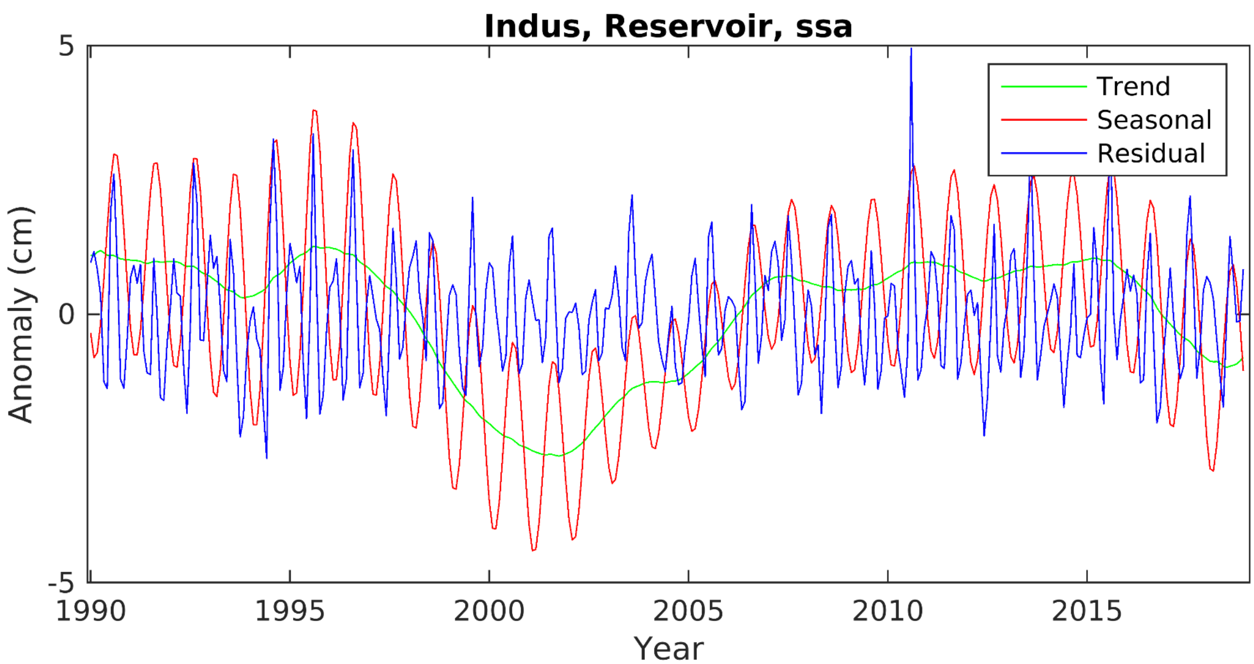


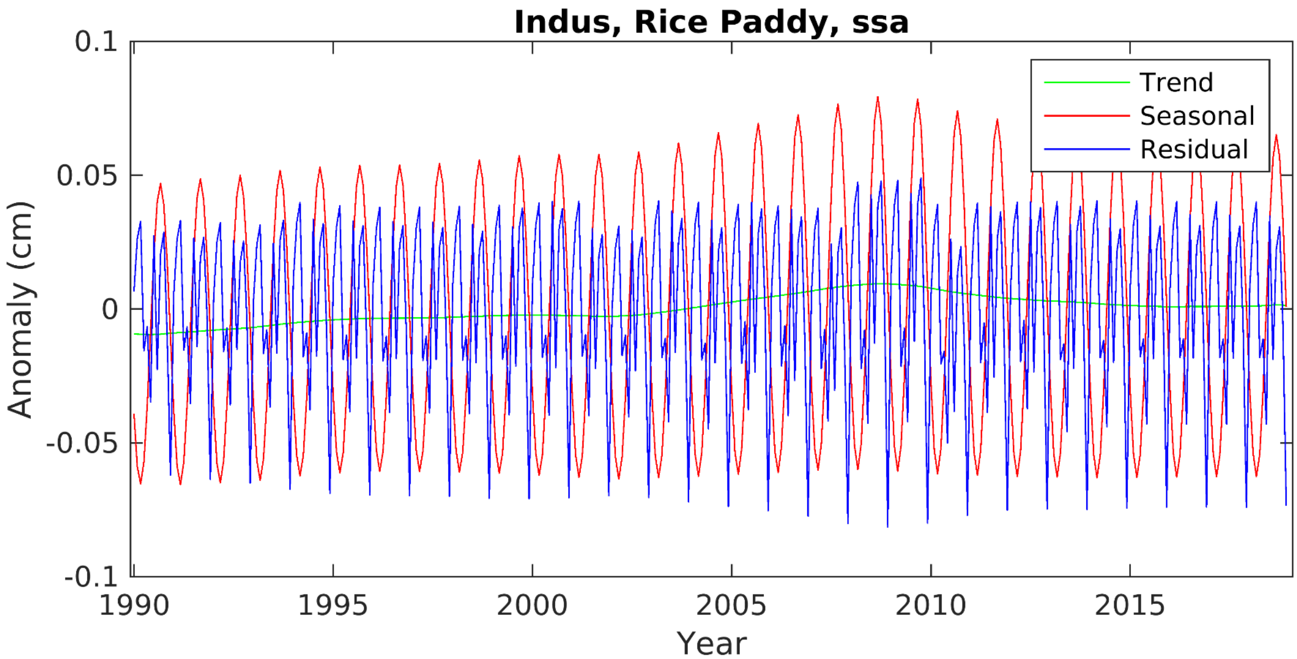
Indus, Aquifer, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
15
10
5
0
-5
-10
-15
1990
1995
2000
2005
2010
2015

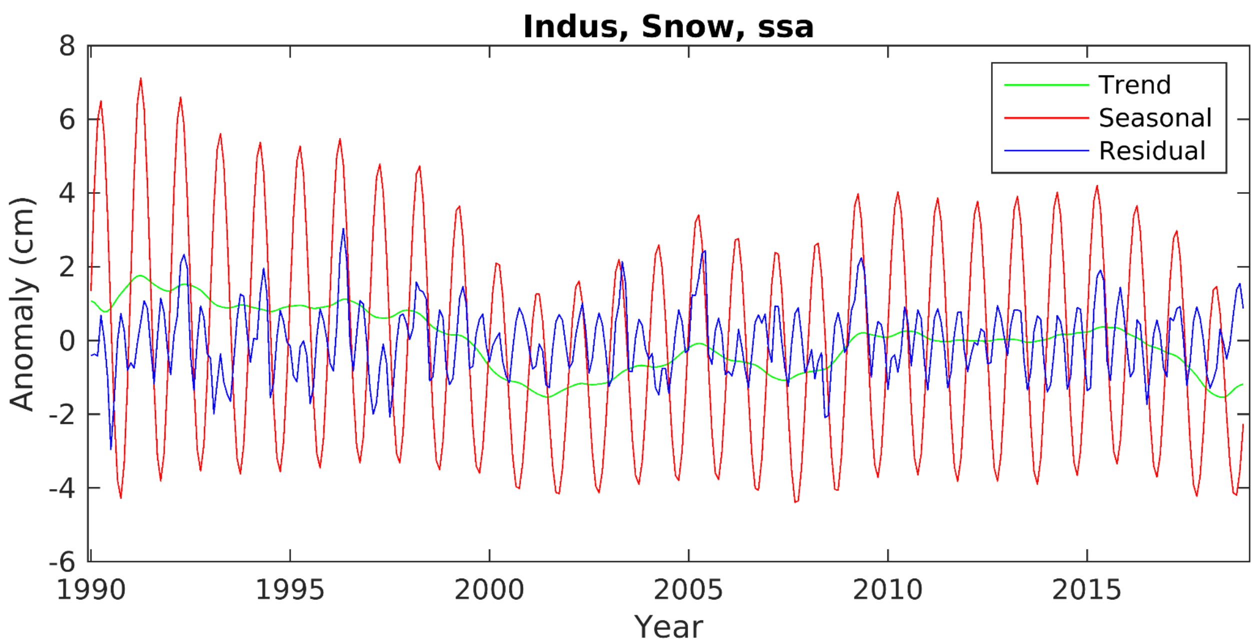

Indus, Glacier, ssa
Trend
Seasonal
Residual
Anomaly (cm)
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Year


Indus, Groundwater, ssa
Trend
Seasonal
Residual
Anomaly (cm)
1.5
1
0.5
0
-0.5
-1
1990
1995
2000
2005
2010
2015
Year


Indus, Irrigation, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1990
1995
2000
2005
2010
2015


Indus, Reservoir, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
5
0
-5
1990
1995
2000
2005
2010
2015


Indus, Rice Paddy, ssa
Trend
Seasonal
Residual
Anomaly (cm)
0.1
0.05
0
-0.05
-0.1
1990
1995
2000
2005
2010
2015
Year


Indus, Snow, ssa
Trend
Seasonal
Residual
Anomaly (cm)
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Year

