NASA Energy and Water Studies Climatology Project: Estimation of human water consumptive use from the world's rivers

Elizabeth A. Clark[1], Justin Sheffield[2], Michelle T.H. van Vliet[3], Aiguo Dai[4], and Dennis P. Lettenmaier[1]

[1]Department of Civil and Environmental Engineering, Seattle, WA

[2]Civil and Environmental Engineering, Princeton University, Princeton, NJ

[3] Earth System Science Group, Wageningen University, Wageningen, The Netherlands

[4] National Center for Atmospheric Research, Boulder, CO

Objectives

- To create an observation-based global runoff data set by combining simulated runoff and in situ observations.
- To estimate human water consumptive use globally based on the difference between simulated natural runoff and this observation-based data set.

Raw Streamflow Observations

Dai et al. (2009) assembled streamflow measurements from 925 stream gaging stations worldwide that are located nearest to each river's outlet to the ocean. They filled in as many gaps in the observed time series as possible by performing a linear regression against streamflow at upstream stations during overlapping data periods. We downloaded these data from http://www.cgd.ucar.edu/cas/catalog/surface/dai-runoff/index.html on Oct. 26, 2009.

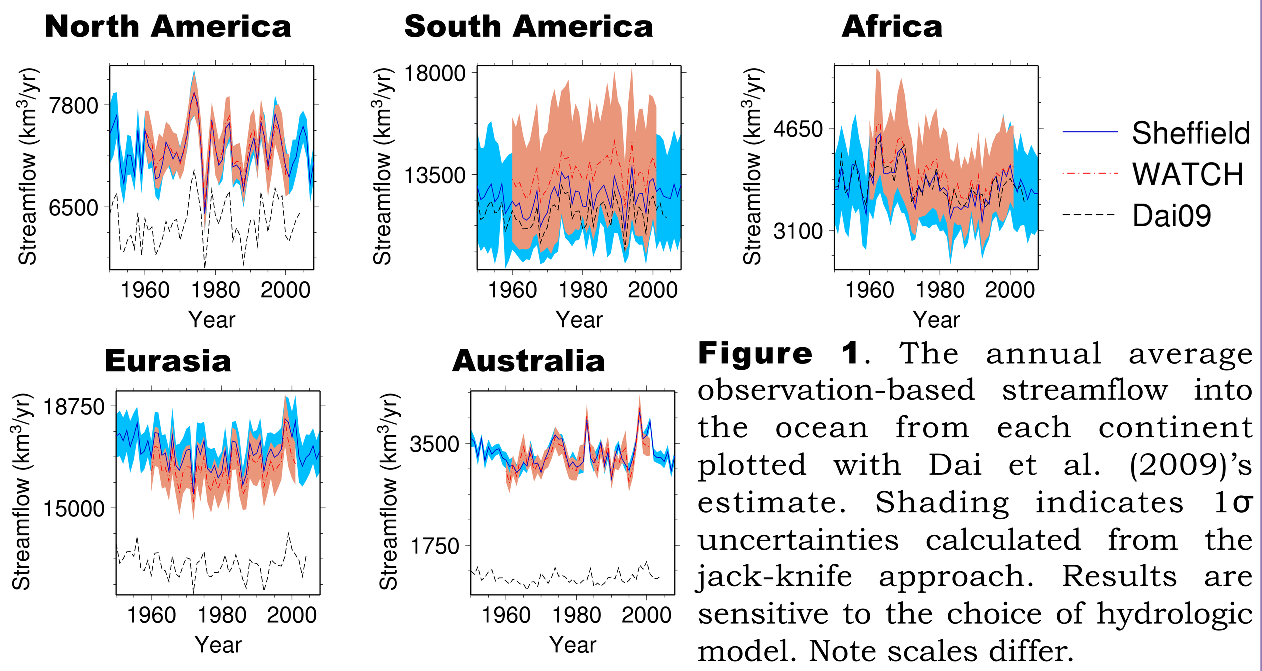
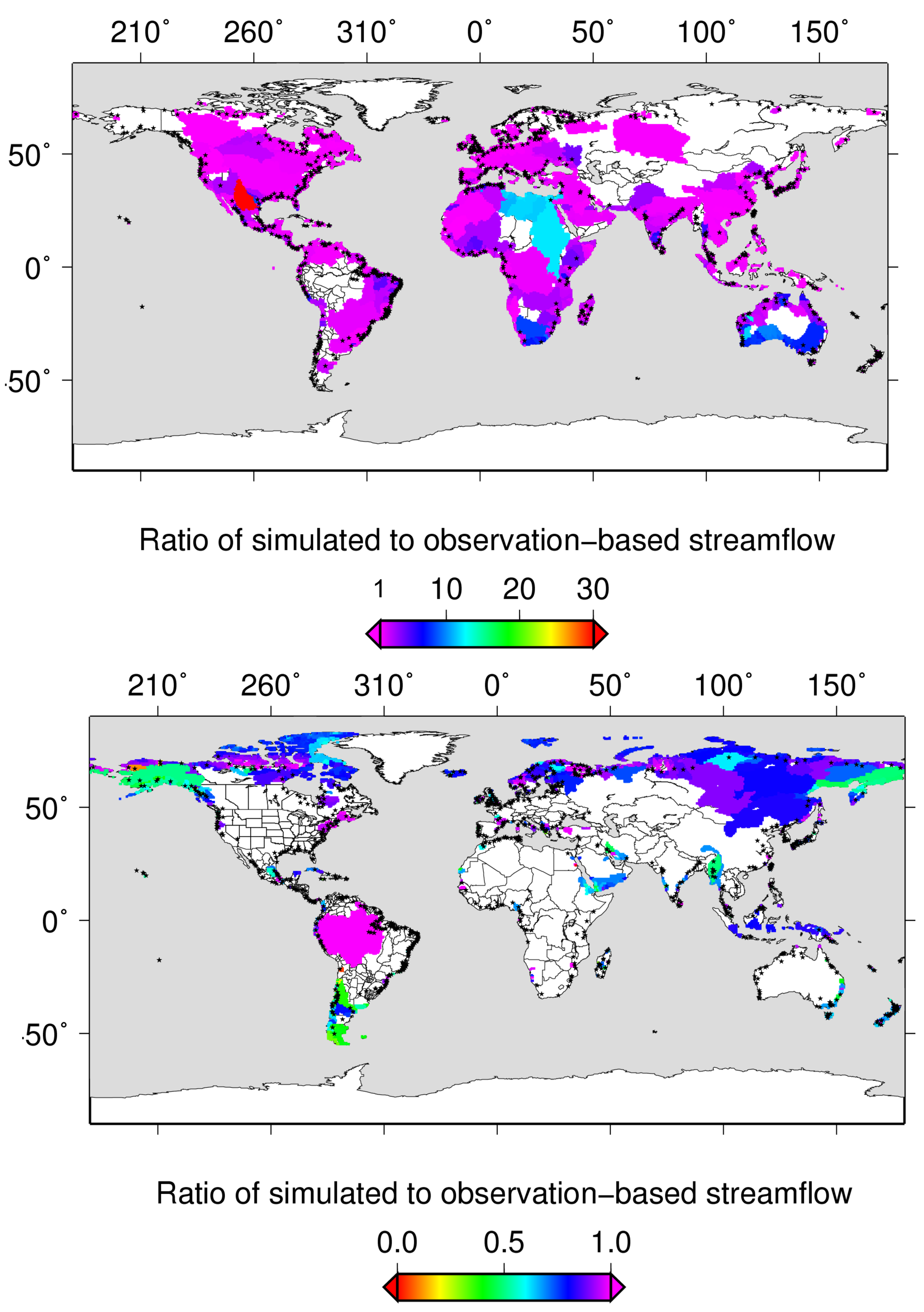


Figure 1. The annual average observation-based streamflow into the ocean from each continent plotted with Dai et al. (2009)'s estimate. Shading indicates 1σ uncertainties calculated from the jack-knife approach. Results are sensitive to the choice of hydrologic model. Note scales differ.

