**Supplementary materials (SM)**

**Multi-model approach to quantify groundwater level prediction uncertainty using an ensemble of global climate models and multiple abstraction scenarios**

Syed M. Touhidul Mustafa 1,\*, M. Moudud Hasan1, Ajoy Kumar Saha1, Rahena Parvin Rannu1, Els Van Uytven2, Patrick Willems 1,2 and Marijke Huysmans 1

\* Correspondence to: Syed Md Touhidul Mustafa (syed.mustafa@vub.be)

**Supplementary materials (SM)**

Supplementary materials (SM)-1: Study area

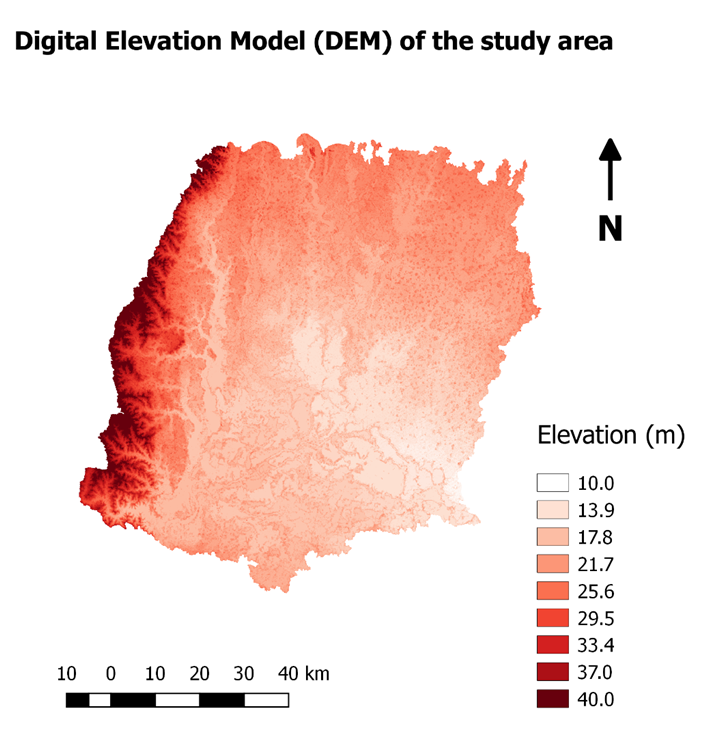


Figure S1: Digital Elevation Model (DEM) of the study area.