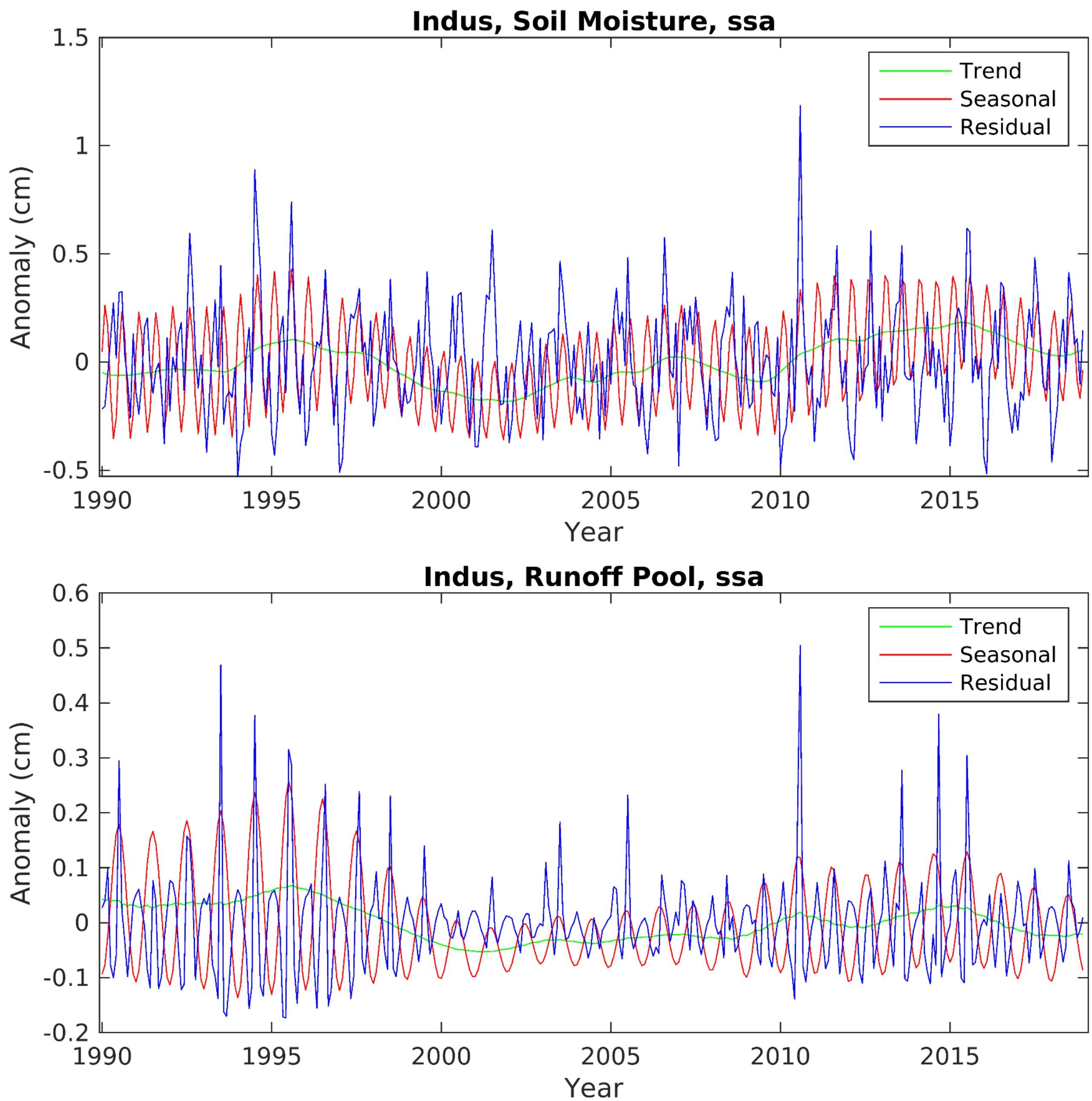
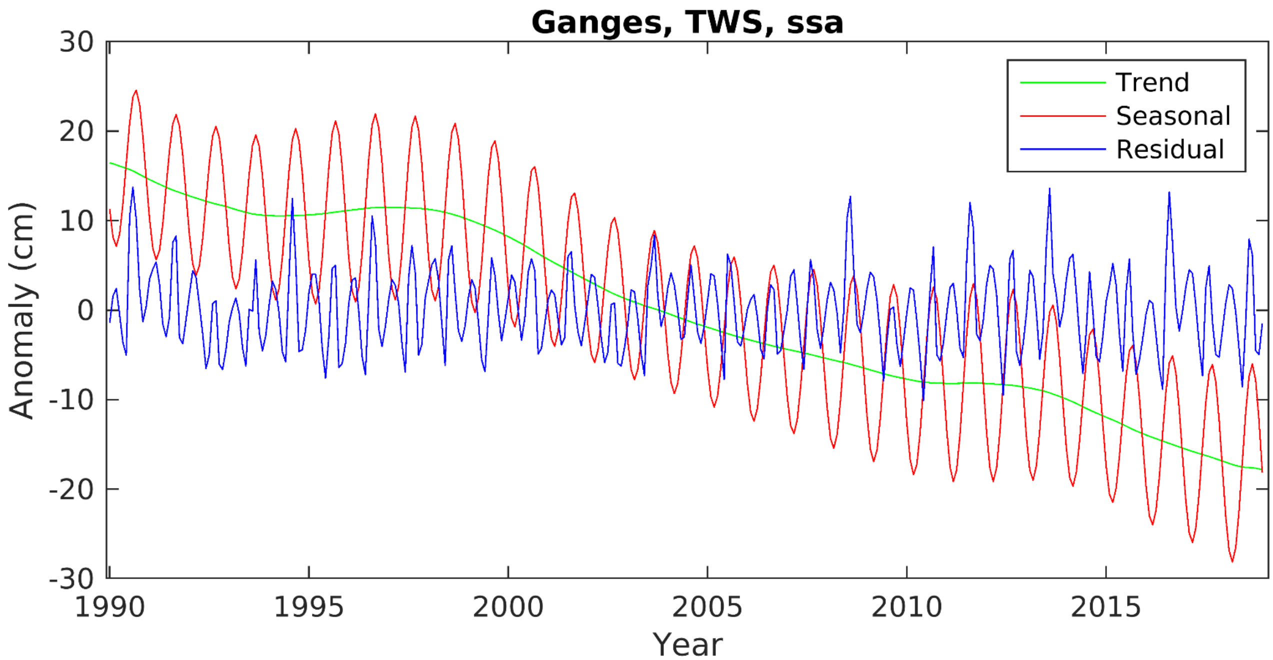
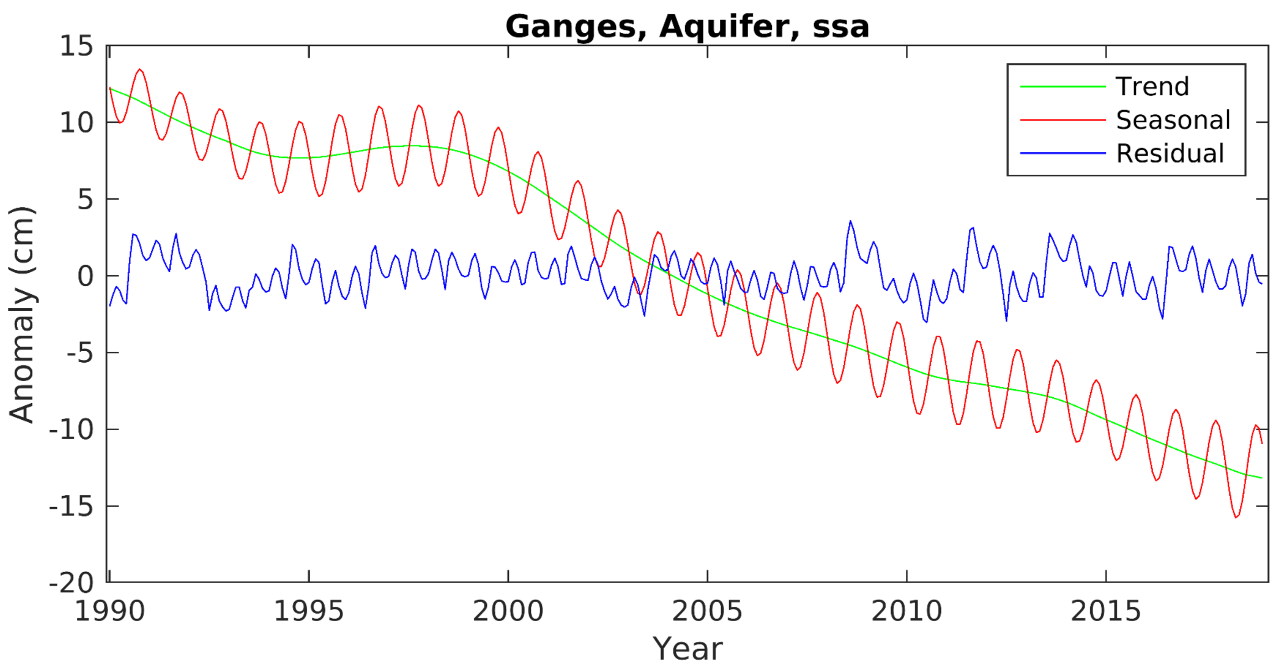
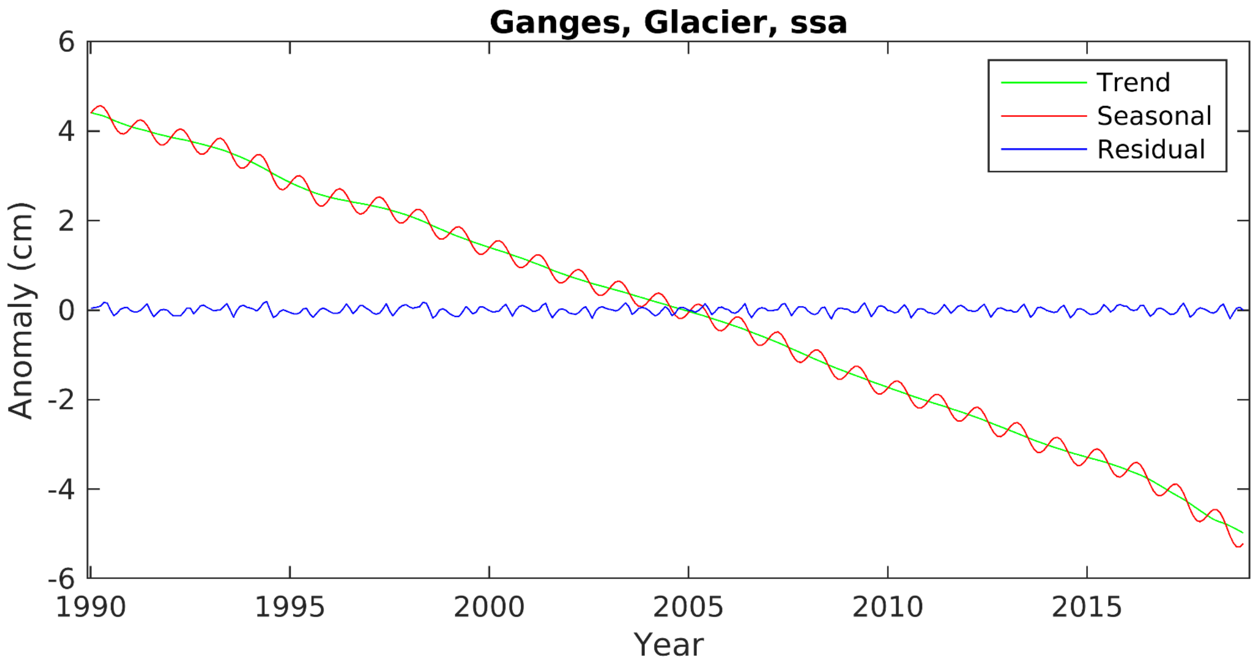