Figure 3. The ratio of annual average (1960-2001) simulated to observed streamflows. One value is plotted per basin. Upper panel shows basins where simulations were larger than observation-based estimates. Lower panel shows basins where simulations were smaller than observation-based estimates. In both figures, values close to one plot as pink.



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Observation-based Runoff Dataset

We modified the methods of Dai and Trenberth (2002) and Dai et al. (2009) slightly to estimate monthly and annual runoff to the ocean from ungaged areas as follows:

1) Extrapolate observed streamflow ($R_{observed,station}$) values to river mouth ($R_{\text{"obs"},mouth}$) using a ratio of model runoff at the mouth to model runoff at the station (corrected for differences in observed drainage area ($A_{obs,station}$) and STN-30p drainage area ($A_{model,station}$)).

$$R_{\text{"obs"},mouth}(j,t) = R_{observed,station}(j,t) * \frac{R_{model,mouth}(j,t)}{R_{model,station}(j,t))} * \frac{A_{model,station}(j)}{A_{obs,station}(j)}$$

2) Estimate values for streamflow at the mouth of ungaged basins based on the ratio of observed streamflow to the mouth (from step 1), smoothed over a 4° moving window, to the mean monthly and annual simulated streamflow for the same areas. This ratio was applied to the monthly and annual average streamflow simulated at the mouth of each unmonitored river basin centered in the moving window.

$$R_{mouth}(j,t) = \bar{R}_{model,mouth}(j) * \frac{R^{smooth}_{\text{"obs"},mouth}(lat(j),t)}{\bar{R}^{smooth}_{model,mouth,monitored}(lat(j))}$$

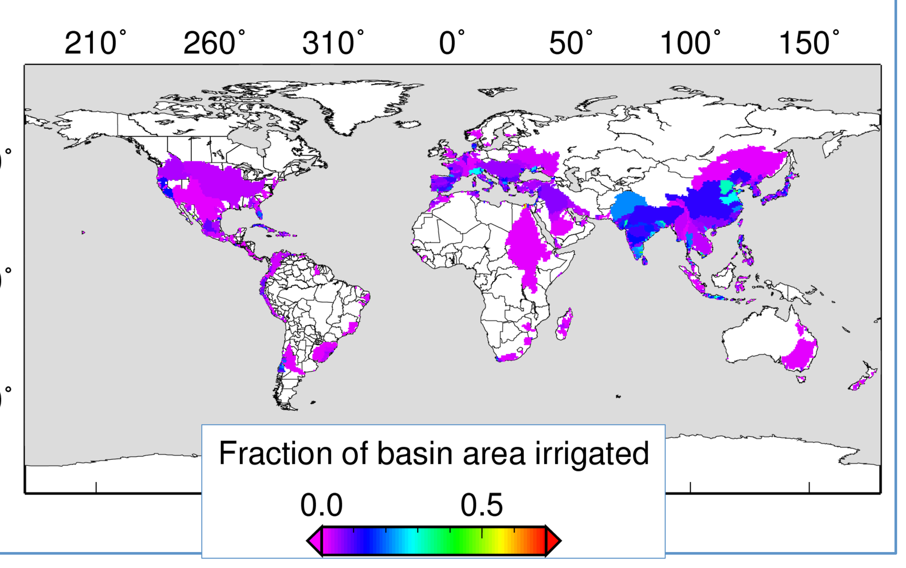
3) Estimate uncertainty in observation-based streamflow using a jack-knife approach. Each of the streamflow observations was individually removed from the analysis, and runoff to each river outlet in the effected latitude band was estimated. Each river outlet then had 2 to 47 realizations of estimated runoff. The standard deviation of these realizations was used as a measure of uncertainty at each outlet resulting from steps 1 and 2.

