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Riparian Vegetated Area in Pre-Dam, Post-Dam, and Environmental Flow Periods in Canyonlands National Park From 1940 to 2022

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ABSTRACT

The Upper Colorado River Basin is the principal water supply of the western United States and includes a series of canyons that provide habitat for disproportionate numbers of flora and fauna. Following the closing of Flaming Gorge and Blue Mesa dams in 1963 and 1966, decreases in peak flows and elevated base flows allowed extensive vegetation encroachment, channel narrowing, and channel simplification. Since 1992, reservoir releases have been modified to increase the ratio of peak to base flows for environmental reasons, including protection of endangered fish. We used remote imagery from 1940 to 2022 to examine rates of vegetation encroachment along three river reaches in Canyonlands National Park during the pre-dam (1940–1966), post-dam (1967–1992), and environmental flows (1993–2022) periods. We found an increase in the vegetated area along the Colorado and Green Rivers upstream of their confluence since 1940. We documented a 6.1% and 4.0% increase in vegetated area in the post-dam period and a 19.5% and 6.5% increase in vegetated area in the environmental flows period on the Colorado and Green Rivers, respectively. The Cataract Canyon reach (Colorado River below the confluence) has been stable since 1966. All three river reaches showed the slowest period of vegetation encroachment, indicative of channel narrowing, in the last 16 years of environmental flows that included a large peakflow in 2011. Environmental flows that mimic the natural hydrograph have not reversed decreases in peak flow and channel width, due in part to decreasing runoff and increasing flow diversion. Flow alterations that reduce the spring peak could cause further narrowing.

1 | Introduction

Across dryland regions of the western United States, large rivers have cut canyons through complex topography, creating a diversity of world-renowned riverine landscapes. In the Upper Colorado River Basin, large rivers and riparian zones provide stark contrast to the surrounding desert environment. Wide, complex channels are maintained by physical disturbance from large annual flow peaks resulting from snowmelt in the

mountain headwaters. These river ecosystems provide habitat for federally listed terrestrial and aquatic species, are intimately intertwined with unique geologic features, and are major recreational destinations.

As demands for water from the Colorado River Basin have increased, water development projects have altered streamflow in virtually all the Colorado River Basin. Demands continue to put pressure on the system through in-basin uses

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and newly proposed trans-basin diversions from upper basin sources. In the Colorado River Basin, the ratio of total reservoir storage volume to mean annual discharge is the largest in North America (Graf 1999), and dams are important to water management in the Upper Basin. In most regulated rivers, peak flows have been reduced and base flows have increased. These changes in streamflow related to water development have resulted in vegetation encroachment, channel narrowing, and simplification (Allred and Schmidt 1999; Dean and Schmidt 2011; Friedman et al. 1998; Grams and Schmidt 2005; Grams, Head, and Kinzel 2022; Hereford 1984; Manners, Schmidt, and Scott 2014; Walker et al. 2020; Williams and Wolman 1984) and typically limit recruitment of some native plant species (Dewine and Cooper 2007; Sankey et al. 2015; Scott, Friedman, and Auble 1996; Sher, Marshall, and Gilbert 2000; Stromberg 1997).

Dams trap sediment causing sediment deficit immediately downstream, resulting in the winnowing of the finer grain sizes of sediment from the channel bed, causing channel incision and coarsening of the bed. The loss of long duration floods caused by dam management may result in channel narrowing further downstream as tributary sediment accumulates within the channel (Dean and Schmidt 2011; Dean et al. 2020; Grams, Schmidt, and Topping 2007; Walker et al. 2020; Williams and Wolman 1984). Channel narrowing is often accompanied by the reduction of geomorphic complexity, aggradation of floodplains/bars resulting in disconnection of the river from its floodplain, and related changes in the width, structure, biodiversity, and composition of riparian vegetation (Graf 2006; Grams and Schmidt 1999; Williams and Wolman 1984). Vegetation encroachment stabilizes sand and gravel bars that are less frequently or no longer inundated by post-dam flows (Grams and Schmidt 1999; Grams, Schmidt, and Topping 2007) mimicking effects of flow decreases caused by drought (Manners, Schmidt, and Scott 2014). In Dinosaur National Monument (430-km upstream of our study sites on the Green River), Grams and Schmidt (1999) found that narrowing was greatest where there was the greatest reduction in stream power due to river regulation. Narrowing occurred by bar stabilization, vertical accretion, and filling of secondary channels on the Green River in Dinosaur National Monument (Grams and Schmidt 1999) and near Green River, Utah (120-km upstream of study location; Allred and Schmidt 1999). In many cases, narrowing has been accompanied and enhanced by the establishment and spread of the nonnative riparian shrub, tamarisk (*Tamarix ramosissima* and hybrids; Birken and Cooper 2006; Dean et al. 2011; Everitt 1993; Manners et al. 2011; Perkins, Scott, and Naumann 2016).

There have been many studies that have documented channel narrowing and occasional temporary widening in the Upper Colorado River Basin. Channel widening can occur when high flows are able to mobilize the shoreline and remove vegetation. In the highly regulated Green River from Flaming Gorge Dam, which closed in 1962 (585-km upstream of study location), to the confluence of the largely unregulated Yampa River (480-km upstream of study location), there has been overall narrowing. Andrews (1986) reported a 13% decrease in width from 1966 to 1977. Similarly, Merritt and Cooper (2000) found a 13% decrease between 1954 and 1977, before the channel widened by 10% from 1977 to 1994 in an alluvial section. They found that the river

has transformed from a deep, meandering river to a shallow, multi-branched channel over the 37 years following construction of Flaming Gorge Dam (Merritt and Cooper 2000). Grams and Schmidt (2002) showed that channels narrowed by 22% in Lodore Canyon in the Green River between 1954 and 1993.

Similar patterns have been observed in the partially regulated Green River between the confluence of the Yampa and the confluence with the Colorado River. Graf (1978) studied 18 sites in and just upstream of Canyonlands National Park (NP), UT. Seventeen of these sites showed narrowing with only one site showing widening. Some of these sites narrowed prior to closing of Flaming Gorge Dam. Andrews (1986) documented a 13% decrease in channel width from 1964 to 1978 and a 10% decrease (15 m) between 1952 and 1981 at sites near Jensen and Green River, UT, respectively. Lyons, Pucherelli, and Clark (1992) measured a stable width between 1952 and 1974 and reported a decrease in channel width of 3%–12% between 1964 and 1974 in a reach upstream of the study location. Grams and Schmidt (2002) showed narrowing between 10% and 25% in Dinosaur NM between pre-dam photographs taken from 1938 and 1954 to post-dam photographs in 1993. Allred and Schmidt (1999) demonstrated that the channel narrowed near Green River, UT, by about 5% between 1938 and 1952. Channel width was then stable from 1952 to 1962. They measured an additional 14% narrowing between 1962 and 1993. Lastly, Walker et al. (2020) found that the channel narrowed 12% over a 61-km reach from 1940 to 2014 on the Green River in and above Canyonlands NP. This process began in the 1930s when total annual and peak annual flows decreased. Narrowing then slowed from the 1940s to the mid-1980s. Significant narrowing occurred in the late-1980s due to floodplain formation in a period of low annual flow. They further speculated that a new phase of narrowing may have begun in 2003. They attributed narrowing to changes due to Flaming Gorge Dam that were then further promoted by increases in native and non-native vegetation.

Studies on the largely unregulated Yampa River have documented channel narrowing at a lesser extent. Merritt and Cooper (2000) looked at Deerlodge Park (74-km upstream of the confluence with the Green River) and found the river channel widened by 18.6 m from 1938 to 1973, remained relatively uniform over the following decade (1973–1984), but experienced rapid channel narrowing following the major flooding that occurred on the Yampa River in 1984. They concluded that the Yampa has remained in a state of relative quasi-equilibrium with discharge and sediment regimes. Manners, Schmidt, and Scott (2014) documented that the Yampa River channel has narrowed by an average of 6% in two of the widest canyon reaches from 1961 to 2011.

There have been considerably fewer studies on the Colorado River in the Upper Basin. Van Steeter and Pitlick (1998) found that the reaches of the Colorado River near Grand Junction (210-km upstream of the Colorado River study location) had narrowed by an average of 20 m between 1937 and 1992 with many side channels and backwaters being lost. This was associated with decreases in annual peaks by 29%–38%. Grams, Head, and Kinzel (2022) found that Meander Canyon on the Colorado River in Canyonlands NP had narrowed by 22% due to expansion of vegetation and alterations to floodplain habitat between

1940 and 2018. The largest decreases in width occurred during periods of low flow from 1993 to 2006.

