Supplementary Information:

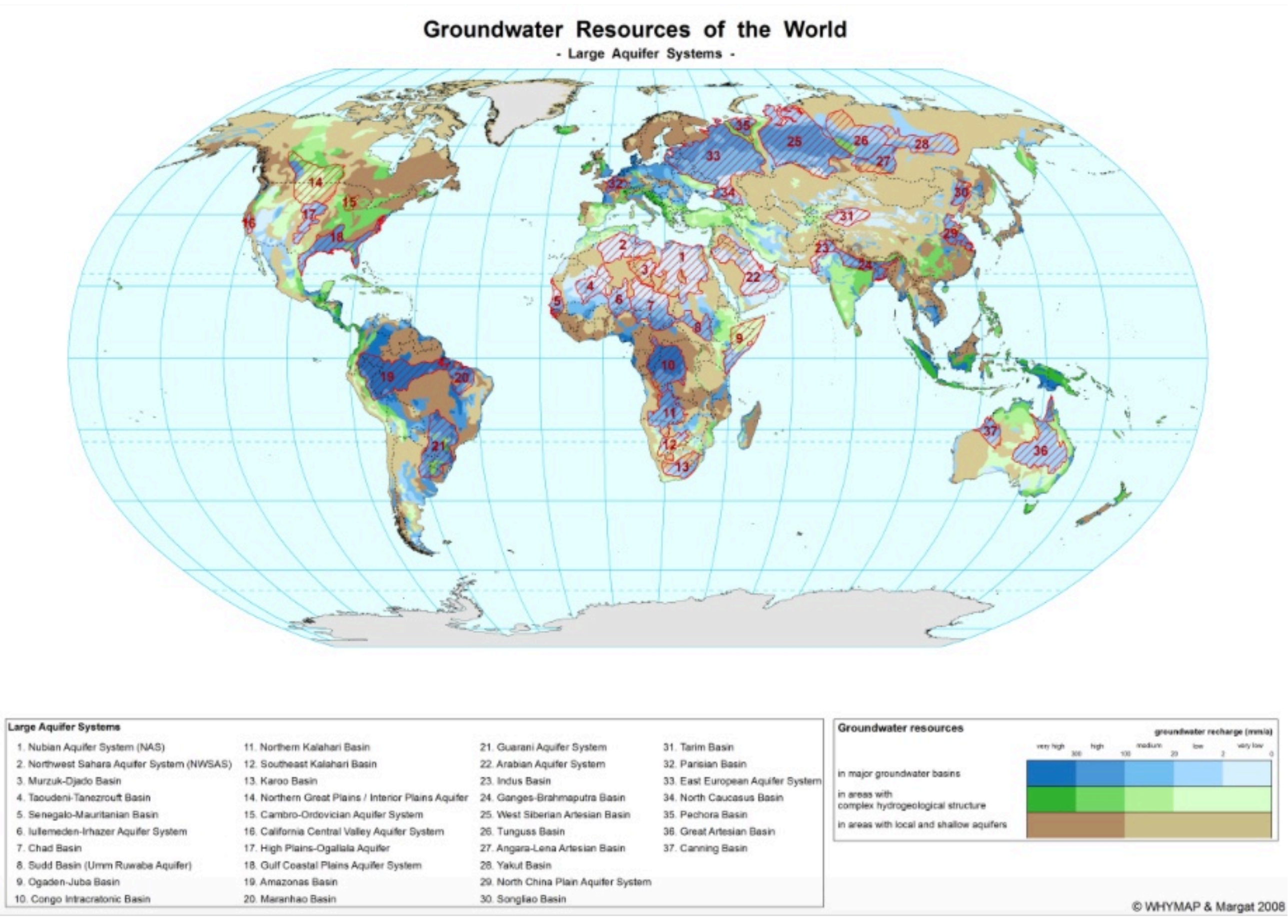