	Streamflow for all basins, 1000 km3/yr			
	UNESCO, 1979	Dai et al., 2009, 1961-2001	Sheffield, 1960-2001	WATCH, 1960-2001
North America	6.63	6.32	7.23±0.24	7.26±0.27
South America	11.76	11.76	12.48±2.20	13.54±2.73
Eurasia	13.52	12.85	16.97±0.82	16.45±0.78
Africa	4.185	3.81	3.80±0.65	4.00±0.65
Australia	0.301	1.18	3.31±0.12	3.27±0.18
Total	36.396	35.92	43.8±2.45	44.48±2.93

Table 1. Summary of long-term annual average (1960-2001) continental streamflow estimates from literature and the observation-based Sheffield and WATCH data sets presented here. For Sheffield and WATCH, the 1σ uncertainties calculated from the jack-knife approach are given.

GRDC (1999) reports that prior estimates vary from 29,485 km³/yr to 44,560 km³/yr. Continental boundaries differ between UNESCO and other studies. Significant differences between the observation-based data sets presented here and Dai et al. (2009) occur in North America, Eurasia, and Australia. Since the same observations were used to create each data set, these differences must reflect differences in simulated runoff and slight differences in steps 1-3 above. Dai et al. (2009) use CLM 3.0 and the Qian et al. (2006) forcings. Our simulations use newer precipitation data sets and the VIC model.

Figure 4. The fraction of basin drainage area that is irrigated, based on FAO Global Map of Irrigated Areas, v. 4.0.1, for basins with at least 1% irrigated area. In general, areas that have notable irrigation correspond to basins in figure 3 that have high simulated natural flows, relative to the observation-based data set. However, many areas (Australia, Nile/northeastern Africa, southern Africa) that have higher simulated flows than observation-based flows in figure 3 do not have notable irrigation. Many of these areas are poorly gauged.



Consumptive Use

- Hydrologic models can simulate natural flows, absent of human alterations. In situ observations near the mouth of the world's rivers, and hence a data set based on these observations, include human effects. The difference in these data sets should give an order of magnitude estimate of consumptive water use.
- Our global estimate of average annual consumptive use from 1960-2001 is 3120 km³/yr. This is somewhat less than Liu et al.'s (2009) estimate of global annual consumptive water use , based on 17 crops, at about 3823 km³/yr for the period 1998-2002.

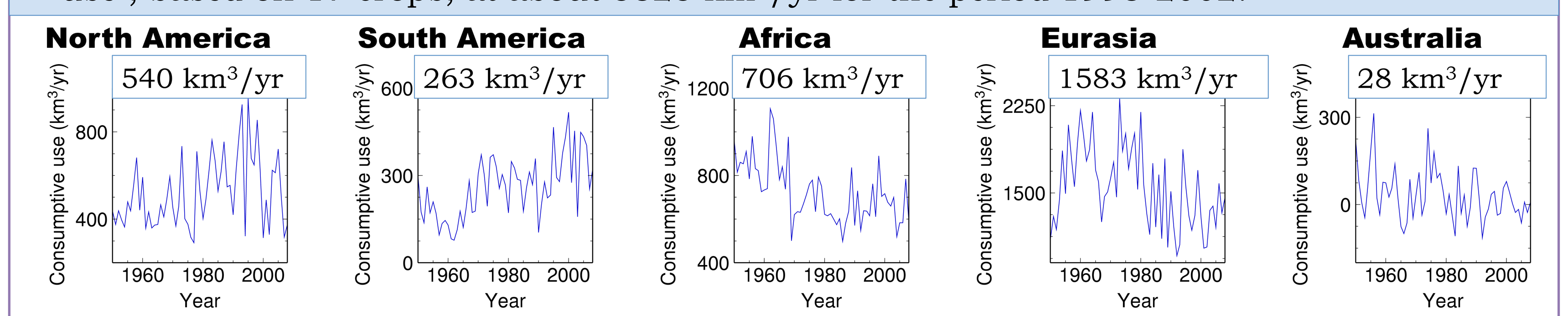


Figure 6. The annual time series of consumptive use estimated as the difference between Sheffield simulated natural streamflow and observation-based streamflow for basins with more than 1% irrigated area. 1960-2001 mean annual consumptive use by continent is reported above each plot.

