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Large scale water yield assessment for sparsely monitored river basins: A case study for Afghanistan

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Abstract

This paper presents results from a study on water yield assessment across five major river basins of Afghanistan. The study was conducted using GR4J and GR4JSG precipitation-runoff models. The river basins were divided into 207 subcatchments and each subcatchment was divided into multiple functional units. The model was calibrated using observed streamflow data from 2008 to 2015 and validated over the 2016 to 2020 period. Model parameters were calibrated for an unregulated subcatchment in each basin and calibrated parameters from the best-performing subcatchment were transferred to other subcatchments. Results show that modelled water yield across the five basins varies from 0.3 mm in the Helmand basin to 248 mm in the Panj-Amu basin, with an average of 72.1 mm for the entire country. In the period of 2008 to 2020, area averaged water yield in the five basins varies from 36 to 174 mm. For the same period, mean annual precipitation for the entire country is 234.0 mm, indicating a water yield of 30.8%. The nation-wide average water yield of 72.1 mm is equivalent to 46.3 billion cubic meters (BCM) of surface water for the country. In addition, about 28.9 BCM generates annually in the neighbouring Tajikistan and Pakistan from snow and glaciers of the Hindu-Kush mountains. The elevated northern parts of Afghanistan, including parts of neighbouring Tajikistan are the primary water source. Water yield across the country varies between years but there is no consistent increasing or decreasing trends. About 60 to 70% of flow occurs between March to June. The study identified the high water yield areas and investigated variability at monthly, seasonal, and annual time scales. An importance finding is the large spatial and temporal variability of water yield across the basins. This information is crucial for long-term water resources planning and management for agricultural development.

1. Introduction

Sustainable water management is a global issue driven by increasing water demand for domestic water consumption and irrigation to feed a growing world population [1–3]. While every

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continent is experiencing water scarcity to some extent [4], the problems of scarcity are especially acute in Central Asia where approximately 80% of the population experiences water stress, and about 50% of the population suffers from water shortages [5–7]. With the growing population water demand in Afghanistan likely to increase in the future, at the same time, climate change is having, and will continue to have, global, regional, and local impacts on water availability. Ensuring that the changing water availability can meet this growing demand without compromising the sensitive aquatic environments from which it is derived, is clearly a huge challenge. This will require strategies and policies informed by quantitative knowledge of the available water resources and being able to detect and manage major changes to the supply [7,8]. Generating this knowledge in a developing country is difficult where the quantification of national water resources is limited by the extent and quality of the gauging infrastructure. The difficulties of producing this knowledge are complicated in Afghanistan at a time when the society is disrupted by armed civil conflict. When it is no longer safe for hydrologists to venture into the countryside to make measurements and maintain and extend the existing gauging infrastructure, it is necessary to devise alternative strategies which innovatively use limited data in modelling to produce realistic estimates at multiple temporal and spatial scales. This paper describes this fusion approach in the context of Afghanistan.

Afghanistan is a landlocked country characterised by a rugged mountainous landscape and scattered human settlements. Water is the major natural resource of Afghanistan, and the national economy largely depends on subsistence agriculture. The climate is mostly semi-arid, and the population depends on rainfall and irrigated agriculture to produce food. Majority of the rural population is farmers who live precariously from small plots of land. River flow from melting of snow and glaciers recharges alluvial aquifers and these aquifers provide reliable sources of groundwater for agriculture and domestic use [9].

Afghanistan's water resources face pressure to support its growing population and continued economic development while the warming climate depletes its glaciers [10–12]. Managing the growing water demand under decreasing water source is a huge challenge requiring accurate estimation of water yield potential across the country. Studies on water availability across the river basins in Afghanistan are very limited. While there are some studies on local scale [13] and basin scale [14], there is no study on national scale water yield assessment. To address this issue, Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) in partnership with Afghanistan National Water Affairs Regulation Authority (NWARA) conducted a research project on developing Afghanistan national water information system in 2019–2021. In this paper, we report key findings of the project on water yield potential across Afghanistan.

We have configured and calibrated a national scale hydrological model using the eWater Source modelling platform [15] and assessed water yield potential in the five major river basins of Afghanistan. The study identified the areas of low- and high-water yields and investigated the flow variability at monthly, seasonal, and annual time scales. The manuscript is structured as follows: Section 2 describes physical and hydroclimate properties of the study area. The methods are described in Section 3 followed by results in Section 4. Major findings and limitations of the study are discussed in Section 5. Finally, a set of conclusions are presented in Section 6.

2. Study area

Afghanistan is located between 29.5˚N to 38.5˚N latitudes and 60.5˚E to 75˚E longitudes and covers an area of 652,860 km^2. It shares borders with Iran to the west, Tajikistan, Uzbekistan and Turkmenistan to the north, and Pakistan to the south and east (Fig 1). About 82% of

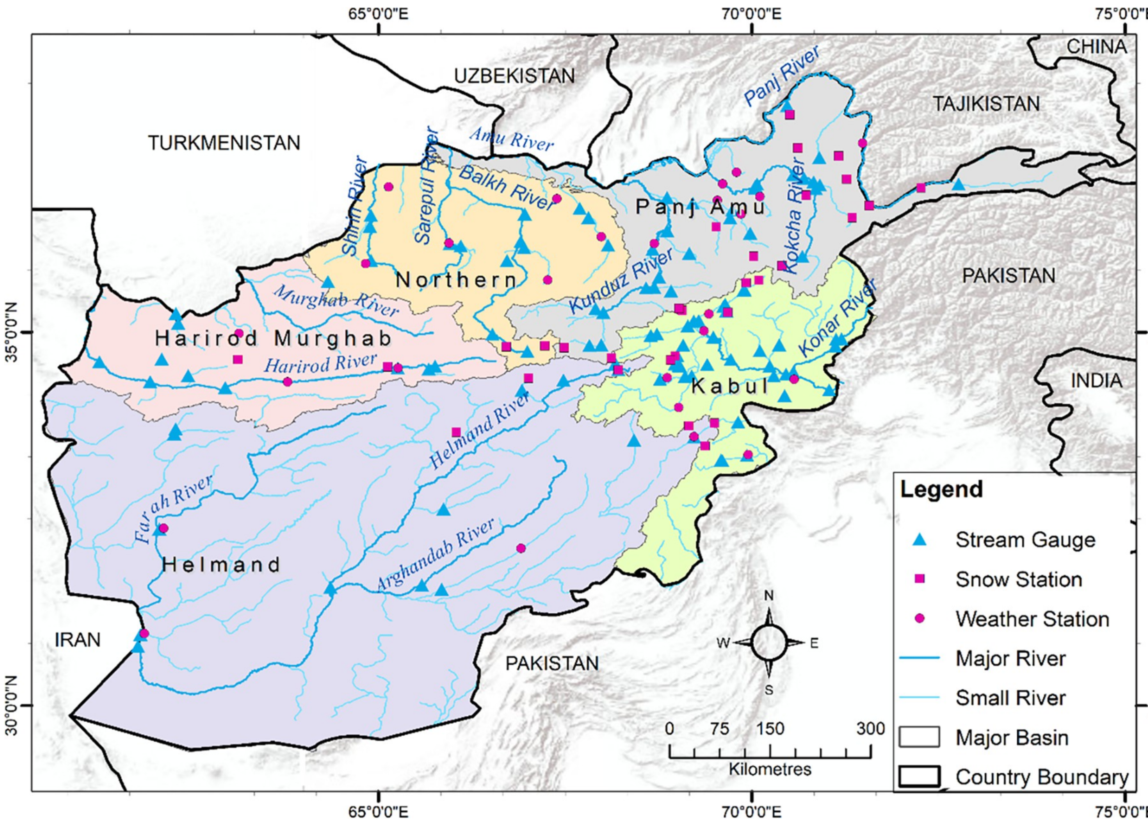

Fig 1. Study area map showing river basins, drainage systems and weather monitoring stations (basemap source: ESRI, https://www.arcgis.com/home/item.html?id=2ef1306b93c9459ca7c7b4f872c070b9).