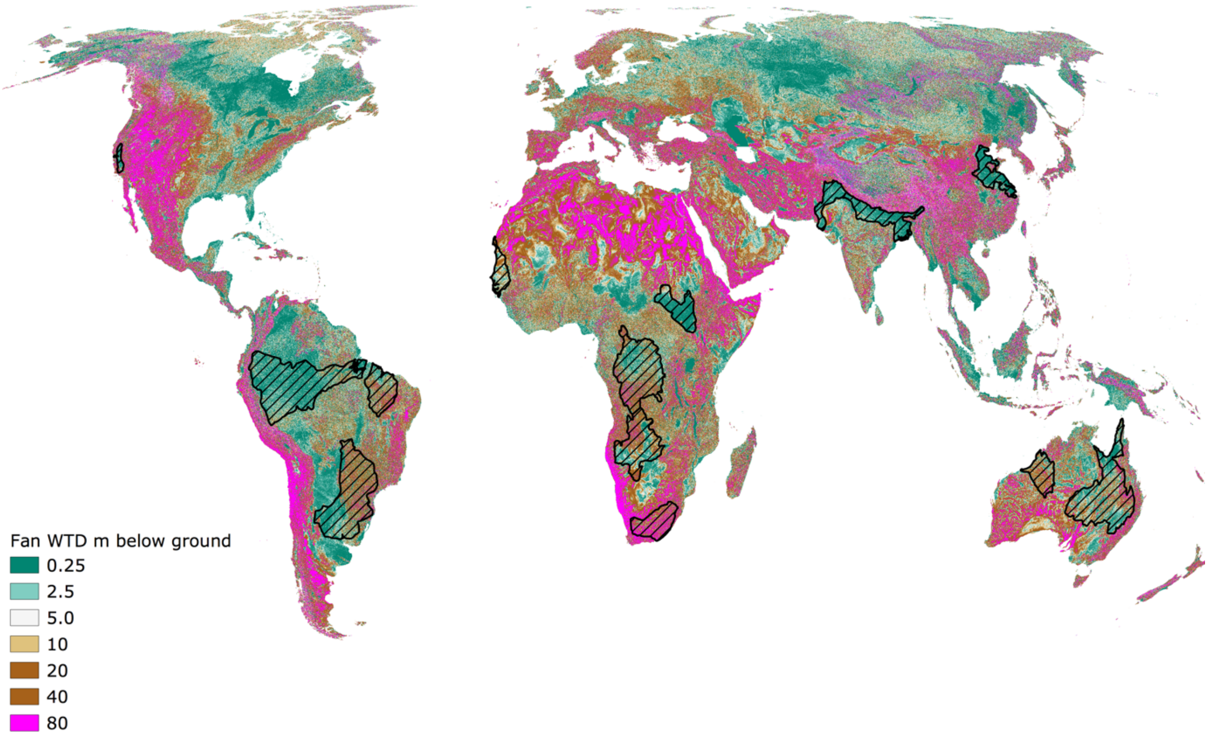
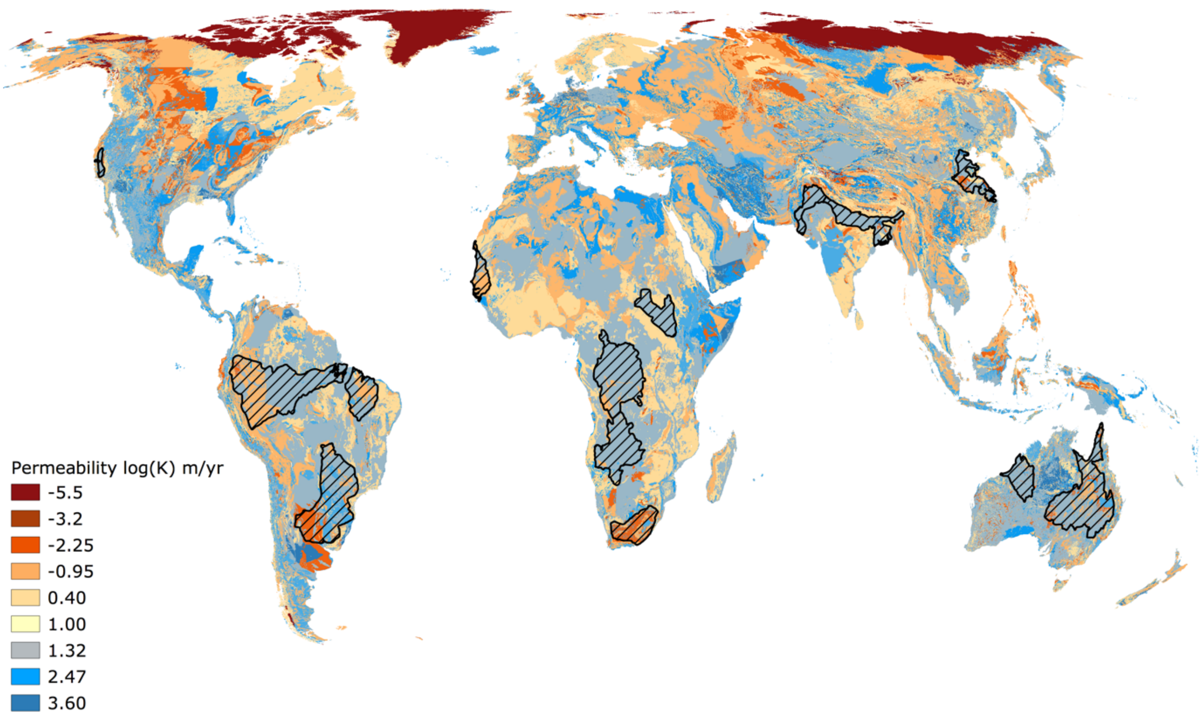