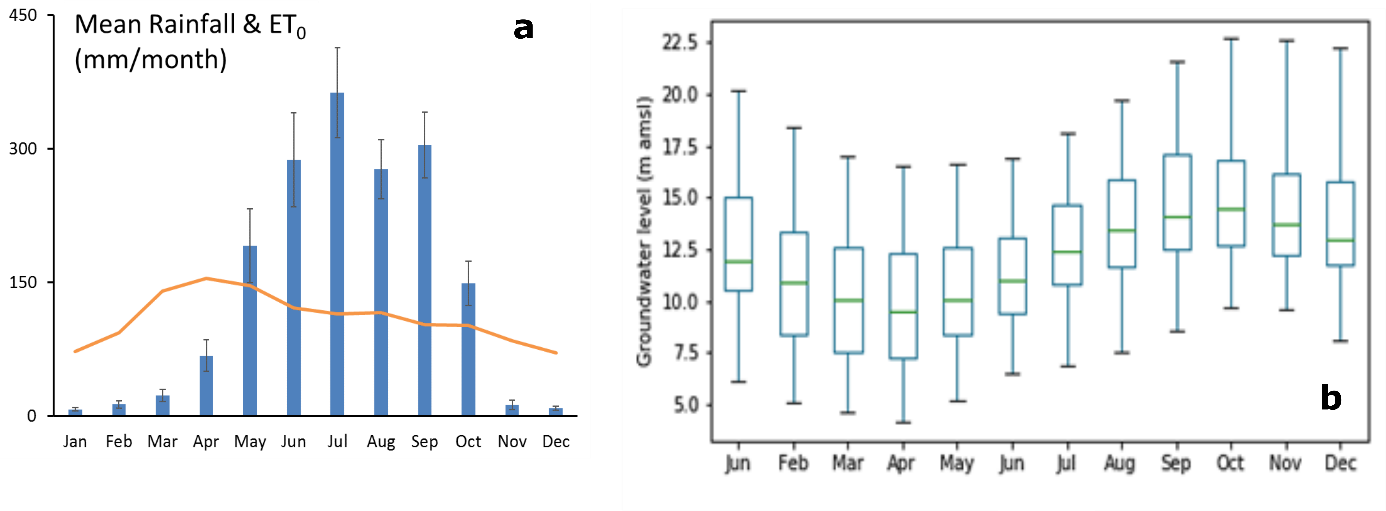


Figure S2: a: Average monthly ET0 amounts (calculated, line) and average monthly precipitation amounts (measured, bars), b: groundwater level (measured, box-plots) distribution of the study area. The boxplot shows the variation of groundwater level in different observation wells in the study area. The green line in the middle of the box represents the median value of the mean monthly groundwater level.



Figure S3: Time series of annual groundwater depth of the study area (box plots), including average (blue line).

Supplementary materials (SM)-2: alternative conceptual groundwater flow models

Table S1: List of alternative conceptual models developed based on different layer types and boundary conditions.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Sl. No. | Layer type | Boundary condition | Model ID | No of parameters | Name of the Parameters |
| 1 | One-layered (L1) | Boundary condition-1 (B1) | L1B1 | 3 | Horizontal hydraulic conductivity  Specific yield  Specific storage |
| 2 | Boundary condition-2 (B2) | L1B2 |
| 3 | Boundary condition-3 (B3) | L1B3 |
| 4 | Boundary condition-4 (B4) | L1B4 |
| 5 | Boundary condition-5 (B5) | L1B5 |
| 6 | Two-layered (L2) | Boundary condition-1 (B1) | L2B1 | 8 | Horizontal hydraulic conductivity-1, 2; Vertical hydraulic conductivity-1, 2; Specific yield-1, 2; Specific storage-1, 2.  Where 1 and 2 are representing 1st and 2nd layer. |
| 7 | Boundary condition-2 (B2) | L2B2 |
| 8 | Boundary condition-3 (B3) | L2B3 |
| 9 | Boundary condition-4 (B4) | L2B4 |
| 10 | Boundary condition-5 (B5) | L2B5 |
| 11 | Three-layered (L3) | Boundary condition-1 (B1) | L3B1 | 12 | Horizontal hydraulic conductivity-1, 2, 3; Vertical hydraulic conductivity-1, 2, 3; Specific yield-1, 2, 3; Specific storage-1, 2, 3.  Where 1, 2 and 3 are representing 1st , 2nd and 3rd layer. |
| 12 | Boundary condition-2 (B2) | L3B2 |
| 13 | Boundary condition-3 (B3) | L3B3 |
| 14 | Boundary condition-4 (B4) | L3B4 |
| 15 | Boundary condition-5 (B5) | L3B5 |

Table S2: List of optimized parameters of one-layered models with optimized value.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | | Parameters | |  |
| Horizontal hydraulic conductivity, Hk (m/s) | Specific yield, Sy (-) | Specific storage, Ss (m-1) |
| Initial value | | 1.05 ×10-03 | 0.25 | 9.40×10-05 |
| Range | | 7×10-10 to 6×10-03 | 0.02 to 0.35 | 4.92×10-05 to2.56×10-03 |
| Optimized value | L1B1 | 6.00×10-03 | 0.35 | 2.56×10-03 |
| L1B2 | 6.00×10-03 | 0.35 | 2.56×10-03 |
| L1B3 | 6.00×10-03 | 0.35 | 1.39×10-04 |
| L1B4 | 6.00×10-03 | 0.35 | 4.92×10-05 |
| L1B5 | 4.45×10-03 | 0.35 | 4.92×10-05 |