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Afghanistan's total land area is rangeland and bare land, less than 2% is covered by forests and about 10% of the territory is arable. Much of it is dominated by the Hindu Kush, the westernmost extension of the Karakoram and the Himalayas. About 65% of Afghanistan is mountain ridges with an average height of 1850 m. The snow line is between 4000 to 5000 m altitude and there are a few important areas with permanent snow and glacier areas [16].

The major drainage systems of Afghanistan include the Panj-Amu, Helmand, Kabul and Harirod rivers (Fig 1)[10,17]. The Amu River originates in the glaciers of the Pamirs and drains an area of approximately 241,000 km^2 in the north-eastern and northern parts of Afghanistan. The Harirod and Murghab rivers form the drainage system in the north-western region. The Harirod River originates in the mountain range of central Afghanistan and flows westward across the Herat Valley. It is the main source of irrigation water for the agriculture along the fertile lands of the valley [18,19]. The Helmand is the longest and biggest river in the southwest Afghanistan. It originates in the mountain range about 80 km west of Kabul and travels 1150 km before draining into seasonal lakes along the Afghanistan-Iran border. The Shirin, Sarepul and Balkh are the large rivers in Northern Basin. The Kabul River is the largest drainage system in the south-eastern region. It originates in the Paghman Range and flows eastward to join the Indus River in Pakistan.

Afghanistan is a semi-arid country with high variability and irregularity in precipitation [9,18]. It receives most precipitation in the form of snow during winter and a smaller amount as rainfall in spring [12,20]. Spatial differences in precipitation are substantial and vary according to the altitude and location. The areas to the south of the Hindu-Kush mountains are characterised by a less-continental climate: summer is relatively cool, winter is relatively moderate, and rainfall is higher. Precipitation in the east and southeast is about 800 mm annually, concentrated during the summer when the monsoon brings rain, and elsewhere in the south, annual precipitations are in the range of 170 to 196 mm [12,14]. Since the 1990s, Afghanistan has suffered recurrent droughts in either all or parts of the country. In recent years especially Northern Afghanistan and areas in the western part of the central highlands have often been plagued by drought [21,22].

Based on surface water drainage systems, the country is divided into five river basins, Harirod-Murghab River Basin (HMRB), Helmand River Basin (HRB), Kabul River Basin (KRB), Northern River Basin (NRB) and Panj-Amu River Basin (PARB); four of these are transboundary basins flowing to neighbouring countries except the Northern Basin. Runoff from the mountains into the Kunduz, Kabul, Helmand, and Harirod rivers is heavy for a brief period during the spring, sometimes causing floods and landslides. Runoff tends to be irregular and low during the rest of the year. Water in small rivers is different and varies over time, especially since most of the small rivers run only for 3 to 4 months. Annual surface water potential of Afghanistan is about 57 BCMs [14]. Majority of them is generated from melting of glaciers and snow in the Panj-Amu and Kabul basins [18].

3. Materials and methods

3.1 Modelling approach

The study used the GR4J conceptual rainfall-runoff model [23] configured within the eWater Source platform, which is an integrated modelling framework for modelling water resource and water quality scenarios [15]. This platform provides a range of tools for rainfall-runoff modelling, including tools for subcatchment delineation, rainfall runoff modelling [23], a calibration tool, and regionalisation methods for modelling ungauged subcatchments and different land use types. The platform provides the flexibility of selecting a separate rainfall-runoff model for each subcatchment. In this study, we used both GR4J model and GR4JSG model, the latter being an extension of GR4J with the addition of snow and glacier (SG) plug-in [24]. The GR4J model is an empirical conceptual, spatially lumped daily-timestep rainfall-runoff model with four parameters, x1 (storage capacity of soil store), x2 (water loss or gain through lateral flow), x3 (storage capacity of routing store) and x4 (time lag parameter for unit hydrograph. The GR4JSG model incorporates snow and glacier accumulation and melt with two additional parameters for snow (DDF_{snow}) and glacier (DDF_{ice}). Air temperature is the main driving force for snow accumulation and melt. The model requires continuous time series of precipitation (P), potential evapotranspiration (PET), maximum temperature (Tmax) and minimum temperature (Tmin) as input. Schematic representation of the four water stores in GR4SG model and their linkage with the climate inputs can be found in Nepal et al. [24].

3.2 Conceptualisation of the system

Each river basin was divided into multiple subcatchments based on topography, river network and water storages to estimate water yield across the basin. Each subcatchment was divided into several functional units (FUs) based on elevation. Initial subcatchment boundaries were generated using ArcGIS Hydro Tools based on DEM and river network and then refined based on major tributary confluences and locations of stream gauges and dams. To accurately predict flows into the rivers, subcatchments in neighbouring countries that drain to Afghanistan were included in the model setup. In total, there were 207 subcatchments– 68 in Helmand Basin, 24 in Harirod-Murghab Basin, 42 in Kabul Basin, 25 in Northern Basin, 30 in Panj-Amu Basin and 18 in neighbouring Tajikistan and Afghanistan that drain to Afghanistan

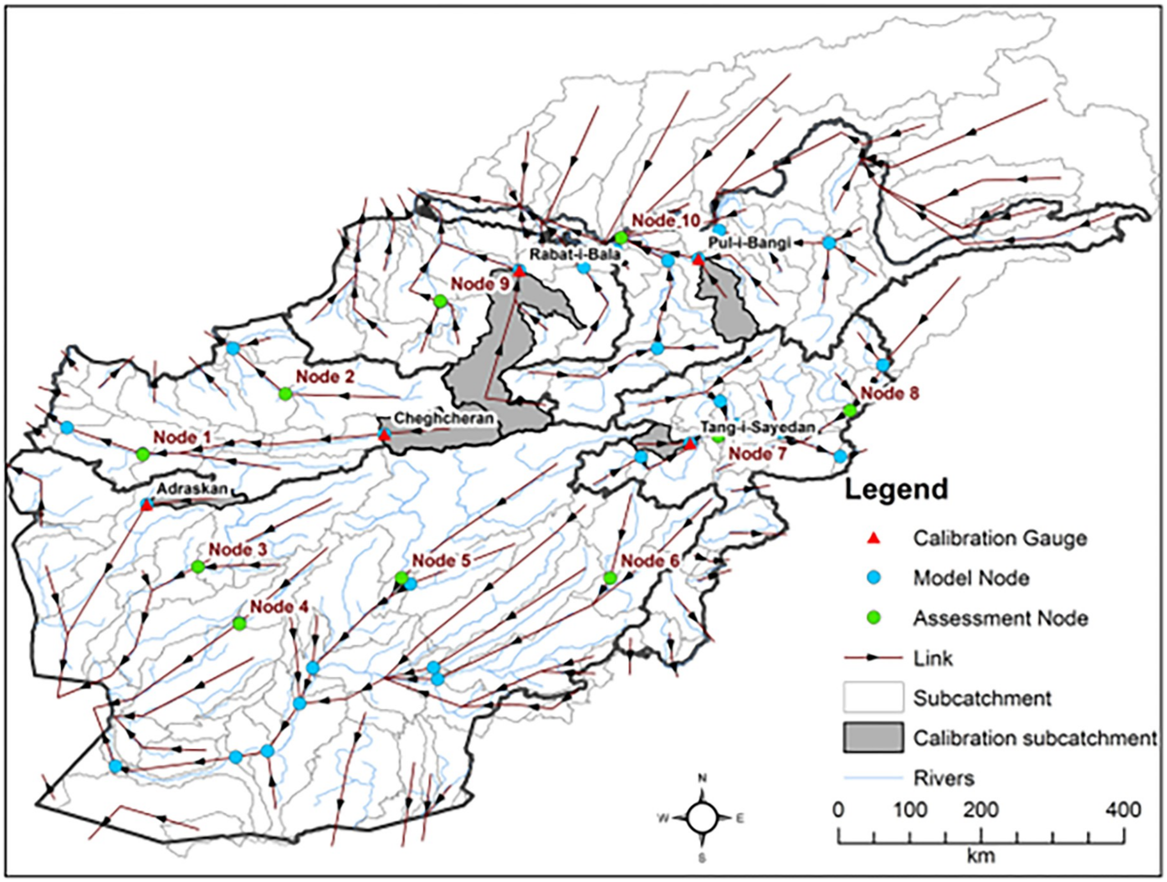

Fig 2. Node-link model configuration for the five river basins of Afghanistan including some subcatchments in neighbouring Pakistan and Tajikistan that drain to Afghanistan. The map shows the 38 model nodes (yellow), the five calibration/validation subcatchments and gauges, and the 10 outflow assessment nodes (green).