In addition to dams, riparian exotic plants likely play a role in channel narrowing in the Upper Colorado River Basin. Friedman, Vincent, and Shafroth (2005) found that *Tamarix ramosissima* and *Elaeagnus angustifolia* are the third and fourth most frequently encountered woody riparian plants in the western United States. Stromberg et al. (2007) noted that *Tamarix ramosissima* is a pioneer species that produces many small wind- and water-dispersed seeds and requires bare, mineral soils for seedling establishment. These traits are shared with native *Populus* and *Salix*. However, *Tamarix ramosissima* is more reproductively opportunistic with viable seeds present over most of the growing season that allows it to establish in reaches where flood timing deviates from the climatic norm.

Allred and Schmidt (1999) suggest that the establishment of exotic species, such as tamarisk, has accelerated the process of channel narrowing on the Green River below the confluence with the Yampa. Manners, Schmidt, and Scott (2014) documented a progressive narrowing process that involved establishment of tamarisk during a series of low-flow years on the downstream end of a large, mid-channel bar when peak flows (1949–1951) did not exceed the 2-year return flood. By 1952, a year with a significant flood peak, the established tamarisk survived the inundation and shear forces associated with this flood, as well as burial by vertically accreted fine sediment. Over the next five decades, tamarisk became established primarily during drought periods and then promoted narrowing by trapping sediment during subsequent floods.

Flaming Gorge Dam closed in October 1962 (Andrews 1986). Blue Mesa Dam (390-km upstream of Colorado River study location) as part of the Aspinall Project on the Gunnison River, a major tributary of the Colorado River, became operational in 1966. Upon closing of these dams, flows were primarily designed for maximum power plant efficiency, decreasing and delaying peak flows, and increasing summer base flows. Since 1992, flows at Flaming Gorge Dam and the Aspinall Unit have been modified to more closely mimic natural hydrographs (E. Knight, Bureau of Reclamation, oral communication, 2022), increasing the ratio of peak to base flows. Additional alterations occurred in 1995 to protect endangered fish under the Endangered Species Act, and for a water right put in place on the Black Canyon of the Gunnison National Park in 2008. Prescription of large peaks from these reservoirs is constrained, however, by concerns about dam safety and downstream flooding. To date, no study has determined whether these dam operations for environmental reasons can overcome decreasing runoff and increasing diversions to slow or even reverse channel narrowing and simplification that has occurred over the last several decades.

We looked at conditions pre-dam (1940–1966) and divided the post-dam period into an initial period when the dam flows were operated strictly for hydropower (from 1966 on the Colorado and 1963 on the Green to 1991) and an environmental flows period (1992–2022) when dam operations started to mimic natural hydrographs to benefit endangered fish, reinstating the late-spring annual peak. We examined vegetated area (> 50% cover) along three reaches (152 km) of the Colorado and Green

river in Canyonlands NP to determine whether three decades of environmental flows have had an effect on long-term channel narrowing. The three study reaches included both the Green and Colorado above their confluence and the Colorado below the confluence, which represents the summation of the semi-natural flow of these rivers before entering Lake Powell (5 km downstream of our study location). Our first objective was to use high-resolution imagery to examine changes in total riparian vegetation response over 80 years for the Colorado and Green Rivers within Canyonlands NP. The second objective was to determine whether the rate of changes in total vegetation was altered by reoperations of dams to more closely mimic the natural hydrograph.

2 | Methods

Our study area was the river system within Canyonlands NP divided into three reaches, a 74-km reach of the Green River extending from the park's northern boundary to the confluence with the Colorado River (slope 0.27 m/km), a 55-km reach of the Colorado River (slope 0.25 m/km) extending from the park's northern boundary to the confluence with the Green River, and a 23-km reach of the Colorado River (slope 1.61 m/km) below the confluence to the southern park boundary, hereafter referred to as Cataract Canyon (Figure 1). Above the confluence, these two rivers exhibit confined meanders with a low gradient and a sand bed with occasional gravel riffles. In Cataract Canyon, the gradient steepens, and the river is a narrower, debris fan-dominated canyon (Schmidt 1990). Elevations range from 1150 to 1210 m. The region is arid to semiarid with mean annual precipitation ranging from 210 to 255 mm and mean annual temperature from 10.7°C to 12.2°C. Both rivers' discharge comes primarily from Rocky Mountain snowmelt in the headwaters, while sediment is contributed lower in the watershed and from tributaries draining the relatively arid Colorado Plateau. Peak snowmelt runoff usually occurs between May and mid-July. Monsoon events can cause local flash floods in tributaries from July through October. In low snowfall years, the monsoonal peak can occasionally exceed the spring runoff.

The riparian community is dominated by native narrowleaf willow (*Salix exigua*), Fremont cottonwood (*Populus fremontii*), and non-native tamarisk (*Tamarix spp.*). Common understory species include redroot flatsedge (*Cyperus erythrorhizos*), common spikerush (*Eleocharis palustris*), teal lovegrass (*Eragrostis hypnoides*), western marsh cudweed (*Gnaphalium palustre*), western goldentop (*Euthamia occidentalis*), and rough cocklebur (*Xanthium strumarium*).

Hydrological information was gathered from the following USGS stream gages: (1) 09180500 Colorado River near Cisco, UT, and (2) 09315000 Green River at Green River, UT, 122 and 119-km upstream of Canyonlands NP, respectively. The Green River and Cisco gages have been in place since 1894 and 1914, respectively. Despite the large distances to the historic stream gages, there are minimal inputs between the gages and the upstream boundary of Canyonlands NP. The only substantial intervening tributary on the Green is the San Rafael, which contributes less than 1% of mean annual flow (Walker et al. 2020). On the Colorado, there are no major tributaries between the Cisco gage and the

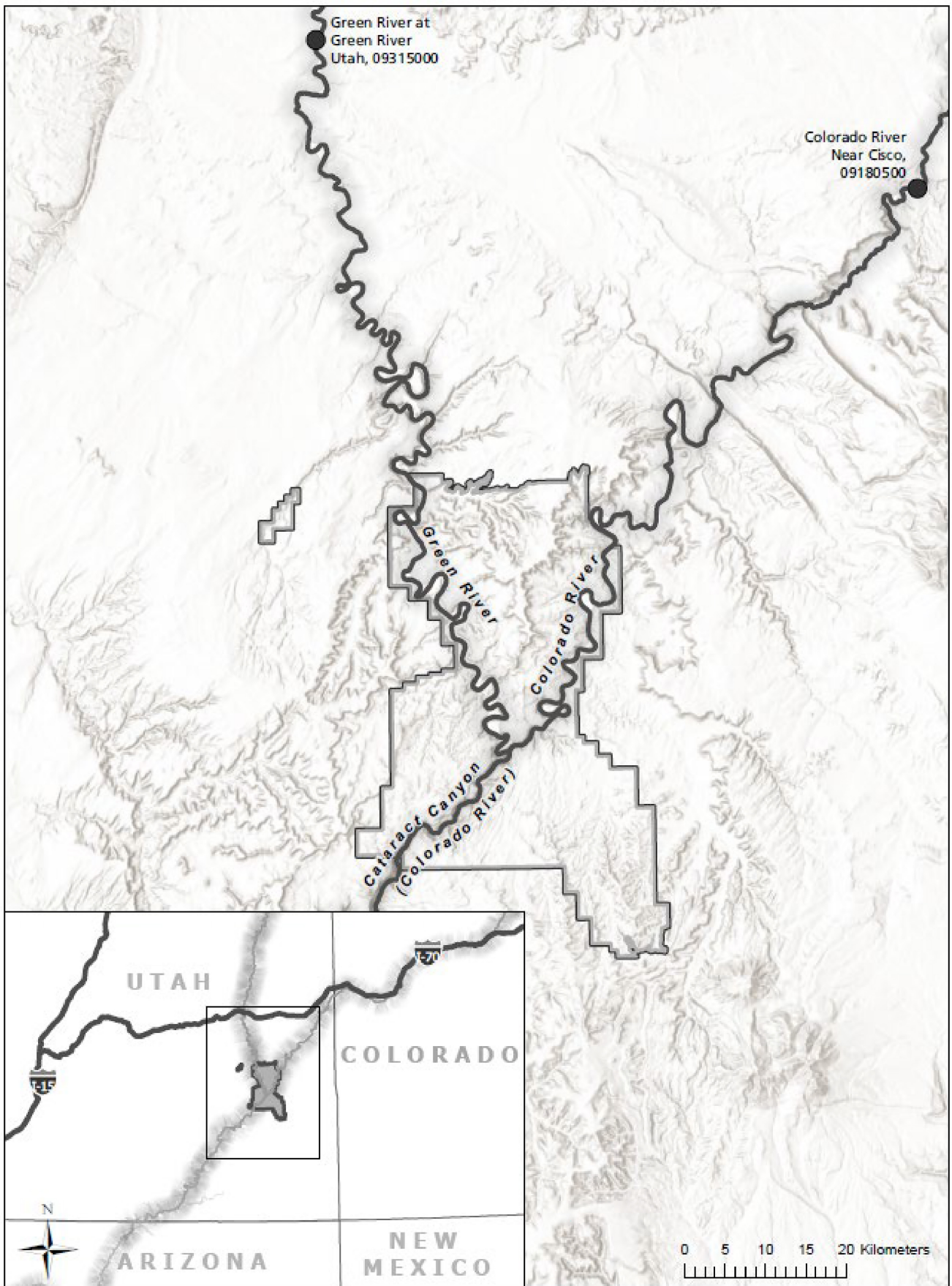


FIGURE 1 | Green River, Colorado River, and Cataract Canyon (Colorado River below confluence of Green and Colorado Rivers) study reaches in Canyonlands National Park, Utah, and USGS gage locations. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/rra.4395)]