Figure S1: 37 Large Aquifer Systems of the World. *Map ©WHYMAP & Margat 2008* a)



Fan WTD m below ground
0.25
2.5
5.0
10
20
40
80

b)



Permeability log(K) m/yr
-5.5
-3.2
-2.25
-0.95
0.40
1.00
1.32
2.47
3.60

c)

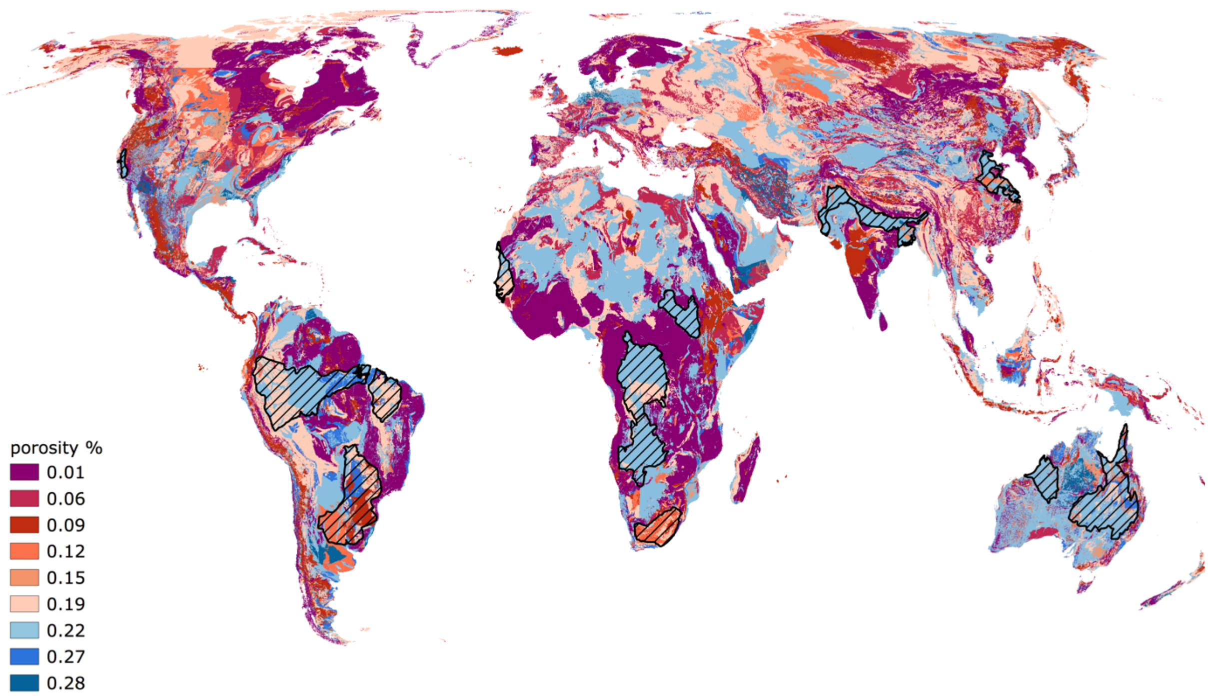


Figure S2: a) WTD *[original dataset from: (Fan et al., 2013)]* b) Hydraulic Conductivity *[original dataset from: (Gleeson et al., 2014)],* c) Porosity *[original dataset from: (Gleeson et al., 2014)]* – all datasets sourced as noted.

Aquifer	Aridity Class	GRT: *log (GRT) [GRT in yrs]*	WTD: *Meters below surface*	Hydraulic Conductivity (K): *log(K) [K in m yr^{-1}]*	Porosity: *%/100*
Upper Kalahari	Semi-Arid	2.95	16.70	1.40	0.21
Karoo	Semi-Arid	5.74	53.51	-0.73	0.14
Senegal	Semi-Arid	5.70	9.68	0.13	0.20
California Central Valley	Semi-Arid	3.01	17.86	1.26	0.21
Great Artesian	Arid	6.33	12.86	0.97	0.21
North China Plains	Dry Sub-Humid	2.74	4.62	0.91	0.19
Umm Ruwaba	Semi-Arid	4.42	2.44	1.45	0.21
Congo	Humid	2.12	15.80	1.26	0.21
Maranhao	Humid	2.55	17.50	0.71	0.20
Indus River	Arid	3.96	4.20	1.32	0.21
Amazon	Humid	2.03	3.08	0.76	0.21
Guarani	Humid	2.20	15.93	0.68	0.16
Ganges-Brahmaputra	Humid	2.10	3.22	1.34	0.21
Canning	Arid	6.46	20.94	1.36	0.21

Table S1: Summary of geomorphological statistics for each aquifer. GRT dataset is skewed so median average is used. All others are mean average. Statistics extracted using QGIS.

Anomalous Climate-Groundwater relationships – Karoo, Maranhao and Guarani aquifer systems:

Figure S2 and **Table S1** show WTD, K and Φ which are direct measures of the physical characteristics of the 14 large-scale aquifer systems. The Karoo Basin has, by a considerable degree, the deepest WTD and the lowest K and Φ of any of the studied aquifers (MacDonald et al., 2012). Despite these exceptional characteristics the anomalously long 7-month lag time between PCP and ΔTWS found for this basin is best explained by the lag between heavy rains that fall in the Angolan Highlands and focused recharge via leakage from the Okavango Delta supplying the northern side of the Karoo Supergroup (Wolski and Murray-Hudson, 2005). Climate-Groundwater responses in the humid Maranhao and Guarani Basins are complicated by regional-scale hydrogeological variations that include relatively deep WTD (both), spatially variable K (both) and low Φ (Guarani). In particular, the Guarani has a complex geomorphology and is separated into two geologically contrasting zones with rapid GRT/deep WTD/greater permeability in the north and slow GRT/shallow WTD/lesser permeability in the south. Approximately 80% of groundwater abstraction from the Guarani aquifer is concentrated in the northern zone (Foster et al, 2009), leaving this section of the aquifer more vulnerable to seasonal variability. This characteristic may explain why the Guarani ΔGWS shows a relatively poor correlation with monthly PCP but a strong correlation with the annual PCPA signal.