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(Fig 2). Since precipitation generally occurs as snowfall over the higher elevations, melting snow and glaciers are significant contributors to streamflow. FUs were derived using elevation bands at 500 m intervals to facilitate snowmelt modelling [25,26]. Each subcatchment was divided into 13 FUs including 4 FUs for no/minimal snow, 5 FUs for snow and 4 FUs for snow and glacier (Table 1). Overall, there were 2488 FUs in 207 subcatchments. FUs elevation, required for snowmelt modelling, was taken as the average elevation for each elevation band. On the river network across river basins, 5 locations were selected for evaluating model simulations and another 10 locations were selected to assess flow variability (Fig 2).

3.3 Model inputs

The main inputs to the model are precipitation, temperature, potential evapotranspiration (PET) and river flow. Observed daily precipitation, temperature and river flow data were obtained from the Surface Water Resources Department of the National Water Affairs Regulation Authority (NWARA) of Afghanistan. The data were collated from automated hydraulic stations, automated weather stations and snow sampling stations.

3.3.1 Streamflow. There were 127 automated stream gauging stations (also known as hydraulic stations) in Afghanistan for measuring water level and discharge across the river network with an average coverage of 5140 km^2 per gauge. Data from all gauging stations were

Table 1. Categorisation of subcatchments into functional units (FUs) based on difference in surface elevation.

Elevation band	FU category	FU elevation	Description
< 500	ng1	300	Assumed no/minimal snow contribution to flows
500–1000	ng2	750	Assumed no/minimal snow contribution to flows
1000–1500	ng3	1250	Assumed no/minimal snow contribution to flows
1500–2000	ng4	1750	Assumed no/minimal snow contribution to flows
2000–2500	ng5	2250	Assumed snow contribution to flows
2500–3000	ng6	2750	Assumed snow contribution to flows
3000–3500	ng7	3250	Assumed snow contribution to flows
3500–4000	ng8	3750	Assumed snow contribution to flows
4000–4500	ng9	4250	Assumed snow contribution to flows
4500–5000	g1	4750	Assumed snow contribution to flows, might have glaciers
5000–5500	g2	5250	Assumed snow contribution to flows, might have glaciers
5500–6000	g3	5750	Assumed snow contribution to flows, might have glaciers
>6000	g4	6000	Assumed snow contribution to flows, might have glaciers

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investigated for consistency, first by comparing with precipitation in the gauging subcatchment and then using a double mass curve. Based on quality of record, we have used data from 101 of these– 13 in HRB, 7 in HMRB, 37 in KRB, 15 in NRB and 29 in PARB. Data gap was a major issue for most of the gauges and based on continuity of data, we have selected the period 2008 to 2020 for further analysis.

3.3.2 Precipitation. A total of 183 precipitation measuring stations were operational at different times between 2008 to 2020. From these, data were available for the 169 stations including 122 at stream gauging sites, 19 at automated weather stations and 28 at snow sampling stations. All data were checked for consistency within and between precipitation measuring stations. Missing data were gap-filled based on data from neighbouring stations using the inverse distance weighting interpolation method [27]. Gauged precipitation data were then interpolated to 207 subcatchments using Thiessen Polygons method [28]. Across the region, annual precipitation in 207 subcatchments varies in the range of just 46 mm to 641 mm with a country average of 234 mm (Fig 3).

3.3.3 Temperature. The main source of temperature data for Afghanistan is the AQUARIUS database (https://aquaticinformatics.com/products/aquarius/aquarius-time-series/) maintained by the NWARA. Observed daily maximum and minimum temperature data from 83 gauging stations were obtained from the AQUARIUS database for the period of 2008 to 2020. Missing data (~4%) were gap-filled and interpolated to 207 subcatchments using the same approach as described in the precipitation data section. Across the region, maximum temperature (Tmax) varies from 1.7 to 32.8˚C with an average of 20.5˚C and minimum temperature (Tmin) from −8.7 to 16.7˚C with an average of 6.9˚C (Fig 3).

3.1.4 PET. Daily PET for 207 subcatchments were estimated using the temperature-based Hargreaves and Samani empirical method based on available temperature data from the AQUARIUS [29]. PET is estimated as a function of minimum and maximum temperature using the following empirical equation.

$$PET = 0.0135\kappa_{R_s}\frac{R_a}{\lambda}\sqrt{(T_{max} - T_{min})}(T_{max} - T_{min}) \quad (1)$$

where Ra is the extraterrestrial radiation (MJ m^{-2} day^{-1}) computed for any given day as a function of the latitude of the site, and l is the latent heat of vaporisation (MJ kg^{-1}) for the mean air temperature T (˚C) that is commonly assumed equal to 2.45 MJ kg^{-1}. The factor 0.0135 is a

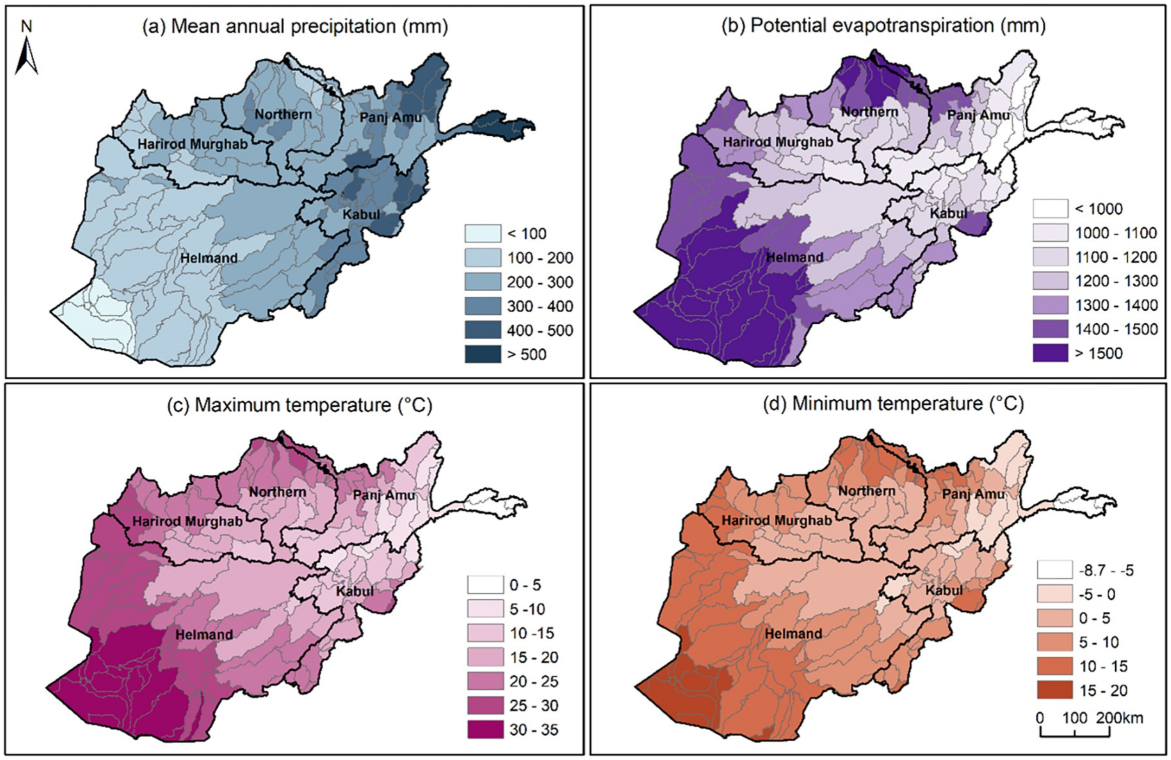

Fig 3. Mean annual precipitation (a), potential evapotranspiration (b), maximum temperature (c) and minimum temperature (d) based on observed data from 2008 to 2020 for the 207 subcatchments of the five river basins of Afghanistan.