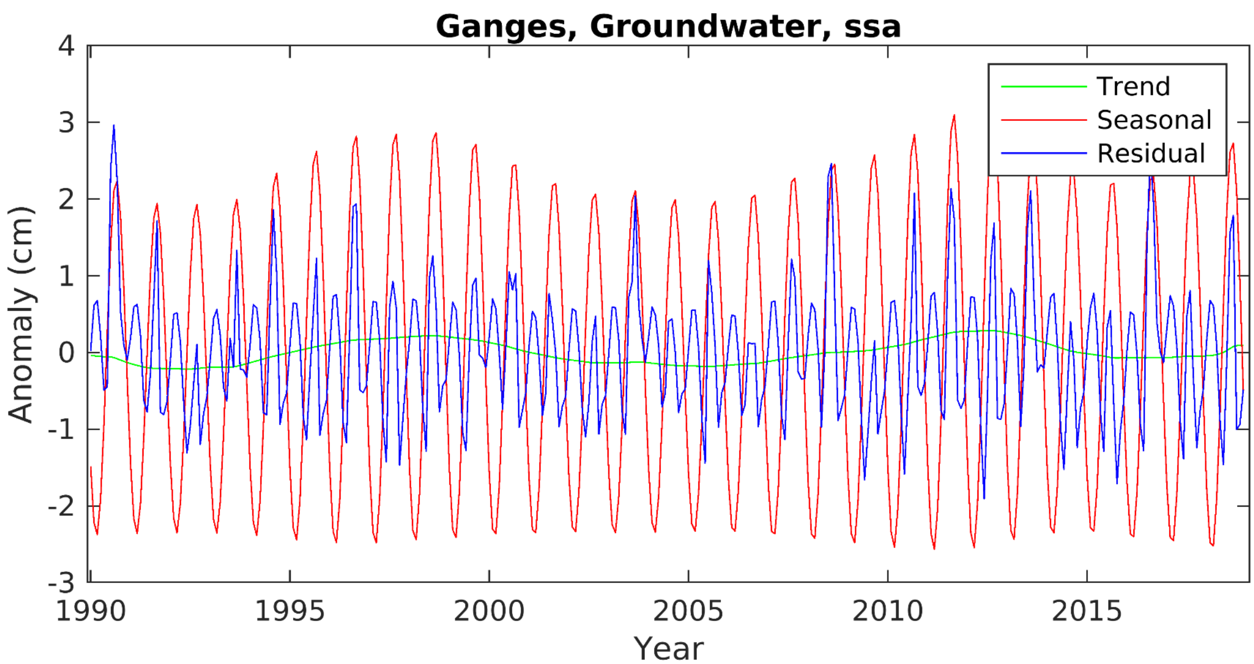
Figure S5. Singular spectral analysis (SSA) decomposition of trend and seasonal signals of total water storage (TWS) and its nine contributing components in Indus basin.


Ganges, TWS, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
30
20
10
0
-10
-20
-30
1990
1995
2000
2005
2010
2015

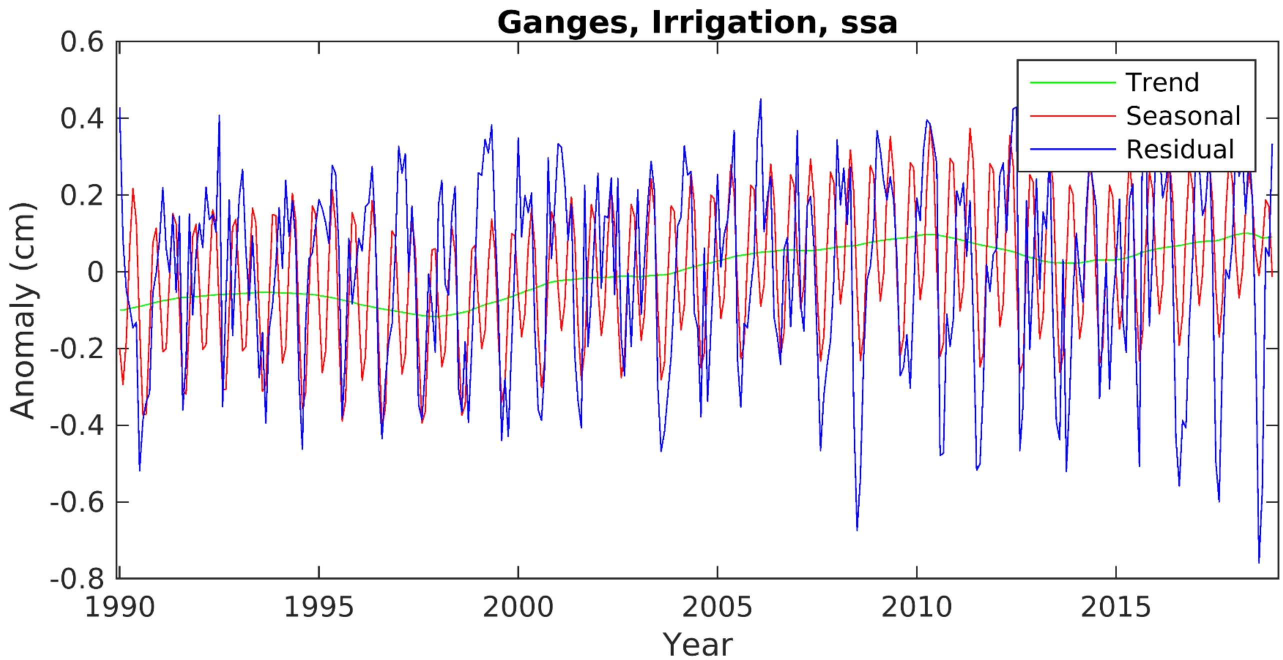

Ganges, Aquifer, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
15
10
5
0
-5
-10
-15
-20
1990
1995
2000
2005
2010
2015