Table S3: List of optimized parameters of two-layered models with optimized value.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Layer | Parameters | Initial value | Range | |  | Optimized value | | | | |
| Minimum | Maximum |  | L2B1 | L2B2 | L2B3 | L2B4 | L2B5 |
| Top layer | 1. Horizontal hydraulic conductivity (m s-1) | 4.6×10-06 | 7×10-10 | 4.6×10-06 |  | 2.54×10-08 | 2.59×10-06 | 4.42×10-09 | 1.10×10-08 | 4.94×10-08 |
| 2. Vertical hydraulic conductivity (m s-1) | 9.9×10-08 | 7×10-11 | 4.6×10-07 |  | 1.18×10-08 | 1.10×10-08 | 1.05×10-08 | 1.20×10-08 | 1.03×10-08 |
| 3. Specific yield (-) | 0.18 | 0.02 | 0.19 |  | 0.19 | 0.19 | 0.19 | 0.19 | 0.19 |
| 4. Specific storage(m-1) | 1.74×10-03 | 9.19×10-04 | 2.56×10-03 |  | 9.19×10-04 | 9.19×10-04 | 9.19×10-04 | 9.19×10-04 | 9.19×10-04 |
| Bottom layer | 5. Horizontal hydraulic conductivity (m s-1) | 1.25×10-03 | 3×10-04 | 6×10-03 |  | 5.28×10-03 | 2.91×10-03 | 6.00×10-03 | 6.00×10-03 | 5.45×10-03 |
| 6. Vertical hydraulic conductivity (m s-1) | 1.25×10-04 | 3×10-05 | 6×10-04 |  | 6.00×10-04 | 6.00×10-04 | 6.00×10-04 | 6.00×10-04 | 5.63×10-04 |
| 7. Specific yield (-) | 0.25 | 0.10 | 0.35 |  | 0.35 | 0.35 | 0.35 | 0.35 | 0.35 |
| 8. Specific storage(m-1) | 9.40×10-05 | 4.92×10-05 | 1.02×10-03 |  | 1.02×10-03 | 4.54×10-04 | 5.19×10-04 | 5.48×10-04 | 5.72×10-04 |

Table S4: List of optimized parameters of three-layered models with optimized value.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Layer | Parameters | Initial value | Range | |  | Optimized value | | | | |
| Minimum | Maximum |  | L3B1 | L3B2 | L3B3 | L3B4 | L3B5 |
| Top layer | 1. Horizontal hydraulic conductivity (m s-1) | 4.6×10-06 | 7×10-10 | 4.6×10-06 |  | 8.26×10-09 | 4.18×10-09 | 8.44×10-08 | 2.54×10-06 | 3.76×10-06 |
| 2. Vertical hydraulic conductivity (m s-1) | 9.9×10-08 | 7×10-11 | 4.6×10-07 |  | 1.10×10-08 | 1.17×10-08 | 9.97×10-09 | 1.05×10-08 | 9.69×10-09 |
| 3. Specific yield (-) | 0.18 | 0.02 | 0.19 |  | 0.19 | 0.19 | 0.17 | 0.19 | 0.19 |
| 4. Specific storage(m-1) | 1.74×10-03 | 9.19×10-04 | 2.56×10-03 |  | 1.36×10-03 | 9.19×10-04 | 9.19×10-04 | 9.19×10-04 | 1.14×10-03 |
| Middle layer | 5. Horizontal hydraulic conductivity (m s-1) | 3×10-04 | 2×10-07 | 3×10-04 |  | 2.40×10-04 | 2.55×10-04 | 3.00×10-04 | 3.56×10-05 | 3.00×10-04 |
| 6. Vertical hydraulic conductivity (m s-1) | 3×10-05 | 2×10-08 | 8×10-05 |  | 7.97×10-05 | 5.07×10-06 | 5.07×10-06 | 8.00×10-05 | 8.00×10-05 |
| 7. Specific yield (-) | 0.25 | 0.10 | 0.32 |  | 0.32 | 0.32 | 0.32 | 0.32 | 0.32 |
| 8. Specific storage(m-1) | 5.74×10-04 | 1.28×10-04 | 1.3×10-03 |  | 1.02×10-03 | 1.02×10-03 | 1.02×10-03 | 1.02×10-03 | 1.02×10-03 |
| Bottom layer | 9. Horizontal hydraulic conductivity (m s-1) | 1.25×10-03 | 5.8×10-04 | 6×10-03 |  | 2.99×10-03 | 4.53×10-03 | 6.00×10-03 | 6.00×10-03 | 5.35×10-03 |
| 10. Vertical hydraulic conductivity (m s-1) | 1.25×10-04 | 3×10-05 | 6×10-04 |  | 6.00×10-04 | 6.00×10-04 | 1.49×10-04 | 6.00×10-04 | 6.00×10-04 |
| 11. Specific yield (-) | 0.32 | 0.15 | 0.35 |  | 0.35 | 0.31 | 0.35 | 0.35 | 0.35 |
| 12. Specific storage(m-1) | 9.40×10-05 | 4.92×10-05 | 2.03×10-04 |  | 2.03×10-04 | 2.03×10-04 | 2.03×10-04 | 2.03×10-04 | 2.03×10-04 |