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constant to convert from Imperial units to International System (SI) units and k_{Rs} is the empirical radiation adjustment coefficient ($^{\circ}C^{-0.5}$). In the common version of the equation, the value $k_{Rs} \sim = 0.17$ is used [30]. Fig 3 shows the spatial PET across the five river basins of Afghanistan. In general, PET is higher in the southern part of Helmand Basin which is relatively dry.

3.4 Parameter calibration

The GR4J/GR4JSG model parameters were calibrated separately for each of the five basins of Afghanistan. Parameters were calibrated for an unregulated subcatchment in each river basin, and these parameters were then transferred to other subcatchments in that river basin. Table 2 presents the name, stream gauge location and size of subcatchments for which model parameters were calibrated. During the calibration process, snow parameters such as melting temperature threshold, snow bucket, initial snow bucket and snow area were investigated and adjusted where necessary.

Table 2. Selected headwater subcatchment for model calibration in the five river basins (refer to Fig 2 for gauge location).

River Basin	Gauge location	River	Catchment ID (in the model)	Catchment area (km^2)
Panj-Amu	Pul-i-Bangi	Bangi	SC-099	4,287
Northern	Rabat-i-Bala	Balkh	SC-107	14,459
Kabul	Tang-i-Sayedan	Kabul	SC-089	1,657
Harirod-Murghab	Cheghcheran	Harirod	SC-115	6,565
Helmand	Adraskan	Adraskan	SC-120	1,954

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Table 3. GR4JSG model calibration parameters, their recommended range and calibrated values for the five river basins of Afghanistan (HRB: Helmand River Basin, HMRB: Harirod-Murghab River Basin, KRB: Kabul River Basin, NRB: Northern River Basin, PARB: Panj-Amu River Basin).

Parameter	Range	Calibrated model parameters				
		HRB	HMRB	KRB	NRB	PARB
x1 (capacity of soil store, mm)	1 to 1500	19.3	2.26	47.87	129.74	20.77
x2 (water loss/gain coefficient, mm)	−10 to 5	−0.95	−1.27	−3.04	+4.28	+4.88
x3 (capacity of routing store, mm)	1 to 500	418.19	233.61	208.04	134.31	452.31
x4 (time parameter for unit hydrograph)	0.5 to 4	3.42	1.44	1.34	1.00	2.29
DDFsnow (degree day factor for snow)	0 to 10	0.79	6.35	5.02	5.14	9.07
DDFice (degree day factor for ice)	0 to 10	6.68	4.10	0.49	1.39	5.17

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Model parameters were calibrated using a combination of automated and manual processes. At first, the sensitivity of the four GR4J parameters, x1 (capacity of soil store), x2 (water loss/gain coefficient), x3 (capacity of routing store) and x4 (time parameter for unit hydrograph) were investigated to understand the physical significance of parameters and their effects on timing and magnitude of peak flow and volume of water [31]. Model simulations were conducted using five objective functions based on Nash-Sutcliffe efficiency (*NSE*) and bias penalty (e.g. *NSE* daily, *NSE* monthly, *NSE* daily and bias penalty, *NSE* monthly and bias penalty, and *NSE* log daily and bias penalty). After an initial assessment of the modelled river flow for different objective functions compared to stream gauge data, *NSE* daily and bias penalty were selected to calibrate the model parameters. Observed river flow for the period of 2008 to 2015 (inclusive) were used for model calibration and 2016 to 2020 (inclusive) for model validation. Calibrated model parameters for the 5 river basins are presented in Table 3. The negative sign for x2 indicates losing water to adjacent subcatchments and positive sign indicates gaining water from neighbouring subcatchments.

Model results were evaluated by comparing simulated discharge with observed gauge data. Peak and low flows, timing of peaks and lows, and total volume of water were the key variables considered during calibration. Results were evaluated graphically as well as statistically. Based on recommended hydrological model evaluation guidelines [32], we used three quantitative statistics, the *NSE*, Pearson's correlation coefficient (*r*), and percent bias (*PBias*). After a satisfactory calibration, simulations were conducted at subcatchment scale as well as 10 assessment nodes (refer to Fig 2 for location).

4. Results

4.1 odel performance evaluation

Model performances to simulate daily and monthly time-scale river flow were evaluated for the headwater subcatchments (for locations of subcatchments and gauges, see Fig 2). Fig 4 shows a comparison of observed and simulated river flow at five gauging sites in the five river basins. While an overall match was obtained between observed and simulated flow hydrographs (*PBias* $<10\%$), there were some differences for peak flows. As our target was to estimate water yield, we focused on volume of water rather than peak events. Among the five river basins, daily *NSE* varied between 0.36 to 0.64 and monthly *NSE* varies from 0.47 to 0.79 (Table 4). As expected, monthly *NSE* values are larger than daily *NSE* for all subcatchments. At validation (2016–2020), model performed relatively poor compared to calibration (2008–2015) for the most gauges. However, model performed slightly better for the Tang-i-Sayedan gauge in the Kabul Basin. This is primarily due to good quality observed data.