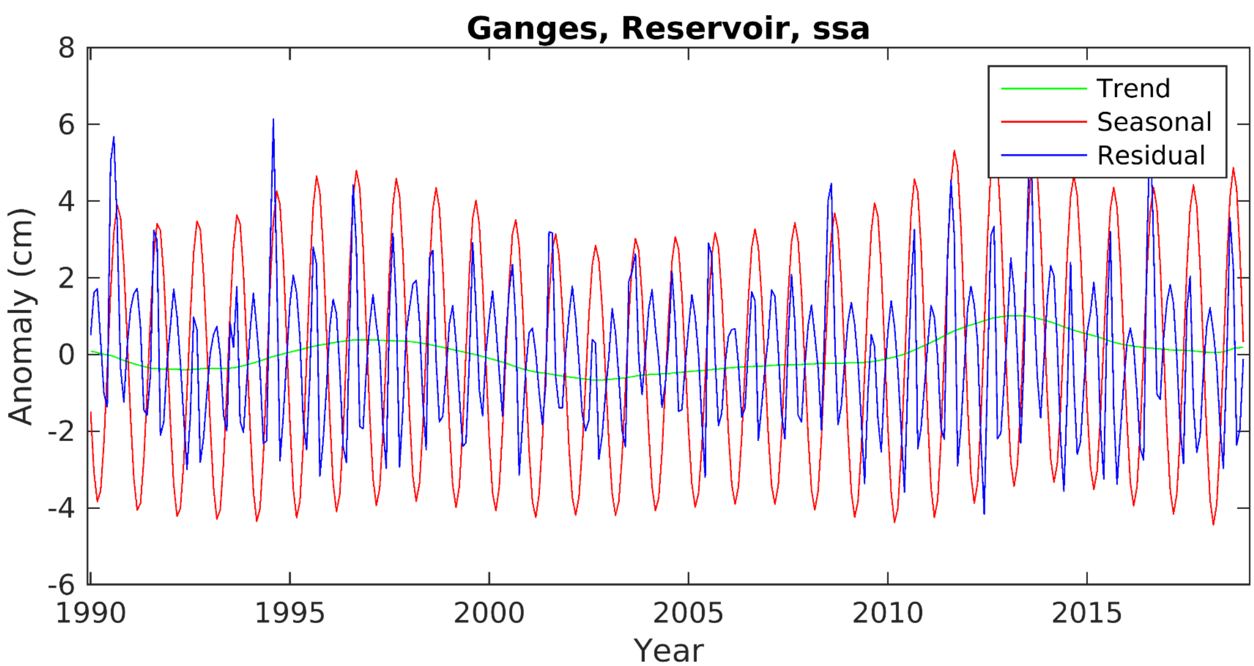


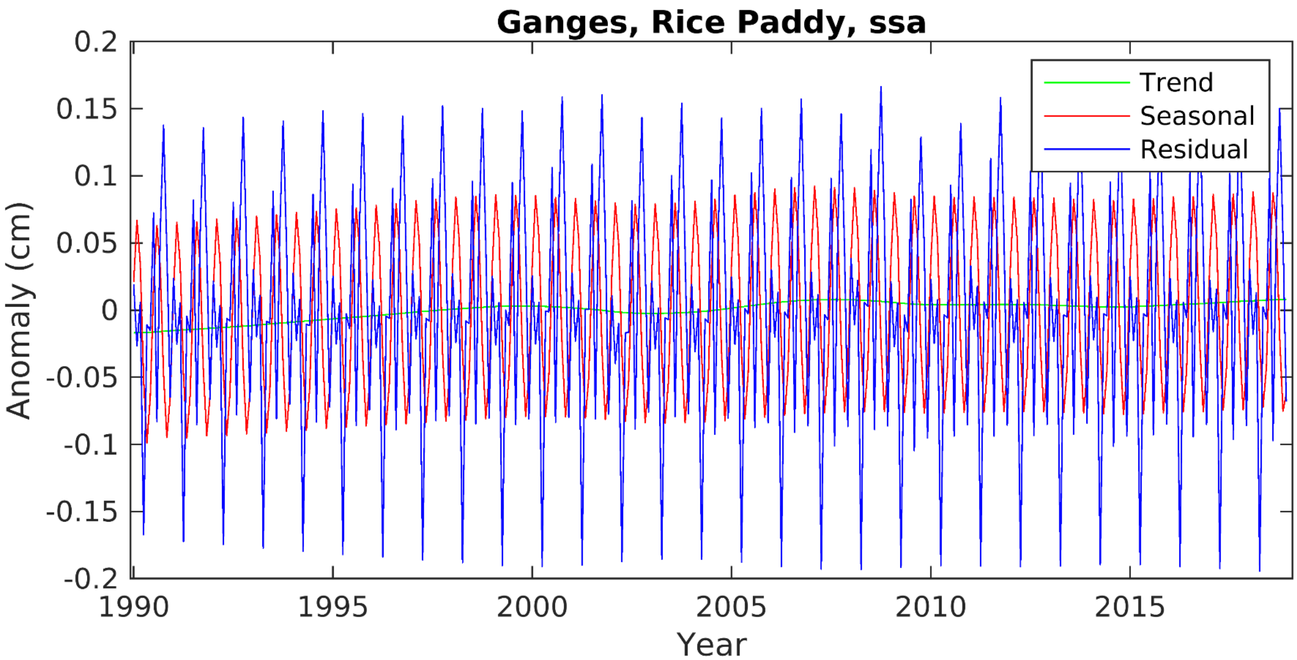
Ganges, Glacier, ssa
Trend
Seasonal
Residual
Anomaly (cm)
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015
Year

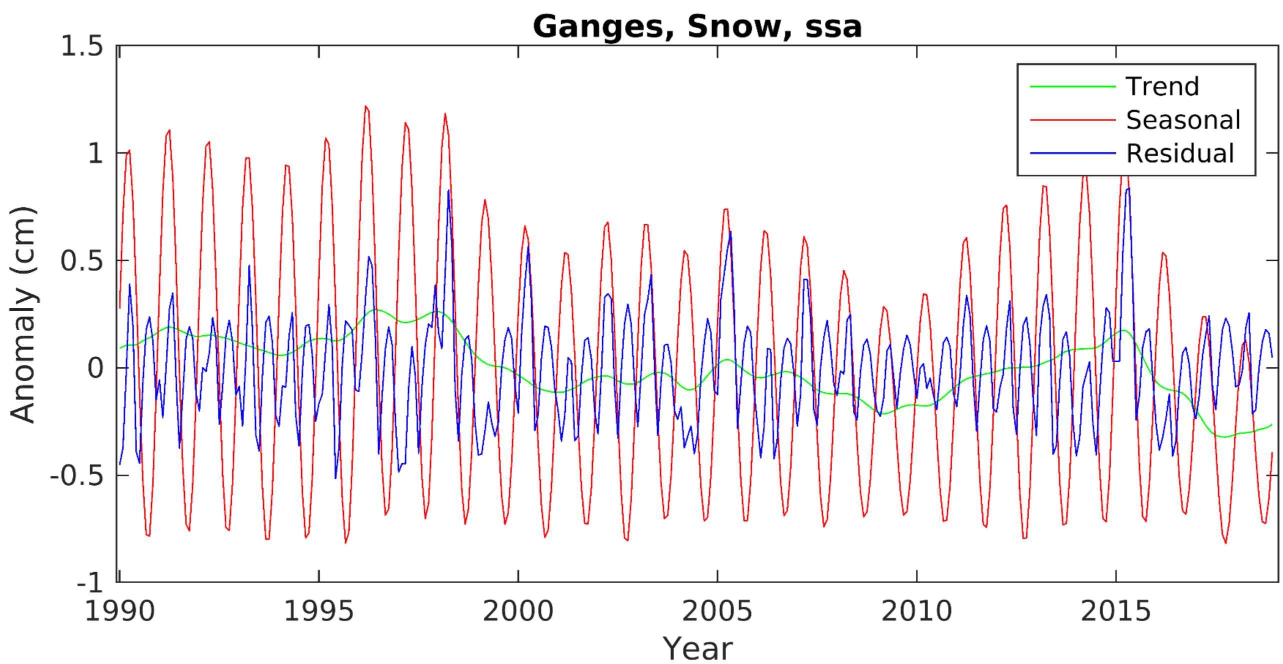


Ganges, Groundwater, ssa
Trend
Seasonal
Residual
Anomaly (cm)
4
3
2
1
0
-1
-2
-3
1990
1995
2000
2005
2010
2015
Year


Ganges, Irrigation, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
1990
1995
2000
2005
2010
2015


Ganges, Reservoir, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
8
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015


Ganges, Rice Paddy, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
1990
1995
2000
2005
2010
2015


Ganges, Snow, ssa
Anomaly (cm)
Year
Trend
Seasonal
Residual
1.5
1
0.5
0
-0.5
-1
1990
1995
2000
2005
2010
2015