Groundwater Storage Decline – Indus River and Canning Basins:

The Indus River Basin has been described as "the most overstressed aquifer system in the world" (Lutz et al., 2016) based on the extent to which the requirement for water for irrigation outstrips precipitation; the basin supports a population of ~210 million people (Immerzeel et al., 2010). Immerzeel et al. (2010) estimate that for the period 2001-2007 this imbalance was more than a factor of 2:1 with average annual precipitation of 423 mm and annual irrigation demand of 908 mm EWH. The basin relies primarily on precipitation in the mountainous upstream area for downstream supply, where recharge of GW in low-lying areas has been estimated to be less than 5 mm per year (Döll et al., 2016; Immerzeel et al., 2012; Miller et al., 2012; Wanders and Wada, 2015). Several major dams exist in the basin catchment to exploit river flows supplied from the Tibetan plateau that include a combination of precipitation and glacier meltwater. The latter of which has been shown to be particularly important to the hydrology of the Indus River Basin (Immerzeel et al., 2010). These dams supply water for extensive irrigation schemes and provide hydroelectric power. The hydrology of the Indus Basin is therefore significantly influenced by human intervention and Cheema et al. (2014) have estimated that in 2007 groundwater depletion in the basin amounted to an annual loss of 121 mm EWH based on a combination of direct observational data and modelled analysis (Cheema et al., 2014).

This study has assessed the GRT of the Indus Basin to be ~9,150 years (Table 4), which suggests that the GRACE/CLM ΔGWS should correlate strongly with annual (HY) ∫PCPA. However, from Table 3 the correlation is not statistically significant, although the PCC is 0.89 if just the period from 2008 is considered. A 'thought experiment' was conducted to investigate the relationship further, given that the slow GRT can be considered robust within the limits of uncertainty previously noted, perhaps as much as 2 orders of magnitude due to the uncertainty of the hydraulic conductivity (K) values (Cuthbert et al., 2019, 2019). Firstly, to increase the HM length of the ∫PCPA dataset a time series of monthly PCP anomalies from the CRU TS4.03 0.5º dataset (Climate Research Unit, University of East Anglia, 2019) for the period 1996-2016 was obtained for the Indus River Basin aquifer from KNMI Climate Explorer (KNMI Climate Explorer, 2018). This extends the timestep **τ** by 6 years relative to the SRP and was introduced to improve the correlation for the initial 2002-2008 portion of the ΔGWS dataset by providing a 'spin-up' period. This time series was then integrated to provide an annual ∫PCPA time series. Secondly, to compensate for the depletion measured by Cheema et al. (2014), a cumulative yearly 12 cm EWH was successively added to the annual ΔGWS values (Cheema et al., 2014), starting in year 2 of the time series (2003) and consequently ending with 156 cm EWH being added in year 14 (2015). The lag is kept the same as for the main investigation and the results of the experiment are shown in **Figure S3**.

INSERT [Figure S3]

The PCC between annual ΔGWS and annual ∫PCPA is 0.81 for the whole period, and improves to 0.95 if taken from 2008. The extension of the ∫PCPA timestep accounts for some improvement in the correlation but the major contribution comes from the annual depletion compensation to ΔGWS. Whilst the framework for this experiment is not rigorous, the result, which may be considered exploratory in nature, is revealing. Extending the HM in the ∫PCPA dataset and compensating for groundwater depletion has resulted in a correlation value that is consistent with other aquifers that can be classified as dry/long HM/slow GRT.

The Canning Basin is consistently an outlier in any patterns established by the investigations of GRACE and other datasets described in this study; the data in Table 3 show weak to no correlation with any of the PCP time series datasets. From the results of this study for drylands and given that the GRT for Canning Basin is ~2.9 million years, a correlation with annual ∫PCPA indicative of a long HM is expected. The Canning Basin is one of six of the large-scale aquifers that show a net decline in GWS over the SRP; the remaining five are Indus, Ganges-Brahmaputra, California Central Valley, North China Plains and Maranhao. Unlike the other five, the Canning Basin is not a centre of agriculture; ~0.4% of irrigation in the basin comes from groundwater whereas the equivalent figures for the other five aquifers are 31%, 56%, 58%, 33% and 37% respectively (data from Table 1). Further it is remote from human intervention with less than 1% of its area covered by population (Richey et al., 2015). Richey et al., (2015), suggest that the GRACE signal is perhaps overwritten by mining activity but most mining happens outside of the extent of the basin (dmp.wa.gov.au, 2019).