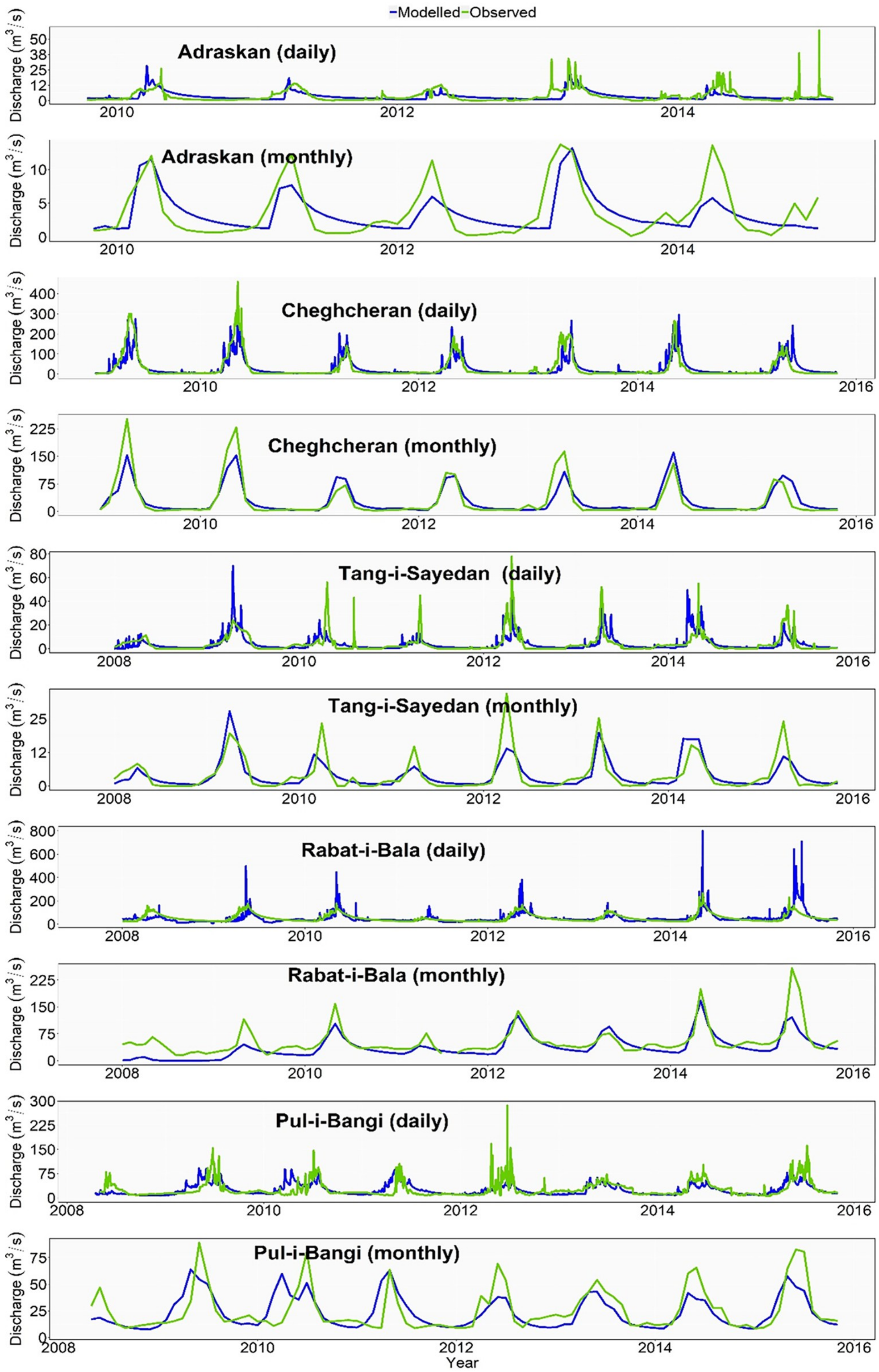

Fig 4. Comparison between modelled and observed daily and monthly flow.

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Table 4. Performance statistics on model simulations for river flow during calibration and validation.

Gauge in Basin	Calibration [2008–2015]				Validation [2016–2020]			
	Correlation coefficient	*PBias* (%)	*NSE* Daily	*NSE* Monthly	Correlation coefficient	*PBias* (%)	*NSE* Daily	*NSE* Monthly
Pul-i-Bangi (PARB)	0.61	−6.41	0.36	0.49	0.58	23.6	0.24	0.46
Rabat-i-Bala (NRB)	0.66	−0.04	0.43	0.58	0.54	−3.9	0.30	0.41
Tang-i-Sayedan (KRB)	0.73	−3.00	0.53	0.70	0.84	10.07	0.69	0.87
Cheghcheran (HMRB)	0.80	−2.93	0.64	0.79	0.79	−4.95	0.60	0.73
Adraskan (HRB)	0.63	−2.74	0.40	0.47	0.63	−33.7	0.23	0.29

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4.2 Spatial water yield

Flow contributions across the 5 river basins were simulated at subcatchment scale. Model simulates flow rate in cubic metre per second (m^3/s) at the outlet of each subcatchment. However, visualising flows using these units show subcatchments with larger areas as having more outflow compared to smaller subcatchments. To improve comparability, we presented water yield as an area-weighted flow depth in millimetre (mm). Fig 5 shows the spatially averaged water yield of each of the 207 subcatchments. The mountainous areas in the north-east (e.g. parts of Panj-Amu and Kabul basins) are the main source of water, particularly from the Hindu Kush mountains. Across the country, modelled water yield in the 207 subcatchments varies from 0.3

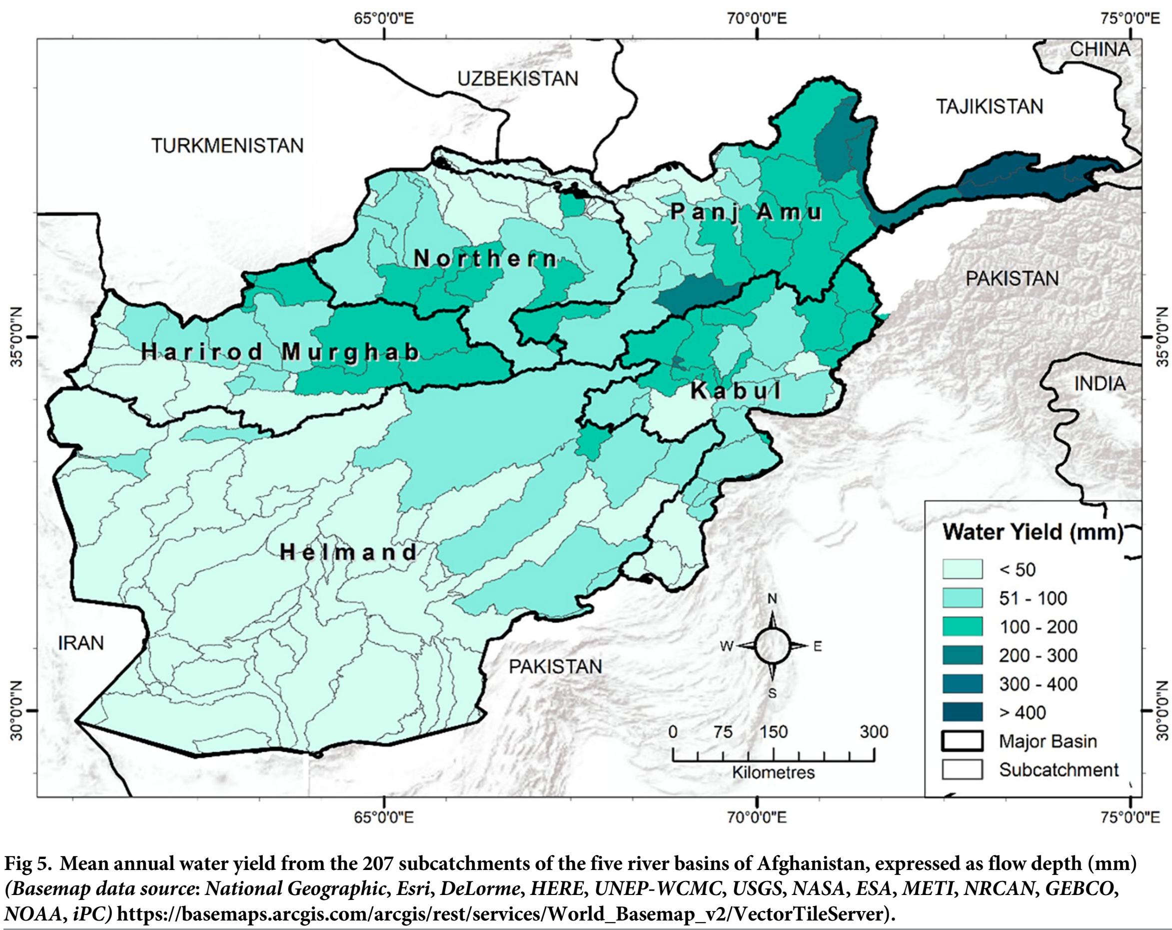

Fig 5. Mean annual water yield from the 207 subcatchments of the five river basins of Afghanistan, expressed as flow depth (mm) ***(Basemap data source: National Geographic, Esri, DeLorme, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC)*** **https://basemaps.arcgis.com/arcgis/rest/services/World_Basemap_v2/VectorTileServer).**

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Table 5. Mean annual precipitation and (modelled) water yield in the 5 river basins of Afghanistan.

River Basin	Drainage area	Area proportion	Spatially averaged Precipitation	Spatially averaged yield	Precipitation volume	Water yield volume
	(km^2)	(%)	(mm)	(mm)	(BCM)	(BCM)
Panj-Amu	92,041	14.3	348.7	173.8	86.4	16.0
Northern	74,688	11.6	251.8	68.9	18.8	5.1
Kabul	71,432	11.1	349.9	96.7	28.6	7.0
Harirod-Murghab	77,616	12.1	220.8	83.3	17.1	6.5
Helmand	326,239	50.8	175.2	36.0	58.4	11.7
Total	642,016	100	-	-	209.3	46.3

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mm in a subcatchment in Helmand Basin to 248 mm in the Panj-Amu Basin, with an average of 72.1 mm for the entire country. Area averaged water yields in the five river basins are 36, 83, 97, 69 and 174 mm in the Helmand, Harirod-Murghab, Kabul, Northern and Panj-Amu basins respectively. For the same period, mean annual precipitation for the entire country is 234.0 mm, indicating a water yield of 30.8%. The nation-wide average water yield of 72.1 mm is equivalent to 46.3 billion cubic meters (BCM) for the entire country. In addition, about 28.9 BCM (about 38% of the total water yield from five river basins) generates annually in the sub-catchments of neighbouring Tajikistan and Pakistan primarily from melting snow and glaciers of the Hindu-Kush mountains. Proportion of this water flows to Afghanistan through Panj and Konar rivers.