Simulated Runoff

- Global runoff was simulated by two implementations of the Variable Infiltration Capacity model (VIC):

  1) "Sheffield"
  - 1-degree latitude-by-longitude, at 3-hourly time step in full energy balance mode.
  - VIC was forced with the atmospheric forcings of Sheffield et al. (2009).
  - Model runoff was calibrated to monthly flows where available.

  2) "WATCH"
  - 1/2-degree latitude-by-longitude, at daily time step in water balance mode.
  - VIC was forced with the atmospheric forcings of the EU-WATCH project (Weedon et al., 2011)
  - Model runoff was not calibrated.
- Runoff from each model was routed to each station in the raw observation network and to each river mouth using the STN-30p v6.01 flow network at ½-degree latitude-by-longitude resolution (Vörösmarty et al., 2000; downloaded from http://www.wsag.unh.edu/Stn-30/stn-30.html).

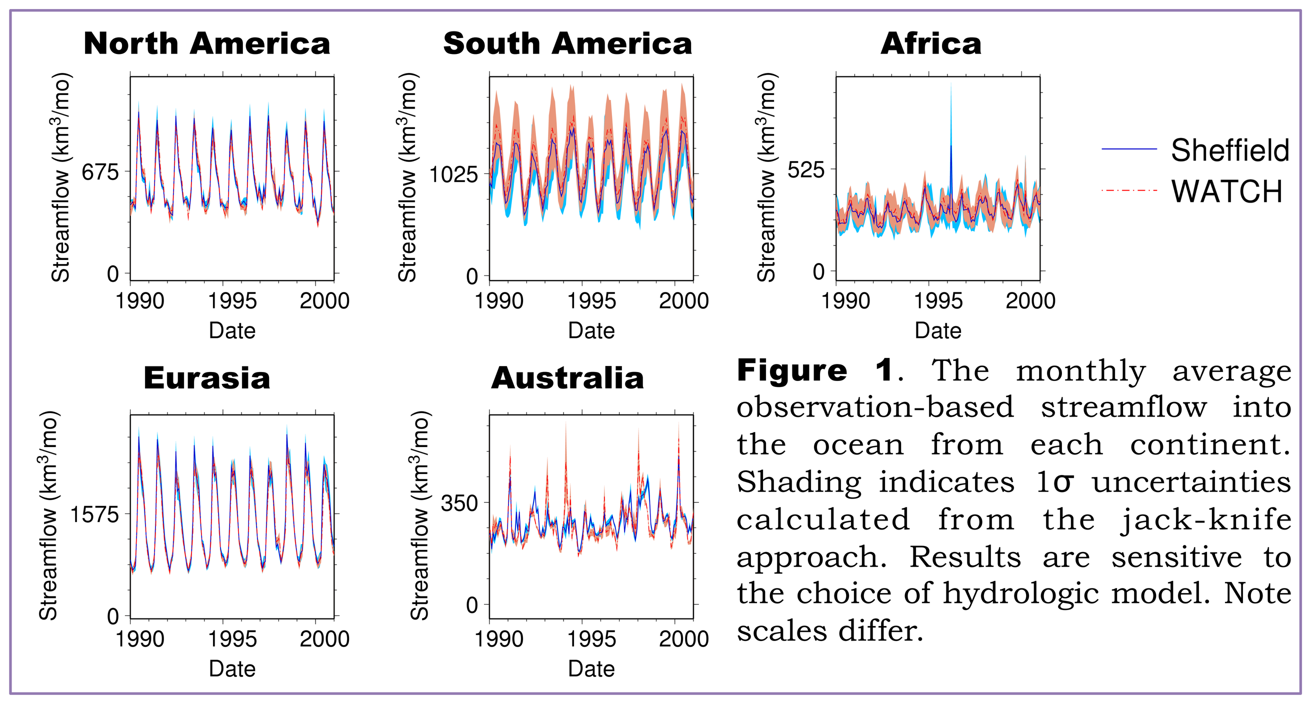


Figure 1. The monthly average observation-based streamflow into the ocean from each continent. Shading indicates 1σ uncertainties calculated from the jack-knife approach. Results are sensitive to the choice of hydrologic model. Note scales differ.