Table S5: Model evaluation statistics for calibration and validation period.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Model  ID | Calibration period | | | |  | Validation period | | | |
| RMSE (m) |  | NSE |  |  | RMSE (m) |  | NSE |  |
| L1B1 | 2.27 |  | 0.55 |  |  | 2.62 |  | 0.45 |  |
| L1B2 | 2.26 |  | 0.55 |  |  | 2.72 |  | 0.41 |  |
| L1B3 | 2.27 |  | 0.55 |  |  | 2.71 |  | 0.42 |  |
| L1B4 | 2.19 |  | 0.58 |  |  | 2.70 |  | 0.42 |  |
| L1B5 | 2.31 |  | 0.53 |  |  | 2.74 |  | 0.40 |  |
|  |  |  |  |  |  |  |  |  |  |
| L2B1 | 2.15 |  | 0.60 |  |  | 2.60 |  | 0.46 |  |
| L2B2 | 2.25 |  | 0.56 |  |  | 2.59 |  | 0.47 |  |
| L2B3 | 2.02\* |  | 0.64\* |  |  | 2.66 |  | 0.44 |  |
| L2B4 | 2.03 |  | 0.64\* |  |  | 2.56 |  | 0.48 |  |
| L2B5 | 2.04 |  | 0.63 |  |  | 2.50\* |  | 0.50\* |  |
|  |  |  |  |  |  |  |  |  |  |
| L3B1 | 2.48 |  | 0.46 |  |  | 2.66 |  | 0.44 |  |
| L3B2 | 2.17 |  | 0.59 |  |  | 2.71 |  | 0.42 |  |
| L3B3 | 2.08 |  | 0.62 |  |  | 2.70 |  | 0.42 |  |
| L3B4 | 2.07 |  | 0.62 |  |  | 2.89 |  | 0.33 |  |
| L3B5 | 2.12 |  | 0.61 |  |  | 2.57 |  | 0.47 |  |

\*Best value

Table S6: Comparison of performance of BMA mean prediction with the best model and ensemble median for both calibration and validation period.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Method | Calibration period | | | |  | Validation period | | | |
| RMSE  (m) |  | NSE |  |  | RMSE  (m) |  | NSE |  |
| Best Model\* | 2.02 |  | 0.64 |  |  | 2.56 |  | 0.48 |  |
| Median | 2.01 |  | 0.65 |  |  | 2.53 |  | 0.49 |  |
| BMA | 1.97 |  | 0.66 |  |  | 2.30 |  | 0.58 |  |

\*Best model based on AIC, AICc, BIC and KIC value.