Across the region, mean annual water yield in the period of 2008 to 2020 is about 11.7 BCM (25% of the total water yield) in the Helmand basin which is the largest river basin in Afghanistan (51% of the country) (Table 5). The Panj-Amu basin is the second largest with an area of 92,041 km^2 within Afghanistan (14.3% of the country) and 146,250 km^2 in neighbouring Tajikistan. The water yield from Panj-Amu basin is about 42.7 BCM comprising 16.0 BCM within Afghanistan and 26.7 BCM in the neighbouring Tajikistan, mostly from glacier melting in the Hindu-Kush mountains. It is important to note that the water yield in the Panj-Amu basin largely depends on flow from neighbouring Tajikistan. Kabul Basin occupies about 11% of country's land and it produces 6.9 BCM water within Afghanistan and 1.9 BCM in the neighbouring Pakistan, primarily through the Kunar River from melting glaciers and snow of the Hindu Kush mountains. The water yield from the Harirod-Murghab basin is relatively small, about 6.5 BCM which is 14% of total water yield within Afghanistan. Northern basin occupies 74,688 km^2 of land (11.6% of total land) and produces 5.1 BCM water (11%) which is the lowest among the five river basins (Table 5).

4.3 Cumulative river flow

Fig 6 shows the water yield along the river network. Flow at the downstream end for each river system is the cumulative of all water from upstream. As seen in the previous section, Panj-Amu Basin is the main source of water and Panj and Amu rivers carry the most water. Kabul and Kunar rivers in Kabul Basin also source of large amounts of water. The large rivers of Helmand, Harirod-Murghab Basin (e.g. Helmand, Arghandab, Harirod, Murghab) carry noticeable water.

River flow across the river network varies based on location primarily due to variation in precipitation in subcatchments. For example, rivers in Kabul and Panj-Amu basins (e.g. Node 8, Node 10 of Fig 2) carry more water compared to other basins because of higher precipitation and glacier melting in the upstream draining subcatchments. Water yield in the Amu and Panj

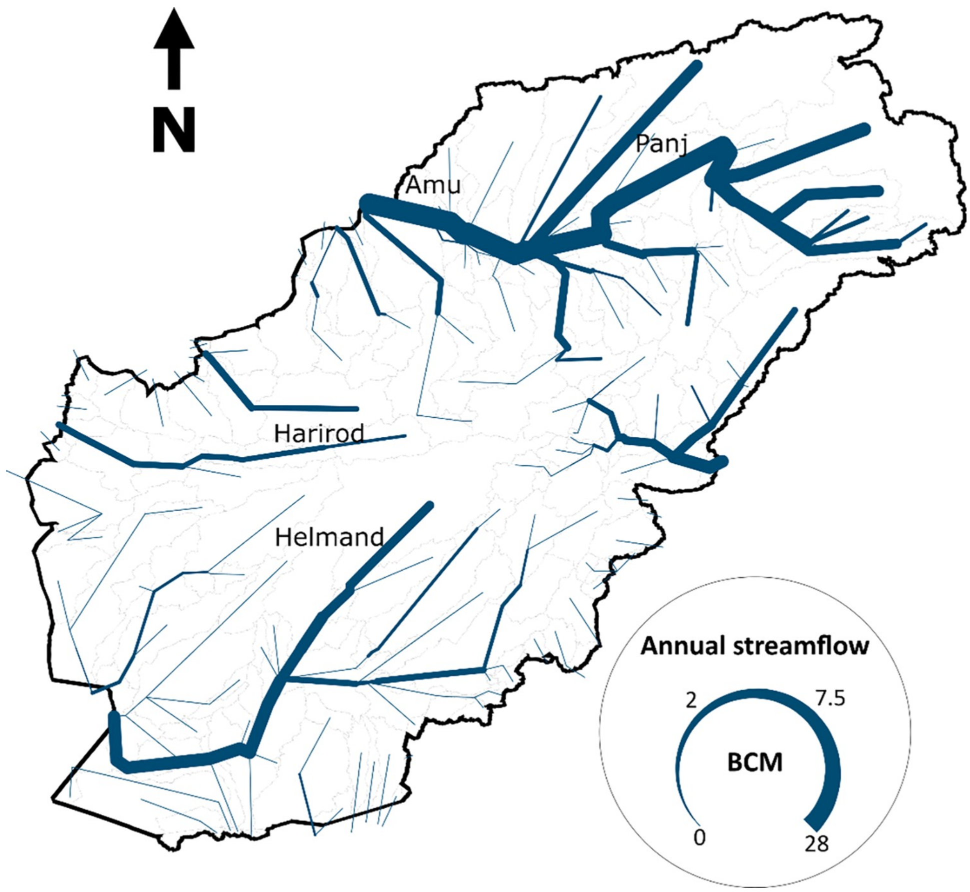

Fig 6. Water yield across the river network in the five river basins of Afghanistan including cross boundary rivers in neighbouring Pakistan and Tajikistan that drain to Afghanistan.

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rivers are especially high because they receive large amount of water from the neighbouring subcatchments in Tajikistan in addition to water generated within Afghanistan.

4.4 Flow variability

River flow in the five basins varies spatially and temporally. Fig 7 shows the water yield at 10 selected sites at an annual scale for the period of 2008 to 2020 (outflow assessment nodes in the model) across the basin. Compared to average yield across the region, the maximum annual yield is 25 to 80% more, and the minimum annual yield is 23 to 63% less based on location. While water yield varies between years, there is no consistent increasing or decreasing trend–for some sites (e.g. Nodes 5, 6 and 7) increasing trends are apparent, and for others (e.g. Node 3, Node 10) decreasing trends are seen.

Compared to the inter-annual flow, water yield between months varies significantly (Fig 8). About 60 to 70% flow occurs between the months of March to June. However, maximum monthly flow varies between locations in the basin. Maximum flow occurs in April in most subcatchments; otherwise, February (e.g. Delaram in Harirod-Murghab Basin), March (Petch Tangi) or May (e.g. Kulukh Tepa). Fig 9 shows the spatial and temporal variations of subcatchment-averaged water yield across the five river basins of Afghanistan. As seen in the previous section, water yield is highest in May.

