

1 Supplementary Material A: Literature overview of studies on global hydrological effects of climate change

<i>Study</i>	<i>Climate model</i>	<i>Scenario</i>	<i>Runoff</i>	<i>Method</i>	<i>Horizon</i>	<i>Parameters</i>	<i>Significance / Consistency</i>	<i>Rivers / Regions</i>	<i>Results</i>
Aerts (2006)	ECBilt-CLIO-VECODE	A2	Hydrological model: STREAM including simplified routing scheme	Direct use of GCM meteo data	21 st century	- Mean decadal change in discharge compared to discharge 1750-2000 - Inter decadal variability compared with natural variability	~ Comparison to past variability	Globe Amazon, Congo, Danube, Ganges, Lena, Mekong, Mississippi, Murray, Nile, Odra, Rhine, Syr-Darya, Yukon, Volga, Volta	Discharge increase: Congo, Mekong, Ganges, Amazon, Rhine, Murray, Volga Discharge decrease: Nile, Danube, Mississippi Seasonal shift: Lena
Alcamo (2002)	ECHAM4 HadCM3	A2, B2	Hydrological model: WaterGAP including routing	Change factor	2020s, 2050s, 2080s	- Annual withdrawal-to-availability ratio - Consumption- to-Q90 ratio - Per capita water availability	Overlap between three parameters selected as indicators of climate change	Globe	Severe water stress: Southwestern USA, central Mexico, northeast Brazil, West Coast Latin America, northern and southern Africa, Middle East
Arnell (1999b)	HadCM2 HadCM3	1% per year CO2 increase	Hydrological model, no routing	Change factor	2020s, 2050s, 2080s	- Average annual runoff - Water Stress	-	Globe 42 rivers	Change in high flow: North-America, east Asia, Ghana Increasing water stress: Mediterranean region, Middle-East, South- Africa, parts of south Asia Seasonal shift: Belarus
Arnell (2003, 2004)	HadCM3 CGCM2 CSIRO Mk2 ECHAM4 GFDL_R30_c CCSR/NIES2	A1, A2, B1, B2	Hydrological model, routing with monthly output	Change factor	2020s, 2050s, 2080s	Average annual runoff Drought runoff InterAnnual variability Flood runoff Annual cycle	Consistency among scenarios, compared to consistency among models	Globe	Runoff increase: High latitudes, east Africa, south and east Asia Runoff decrease: Southern and eastern Europe, western Russia, Middle East, Africa and much of North- and South-Africa
Arora and Boer (2001)	CGCM1	GHG+A based on IS92a	runoff from from GCM as input for routing model	Direct use of GCM runoff fields	2070-2100	Mean discharge, amplitude and phase, flood discharge, annual max discharge and sdv, flow duration curve	-	Globe 23 rivers	Runoff decrease: Africa, Amazon, Yangtze, Mekong. Global decrease 14% Seasonal shift, decrease in amplitude: Mid- and High latitude rivers

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Manabe (2004)	GFDL-GCM ensemble of 8 experiments	IS92a, CO2 quadrupling	Discharge derived from runoff fields GCMs	Direct use of GCM runoff fields	2050	Change in annual mean runoff Spatial pattern of change in seasonal soil moisture	-	Globe 42 rivers	Discharge increase: globally 7.3% by 2050, Arctic rivers, Brazil, Andes, northern India, Tibet, Indonesia, West-Africa, Amazon, Ganges, Brahmaputra Discharge decrease: Nile, Mekong Soil moisture decrease: North-America, Mediterranean Coast, northeast China, grasslands of Africa and southern and western regions of Australia
Milly (2005)	12 GCMs (best models from ensemble of 21 IPCC AR4 models)	A1B	Runoff fields from GCMs as input for routing model	Direct use of GCM runoff fields	2041-2060	Annual mean change compared with past trends	Number of models showing positive changes minus number of models showing negative change	Globe	Runoff decrease: Southern Europe, Middle-East, mid-latitude western North-America, southern Africa Runoff increase: High latitude North-America, Eurasia, South-America, eastern equatorial Africa
Nohara (2006)	ensemble of 19 AOGCMs (part of IPCC AR4)	A1B	runoff fields from GCM as input for routing model	Direct use of GCM runoff fields	2100	Mean annual change in runoff River regimes	- Ensemble change relative to intermodel variability of the change signal - GCM deviations for control run	Globe, 24 major rivers	Discharge increase: Northern Hemisphere (Arctic rivers), southern to eastern Asia (Mekong, Ganges), central Africa Discharge decrease: Central America, southern Africa, Mediterranean region, southern North-America, Rhine, Danube Seasonal shift: Arctic and mid-latitude rivers