Canyonlands NP boundary. The Green River is only partially regulated because over 50% of its flow comes from the largely unregulated Yampa River (Grams et al. 2020). Van Steeter and Pitlick (1998) found that the annual peak flows in the Colorado River had declined by 29–38% since 1950.

We analyzed available aerial imagery from 1940 to 2022 to investigate the vegetation along 152 km of the Colorado and Green Rivers in Canyonlands NP (Table 1). Early imagery (1940, 1948, and 1976 on the Green River, and 1940, 1948, 1975, and 1976 on the Colorado River) did not cover the entire extents of study reaches; we had only 45, 26, and 13 km covered in all years for the Colorado, Green, and Cataract Canyon reaches, respectively. We compared these incomplete image sets to complete image sets to look for differences in the vegetated areas (cover > 50%) across the different years.

For the years 1940, 1948, and 1976, we scanned photographs and rubbersheeted images to high-resolution images from 2002 that had been flown for Canyonlands NP. Rubbersheeting is the process of aligning one data layer (image) to another that is accurate locationally (a rectified image). This is a simple form of georeferencing. The root mean square error of the rectified images ranged between 0.21 and 11.58 m, depending on scale of the photo series (Table 1).

We used digital orthophoto quarter quads (DOQQ) (<https://lta.cr.usgs.gov/DOQQs>) from 1966 and 2002 for both rivers and 1974 for the Green River and 1975 for the Colorado River. These DOQQs are aerial photographs with 1-m resolution rectified to ground points and delivered in Quarter Quad tiles. The maps were drawn on overlays on the aerial photographs, which were digitized into a GIS using control points identified on digital orthophotographs for geo-referencing. We also obtained NAIP (National Agriculture Imagery Program, <https://naip-usdao.nline.hub.arcgis.com/>, <https://gis.utah.gov/products/sgid/aerial-photography/naip/>) imagery for 1993, 2006, 2009, 2011, 2014, 2016, 2018, 2021, and 2022. Since the mid-2000s, NAIP imagery has been completed statewide during growing seasons every 3 years, at 1 m resolution, and is available free of charge from USDA Geospatial Data Gateway (<https://gdg.sc.egov.usda.gov/>). Images were all taken during summer base flows, with the exception of 1948, 1993, and 2011, which were taken during higher spring flows, which could have covered some vegetation.

We digitized vegetation polygons in ArcGIS Pro Version 3.2.2 (Figure 2 shows an example of the digitization process). We used a map of vegetation communities (Tendick et al. 2012) with imagery from 2002 to locate the upland boundary based on occurrence of communities dominated by obligate upland species. We assumed this upland boundary was the same for all years. We considered a polygon vegetated if there was more than 50% cover based on a visual observation of the image. We arrived at the 50% threshold by extensive examination of our digitized maps in the field in comparison to the actual vegetation. We observed that once an area reaches 50% cover, it generally remains fully vegetated. We used 0.01 ha (0.03 acres) as a minimum mapping area for vegetated polygons. For each aerial imagery series, we calculated a standard error by repeatedly digitizing a 1.6-km reach of river each on the Green, Colorado, and Cataract Canyon River reaches (Table S1).

In each year of imagery, we calculated the total number of vegetated hectares for the river corridor within park boundaries. We evaluated vegetation change in three time periods. The pre-dam period was 1940 to 1966, with 1966 being the year Aspinall became operational and 4 years after dam closure of Flaming Gorge Dam in 1962. The 1966 image is the closest we have to a pre-dam status. Dams were operated strictly for hydropower until 1992 when dams started to be operated with environmental flows in mind in response to the Endangered Species Act. We set the post-dam period as 1967 to 1992 and the environmental flows period from 1993 to 2022. In 2011, we had the largest annual peak flow on the Green River in 38 years and the largest annual peakflow in the environmental flow period. This peak flow was the second largest (1387 m³s) on the Colorado River in the environmental flow period, with the largest occurring in 1993 (1396 m³s). We sought to determine whether a large peak in the environmental flow period would alter the rates of vegetation expansion and divided the environmental flow era into two approximately equal periods from imagery, 1993–2006 and 2006–2022.

We calculated average peak and average mean annual discharge from the Green River Near Green River and Colorado River Near Cisco gages for the pre-dam, post-dam, and environmental flow periods. We also calculated 2- and 5-year return intervals for these same time periods. Recurrence intervals were determined using the Log-Pearson Type III distribution.

3 | Results

In all three sections of river, we had spatially incomplete imagery for the 1940s and spatially complete imagery beginning in the 1960s. When we limited the post-1960 data to the subset covered by the 1940s data, the time trend in vegetated area for the subset was almost identical to that for the complete data set (Figure 3). Because spatially incomplete imagery is representative of the entire area, we use this subset of river miles for the comparisons below.

There has been a large increase in the vegetated area along the Colorado River reach above the confluence and a lesser increase in vegetated area on the Green River above the confluence since 1940 (Table S2, Figures 3 and 4). The Cataract Canyon reach below the confluence has only seen a small increase in vegetated area since 1948 and has been relatively stable since 1966 (Figure 3). All three sections of river showed a decrease in vegetated area after the 2011 flood which was the highest peak flow in the last 38 years (Figures 3 and 4), followed by an increase in vegetated area similar to levels before the 2011 flood.

On the Colorado River above the confluence, there has been a large increase in vegetated area since 1940. Imagery was only available from 1940 and 1966 in the pre-dam period with Aspinall closing in 1966 (Figure 4). There was a small (1.5%) increase in vegetated area over that 26-year period. After dam construction, there was a 6.1% increase in vegetated area over 27 years (1966–1993) this included the high peak flow years of 1983 and 1984, the two highest peak flows in the post-dam period (Table S2). The high peak flows of 2011 resulted in a temporary 4.8% decrease in vegetated area, but vegetated area then

TABLE 1 | Dates, discharge in cubic meters per second at time of imagery and type of imagery for the Colorado and Green Rivers, Canyonlands National Park, UT.

Imagery date	Green River Gage (09315000) discharge (cubic meters/s)	Colorado River Gage Cisco (09180500) (cubic meters/s)	Imagery type/description	RMSE or equivalent	Comments
8/30/1940	37	81	Rectified	BLM Utah state office rectified 9 × 9 scans. RMSE x = 2.822, rmse y = 3.018	Black and white. Partial coverage. https://imagery.geology.utah.gov/
5/5/1948	433	48	Rubbersheeted	NA—consistent control features used to rubbersheet	Black and white. Partial coverage. In-house (NPS) dataset
7/12–19/1966	56–65	65–71	Rectified (DOQQ)	BLM Utah state office rectified 9 × 9 scans. “...meet National Standard for Spatial Data Accuracy (NSSDA) 95% confidence level of 11.588 m ...”	Black and white https://imagery.geology.utah.gov/
8/17/1974	88		Rectified (DOQQ)	BLM Utah state office rectified 9 × 9 scans. “... meet NSSDA 95% confidence level of 11.588 m ...”	No coverage on Colorado. https://imagery.geology.utah.gov/
7/23/1975		263	Rectified (DOQQ)	BLM Utah state office rectified 9 × 9 scans. “... meet NSSDA 95% confidence level of 11.588 m ...”	Partial coverage on Colorado, no coverage on Green. https://imagery.geology.utah.gov/
9/2/1976	80	55	Rubbersheeted	NA—consistent control features used to rubbersheet	https://imagery.geology.utah.gov/
6/14–19/1993	391–467	665–878	Rectified (NAIP)	7.0 m RMSE	Black & white https://gis.utah.gov/products/sgid/aerial-photography/digital-orthophoto-quadrangle/
6/19/2002	61	52	Rectified (DOQQ)	The horizontal RMSE is: X—RMSE = 0.276 m Y—RMSE = 0.260 m The X-Y vector is 0.379 m. The vertical RMSE is: Z—RMSE = 0.211 m (for the airborne GPS for this area of the project).	Used as baseline for past and future datasets (vegetation map created using this imagery dataset) https://irma.nps.gov/DataStore/Reference/Profile/2233619