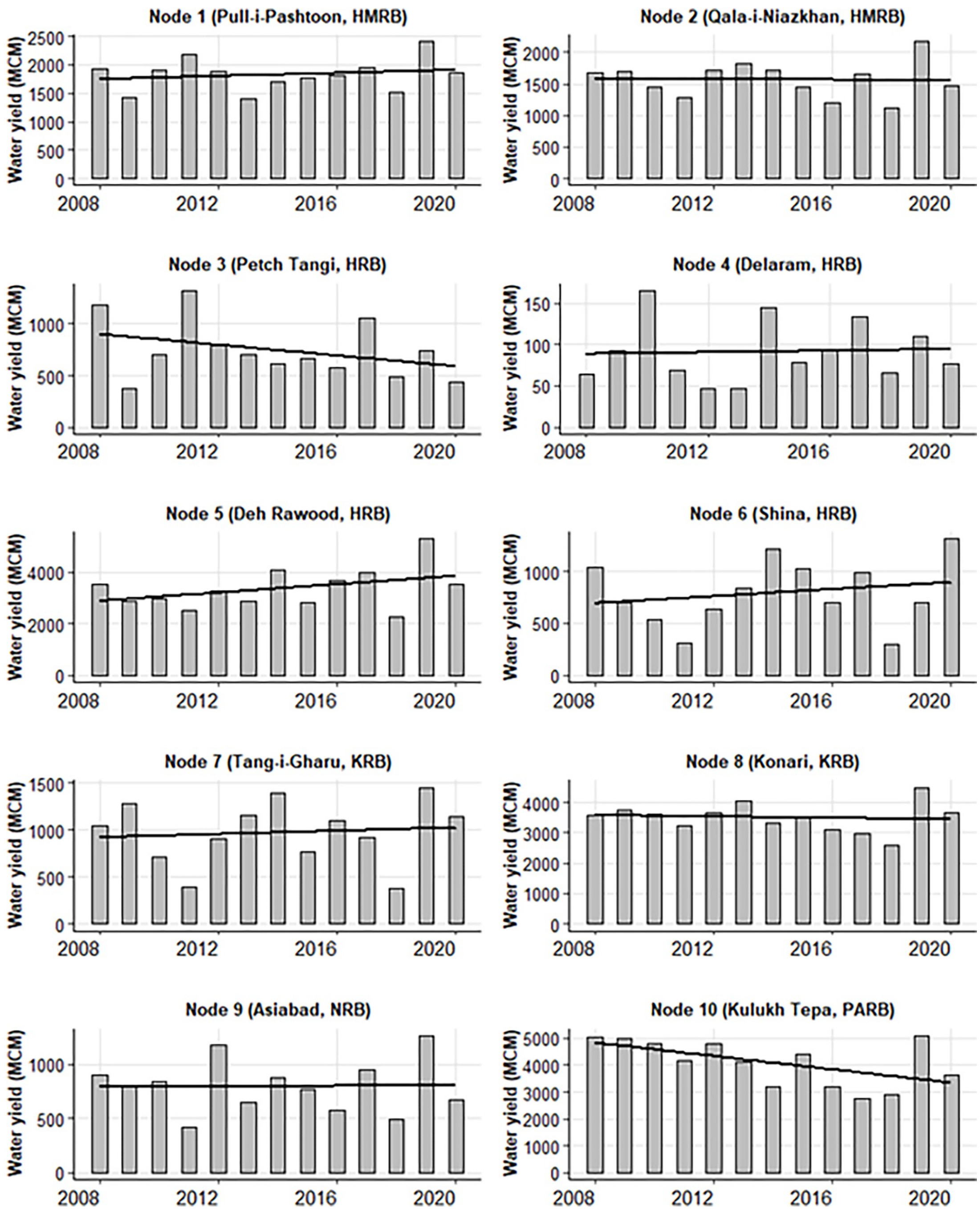

Fig 7. Simulated inter annual flow variability at the 10 outflow assessment nodes in the five river basins over the 2008 to 2020 period. Each plot includes a linear trend line highlighting those with increasing or decreasing trend over the period.

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5 Discussion

Data quality and adequacy remain a challenge with hydrological studies in Afghanistan. Despite that we configured and calibrated detailed hydrological model and obtained an overall match between observed and simulated river flow (*NSE* of 0.4 to 0.6 and less than 10% bias) and provided an overview of water availability across the major basins of Afghanistan. While

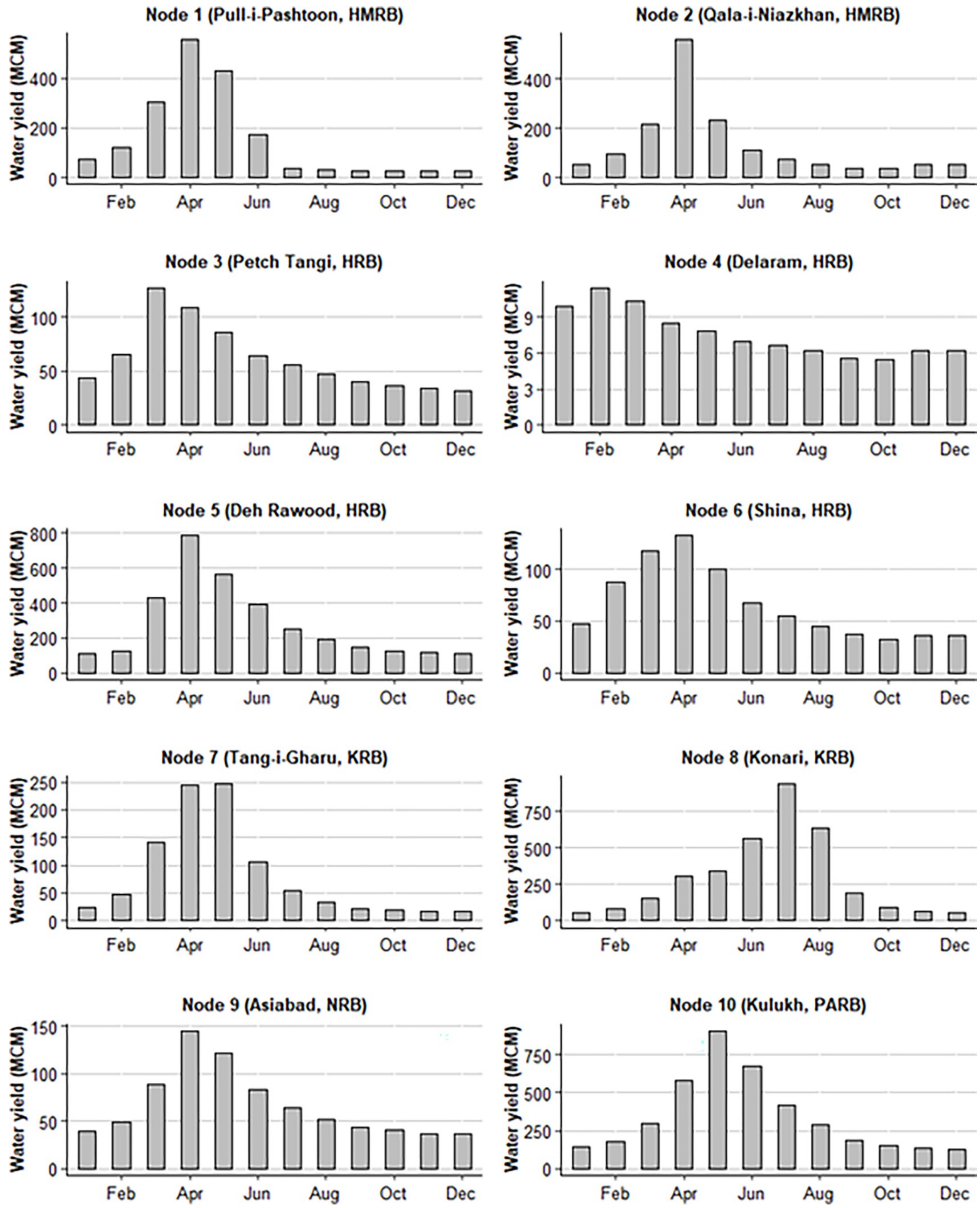

Fig 8. Simulated average monthly flow at the 10 outflow assessment nodes in the five river basins over the 2008 to 2020 period (HMRB: Harirod-Murghab River Basin, HRB: Helmand River Basin, KRB: Kabul River Basin, NRB: Northern River Basin, PARB: Panj Amu River Basin) for the period of 2008 to 2020.