Study	Climate model	Scenario	Runoff	Method	Horizon	Parameters	Significance / Consistency	Rivers / Regions	Results
Nijssen (2001)	HCCPR-CM2, HCCPR-MC3, ECHAM4, DOE-PCM3 (selected on resolution out of eight GCMs)	IS92a, A,B,C	Hydrological model: VIC including routing	Basin wide change factor	2025 2045	Annual hydrological cycle Change in water balance Seasonal change Moisture deficit periods Basin sensitivity	-	Amazon, Amur, MacKenzie, Xi, Mekong, Yellow River, Yenisei, Mississippi, Severnaya Dvina	Discharge increase: Arctic rivers Discharge decrease: mid-latitude and tropic basins Seasonal shift: Arctic rivers
Vörösmarty (2000)	HadCM2, CGCM1		Hydrological model: WBM including routing	Direct use of GCM meteorological data Change factor for discharge change	2025	Water stress Annual runoff	-	Globe	Decreased water availability: East Africa, southeast Asia, Mexico, Spain, parts of North- and South-America
This study	BCM2.0, CGCM3.1, CGCM2.3.2, CSIRO-Mk3.0, ECHAM5, ECHO-G, GFDL-CM2.1, GISS_ER, HADGEM1, IPSL-CM4, MIROC3.2medres, NCAR-CCSM3	A1B and A2	Hydrological model: PCRGLOB-WB including routing	Direct use of meteorological data	2100	Mean, max and minimum annual runoff, annual cycle, inter-annual variability	- Significance compared to natural variability and ensemble uncertainty - Consistency amongst GCMs	Globe, 20 major rivers	Discharge increase: Arctic rivers Discharge decrease: Southern Australia, southern Africa, Mediterranean region, southwest South-America Seasonal shift: Sub-Arctic rivers

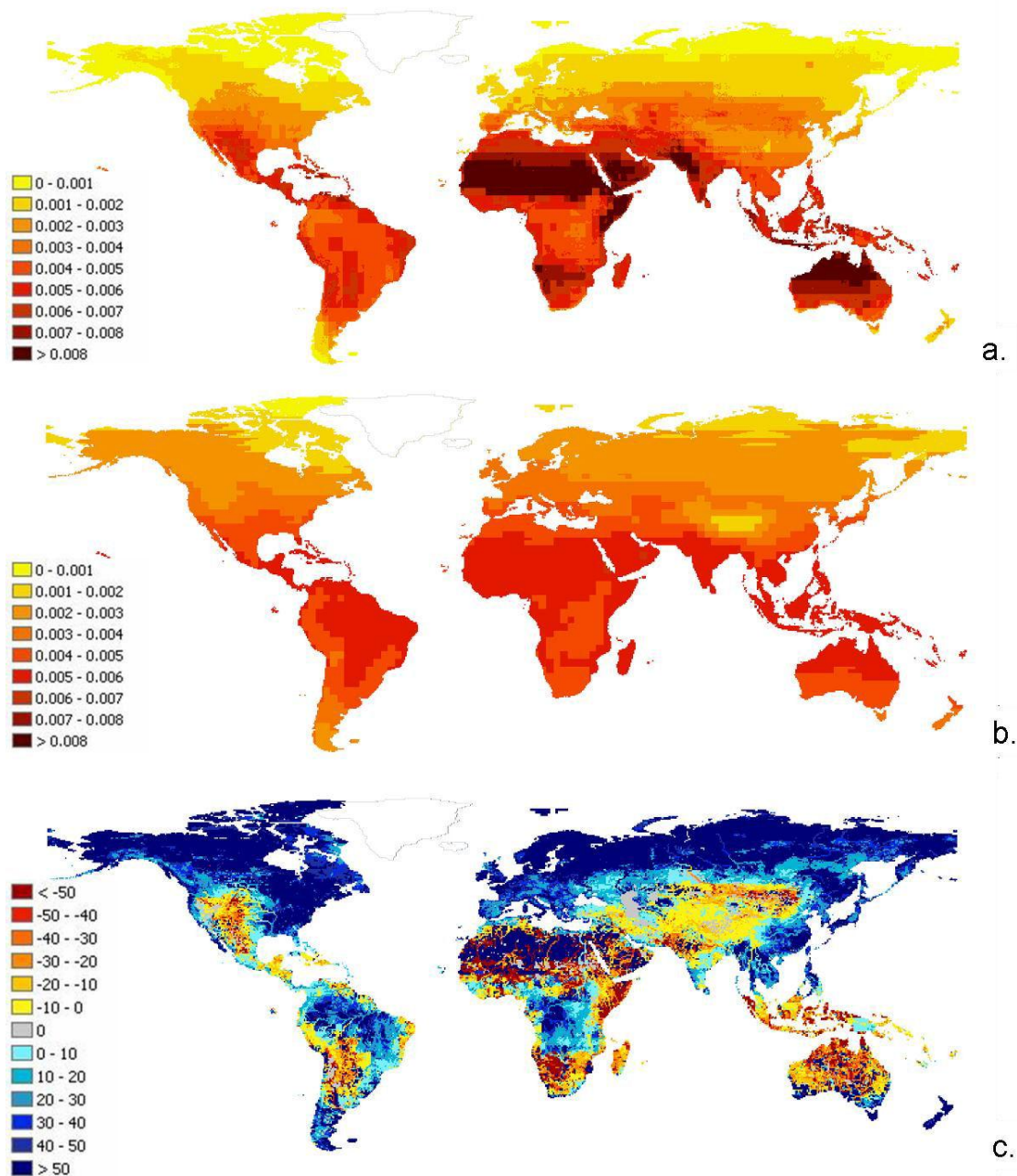
4 **Supplementary Material B: Penman-Monteith vs Blaney-Criddle**