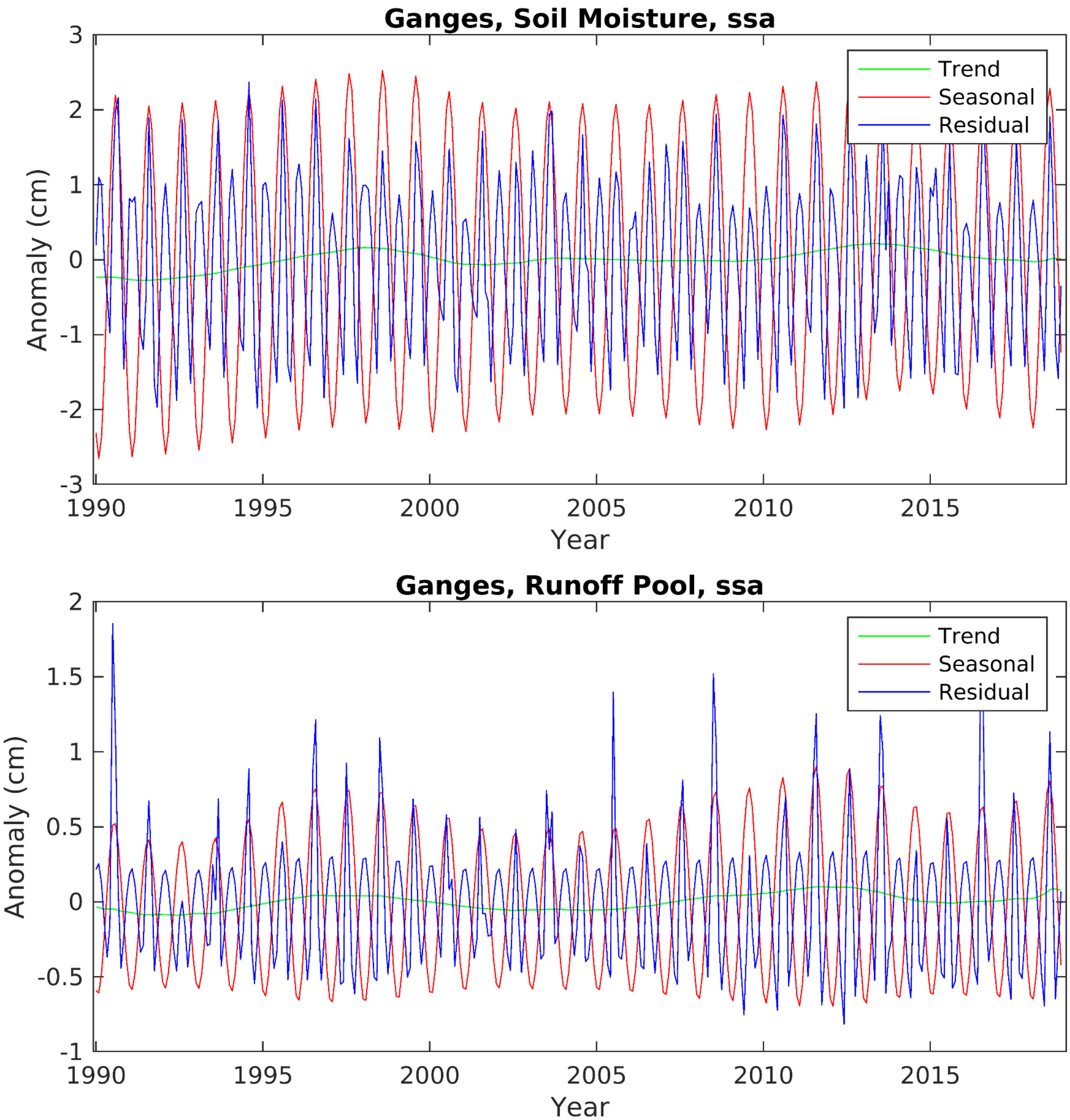
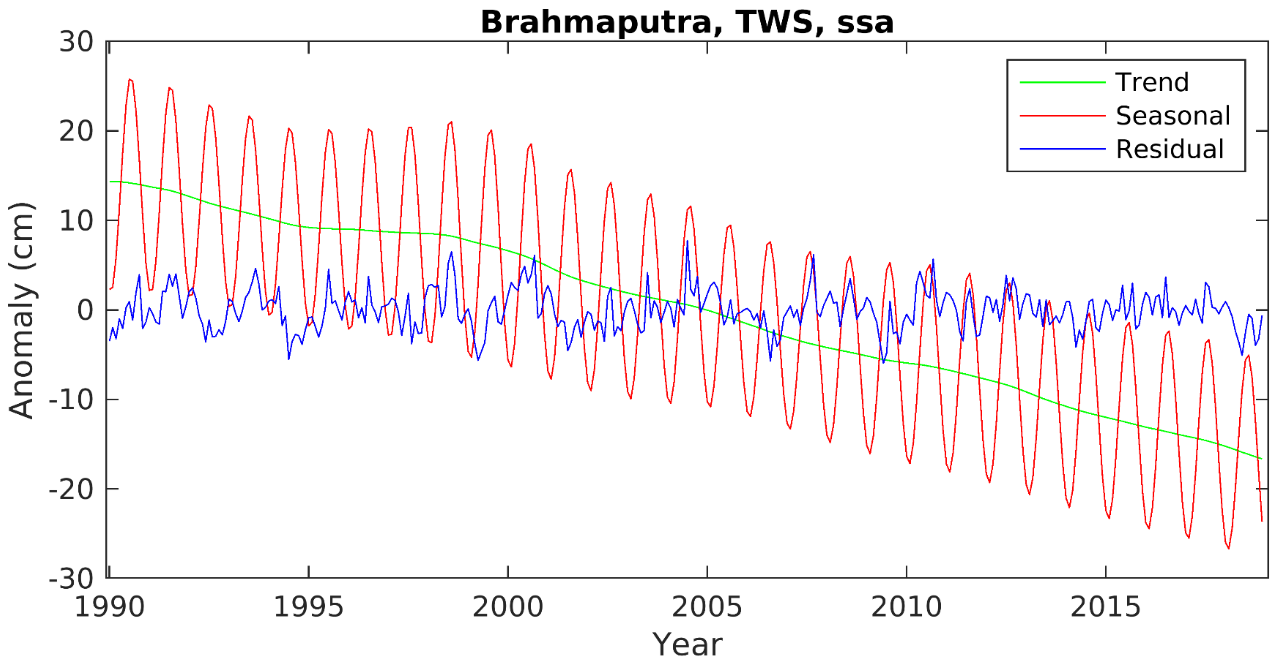
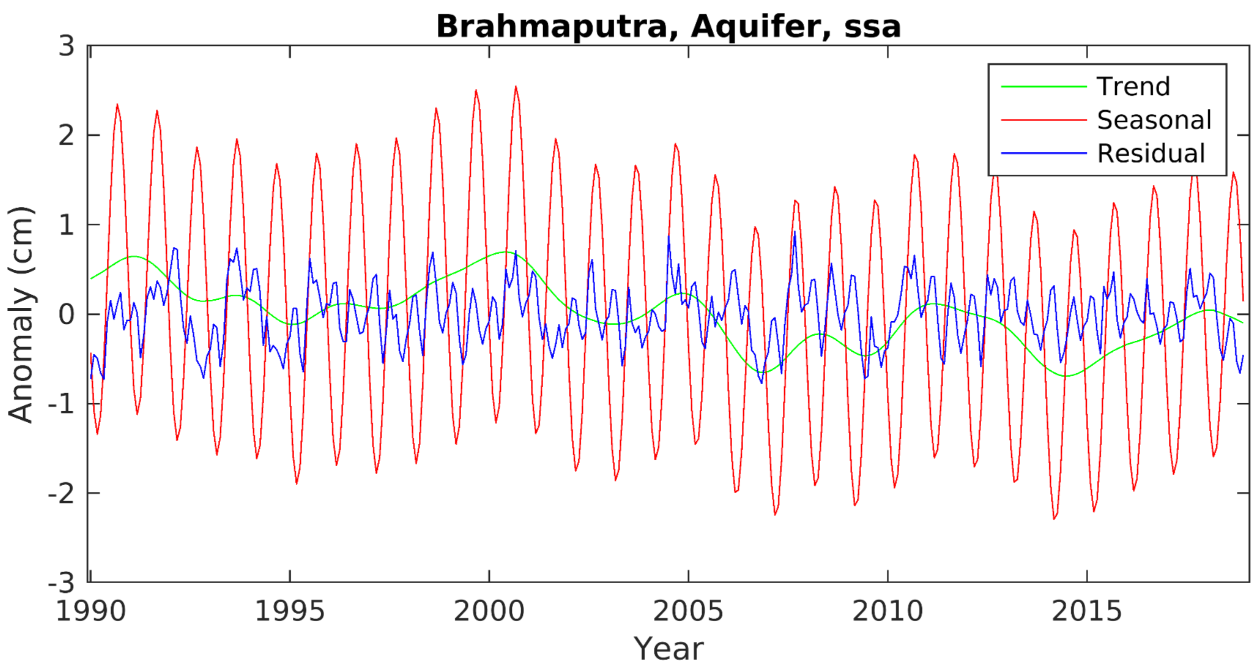
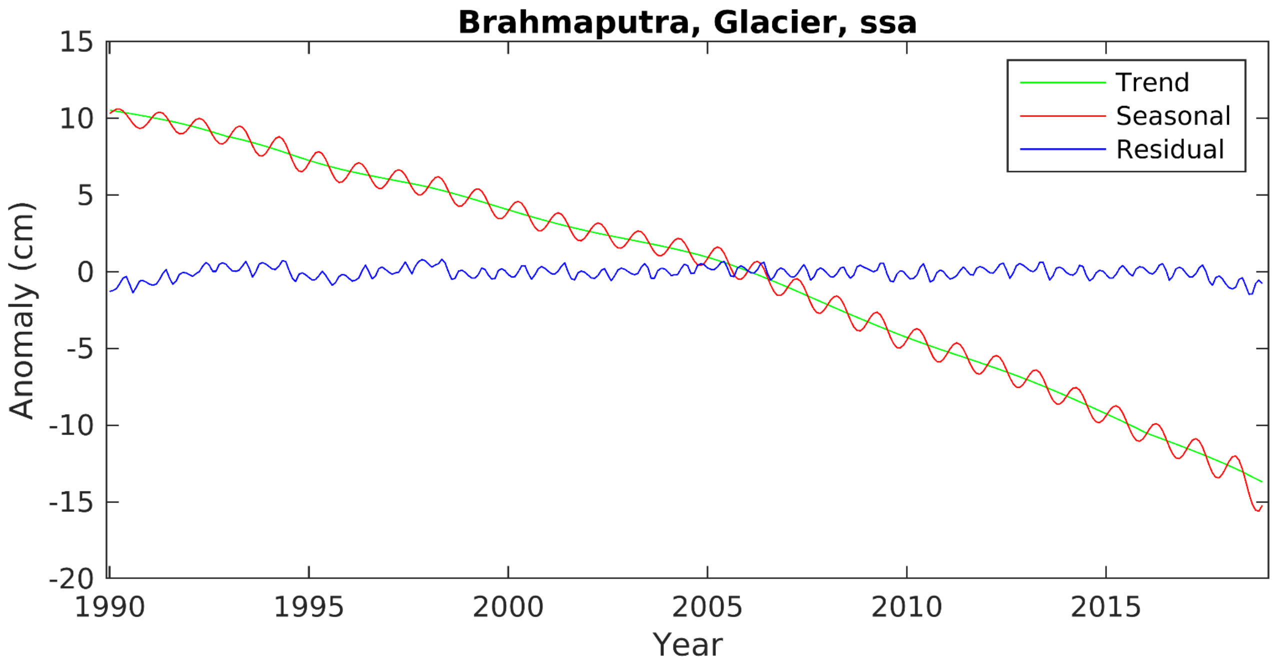
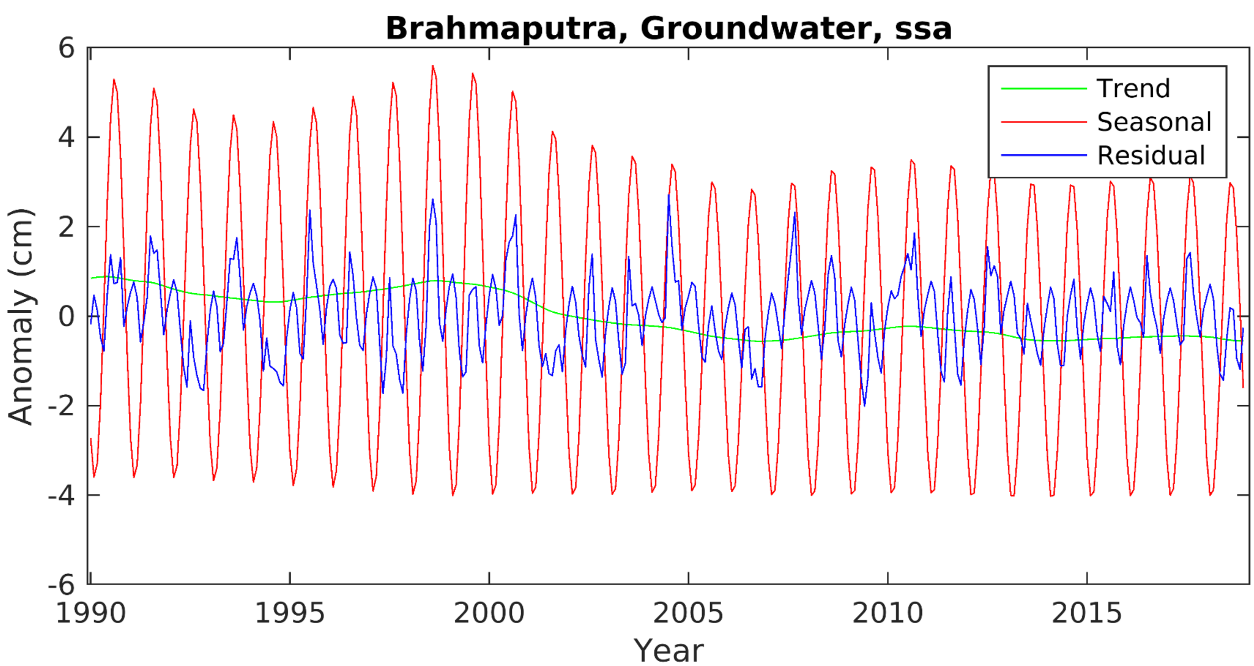