(Continues)

TABLE 1 | (Continued)

Imagery date	Green River Gage (09315000) discharge (cubic meters/s)	Colorado River Gage Cisco (09180500) (cubic meters/s)	Imagery type/description	RMSE or equivalent	Comments
7/13/2006	78	205	Rectified (NAIP)	The positional accuracy for the digital data is tested by visual comparison to a data source with a higher order of accuracy.	https://gis.utah.gov/products/sgid/aerial-photography/naip/
7/14/2009		248	Rectified (NAIP)	± 0.25 m RMSE in X,Y,Z	No coverage on Colorado https://gis.utah.gov/products/sgid/aerial-photography/naip/
8/7/2009	88		Rectified (NAIP)	± 0.25 m RMSE in X,Y,Z	No coverage on green https://gis.utah.gov/products/sgid/aerial-photography/naip/
9/16/2010		97	Rectified (Lidar)	Horizontal and vertical 95% of all well-defined points will fall within 3 m of true ground location.	No coverage on green In-house (NPS) Lidar dataset
6/22–23/2011	1198	793–852	Rectified (NAIP)	Horizontal accuracy of within ± 5 m of reference digital ortho quarter quads (DOQQ's) from the National Digital Ortho Program (NDOP)	Green River done on 6/22, Colorado done on 6/22–23. https://gis.utah.gov/products/sgid/aerial-photography/naip/
9/3–11/2014	110	126–206	Rectified (NAIP)	± 0.25 m RMSE in XYZ	Green River done on 9/11, Colorado done on 9/3 and 9/11. https://gis.utah.gov/products/sgid/aerial-photography/naip/
7/7/2016	221	246	Rectified (NAIP)	± 6 m to ground specification	https://gis.utah.gov/products/sgid/aerial-photography/naip/
9/7/2018	57	65	Rectified (NAIP)	± 6 m to ground specification	https://gis.utah.gov/products/sgid/aerial-photography/naip/
9/17/2021	46	76	Rectified (NAIP)	± 4 m to true ground	https://gis.utah.gov/products/sgid/aerial-photography/naip/
10/5/2022	82	161	Rectified (satellite)		EarthObservation

Abbreviations: BLM, Bureau of Land Management; DOQQ, digital orthophoto quarter quads; NA, not applicable; NAIP, National Agriculture Imagery Program; RMSE, root mean square error.

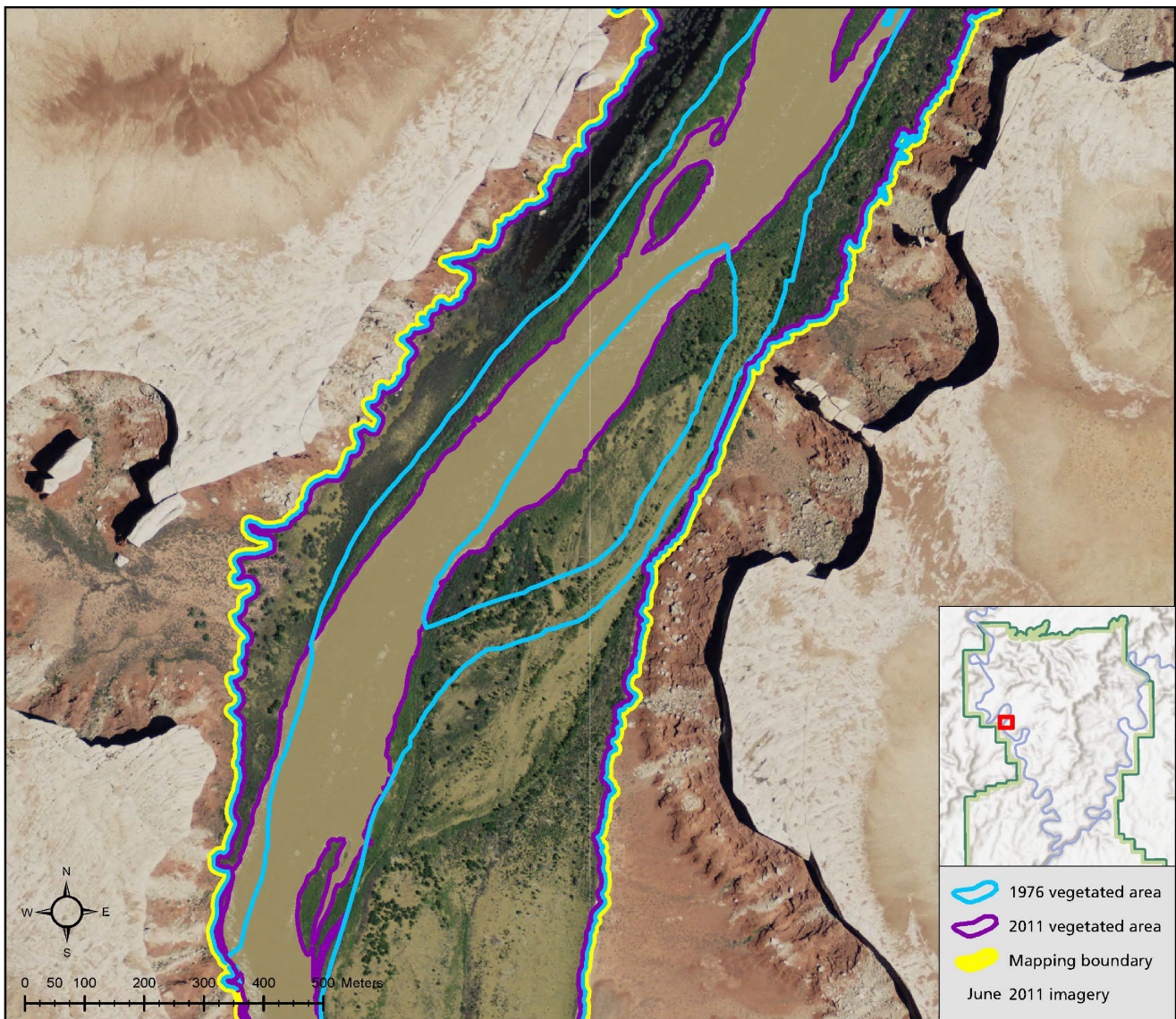


FIGURE 2 | An example of digitization along the Green River in Canyonlands National Park. Imagery is from 2011, the red lines are the extent of vegetation in 1976 and purple lines are the extent of vegetation in 2011. National Agriculture Imagery Program image <https://naip.usdaonline.hub.arcgis.com>. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

increased from 2011 to 2022 by 7.3% resulting in 2.2% more vegetated area in 2022 than in 2010, prior to the 2011 flood (Table S2). There has been a 19.5% increase in vegetated area in the environmental flow period from 1993 to 2022. This increase was rapid in the first 13 years from 1993 to 2006 (0.9%/year), but the rate slowed to just 0.5%/year from 2006 to 2022 (Table S2). Overall, from 1940 to 2022, the vegetated area increased by 28.8%. The increase in vegetated area has been greater on the Colorado River above the confluence than the Green River (Figure 4).

The increase in vegetated area has been less on the Green River than on the Colorado River above the Green River confluence (Figure 4). On the Green River, the vegetated area decreased by 1.2% in the pre-dam period from 1940 to 1966 (Table S2). There was then a 4.0% (0.2%/year) increase in vegetated area in the post-dam period which was lower than the increase in vegetated area in the environmental flows period

(6.5%, 0.2%/year). The high peak flows in 2011 resulted in a 1.7% decrease in vegetated area between 2009 and 2011. The increase in vegetated area was greater in the first 13 years of environmental flows from 1993 to 2006 (0.4%/year), than in the last 16 years of environmental flows (0.1%/year) from 2006 to 2022. Overall, from 1940 to 2022, the vegetated area increased by 9.4%.