5 For most GCMs reference potential evaporation is calculated with a modification of the
6 Penman-Monteith equation (Allen et al., 1998; Van Beek, 2008; Sperna Weiland et al.,
7 2010). However, for some GCMs several input variables (e.g. wind speed, air pressure,
8 radiation) required to calculate the Penman-Monteith evaporation were missing. For these
9 GCMs the Blaney-Criddle equation is used (Brouwer and Heibloem, 1986; Oudin et al.,
10 2005). The Blaney-Criddle equation is a simple temperature based potential evaporation
11 estimator, whereas Penman-Monteith considers aerodynamics and radiation as well.

12 For several GCMs we compared potential evaporation calculated with the Penman-
13 Monteith and the Blaney-Criddle equations and their resulting discharges. For brevity
14 results are only shown for the CGCM2.3.2 model (Fig. 11a and b). For most GCMs
15 potential evaporation calculated with the Penman-Monteith equation is high compared to
16 Blaney-Criddle potential evaporation in Northern Australia, the Sahara, Southern Africa,
17 the southwest US and Northern India and relatively low for Europe, the northern US,
18 Canada, Russia, southeast Asia and the Amazon. However, only for specific periods, and
19 in regions where evaporation limitation by soil moisture conditions is small, deviations in
20 potential evaporation will introduce deviations in actual evaporation and runoff. Fig. 11c
21 shows the percentage difference in discharge calculated using either the Blaney-Criddle
22 or the Penman-Monteith potential evaporation. Deviations are large for the northern
23 regions of the northern Hemisphere, the Amazon basin, Europe and parts of southeast
24 Asia where discharge calculated with Penman-Monteith potential evaporation is
25 relatively high. The Penman-Monteith based discharge is relatively low in arid regions,
26 the Indus basin and Himalayas. Unfortunately hydrological studies are restricted to the
27 available GCM datasets and, since not all required Penman-Monteith variables are
28 reported for all GCMs, the use of a simple temperature based equation like Blaney-
29 Criddle can not be avoided. Still, for those GCMs where all variables were available we
30 preferred to use the FAO recommended Penman-Monteith equation (Allen et al., 1998).

31 In this study not the absolute discharge quantities, but the changes in average discharge
32 and discharge extremes were of interest. Therefore we analyzed the influence of using
33 either Blaney-Criddle or Penman-Monteith potential evaporation as input to the
34 hydrological model on the resulting discharge changes. Hereto discharge changes derived