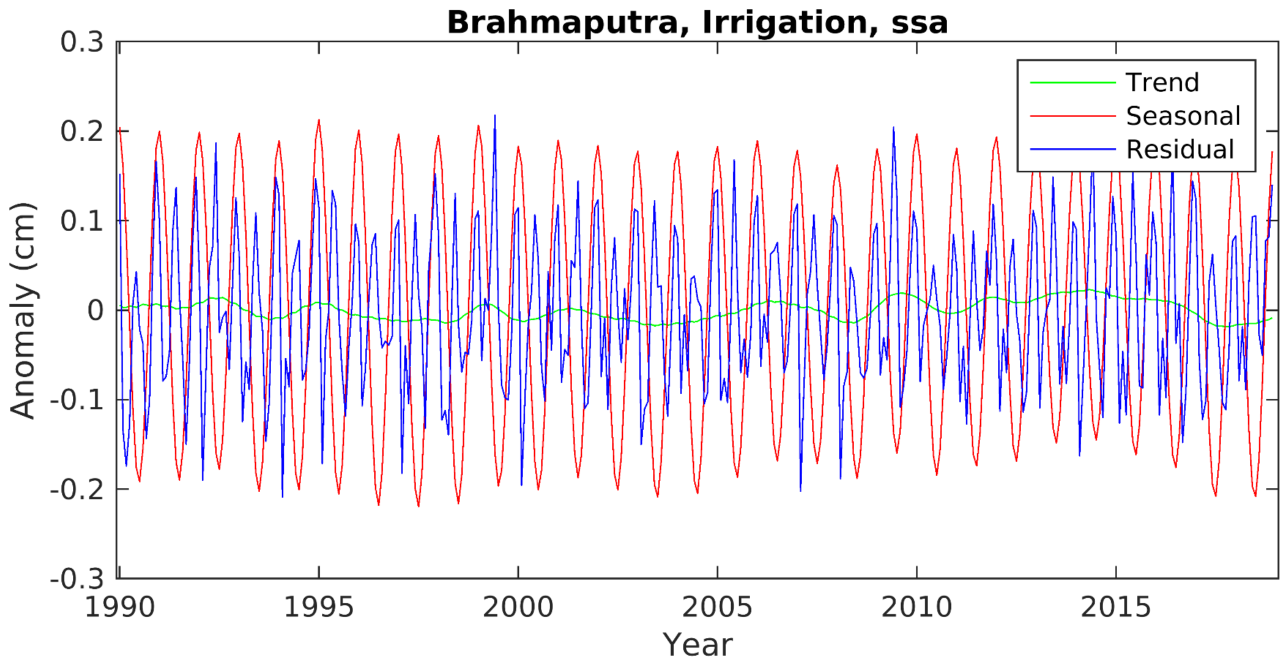
Figure S6. Singular spectral analysis (SSA) decomposition of trend and seasonal signals of total water storage (TWS) and its nine contributing components in Ganges basin.

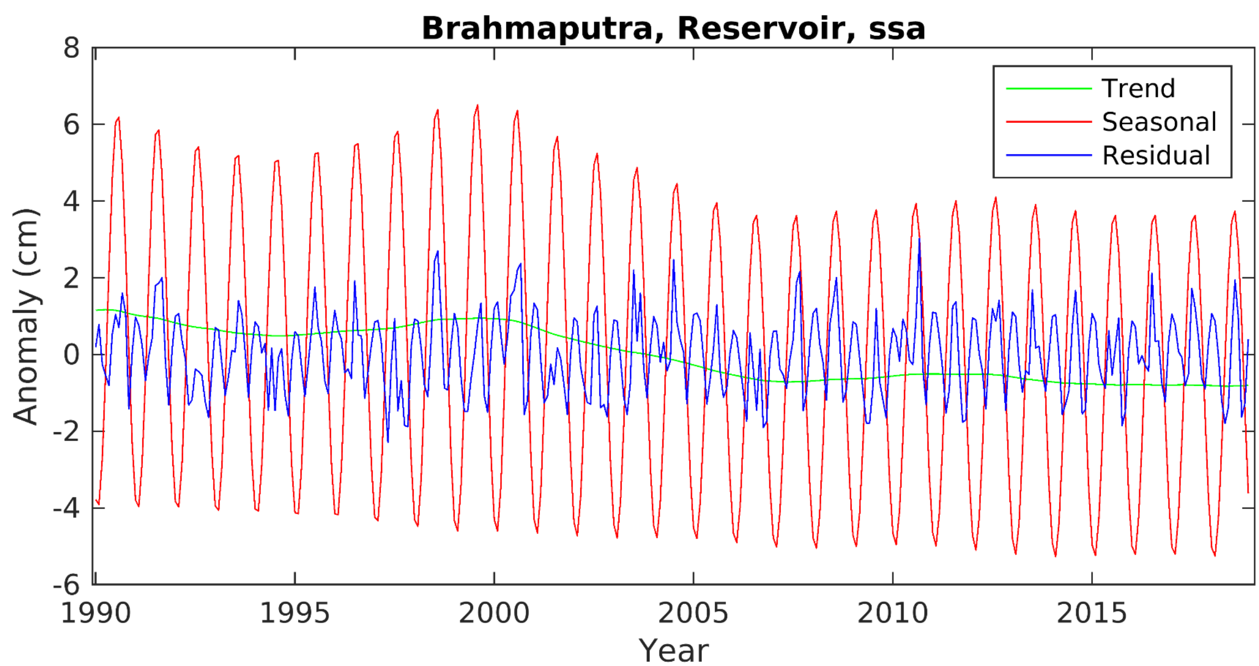

Brahmaputra, TWS, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
30
20
10
0
-10
-20
-30
1990
1995
2000
2005
2010
2015

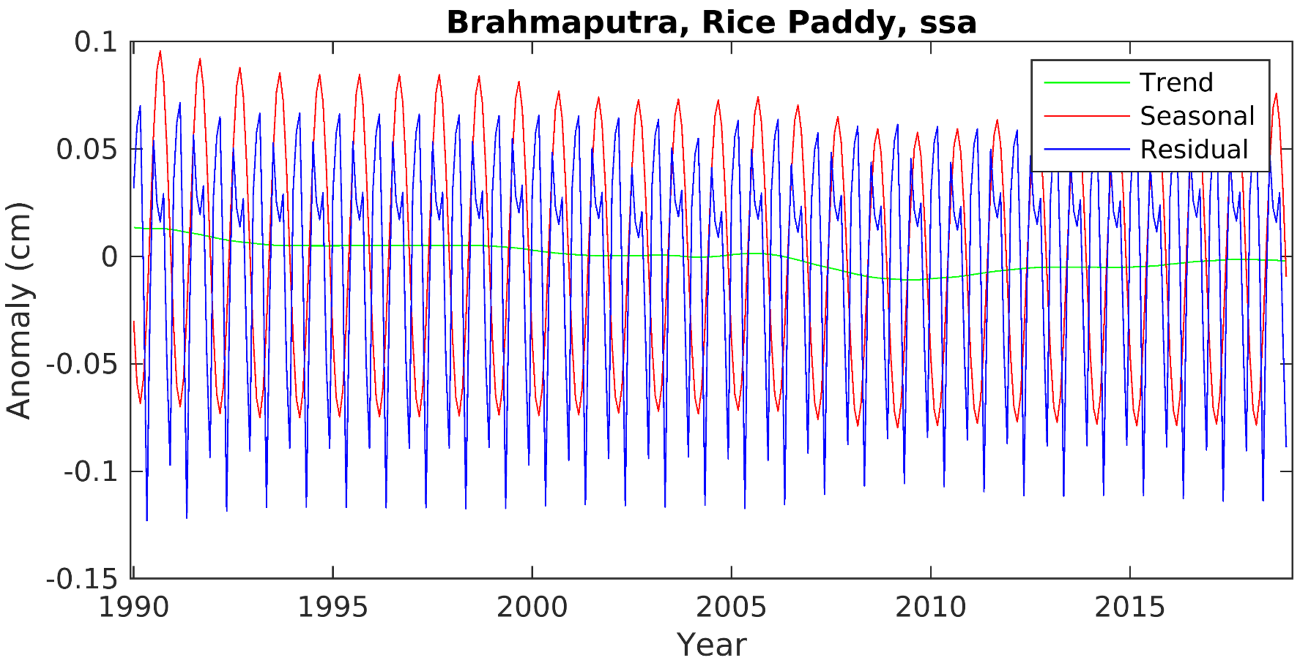

Brahmaputra, Aquifer, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
3
2
1
0
-1
-2
-3
1990
1995
2000
2005
2010
2015


Brahmaputra, Glacier, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
15
10
5
0
-5
-10
-15
-20
1990
1995
2000
2005
2010
2015