Pilbara, a region just to the South West of the Canning Basin, is the centre of Iron Ore mining in Western Australia (WA), an industry that has seen rapid growth in the 21st Century with the increasing global demand for steel (Mercier, 2019). In 2017, Iron Ore delivered royalties of 4.7 billion $Aus to the WA state government, up from 285 million $Aus in 2000 (dmp.wa.gov.au, 2019). Iron ore extraction and processing are very water intensive and the only source of freshwater in most of the mining area is groundwater (Western Australia Department of Water, 2011). A report by the Commonwealth Scientific and Industrial Research organisation (CSIRO) puts the water used by the mining sector in 2008 at 5.08 $\times 10^8$ m^3 and this is predicted to rise to 9.4 $\times 10^8$ m^3 by 2020 with the growth principally expected in the iron-ore sector (Prosser et al., 2011). The quantity of water required has also increased as a result of increased exploitation of lower grade magnetite ore which requires water in all stages of processing and transport; each new licensed project is expected to add 3.7 x10^7 m^3 per year to the water demand (Western Australia Department of Water, 2011). To meet this demand, groundwater is commonly abstracted from the Canning Basin and piped directly to the mine works, with a newly announced magnetite mining project including a 195 km pipeline for this purpose (Jamasmie, 2019). BHP, one of the three largest mining companies in WA, report that 37% of their global water requirement comes from groundwater of which only 0.8% is returned to aquifers (BHP, 2019). Precise groundwater usage data are difficult to obtain and are commonly under-reported (Prosser et al., 2011).

To test whether Iron ore mining might be impacting the Canning Basin, we plot the Canning Basin annual GRACE/CLM ΔGWS data, adjusted for calendar year, against the annual production of iron ore, measured in million tonnes per year (dmp.wa.gov.au, 2019). The result, shown in **Figure S4** provides a plausible argument that GW abstraction for iron-ore mining has had an impact on the Canning Basin consistent with the GRACE/CLM ΔGWS data. However, the data is not evidence of a causal relationship and does not establish an unequivocal connection between mining use and groundwater depletion in the Canning Basin.

INSERT [Figure S4]

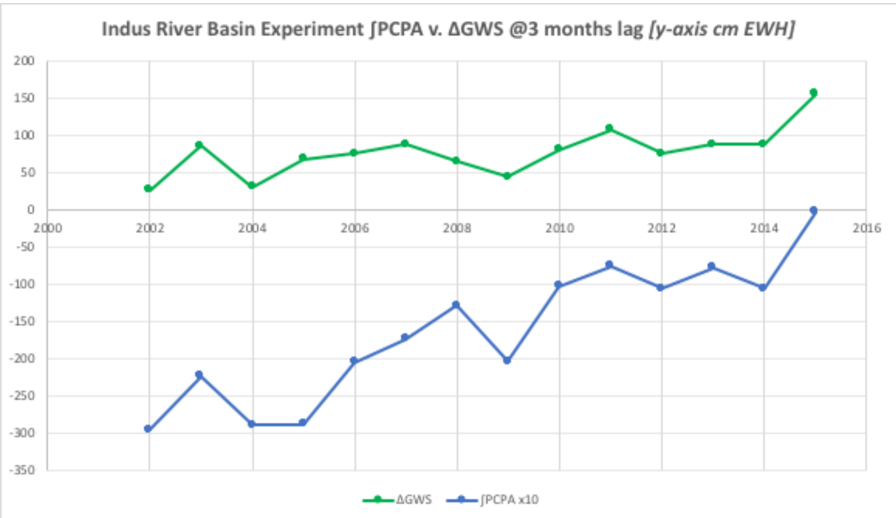
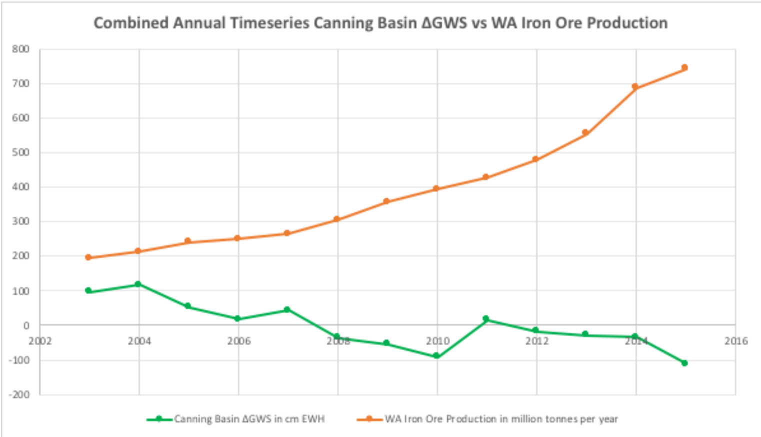