Supplementary materials (SM)-3: Climatic models

Table S7: Ensemble of climate models used in this study

|  |  |  |  |
| --- | --- | --- | --- |
| Institution | Climate model run | |  |
| Commonwealth Scientific and Industrial Research Organization/ Bureau of Meteorology (CSIRO-BOM) | ACCESS1.0 | r1i1p1 | RCP 8.5 |
| Beijing Climate Center, China Meteorological Administration | BCC-CSM1.1m | r1i1p1 | RCP 4.5, RCP 8.5 |
| College of Global Change and Earth System Science, Beijing Normal University | BNU-ESM | r1i1p1 | RCP 4.5 |
| Canadian Centre for Climate Modelling and Analysis | CanESM2 | r1/r2/r4/r5i1p1 | RCP 4.5, RCP 8.5 |
| Centro Euro-Mediterraneo per I Cambiamenti Climatici | CMCC-CESM | r1i1p1 | RCP 8.5 |
| CMCC-CMS | r1i1p1 | RCP 4.5, RCP 8.5 |
| Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique (CNRM/CERFACS) | CNRM-CM5 | r1i1p1 | RCP 4.5, RCP 8.5 |
| Commonwealth Scientific and Industrial Research Organization/ Queensland Climate Change Centre of Excellence (CSIRO-QCCCE) | CSIRO-Mk3.6.0 | r10i1p1 | RCP 4.5, RCP 8.5 |
| EC-EARTH consortium | EC-EARTH | r12i1p1 | RCP 4.5 |
| Geophysical Fluid Dynamics Laboratory | GFDL-ESM2G | r1i1p1 | RCP 8.5 |
| GFDL-ESM2M | r1i1p1 | RCP 8.5 |
| NASA Goddard Institute for Space Studies | GISS-E2-H | r6i1p3 | RCP 4.5 |
| GISS-E2-R | r6i1p1/p3 | RCP 4.5 |
| Met Office Hadley Centre | HadGEM2-ES | r1i1p1 | RCP 8.5 |
| Institute for Numerical Mathematics | INM-CM4 | r1i1p1 | RCP 4.5, RCP 8.5 |
| Institute Pierre-Simon Laplace | IPSL-CM5A-LR | r2i1p1 | RCP 4.5, RCP 8.5 |
| IPSL-CM5A-MR | r1i1p1 | RCP 4.5, RCP 8.5 |
| Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology | MIROC-ESM | r1i1p1 | RCP 4.5, RCP 8.5 |
| MIROC5 | r1i1p1 | RCP 8.5 |
| MIROC5 | r2/r3i1p1 | RCP 4.5, RCP 8.5 |
| Max Planck Institute for Meteorology (MPI-M), Germany | MPI-ESM-LR | r1i1p1 | RCP 4.5, RCP 8.5 |
| Meteorological Research Institute | MRI-CGCM3 | r1i1p1 | RCP 4.5, RCP 8.5 |

Table S8: 25th, 50th, 75th percentile changes in monthly precipitation amount, minimum, mean and maximum daily temperature and potential evapotranspiration for April and September (all GHSs combined, 1975-2035)

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | April | | | September | | |
| 25th | 50th | 75th | 25th | 50th | 75th |
| Monthly precipitation amount (%) | -19.80 | -8.20 | 11.70 | -0.60 | 11.10 | 17.00 |
| Minimum daily temperature (°C) | 1.33 | 1.74 | 2.00 | 1.06 | 1.35 | 1.72 |
| Mean daily temperature (°C) | 0.98 | 1.40 | 1.87 | 0.79 | 1.28 | 1.68 |
| Maximum daily temperature (°C) | 0.57 | 1.24 | 1.91 | 0.65 | 1.28 | 1.67 |
| Evapotranspiration (%) | -1.60 | 1.50 | 3.60 | -1.10 | 1.00 | 3.40 |

Supplementary materials (SM)-4: Trend analysis

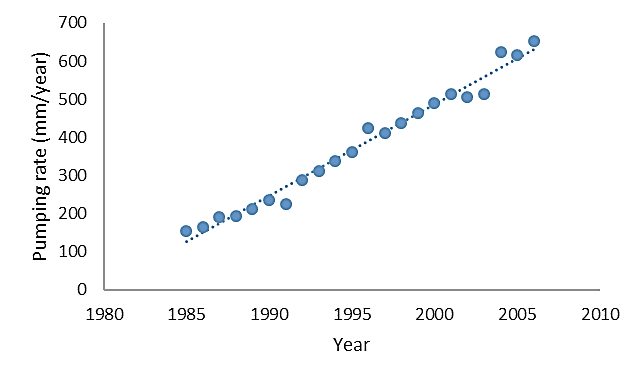


Figure S4: General groundwater abstraction trend in the study area from 1985 to 2006.