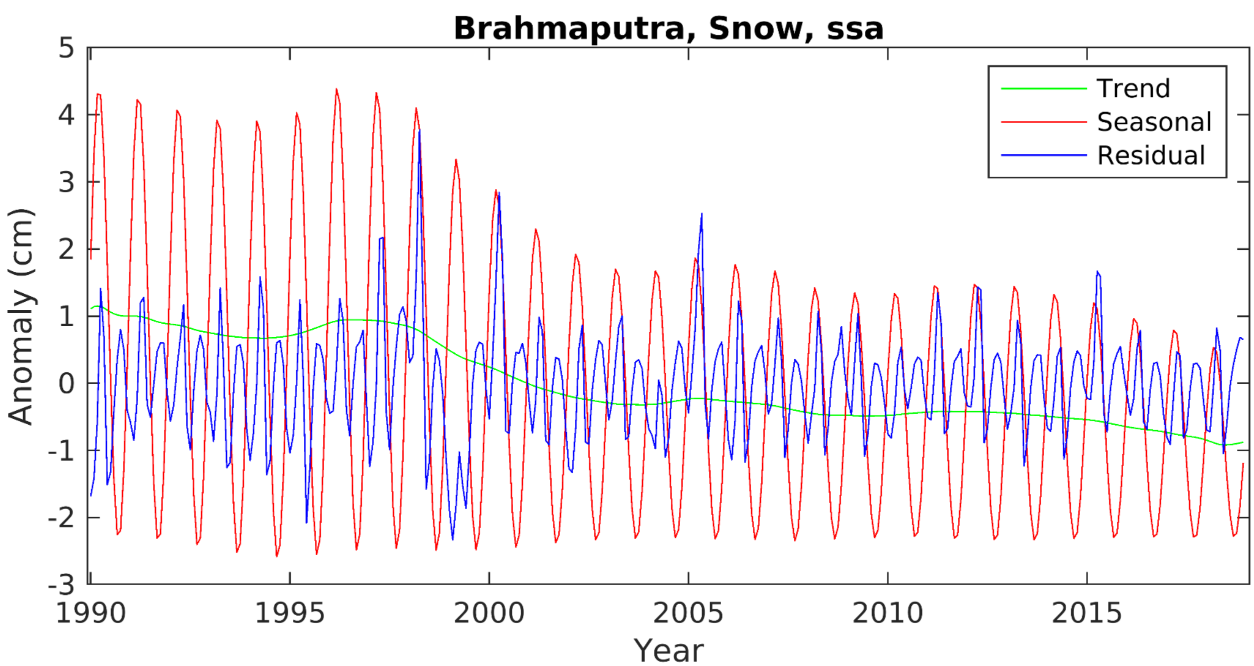

Brahmaputra, Groundwater, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
6
4
2
0
-2
-4
-6
1990
1995
2000
2005
2010
2015


Brahmaputra, Irrigation, ssa
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Anomaly (cm)
1990
1995
2000
2005
2010
2015
Year
Trend
Seasonal
Residual

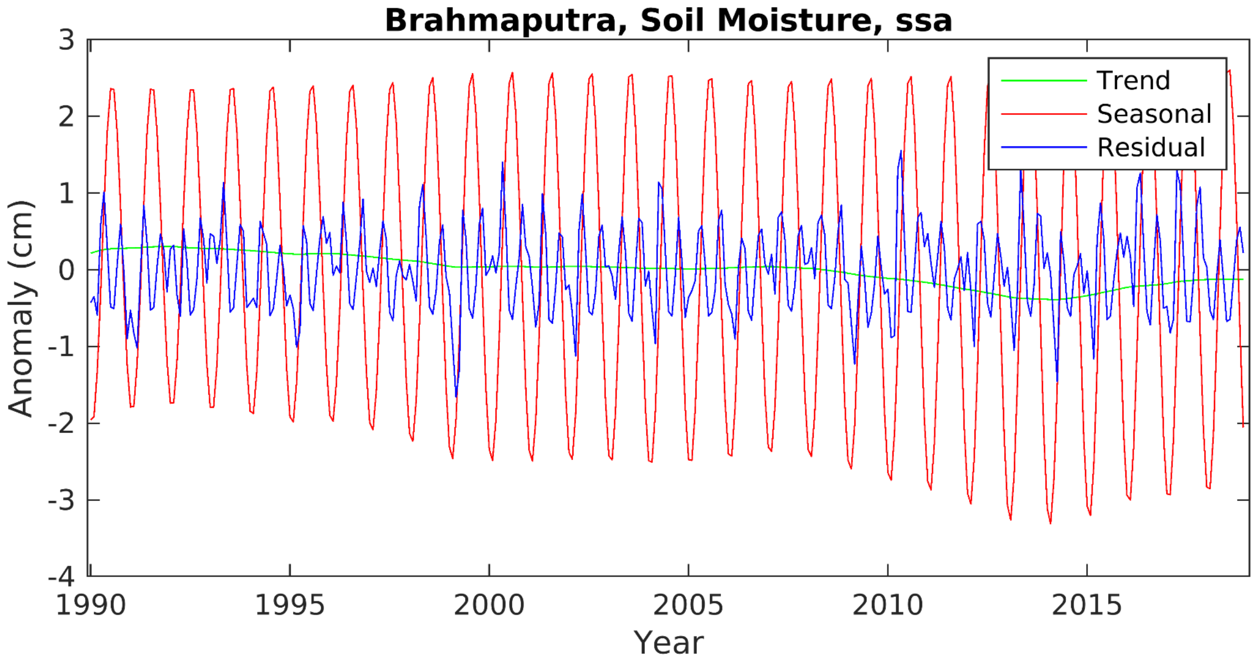

Brahmaputra, Reservoir, ssa
8
6
4
2
0
-2
-4
-6
Anomaly (cm)
1990
1995
2000
2005
2010
2015
Year
Trend
Seasonal
Residual



Brahmaputra, Rice Paddy, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
0.1
0.05
0
-0.05
-0.1
-0.15
1990
1995
2000
2005
2010
2015



Brahmaputra, Snow, ssa
Trend
Seasonal
Residual
Anomaly (cm)
Year
5
4
3
2
1
0
-1
-2
-3
1990
1995
2000
2005
2010
2015



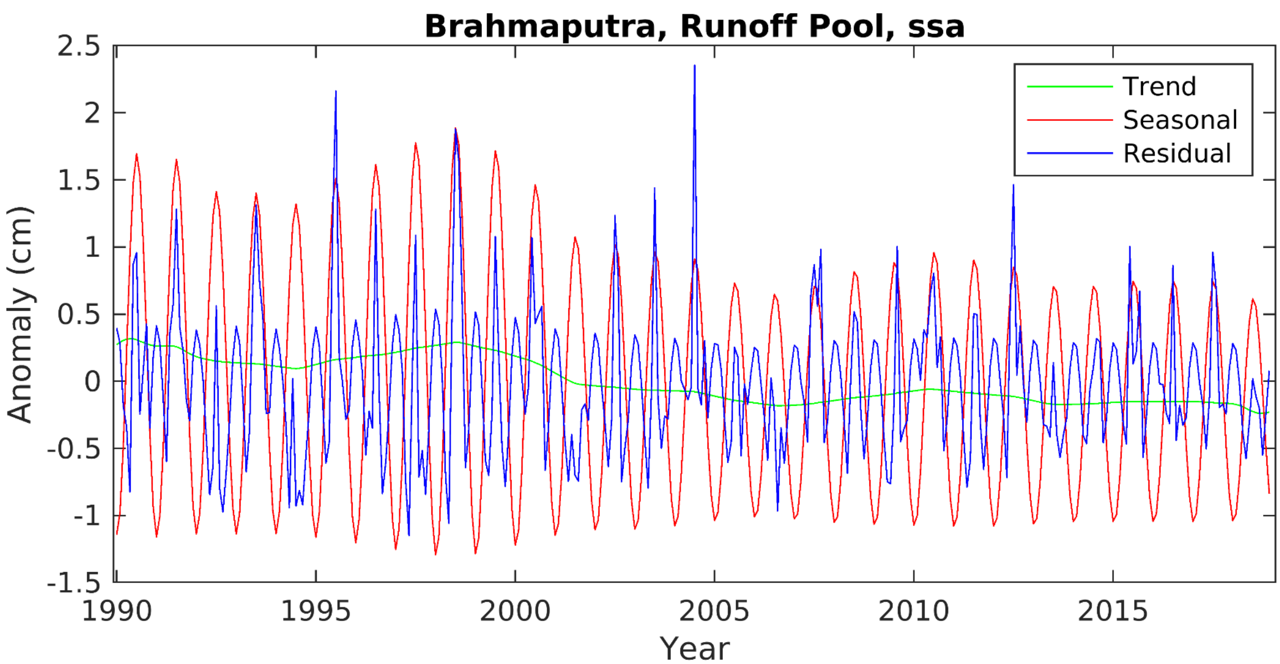


Figure S7. Singular spectral analysis (SSA) decomposition of trend and seasonal signals of total water storage (TWS) and its nine contributing components in Brahmaputra basin.

b. Evaluation of TWS long term trend (**Figure S8**) and Seasonal variability (**Figure S9**) contributions from TWS components

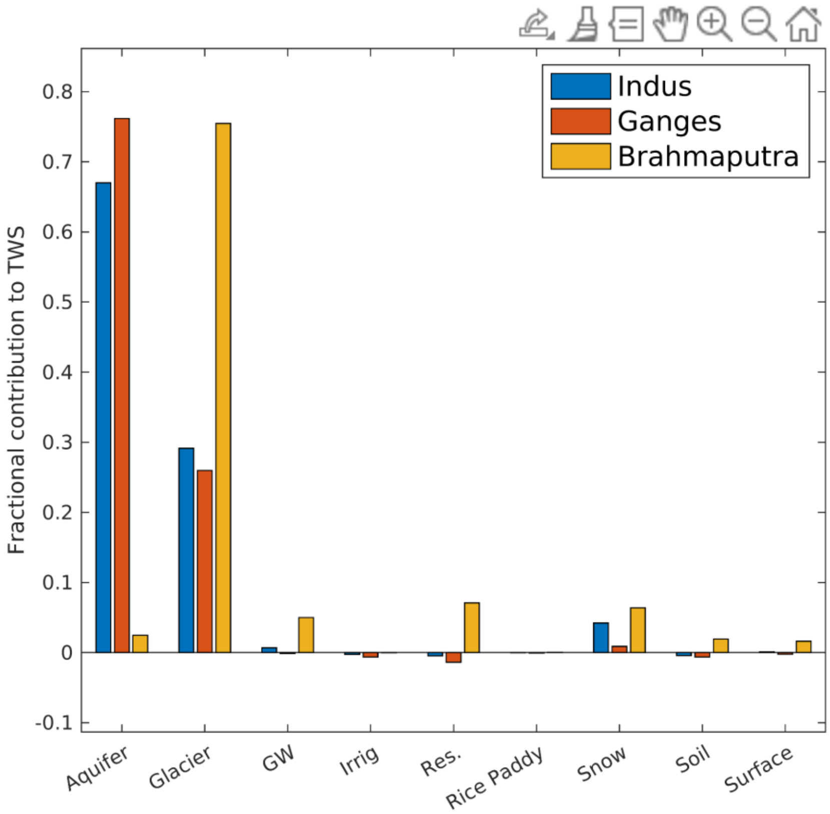


Figure S8. Contribution of specific water storage components to the total water storage (TWS) trends for the three study basins from results of the SSA time series decomposition. Y-axis is the contribution, defined as the ratio of delta-Y change over 1990-2018 of straight lines fit to classically estimated trend components of the variables on x-axis to the corresponding change in trend component of TWS. Fractional components in a given basin have been normalized to sum to 1 before plotting.