Figure S3: Indus River Basin experiment with HY ∫PCPA extracted from period 1996-2016. ΔGWS is adjusted to replace estimated depletion of 12cm EWH per year (Cheema et al., 2014). PCC is 0.81 for SRP.

a)



b)

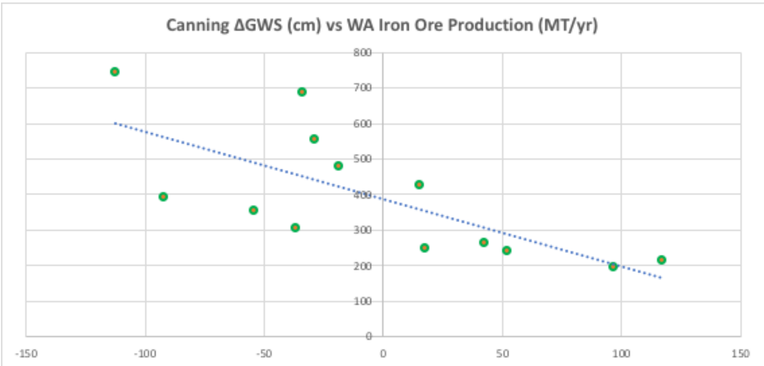


Figure S4: a) Combined annual timeseries of Canning Basin ΔGWS (data from this study) with WA annual Iron Ore production in Million Tonnes per year ((dmp.wa.gov.au, 2019). b) Plot of same data with trend line giving a PCC of -0.72.

References:

BHP, 2019. BHP | A leading global resources company [WWW Document]. BHP. URL https://www.bhp.com/ (accessed 8.23.19).

Cheema, M. j. m., Immerzeel, W. w., Bastiaanssen, W. g. m., 2014. Spatial Quantification of Groundwater Abstraction in the Irrigated Indus Basin. Groundwater 52, 25–36. https://doi.org/10.1111/gwat.12027

Climate Research Unit, University of East Anglia, 2019. CRU TS Version 4.01 [WWW Document]. CRU TS Version 4.01. URL https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.01/ (accessed 8.20.19).

Cuthbert, M.O., Gleeson, T., Moosdorf, N., Befus, K.M., Schneider, A., Hartmann, J., Lehner, B., 2019. Global patterns and dynamics of climate–groundwater interactions. Nature Climate Change 1. https://doi.org/10.1038/s41558-018-0386-4

dmp.wa.gov.au, 2019. Department of Mines, Industry Regulation and Safety [WWW Document]. Department of Mines, Industry Regulation and Safety. URL http://www.dmp.wa.gov.au/ (accessed 8.23.19).