In Cataract Canyon on the Colorado River below the confluence the vegetated zone is narrow, changes in vegetated area are small, and the long-term change (an increase of 14.6% from 1948 to 2022) is smaller than some of the changes from one image year to the next (e.g., an increase of 26.9% from 1993 to 2002; Figure 3, Table S2). These results indicate no clear long-term trend in vegetated area in this reach. Short-term changes in this reach are similar to those in the other two reaches. For example, the decrease in vegetated area from the 2011 flood followed by a return of vegetated area in 2022 to approximately the same

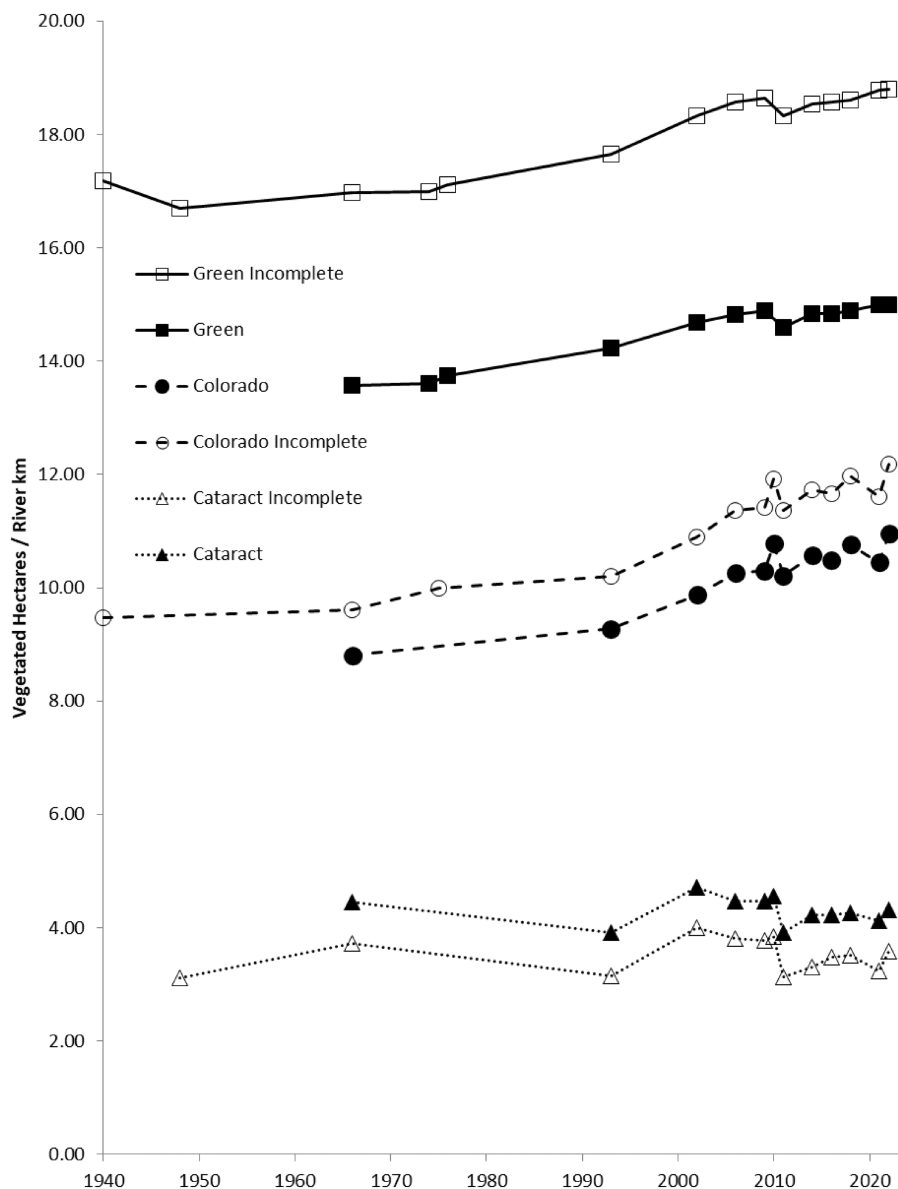


FIGURE 3 | Incomplete imagery for vegetated hectares per river kilometer along the Colorado River, Green River, and Cataract Canyon in Canyonlands National Park 1940–2022 (unfilled markers) and complete imagery (filled markers) 1966–2022. Note that the shape of the incomplete and complete lines for each reach are similar. Figure shows increases in vegetated hectares over time in the Colorado and Green River reaches, while Cataract Canyon remains relatively stable.

level as was present prior to the flood is similar to what occurred in the other two river reaches in this study. There has been a 13.6% increase in vegetated area in the environmental flow period from 1993 to 2022. This increase in vegetation was positive 1.6%/year from 1993 to 2006, but the rate was negative −0.4%/year from 2006 to 2022.

Implementation of environmental flow releases beginning in 1992 on the Green and Colorado Rivers dampened, but did not reverse, the trend of decreasing peak flows. For the Colorado River, average peak flows were higher in the pre-dam period (1046 m³s) than in the post-dam (826 m³s) and environmental flows periods (728 m³s; Table 2). This pattern was also observed on the Green River with average peak flows of 752, 643, and 592 m³s pre-dam, post-dam, and environmental flow periods, respectively. For average annual flows, flows were highest in the

pre-dam period, followed by environmental flows and post-dam periods. There is a similar pattern for average annual flows as well. For the Colorado River above the confluence average annual flows were 194, 202, and 170 m³s, and for the Green River, they were 156, 164, and 138 m³s for the pre-dam, post-dam, and environmental flow periods, respectively. The majority of large floods (greatest 20%) were in the pre-dam period for both rivers (Table 2, Figures 5 and 6). On the Colorado River above the confluence, the post-dam 2- and 5-year recurrence interval flows have decreased by 22% and 13%, respectively, relative to pre-dam. Similarly, these flows were 8% lower for both 2- and 5-year recurrence intervals on the Green River for the same periods (Table 2). In the environmental flows time period, the 2- and 5-year recurrence interval flows decreased 29% and 21% when compared to the pre-dam period on the Colorado River and 14% and 17% on the Green River.

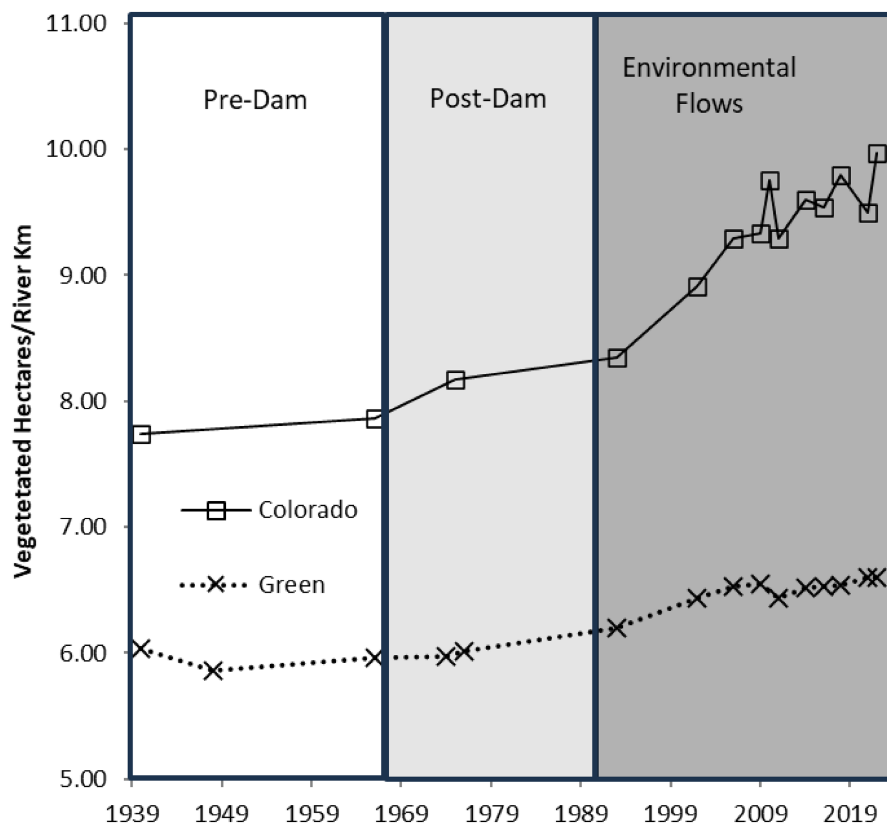


FIGURE 4 | Vegetated hectares per river kilometer along the Green River (dashed line) and Colorado River (solid line) above the confluence with the Green River in Canyonlands National Park in the Pre-dam, Post-dam, and Environmental flows time periods, 1940–2022. This shows a larger increase in vegetated area on the Colorado than on the Green. It also shows both rivers have reacted similarly since the 2011 high flows. These are the same data as in Figure 2. [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com/doi/10.1002/tra.4395)]

As expected, environmental flow releases increased the ratio of peak to summer base flows on the Green River (Table 2). However, mean annual flow decreased at the same time because of decreased runoff and increased flow diversions, causing peaks to decline in spite of environmental flows. Similarly, despite environmental flows being implemented at the Aspinall Unit on the Gunnison River, the ratio of peak to summer base flow has actually decreased and peak flows declined as on the Green River (Table 2, Figures 7 and 8). In summary, peak flows declined on both the Green and Colorado Rivers between 1992 and 2022, but not as much as they would have declined in the absence of environmental flows.