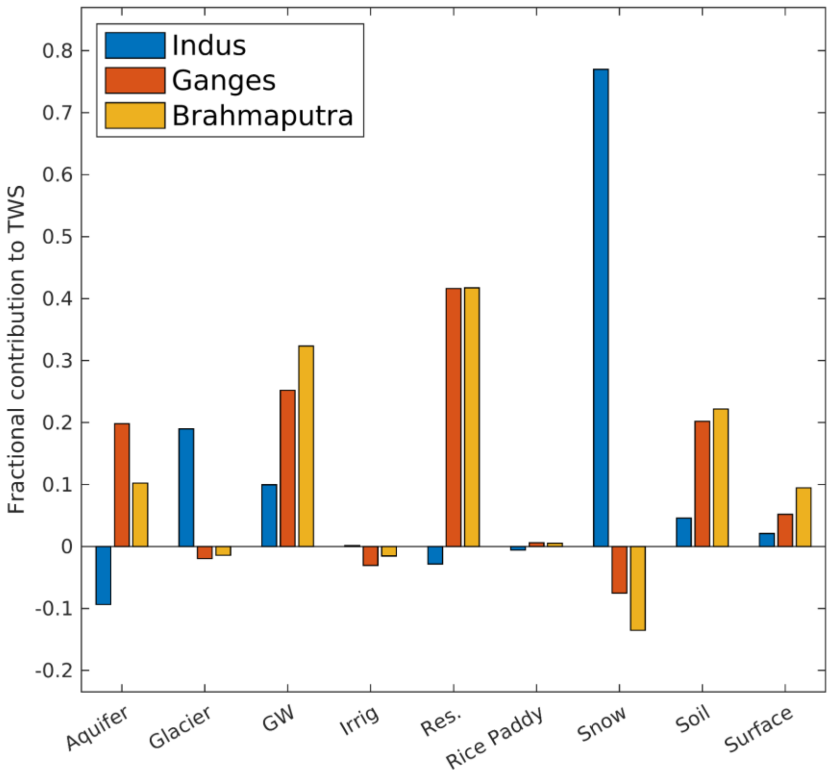


Figure S9. Contribution of water storage components to the total water storage (TWS) seasonal variability for the three study basins from results of the SSA time series decomposition. Fractional components normalized to sum to 1 for each basin.

S3. Additional figures

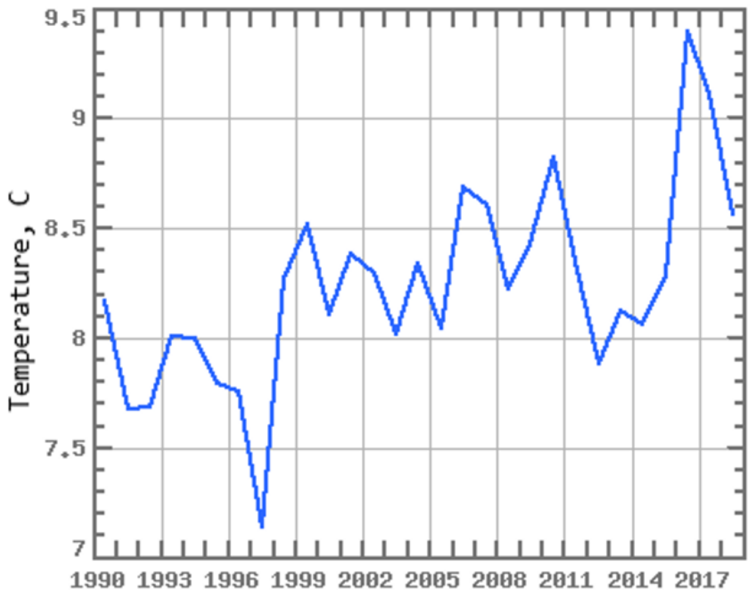


Figure S10. Average ERA5 temperature (2-meter above surface, in Celsius) for elevations above 2000 m in the Indus basin.

S4. Streamflow validation

WBM streamflow validation analysis for the IGB-TWS simulation was carried out using a standard WBM validation tool (WBM Contributors, 2022) by matching the simulated to observed streamflow from Global GRDC data (GRDC, 2025) which has 7 sites within the study domain. The Nash-Sutcliffe Coefficient for those ranges between 0.68 and 0.97 which indicates a statistically valid and good match. Archive file of the Web page for the validation output is attached to this publication as a supplementary file "***WBM_Validation_by_Streamflow.zip***". Its use instructions are -

1. Uncompress the WBM_Validation_by_Streamflow.zip file which creates the "*WBM_Validation_by_Streamflow*" folder in a user selected directory.
2. Double click on the "***index.html***" file in the uncompressed folder which opens the validation results in the user default Web browser.

S5. Comparison of modeled and observed groundwater and aquifer storages

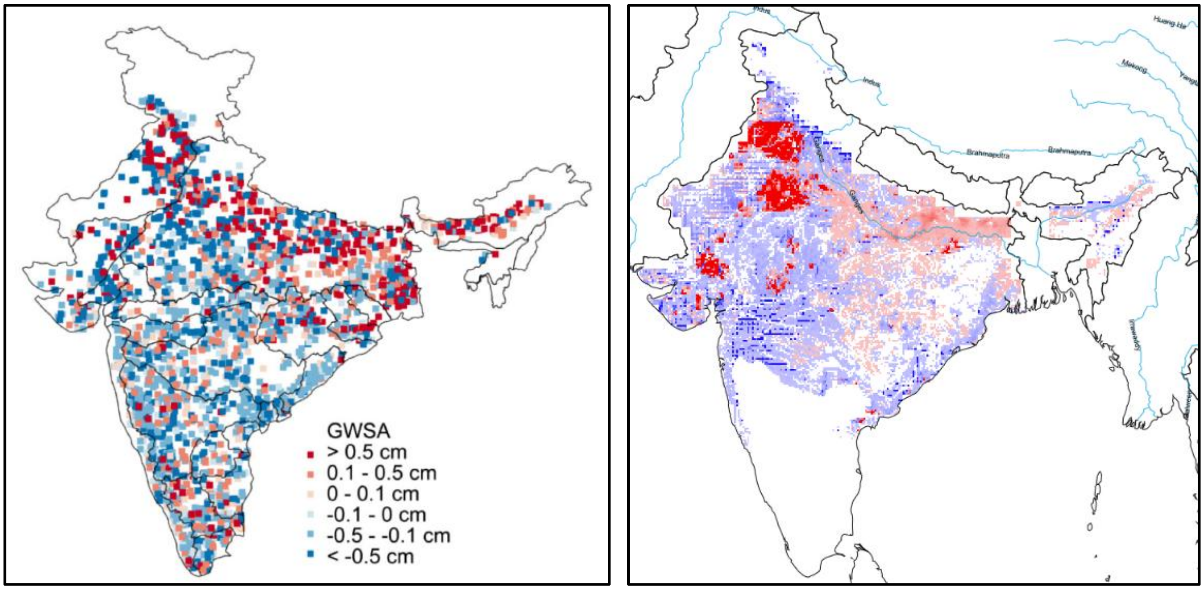


Figure S11. A qualitative comparison of spatial patterns for the groundwater storage changes by in-situ well data (Bhanja et al., 2020) (left panel) vs. the model output data (right panel) which indicates a reasonable match.

The comparison of ground-based groundwater level measurements in terms of the metric of groundwater storage anomalies ($GWSA_{obs}$) and GRACE mascons ($GWSA_{MS}$), both from (Bhanja et al., 2020), and those aggregated from WBM simulated aquifers for India portions of the simulation domain ($GWSA_{WBM}$) is given in **Table S1**.

Table S1. Comparison of observed ($GWSA_{obs}$) and modeled ($GWSA_{wbm}$) basin-wide aquifer storage trends

Basin's Domain (Bhanja et al., 2020)	$\mathbf{GWSA_{obs}}$ (Bhanja et al., 2020)	$\mathbf{GWSA_{WBM}}$ This study	$\mathbf{GWSA_{MS}}$ (Bhanja et al., 2020)
Indus	1.06	0.86	-1.52
Ganges	-1.02	-4.87	-13.81
Brahmaputra	-0.40	0.16	-5.56

Notes for data in **Table S1**:

1) GWSA units are km^3/year.
2) Basin area corresponds to those from Table 1 of (Bhanja et al., 2020) with indices of Indus, Ganges, and Brahmaputra being 1, 2a, and 2b which include only country of India portions of the indicated river watersheds.
3) Values in the column $GWSA_{WBM}$ are calculated from WBM simulated aquifer storages for the corresponding portions of the IGB basins reported in (Bhanja et al., 2020).
4) Values in the column $GWSA_{obs}$ and $GWSA_{MS}$ are taken from Table 2 of (Bhanja et al., 2020). Note, according to (Bhanja et al., 2020), the GRACE mascon anomalies ($GWSA_{MS}$) correspond solely to aquifers while this study found it to be impacted by changes in glacier water storages and other TWS

components. The latter explains a higher deviation of $GWSA_{MS}$ from the $GWSA_{obs}$ as compared to WBM aquifer data which fits better to the observations.

5) The range of trend years is 2003-2014 which corresponds to those in (Bhanja et al., 2020).

S6. Spreadsheet of the data and calculations

File attachment with Excel spreadsheet "***WBM_IGB_TWS_v4.xlsx***". Content:

- WBM simulation output data for Total Water Storage and its components (see **Table 1** of the paper) for Indus, Ganges, and Brahmaputra basins
- Calculations and results of Classical time series decomposition time series data for all items above
- Graphs based on the data and calculations above used in this paper
- WBM simulation metadata