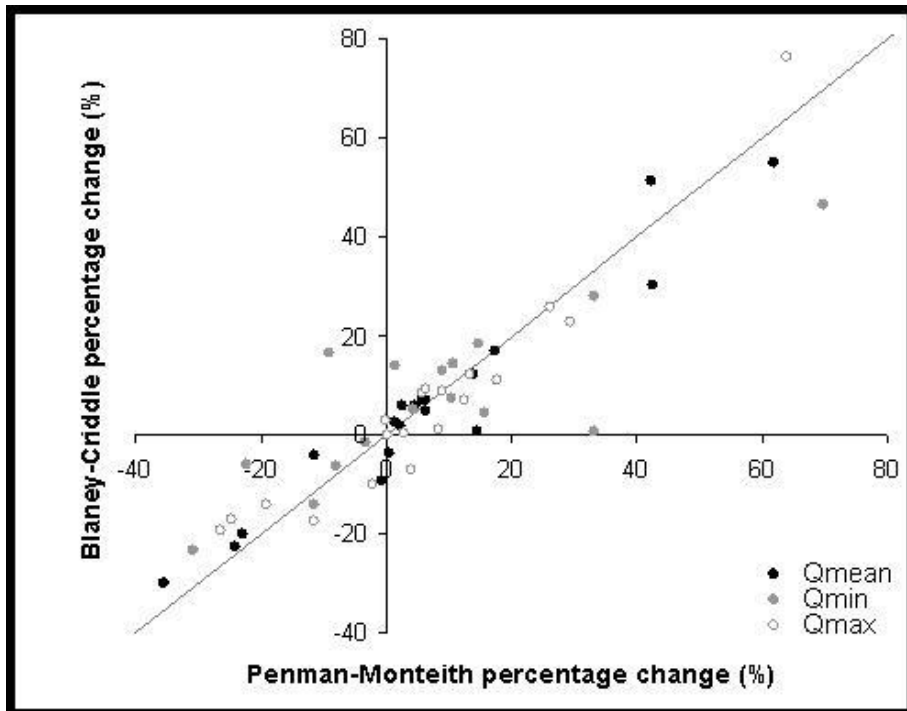
35 with the hydrological model forced with Blaney-Criddle potential evaporation are
36 regressed on discharge changes derived with the hydrological model forced with Penman-
37 Monteith potential evaporation (Fig. 12). For this analysis we used data from the first
38 realization of CGCM2.3.2 for the 20C3M experiment and A1B scenario. Overall, for
39 2100, the different potential evaporation equations result in similar directions of change.
40 There are two exceptions. The first is the direction of change for maximum discharge in
41 the MacKenzie, which is negative when using the Blaney-Criddle equation and positive
42 for the Penman-Monteith equation. This is a result of the large differences in absolute
43 discharge quantities for the MacKenzie which tend to be twice as high for the Penman-
44 Monteith equation. The second exception is the Ganges where minimum discharge
45 decreases with the Penman-Monteith method, while it increases for the Blaney-Criddle
46 method. For the remaining catchments directions of change in minimum, maximum and
47 mean discharge are the same when using either two equations. In general the projected
48 changes follow the 1:1 slope, although differences in magnitude of projected change
49 exist.



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51 Figure 11: Maps with reference potential evaporation (m/day) and resulting percentage discharge
 52 difference (%). Fig. 11a. twenty year average reference potential evaporation (m/day) calculated
 53 with the Penman-Monteith equation. Fig. 11b. twenty year average reference potential
 54 evaporation (m/day) calculated with the Blaney-Criddle equation and Fig. 11c. percentage
 55 difference (%) between twenty year average discharges calculated with PCR-GLOBWB from
 56 either Penman-Monteith or Blaney-Criddle.

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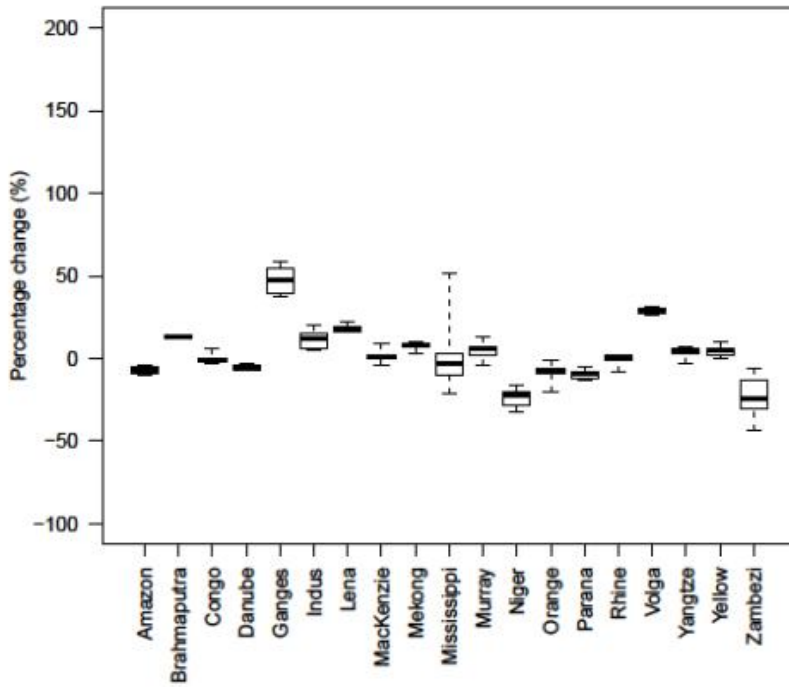
59 Figure 12: Percentage change in discharge calculated using potential evaporation derived with
 60 Blaney-Criddle vs Penman-Monteith. Black dots represent projected change in average discharge,
 61 grey dot represent changes in high flows (Qmax), white dots represent changes in low flows
 62 (Qmin). The solid line represents the 1:1 slope.