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an overall match was obtained between observed and modelled discharge, there were some differences for peak flows which may be attributed to the uncertainty in gauged data estimated using in-channel rating curves that do not take overbank floods into account. We also noticed inconsistencies between the observed precipitation and streamflow measurements at some of the gauges. While significant efforts were made to calibrate the model across the river basins,

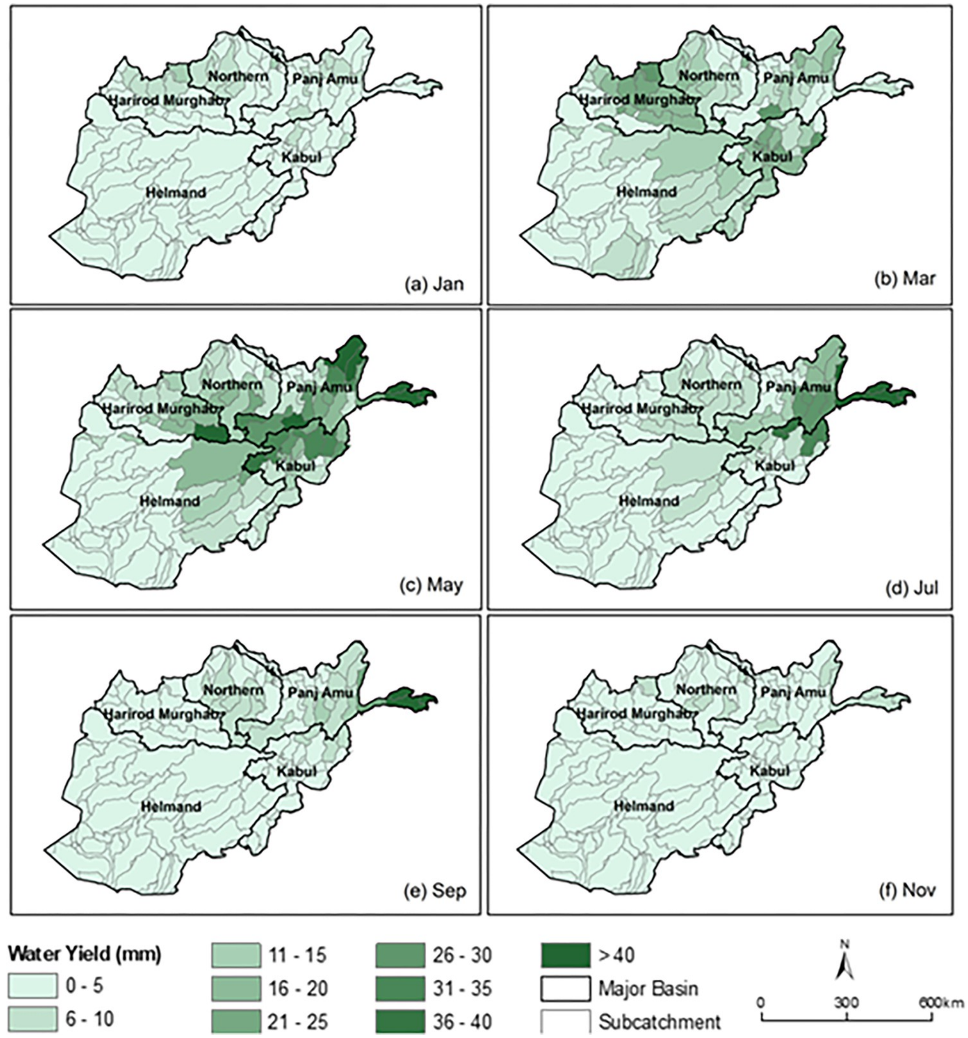

Fig 9. Monthly water yield across 207 subcatchments in the five river basins of Afghanistan.

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rigorous testing of model results at multiple locations was not possible because of limited data availability. Furthermore, information on water storages and diversions for irrigation was not available and therefore those were not included in the current assessment. Moreover, low yields in some subcatchments and high transmission losses through lowland rivers cause cease-to-flow at many parts of the river network. Consequently, actual water availability across the river network could be different from that shown in Figs 5 and 6. The period 2008–2015 was selected for model calibration based on the availability of reliable, consistent hydroclimate data for Afghanistan. Several international and local projects worked in Afghanistan to improve hydrometeorological monitoring during that time. The collected data provided an opportunity to analyse it confidently. The chosen period also witnessed several droughts and flood events, allowing us to establish a representative baseline. We recognise that climate change has probably changed hydroclimate patterns since 2015, and our study provides a foundation for assessing the magnitude and direction of change. We believe an improved understanding of baseline hydroclimate is valuable in guiding adaptation and mitigation plans.

Much of Afghanistan regions are dry and produces very little useable water. The mountainous areas particularly from the Hindu-Kush range in the north-east (e.g. parts of Panj-Amu and Kabul basins) are the main source of water due to high precipitation and low evapotranspiration. An estimated 75.2 BCM of water is produced in Afghanistan annually of which 28.9 BCM comes from neighbouring Pakistan and Tajikistan. Water yield is highest in Panj-Amu basin followed by Helmand. However, area averaged water yield is the minimum in the Helmand basin (36 mm) due to its dry climate compared to Harirod-Murghab (83.3 mm), Kabul (96.7 mm), Northern (68.9 mm) and Panj-Amu (173.8mm). Our estimates resemble with previous studies on water potential in Afghanistan [18]. Among 5 basins, Panj-Amu shows higher water potential (42.7 BCM) including 26.7 BCM from neighbouring Tajikistan primarily from melting snow and glaciers. As the water availability in Afghanistan is significantly influenced by the snow and glacier melting in the mountain regions and partly by the water control measures in neighbouring countries the runoff coefficients are much larger than normally expected for a dry region (Table 5). Our modelled water yield includes both snowmelt and rainfall. However, water from neighbouring Tajikistan and Pakistan is mostly from the melting of glaciers and snow in the Hindu-Kush mountains. Our estimate shows that the water yield outside Afghanistan is 28.6 BCM, which is about 38% of the total water yield from five river basins. However, we are unable to verify these estimates with in-situ measurements (e.g. isotopic analyses) and the models may produce different estimates because of parameter uncertainty as described in Dolk et al. [31].

Similar to other South Asian countries, water yield in Afghanistan varies spatially and temporally. Yields are higher in the Kabul and Panj-Amu Basin compared to other basins primarily due to higher precipitation and partly due to low evapotranspiration loss. While water yield in some years is more than other years, there is no consistent increasing or decreasing trend. At some locations (e.g. Nodes 5, 6 and 7), increasing trends are noticed and at other locations (e.g. Node 3 and Node 10) decreasing trends are noticed. Compared to the inter-annual flow, water yield between months varies significantly (Fig 8) with about 60 to 70% occurring between March and June. This indicates the need to find alternative sources for irrigation and domestic use during the dry period.

Finally, limited data, anomaly in observed data and the recent collapse of the institutional setup make it difficult to estimate the true picture of current water availability in Afghanistan. In many instances, inconsistencies between precipitation and streamflow were found. Therefore, a conscious and sustained effort is needed to collect all existing information and data from local institutions, private organisations and international agencies to improve and cross-validate current estimates.

6 Conclusion

This study provides an assessment of water yield across the five major river basins of Afghanistan using a combined GR4J and GR4JSG precipitation-runoff models. Each river basin was modelled separately with model parameters determined through calibration for headwater subcatchments in the basin. The calibrated parameters were then transferred to all other subcatchments in that basin. Average water yields from the 207 subcatchments were estimated using simulated daily flow for 2008 to 2020 period. Mean annual water yield across the region varies from 0.3 mm in the Helmand Basin to 248 mm in the Panj-Amu Basin, with an average of 72.1 mm for the entire Afghanistan, equivalent to 7.2 million cubic meters of water from an area of 100 km^2.

Our modelled water yield includes both snowmelt and rainfall and we found that north-eastern part of Panj Amu and Kabul basins are the main source of water in Afghanistan. It is important to note that 28.6 BCM of water generate outside Afghanistan (26.7 BCM in Tajikistan and 1.9 BCM in Pakistan) which is about 38% of the total water yield in the five river basins. Major proportion of this water generates from melting of glaciers and snow in the Hindu-Kush mountains in neighbouring Tajikistan and Pakistan.

There is no consistent increasing or decreasing trends. Compared to inter-annual flow, water yield between months varies significantly. About 60 to 70% of annual flow occurs between the months of March to June. However, maximum monthly flow varies depending on location within the basin. The study identified the areas of major water sources in the basin and investigated the flow variability at monthly, seasonal, and annual time scale. This information is crucial for long term planning for water resources and agricultural development.

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