Table S9: Annual groundwater level trend in 50 observation wells for different abstraction scenarios (PLinear, PConstant, PReduced\_30) and recharge scenarios (Low, High) in the baseline (1985–2006) and simulated future (2026–2047) period.

| Observation Wells | Baseline period | Simulated future period | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| PLinear | |  | PConstant | |  | PReduced\_30 | |
| Low | High |  | Low | High |  | Low | High |
| Slope (m/year) | | | | | | | | |
| BOG001 | -0.15\* | -0.34\* | -0.31\* |  | -0.08\* | -0.06 |  | -0.04 | -0.04 |
| BOG004 | -0.49\* | -1.01\* | -0.95\* |  | -0.46\* | -0.37\* |  | -0.25\* | -0.14 |
| BOG009 | -0.15\* | -0.36\* | -0.34\* |  | -0.11\* | -0.07 |  | -0.06\* | -0.03 |
| BOG013 | -0.25\* | -0.49\* | -0.47\* |  | -0.21\* | -0.17\* |  | -0.12\* | -0.07 |
| BOG014 | -0.05\* | -0.09\* | -0.09\* |  | -0.04\* | -0.03 |  | -0.02 | -0.02 |
| JOY003 | -0.06\* | -0.07\* | -0.08\* |  | -0.03 | -0.03 |  | -0.02 | -0.01 |
| JOY005 | -0.21\* | -0.41\* | -0.40\* |  | -0.15\* | -0.13 |  | -0.09 | -0.05 |
| NAO001 | -0.07 | -0.22\* | -0.20\* |  | -0.07\* | -0.04\* |  | -0.04\* | -0.01 |
| NAO002 | -0.08\* | -0.16\* | -0.16\* |  | -0.03\* | -0.02 |  | -0.02 | -0.01 |
| NAO004 | -0.08 | -0.13\* | -0.13\* |  | -0.01 | -0.01 |  | -0.01 | -0.01 |
| NAO008 | -0.08\* | -0.11\* | -0.11\* |  | -0.01 | -0.01 |  | -0.01 | -0.01 |
| NAO009 | -0.10 | -0.13\* | -0.13\* |  | -0.01 | -0.01 |  | -0.01 | -0.01 |
| NAO013 | -0.06 | -0.06\* | -0.06\* |  | -0.01 | -0.01 |  | -0.01 | -0.01 |
| NAO014 | -0.12 | -0.18\* | -0.17\* |  | -0.03\* | -0.03 |  | -0.02 | -0.02 |
| NAO015 | -0.19 | -0.40\* | -0.38\* |  | -0.06 | -0.03 |  | -0.03 | -0.01 |
| NAO018 | -0.23 | -0.38\* | -0.36\* |  | -0.14\* | -0.09 |  | -0.08\* | -0.05 |
| NAO019 | -0.15 | -0.30\* | -0.27\* |  | -0.06\* | -0.03 |  | -0.03 | -0.01 |
| NAO020 | -0.19 | -0.35\* | -0.33\* |  | -0.04 | -0.02 |  | -0.02 | -0.01 |
| NAO021 | -0.25 | -0.50\* | -0.44\* |  | -0.22\* | -0.14\* |  | -0.13\* | -0.06 |
| NAO022 | -0.14 | -0.32\* | -0.28\* |  | -0.08\* | -0.03 |  | -0.03 | -0.01 |
| NAO023 | -0.24 | -0.57\* | -0.52\* |  | -0.27\* | -0.18\* |  | -0.16\* | -0.07 |
| NAO024 | -0.40 | -1.15\* | -1.09\* |  | -0.55\* | -0.38\* |  | -0.32\* | -0.13\* |
| NAO026 | -0.14 | -0.25\* | -0.24\* |  | -0.03 | -0.02 |  | -0.02 | -0.01 |