Döll, P., Douville, H., Güntner, A., Müller Schmied, H., Wada, Y., 2016. Modelling Freshwater Resources at the Global Scale: Challenges and Prospects. Surv Geophys 37, 195–221. https://doi.org/10.1007/s10712-015-9343-1

Fan, Y., Li, H., Miguez-Macho, G., 2013. Global Patterns of Groundwater Table Depth. Science 339, 940–943. https://doi.org/10.1126/science.1229881

Foster, S. et al, 2009. The Guarani Aquifer initiative:towards realistic groundwater management in a transboundary context [WWW Document]. URL https://scholar.google.co.uk/scholar?hl=en&as_sdt=0%2C5&q=Foster%2C+S.+et+al.+The+Guarani+Aquifer+Initiative+%E2%80%94+Towards+Realistic+Groundwater+Management+in+a+Transboundary+Context+%28World+Bank%2C+2009%29.&btnG= (accessed 8.4.19).

Gleeson, T., Moosdorf, N., Hartmann, J., van Beek, L.P.H., 2014. A glimpse beneath earth's surface: GLobal HYdrogeology MaPS (GLHYMPS) of permeability and porosity. Geophysical Research Letters 41, 3891–3898. https://doi.org/10.1002/2014GL059856

Immerzeel, W.W., van Beek, L.P.H., Bierkens, M.F.P., 2010. Climate Change Will Affect the Asian Water Towers. Science 328, 1382–1385. https://doi.org/10.1126/science.1183188

Immerzeel, W.W., van Beek, L.P.H., Konz, M., Shrestha, A.B., Bierkens, M.F.P., 2012. Hydrological response to climate change in a glacierized catchment in the Himalayas. Climatic Change 110, 721–736. https://doi.org/10.1007/s10584-011-0143-4

Jamasmie, C., 2019. Fortescue OKs $2.6B expansion of Iron Bridge magnetite project. URL https://www.mining.com/fortescue-oks-2-6b-expansion-iron-bridge-magnetite-project/ (accessed 8.14.19).

KNMI Climate Explorer, 2018. Climate Explorer: Starting point [WWW Document]. KNMI Climate Explorer. URL https://climexp.knmi.nl/start.cgi?id=b08c094a879f19247ae5839cc6377977 (accessed 12.22.18).

Lutz, A.F., Immerzeel, W.W., Kraaijenbrink, P.D.A., Shrestha, A.B., Bierkens, M.F.P., 2016. Climate Change Impacts on the Upper Indus Hydrology: Sources, Shifts and Extremes. PLOS ONE 11, e0165630. https://doi.org/10.1371/journal.pone.0165630

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.É.Ó., Taylor, R.G., 2012. Quantitative maps of groundwater resources in Africa. Environ. Res. Lett. 7, 024009. https://doi.org/10.1088/1748-9326/7/2/024009

Mercier, F., 2019. Steel market developments 46.

Miller, J.D., Immerzeel, W.W., Rees, G., 2012. Climate Change Impacts on Glacier Hydrology and River Discharge in the Hindu Kush–Himalayas. mred 32, 461–467. https://doi.org/10.1659/MRD-JOURNAL-D-12-00027.1

Prosser, I., Wolf, L., Littleboy, A., 2011. Water in mining and industry 12.

Richey, A.S., Thomas, B.F., Lo, M.-H., Reager, J.T., Famiglietti, J.S., Voss, K., Swenson, S., Rodell, M., 2015. Quantifying renewable groundwater stress with GRACE. Water Resources Research 51, 5217–5238. https://doi.org/10.1002/2015WR017349

Wanders, N., Wada, Y., 2015. Human and climate impacts on the 21st century hydrological drought. Journal of Hydrology 526, 208–220. https://doi.org/10.1016/j.jhydrol.2014.10.047

Western Australia Department of Water, 2011. Capacity of water resources in the Mid west to meet mining and industrial growth: a status report. Dept. of Water, Perth, W.A.

Wolski, P., Murray-Hudson, M., 2005. Flooding dynamics in a large low-gradient alluvial fan, the Okavango Delta, Botswana, from analysis and interpretation of a 30-year hydrometric record. Hydrology and Earth System Sciences Discussions 2, 1865–1892.