4 | Conclusions

We have documented a large increase in vegetated area on the Green River and the Colorado River above the confluence with the Green River from 1940 to 2022. Because the new vegetated areas replaced what was formerly channel, our observations also document channel narrowing. This is largely consistent with the literature documenting channel narrowing and floodplain growth along the Green (Allred and Schmidt 1999; Andrews 1986; Graf 1978; Grams and Schmidt 2002; Lyons, Pucherelli, and Clark 1992; Merritt and Cooper 2000; Walker et al. 2020), Colorado (Grams et al. 2020; Van Steeter and Pitlick 1998), and Yampa Rivers, a major tributary (Manners, Schmidt, and Scott 2014). The increases in vegetated area on the Green and Colorado reaches are likely

due to a combination of river regulation (Dean and Schmidt 2011; Dean et al. 2020; Lyons, Pucherelli, and Clark 1992; Grams and Schmidt 1999; Grams, Schmidt, and Topping 2007; Hereford, Jacoby, and McCord 1996; Walker et al. 2020), non-native tamarisk invasion (Birken and Cooper 2006; Dean et al. 2011; Everitt 1993; Manners et al. 2011), decreased peaks (Allred and Schmidt 1999; Grams and Schmidt 1999; Grams, Head, and Kinzel 2022; Williams and Wolman 1984), and increased base flows (Sankey et al. 2015). We also examined change in vegetated area in Cataract Canyon from 1948 to 1966, which has not been the subject of previous research. However, unlike the Green and Colorado Rivers, the vegetated area has stayed relatively constant in Cataract Canyon from 1966 to 2022. We think that vegetation in Cataract Canyon has stayed relatively stable due to the Canyon's steep topography, high gradient, and narrow channel. There is little room for the river to narrow even with changes in hydrology, and the high channel gradient results in enough shear stress to remove encroaching vegetation in spite of the observed decreases in peak flows.

We evaluated changes in vegetated area in the pre-dam, post-dam, and environmental flows time periods. From limited imagery samples, the vegetated area along the Green and Colorado reaches stayed relatively constant in the pre-dam period, from 1940 to 1966. There was actually slightly less vegetated area in 1966 than 1940 (Figure 4) on the Green River demonstrating relatively little change to the vegetated area in the pre-dam era. Allred and Schmidt (1999) found that channel width was stable in the 1940s and 1950s on the Green River near Green

TABLE 2 | Average peak discharge, average annual discharge, the summer baseflow as a percentage of the average annual peak discharge, the number of peak flows that are greater than 80% of the peak flows for the entire time period (1895–2022), and the 2- and 5-year recurrence interval for various time periods from the Green River at Green River, UT, and Colorado River near Cisco, UT gages.

Pre-dam, post-dam, environmental flows													
Green River							Colorado River						
Time period	Average			Recurrence interval			Average			Recurrence interval			
	Peak discharge (m³/s)	Annual discharge (m³/s)	Aug Sep base flow % of Peak	No. of peak flows > 80% percentile (>994 m³/s)	2-Year discharge (m³/s)	5-Year discharge (m³/s)	Time period	Peak discharge (m³/s)	Annual discharge (m³/s)	Aug Sep base flow % of peak	No. of peak flows > 80% percentile (>1047 m³/s)	2-Year discharge (m³/s)	5-Year discharge (m³/s)
1930–1962	752	156	10.3	12	649	936	1930–1966	1046	194	9.8	13	942	1318
1963–1991	643	164	15.5	4	595	864	1967–1991	826	202	16.0	3	732	1145
1992–2022	592	138	12.2	3	556	780	1992–2022	728	170	19.4	3	668	1043
1992–2006	607	141	12.7	2	569	817	1992–2006	744	177	19.4	2	688	1061
2007–2022	577	134	11.7	1	544	754	2007–2022	712	163	19.5	1	652	1042

Note: All discharges are cubic meters per second.

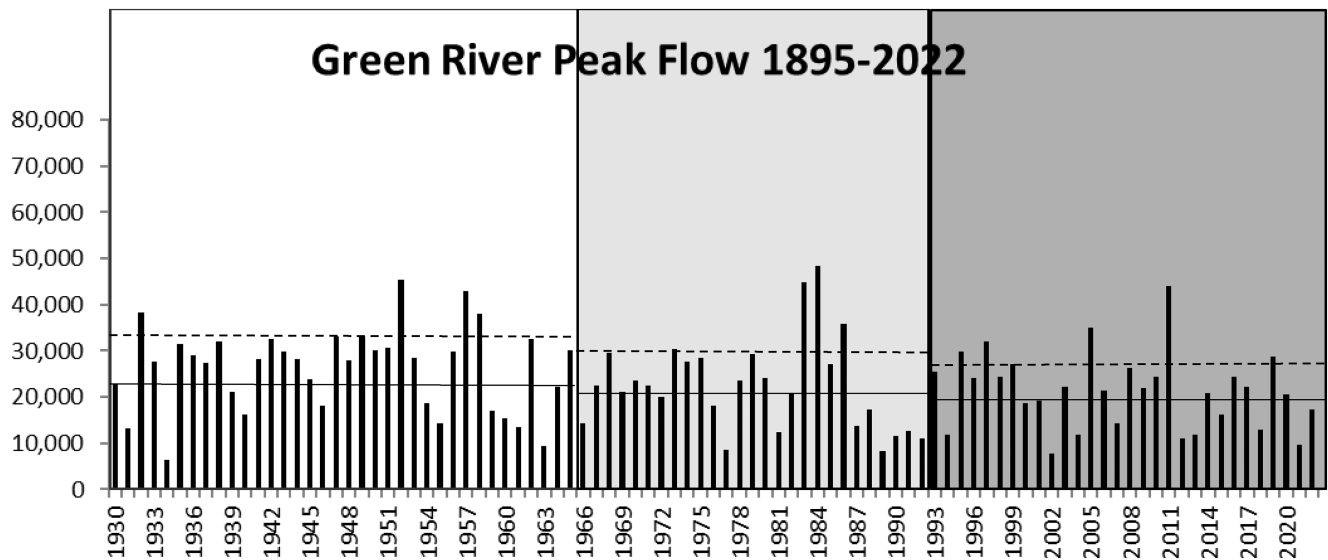


FIGURE 5 | Peak flows (cubic feet per second) of the Green River at Green River, Utah (station 09315000) from 1895 to 2022. The 2-year (solid line) and 5-year (dashed line) recurrence intervals are plotted for each the pre-dam (no shading), post-dam (light shading), and environmental flows (dark shading) periods.

Colorado Peak Flow 1914-2022

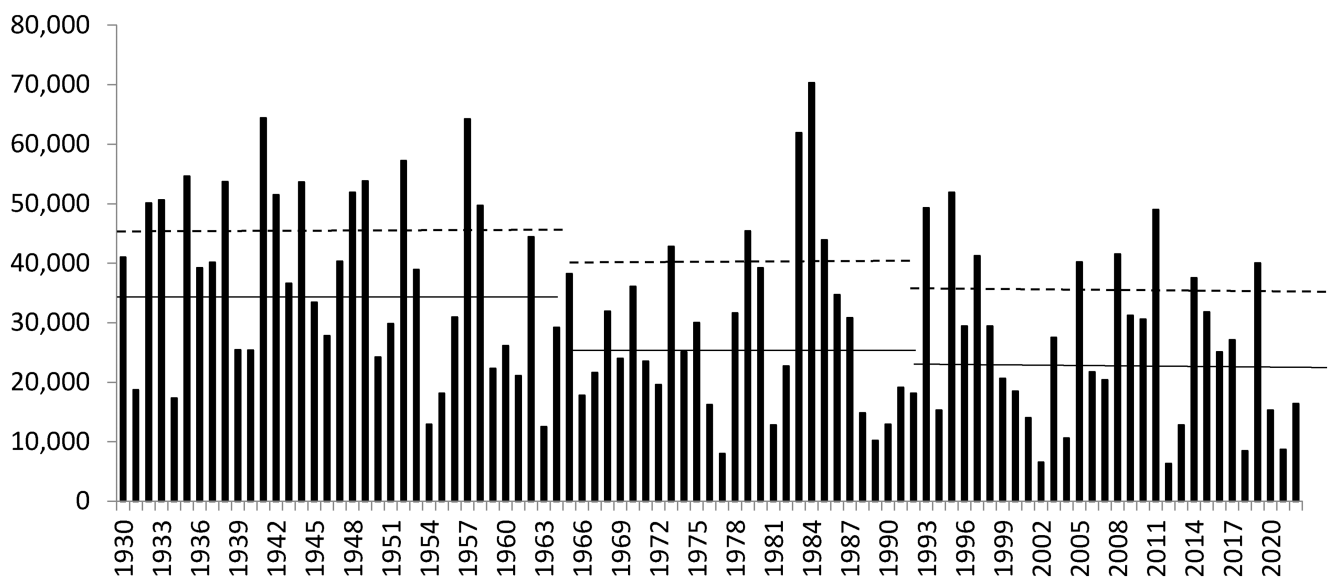


FIGURE 6 | Peak flows (cubic feet per second) of the Colorado River at Cisco, Utah (station 0918500) from 1914 to 2022. The 2-year (solid line) and 5-year (dashed line) recurrence intervals are plotted for each the pre-dam (no shading), post-dam (light shading), and environmental flows (dark shading) periods.