63 **Supplementary Material C: Consistency of change for multiple realizations**
64 **of one GCM**

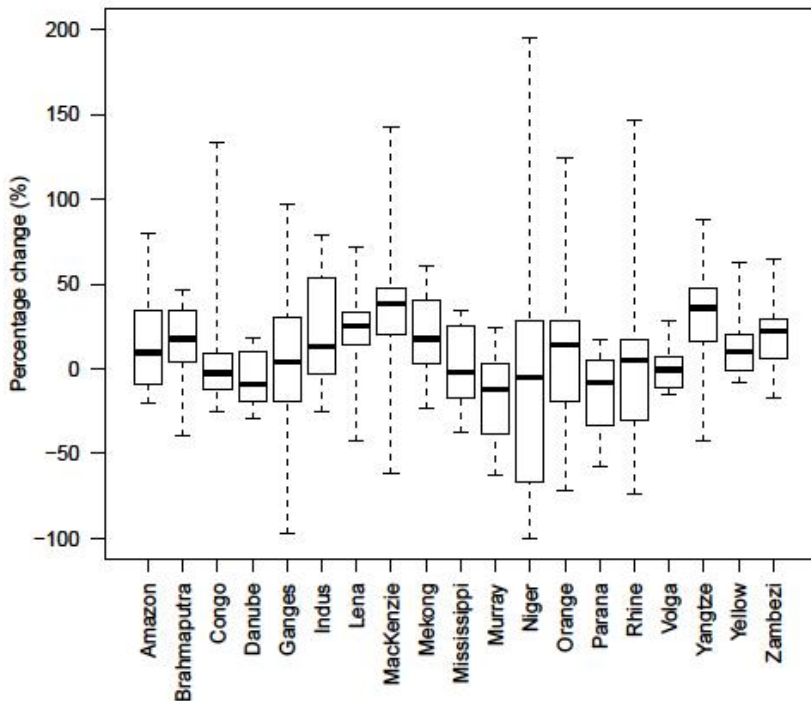
65 For CGCM2.3.2, the GCM with the highest number of realizations for both the 20C3M
66 experiment and the A1B scenario, we calculated change in discharge by 2100 for all five
67 available realizations. Boxplots of projected changes for the 19 catchments are shown in
68 Fig. 13a. Fig. 13b shows boxplots of changes projected by the twelve individual GCMs
69 included in our ensemble. The boxplots of the five realizations of CGCM2.3.2 cover
70 much smaller ranges than the boxplots derived from the ensemble of GCMs.
71 Furthermore, for 13 out of 19 catchments the direction of change is consistent for all five
72 realizations of the CGCM2.3.2 model. In Fig. 14a a global map with the number of
73 CGCM2.3.2 realizations projecting change in the dominant direction (the direction of
74 change projected by the majority of GCMs) is shown. For 55% of the globe all five
75 realizations agree on the projected direction of change, for 81% of the globe at least four
76 realizations agree on the direction of change and for the remaining 19% only three
77 realizations are consistent.

78 From these results two conclusions can be drawn. Firstly, Fig. 13 shows the inter-model
79 uncertainty is much larger than the intra-model uncertainty, at least for the GCM data we
80 have at our disposal. And secondly, for the majority of catchments the projected
81 directions of change are consistent for the five realizations. This indicates that including
82 different numbers of realizations for the individual GCMs in our ensemble would result
83 in overweighting the direction of change projected by the GCMs with multiple
84 realizations. Therefore we restricted ourselves to a single realization for each of the
85 twelve GCMs included in the ensemble.

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109 Figure 13a. Boxplots of changes projected by the five available realizations of the GCM CGCM
110 2.3.2 for the A1B scenario for 2100. Whiskers mark the maximum and minimum projected
111 changes, boxes span the quartile range and horizontal dashes represent the median of projected
112 changes. Figure 13b. same as Fig. 13a. but now for the changes projected by the ensemble of 12
113 GCMs.



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115 Figure 14: Map showing the number of realizations of CGCM2.3.2 projecting mean change in the
116 dominant direction. Black indicates regions where the five realizations project changes in the
117 same direction, grey indicates regions where four realizations project similar directions of change
118 and in the white regions only three realizations project the same direction of change. The
119 dominant direction is the direction of change projected by the majority of models.