water

Supplemental Materials and Information: CRB Geography

Study Area Detail

The 283,384 km^2 Upper Colorado River Basin (UCRB) drains the West Slope of the Rocky Mountains and the stratigraphically largely undeformed Colorado Plateau section of the Rocky Mountains geologic province. Colorado Plateau strata range in age from early Proterozoic (1.84 billion years ago) metamorphic crystalline basement rock, to Precambrian through early Cenozoic sedimentary strata, with late Cenozoic basalts [32], and ranging in elevation from 4352 m down to 350 m on Lake Mead Reservoir.

Every natural CRB tributary we have examined thus far arises from springs, springfed wetlands, or small groundwater-fed lakes e.g., [21]. For example, UCRB mainstream flow arises from two primary sources [12,13]. The 1112 km-long Green River sources at an unnamed springfed fen 2 km southwest of Mt. Wilson in the Wind River Range in Sublette County, Wyoming, and also receives surface snowmelt water from Minor Glacier and other snowfields near Gannet Peak (4087 m). Along its course, the Green River receives flow from the Yampa and White Rivers, and delivers a long-term mean discharge at its mouth of 173 m^3/sec. Similarly, the upper Colorado River similarly arises from a springfed fen at La Poudre Pass in the Rocky Mountains of Colorado, and receives flow downstream from the Gunnison, Dolores, and other rivers and streams [13]. Downstream from the Green and Colorado Rivers confluence in Canyonlands National Park, Utah the mainstream is joined by the flows of: the Fremont/Muddy, San Juan, and Escalante Rivers in Lake Powell Reservoir, and the Paria River near Lees Ferry, Arizona. The Green and Upper Colorado Rivers contribute 75% of the river's total flow, and the UCRB produces 90% of that total [26], with nearly half (seasonally varying) of UCRB baseflow is derived from groundwater [11,22]. Overall, the UCRB serves as an exploitation/extraction-dominated basin, with geologic, forest, agricultural, water and hydropower, and recreational resources extracted and exported or used downstream and elsewhere in the Southwest.

The 344,440 km^2 Lower Colorado River Basin (LCRB) lies in the Basin and Range geologic province, a late Cenozoic, tectonically extensional terrain dominated by horst and graben mountain ranges, and Proterozoic metamorphic, Phanerozoic sedimentary strata, and mid-late Tertiary igneous parent rock geology [29]. The LCRB downstream from Lee Ferry, Arizona receives perennial flow from: the Little Colorado River in Grand Canyon, as well as Kanab, Havasu, Diamond, and other creeks in Grand Canyon. Downstream from Grand Canyon, the Virgin River contributes on average 4390 L/s of largely groundwater-derived baseflow [33] and the Muddy River contributes 1218 L/s [27]. The only other substantial LCRB tributary contributions are return flow of Las Vegas Wash effluent (mean baseflow = 5663 L/s) [28], the minor flow of the Bill Williams River, and irrigation return flows (e.g., the lower Gila River in the Wellton-Mohawk canal system near Yuma, Arizona) [14,27]. Several major dams and diversions normally abstract all of the LCRB flow, and virtually all of the Colorado River's flow normally is lost to diversion, infiltration, and evapotranspiration in the LCRB just before it crosses the US-Mexico border [12–15,22].

Lying between the two geologic provinces, the Grand Canyon ecoregion (GCE) occupies 35,000 km^2 of the CRB that drains into Grand Canyon, Arizona's world-renowned, deeply incised canyon. The GCE extends from lower Lake Powell Reservoir 500 km downstream to Lake Mead reservoir. Grand Canyon, as well as other national, state, and county parks, and wildlife preserves, refuges, and wilderness areas contain many ecologically intact springs in the CRB. These springs can serve as relatively undisturbed sentinel sites for understanding aridlands springs ecosystem and conservation ecology e.g., [8,16,34,35]. To investigate the extent to which springs provide the primary source of baseflow for perennial CRB streams, we also studied the sources of the 270 km-long, 17,130 km^2 Verde River Basin in north-central Arizona. We selected the Verde River for this analysis because it heads at 3850 m on the San Francisco Peaks, crosses the Colorado Plateau margin, and mouths at 404 m

elevation at its confluence with the Salt River northeast of Phoenix. The Verde River basin has a long-term mean discharge of 0.36 km^3/yr and supports diverse natural and human communities, and is threatened by groundwater appropriation [36–38]. We also investigated the sources of the Virgin River in southwestern Utah [39].

The CRB also has been politically divided into upper and lower basins, the former including the states of Colorado, New Mexico, Utah, and Wyoming, and the latter including the states of Arizona, California, and Nevada. The boundary between those two basins is Lee Ferry, as defined by the 1922 Colorado River Compact (Figure 1) [17,40]. The Compact established water delivery guidelines, famously over-estimating the river's flow, and it established the legal framework for water delivery (the "Law of the River") and the eventual construction of a dozen large federal dams and diversions that now regulate the Colorado River's flow through the CRB. The river's managing agencies, Native American tribes, and the public are increasingly concerned over persistent drought, declining water tables, and the sustainability of mainstream flows and water storage e.g., [12].

Also arising from this political division, transbasin and intra-basin CRB flow is diverted through several large canals across the Rocky Mountains, the Wasatch Front in Utah, from Lake Mead to Las Vegas, and through the Central Arizona Canal, the All American Canal, and the Mexican Canal, the latter fully dewatering the river. The only transbasin diversion that contributes flow into the CRB lie is a small irrigation ditch from the East Fork of the Sevier River into the Paria River south of Bryce Canyon National Park, Utah. Irrigation return flows mixed with groundwater include Las Vegas effluent from Las Vegas Wash into Lake Mead (0.004 km^3/yr from 1992–2018 [27,28] and, farther downstream, irrigation return flows from agricultural operations.

Prior to extensive CRB impoundment during the 20th Century, Colorado River discharge varied seasonally, with instantaneous flows ranging from near 0 to 10,900 m^3/sec [13,27]. Contemporary total UCRB discharge averages 16.3 km3/yr, varying inter-annually from 7.4 to 25 km^3/yr, of which an average of 53% is contributed by groundwater [11]; however, drought conditions have predominated in the 21st Century, prompting grave concerns about the sustainability of water delivery and groundwater availability [12].