Other Error Sources

- Rating curves for in situ gauges must be updated regularly and gauges must be maintained in order to be accurate. In situ observations in some regions may have errors on the order of 20% of flow.
- Model simulations do not include reservoirs, lakes, wetlands, and may have inaccurate parameters in some regions.
- Model forcing data, particularly precipitation, depend on the accuracy and density of in situ rain gage networks and of satellite observations. In many cases, precipitation estimates are sensitive to interpolation methods. This propagates into the simulated runoff.
- We assume that hydrologic conditions are similar between basins at similar latitudes. This is not always the case.
- This product should be viewed as a "best guess" based on available data.

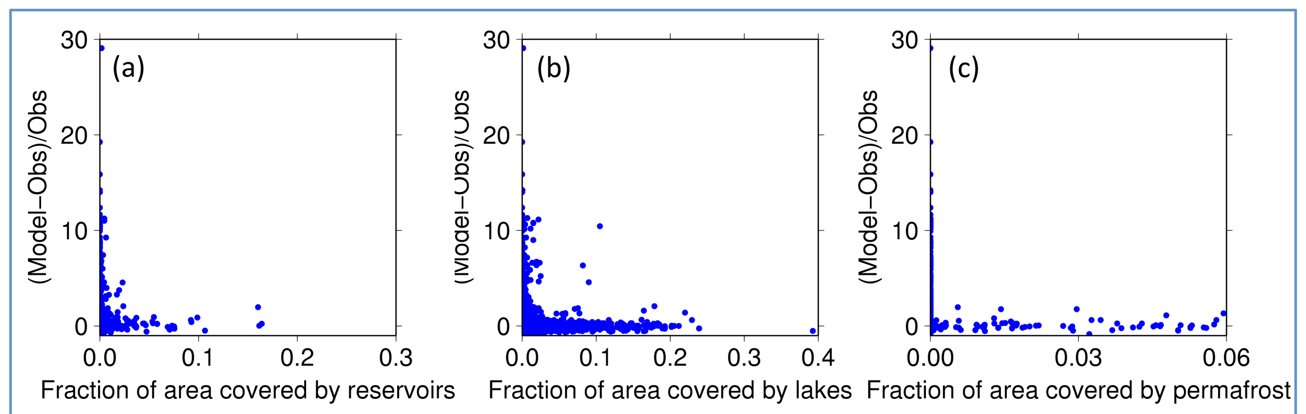


Figure 5. Relative bias between the simulated natural flows (Model) and observation-based flows (Obs) versus (a) fraction of area covered by reservoirs, (b) fraction of area covered by lakes, (c) fraction of area impacted by permafrost. Reservoir and lake areas were calculated from the GLWD level 3. Permafrost extent was taken from the NSIDC Circum-Arctic Map of Permafrost and Ground Ice Conditions. Each dot is the annual average flow for an individual basin (n=5632). This relationship holds for monthly flows, for floodplain area, and for glacier extent.

The VIC implementations presented here do not include lakes, wetlands or reservoirs. Many hydrologic models also have difficulty in Arctic regions. Despite this, land cover type does not correlate with the Sheffield model bias relative to the Sheffield observation-based annual average streamflow.

Conclusions

- We estimate global (excluding Antarctica and Greenland) average annual runoff to the oceans from 1960-2001 at 43,800±2450 km³/yr. This is higher than many previous estimates.
- We estimate global average annual consumptive use from 1960-2001 at 3120 km³/yr (~7% of total runoff to ocean).
- More than half of our estimated global consumptive use occurs in Eurasia, with most of the rest in Africa, North America, and South America – in that order.