| NAO027 | -0.14 | -0.27\* | -0.26\* |  | -0.05\* | -0.02 |  | -0.02 | -0.01 |
| NAO031 | -0.30\* | -0.25\* | -0.23\* |  | -0.40\* | -0.33\* |  | -0.27\* | -0.21\* |
| NAO035 | -0.18\* | -0.15\* | -0.14\* |  | -0.11\* | -0.09\* |  | -0.08\* | -0.05 |
| NAO036 | -0.23 | -0.25\* | -0.23\* |  | -0.15\* | -0.11\* |  | -0.10\* | -0.07 |
| NAO040 | -0.15\* | -0.18\* | -0.17\* |  | -0.05\* | -0.04 |  | -0.03 | -0.03 |
| NAO043 | -0.27 | -0.29\* | -0.28\* |  | -0.26\* | -0.20\* |  | -0.18\* | -0.12\* |
| NAO047 | -0.14\* | -0.29\* | -0.28\* |  | -0.05\* | -0.03 |  | -0.03 | -0.03 |
| NAO048 | -0.18\* | -0.36\* | -0.34\* |  | -0.06\* | -0.05 |  | -0.04 | -0.04 |
| RAJ001 | -0.23 | -1.54\* | -1.30\* |  | -0.44\* | -0.23\* |  | -0.23\* | -0.05 |
| RAJ002 | -0.26 | -1.15\* | -0.99\* |  | -0.44\* | -0.26\* |  | -0.24\* | -0.06 |
| RAJ003 | -0.20 | -0.98\* | -0.84\* |  | -0.34\* | -0.19\* |  | -0.18\* | -0.04 |
| RAJ004 | -0.29 | -1.66\* | -1.41\* |  | -0.57\* | -0.32\* |  | -0.30\* | -0.07 |
| RAJ005 | -0.29 | -3.35\* | -2.87\* |  | -0.89\* | -0.53\* |  | -0.46\* | -0.12\* |
| RAJ006 | -0.50 | -2.29 | -2.80\* |  | -1.01\* | -0.53\* |  | -0.48\* | -0.10\* |
| RAJ015 | -0.39 | -2.74\* | -2.28\* |  | -0.83\* | -0.47\* |  | -0.43\* | -0.11 |
| RAJ020 | -0.67 | -3.89\* | -3.68\* |  | -1.88\* | -1.54\* |  | -1.13\* | -0.79\* |
| RAJ021 | -0.72 | -3.80\* | -3.57\* |  | -1.65\* | -1.30\* |  | -0.99\* | -0.65\* |
| RAJ024 | -0.66 | -3.89\* | -3.71\* |  | -1.84\* | -1.48\* |  | -1.10\* | -0.76\* |
| RAJ030 | -0.47 | -1.59\* | -1.49\* |  | -0.76\* | -0.51\* |  | -0.42\* | -0.18\* |
| RAJ031 | -0.63 | -1.96\* | -1.92\* |  | -1.12\* | -0.78\* |  | -0.62\* | -0.29\* |
| RAJ035 | -0.37 | -3.29\* | -2.74\* |  | -0.86\* | -0.48\* |  | -0.44\* | -0.09\* |
| RAJ036 | -0.38 | -3.40\* | -2.91\* |  | -0.98\* | -0.60\* |  | -0.52\* | -0.16\* |
| RAJ038 | -0.41 | -3.41\* | -2.95\* |  | -1.02\* | -0.63\* |  | -0.55\* | -0.18\* |
| RAJ041 | -0.33 | -2.54\* | -2.15\* |  | -0.65\* | -0.35\* |  | -0.34\* | -0.07 |
| RAJ042 | -0.21 | -1.47\* | -1.23\* |  | -0.39\* | -0.21\* |  | -0.21\* | -0.04 |
| RAJ043 | -0.22 | -2.00\* | -1.67\* |  | -0.50\* | -0.27\* |  | -0.27\* | -0.05 |
| RAJ046 | -0.90 | -1.72 | -2.29 |  | -1.37\* | -1.02\* |  | -0.74\* | -0.43\* |

\*The trend is significant at 0.05 level.