River, UT, while Grams and Schmidt (2005) found narrowing on the Green River just downstream from Flaming Gorge Dam from 1940 to 1948, and Walker et al. (2020) found narrowing occurred in the 1930s at a site on the Green River in Canyonlands NP. Our findings are inconsistent with Walker et al. (2020) and with Birken and Cooper (2006) who concluded that the majority of narrowing occurred long before river regulation by Flaming Gorge Dam along three reaches of the Green River near Ouray, UT, Gray Canyon (148-km upstream), and Labyrinth Canyon in Canyonlands NP. Birken and Cooper (2006) found that riparian vegetation cover was nearly identical between 1951 and 2002 along the Green River in Canyonlands NP and Gray Canyon.

During a similar time period, we found a 9.8% increase in vegetated area between 1948 and 2002 on the Green River in Canyonlands NP. Our study covers a much larger spatial area than the other studies mentioned, with the exception of Walker et al. (2020).

There were increases in vegetated areas on the Colorado River above the confluence (6.1% overall, 0.2%/year) and the Green River (4.0% overall, 0.2%/year) in the post-dam flow period. This period included the two largest peaks post-dam for both rivers in 1983 and 1984. Our findings are similar to those of Grams and Schmidt (2005) who found narrowing on the Green

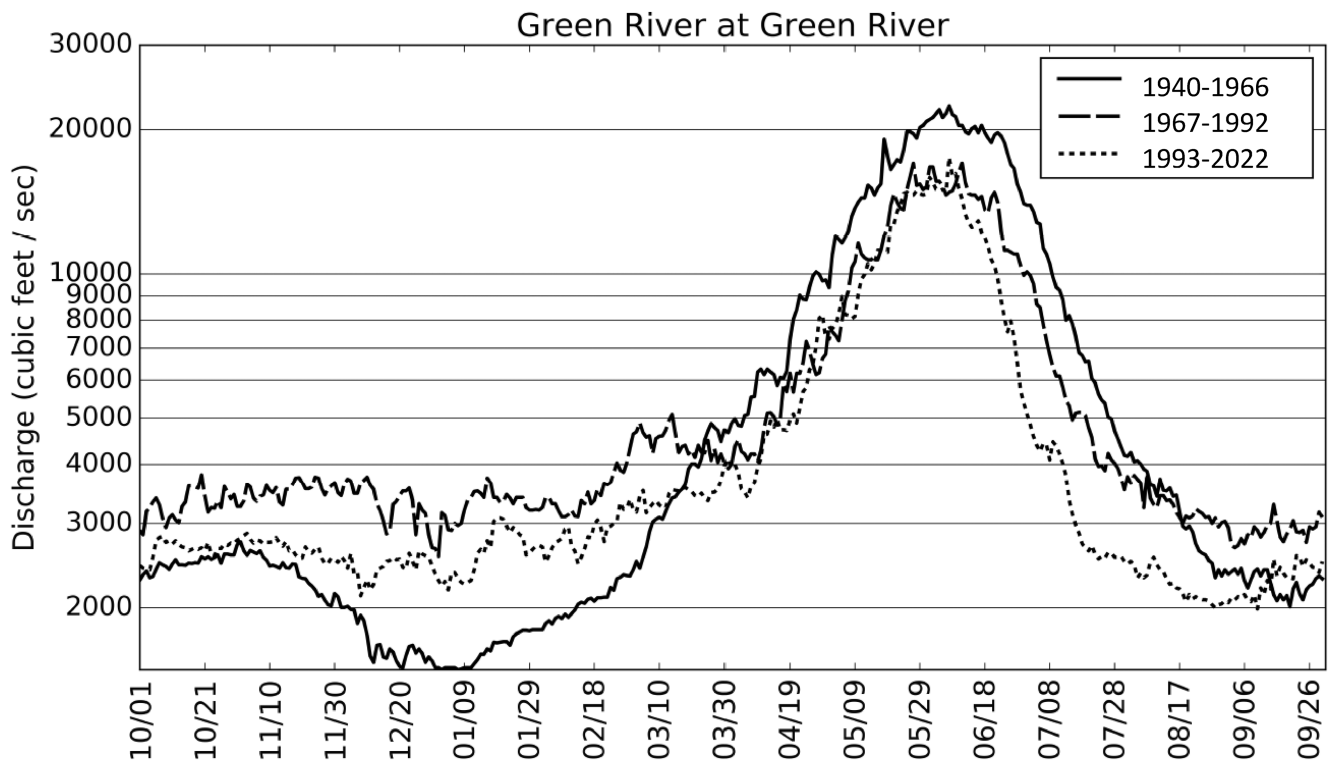


FIGURE 7 | Average hydrographs for the Green River at Green River, UT gage for pre-dam (1940–1962), post-dam (1963–1991) and environmental flows (1992–2022). Note that the peaks remain as high with environmental flows as pre-environmental flows, but the base flows in summer (July–Sep) are lower.

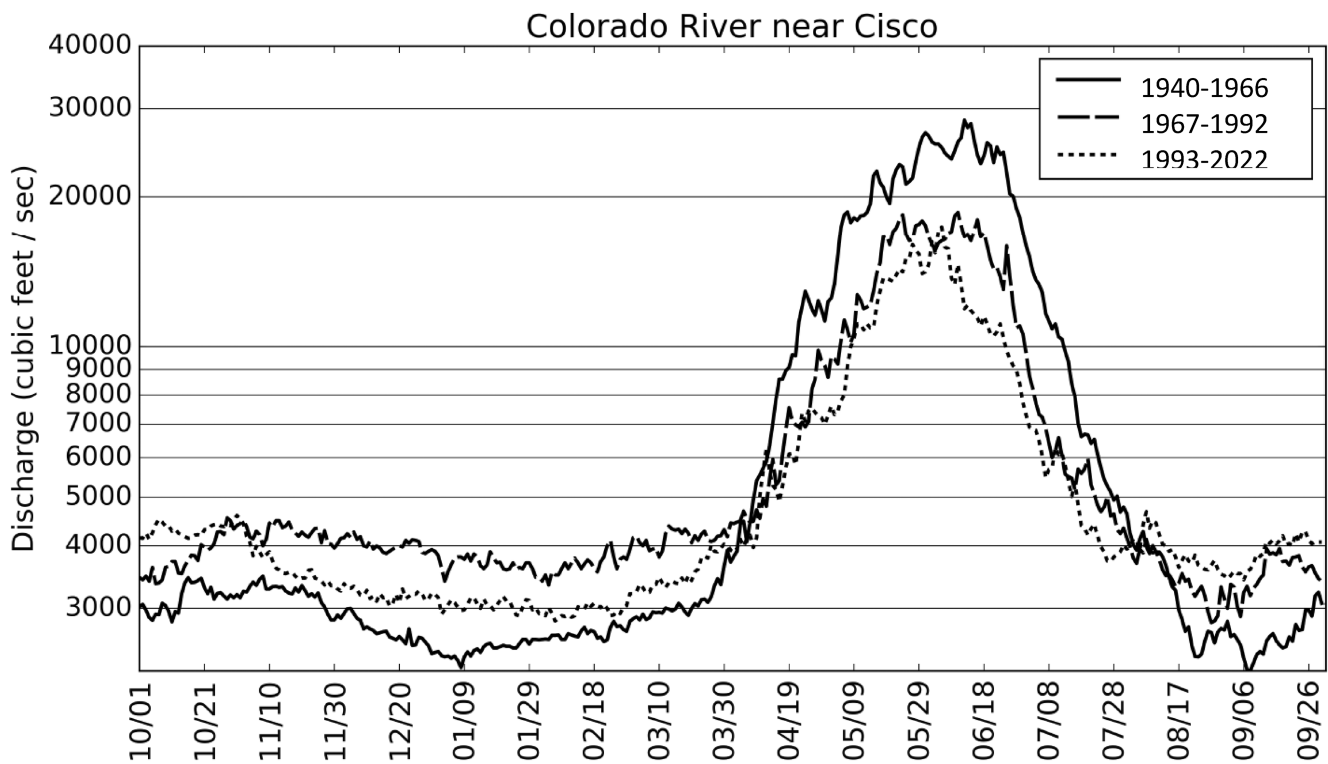


FIGURE 8 | Average hydrographs for the Colorado River near Cisco, UT gage for pre-dam (1940–1966), post-dam (1966–1991), and environmental flows (1992–2022). The peaks and the summer base flows are very similar between the post-dam and environmental flow periods.

River just downstream from Flaming Gorge Dam from 1959 to 1999. Walker et al. (2020) also found significant narrowing in the 1980s on the Green River in Canyonlands NP. Narrowing

is often associated with a sustained period of low peak flows when vegetation can colonize parts of the active channel (Allred and Schmidt 1999; Birken and Cooper 2006; Grams and

Schmidt 2005), although Birken and Cooper (2006) state that large floods are needed first then low flows. This occurred in the post-dam period, with large peaks in 1983 and 1984 followed by a number of lower flow years.

Implementation of environmental flow releases beginning in 1992 on the Green and Colorado rivers damped but did not reverse the trend of decreasing peak flows. This trend was driven by large decreases in mean daily flow (Table 2), resulting from decreased runoff and increased flow diversions. We found a 10% and 12% decrease in mean daily flow between the pre-dam period and the environmental flow period on the Green and Colorado Rivers above the confluence, respectively. As peaks have declined, there have continued to be increases in vegetated area on the Colorado (19.5% overall, 0.7%/year) and Green River (6.5% overall, 0.2%/year) from 1993 to 2022. These rates are actually higher than in the post-dam period. Environmental flows have not yet been able to reverse channel narrowing that has occurred, nor overcome lower annual flows to slow the increase in vegetated area.

On the Green River, the first 13 years of environmental flows had lower annual flows and peak flows than the subsequent 16 years. In addition, the first decade had two large peak flows while the second decade had one large peak. The increase in vegetated area has slowed over the last 16 years (0.08%/year) compared to the first 13 years (0.40%/year). Similarly, Walker et al. (2020) found that a new phase of narrowing began in 2003 based on analyses of floodplain sedimentation in a floodplain trench and that channel width decreased by 7% from 1993 to 2009, but they also found no change in the mean width from 2009 to 2014 on the Green River (see Table S2). The Colorado River and Cataract Canyon also had lower rates of vegetation encroachment in the 2006–2022 period compared to 1993–2006.

While annual flows and average peak flows were actually higher from 1993–2006 than 2007–2022 on both the Colorado and Green Rivers, the largest peak flow in the environmental flow period occurred in 2011 on the Green River. This was also the second largest peak flow on the Colorado River; the flow of 1993, 8 m³s larger than the flow of 2011, occurred at the beginning of the environmental flows period. The large 2011 peak resulted in a decrease in vegetated area along all three river reaches. Large peak flows are clearly important as resetting events that result in a reduction in vegetated area. The large flows in 1983 and 1984 may have helped to keep the annual increase in vegetated area lower in the post-dam period than the environmental flow period, although we do not have frequent enough imagery to determine that definitively. Van Steeter and Pitlick (1998) found that the major floods of 1983 and 1984 expanded side channels on the Colorado River, increasing channel complexity following an era where the river had gotten less complex.

Several authors have identified tamarisk as a potential cause or at least a symptom of channel narrowing and vegetation expansion. Manners, Schmidt, and Scott (2014) demonstrated that narrowing can occur due to non-native tamarisk even when the flood regime and sediment supply are not dramatically altered. Mortenson and Weisberg (2010) found that flow alteration was

negatively correlated with *Populus* cover and positively related to *Tamarix* cover in 20 river segments in the southwestern United States. They found rivers with a large drainage area and low flow variability were more vulnerable to non-native vegetation invasions. Tamarisk began to establish itself in and near Canyonlands NP from 1925 to 1931 (Graf 1978) and may have been partially responsible for the increase in vegetated area (Birken and Cooper 2006; Graf 1978) around the time of Flaming Gorge completion on the Green River. Graf (1978) found that there had been an average of 27% narrowing on the Green River in and near Canyonlands NP based on photographs taken in 1871 or 1914 and compared to photographs in either 1951, 1968, or 1971. Graf (1978) found narrowing in photographs that were taken pre-dam (1951) and post-dam (1968 and 1975). However, we found relatively little expansion of the vegetated area on the Green or Colorado Rivers that corresponds to the pre-dam time period (1940–1966) when tamarisk was expanding. Our understanding of the timing and rate of narrowing of the post-dam channel is limited by the long time intervals between aerial imagery and absence of aerial imagery prior to the 1930s.

Tamarisk has a longer and later season of seed dispersal than native cottonwood and willow, and when natural flows are altered by delaying the peak, tamarisk can outcompete native species (Horton, Mounts, and Kraft 1960). Flood peaks on the Green River that were delayed by Flaming Gorge Reservoir promoted establishment of tamarisk during the post-dam period (Cooper et al., 2003). During the environmental flow period, the trend toward late flow peaks has been partially reversed, apparently benefiting native vegetation. Young tamarisk are inferior competitors when compared with native, riparian trees of the southwestern United States when there is a natural hydrograph (Bhattacharjee et al. 2009; DeWine and Cooper 2010; Sher and Marshall 2003; Stevens 1989). Taylor, Wester, and Smith (1999); Taylor, Smith, and Haukos (2006) found that native *Populus* establishment was facilitated by intentional floods that took place during the historic flood season on the Rio Grande. Restoration flows along the Bill Williams River reduced *Tamarix* seedling stem density more than *Salix* (Shafroth et al. 2010) and a restoration flood on the Colorado River in Grand Canyon prevented germination and establishment of *Tamarix* (Stevens et al. 2001). Perkins, Scott, and Naumann (2016) found that tamarisk presence was lower on the relatively natural Yampa River when compared to the highly regulated Green River below Flaming Gorge Dam in Dinosaur National Monument.

Tamarisk beetles (*Diorhabda* spp.) were introduced to the Moab, UT, area in 2004. They have now spread throughout Canyonlands NP. After several years of defoliation, we have observed tamarisk mortality and weakening of tamarisk such that the environmental river flows can now erode the bank beneath the tamarisk resulting in the trees and the banks falling into the river. González et al. (2020) found that a 40-year flood when combined with *Diorhabda* introduction resulted in a 75% reduction in *Tamarix* cover over 7 years along the lower Virgin River in Nevada. *Tamarix* was subsequently replaced by the native *Pluchea sericea*. *Diorhabda* has also resulted in 90% reduction in cover on the Humboldt and Walker Rivers in Nevada (Pattison et al. 2011), and approximately 15% to 56% reduction in several rivers in the Colorado River Basin (Hultine et al. 2015;

González et al. 2017; Henry et al. 2018; Kennard et al. 2016). Using MODIS Enhanced Vegetation Index, others studying the Virgin River have found an estimated 50% (Nagler et al. 2014) and 75% (Nagler et al. 2018) reduction in leaf area index, a proxy of vegetation cover obtained through remote sensing. Potential increases in tamarisk mortality in Canyonlands NP may help facilitate channel widening in the future, depending upon which species replace tamarisk, and to what extent the new species can stabilize bank sediments.

We concur with Sankey et al. (2015) that changing dam operations in order to optimize a regulated flood regime could rehabilitate and increase the resilience of riparian ecosystems, or at least prevent additional alteration. Flows from dams should be designed with the knowledge of native and non-native species' life history strategies. Large periodic peak flows are a necessary accompaniment to mimicking a natural hydrograph. Flow regulation and water withdrawals in the Green and Colorado Rivers have decreased and delayed flood peaks resulting in channel narrowing and promoting invasive tamarisk. Environmental flow releases from Flaming Gorge Dam and the Aspinall Unit have reduced the severity of this trend, but not reversed it. Managed flows that reduce the peak further should be evaluated with caution. Detailed assessments of the response of vegetation to changes in dam operations during long time periods are essential to understand and predict the long-term effects of altered flow regimes on riparian ecosystems (Christensen et al. 2004; Dixon et al. 2012; Grantz et al. 2007; Johnson 1994).

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Data Availability Statement

Data generated in this study are available from the National Park Service.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.