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Potential Climate and Human Water-Use Effects on Water-Quality Trends in a Semiarid, Western U.S. Watershed: Fountain Creek, Colorado, USA

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Abstract: Nutrients, total dissolved solids (TDS), and trace elements affect the suitability of water for human and natural needs. Here, trends in such water-quality constituents are analyzed for 1999–2022 for eight nested monitoring sites in the 24,000 km^2 Fountain Creek watershed in Colorado, USA, by using the weighted regressions on time, discharge, and season (WRTDS) methodology. Fountain Creek shares characteristics with other western U.S. watersheds: (1) an expanding but more water-efficient population, (2) a heavy reliance on imported water, (3) a semiarid climate trending towards warmer and drier conditions, and (4) shifts of water from agricultural to municipal uses. The WRTDS analysis found both upward and downward trends in the concentrations of nutrients that reflected possible shifts in effluent management, instream uptake, and water conservation by a watershed population that grew by about 40%. Selenium, other trace elements, and TDS can pose water-quality challenges downstream and their concentrations were found to have a downwards trend. Those trends could be driven by either a warming and drying of the local climate or decreased agricultural irrigation, as both would reduce recharge and subsequent mobilization from natural geologic sources via groundwater discharge. The patterns illustrate how changes in climate and water use may have affected water quality in Fountain Creek and demonstrate the patterns to look for in other western watersheds.

Keywords: effluent; nitrogen; phosphorus; salinity; selenium; trend analysis; water conservation

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1. Introduction

Population growth and a limited water supply are linked challenges that have driven the need for a science-based understanding and the management of water in the western United States [1]. The Fountain Creek watershed, located along Colorado’s Front Range, exemplifies such challenges. In Colorado, average annual temperatures have risen by about 1.1 °C in the past 30 years, and although the trends in precipitation are less certain, soil moisture droughts have become more common and most projections of annual streamflow show decreases [2,3]. Local surface water and groundwater resources are relatively limited, and water is imported via several collection and diversion systems. Most drinking water used in Colorado Springs, the main municipality, is imported via pipelines from sources 160 km away in the Rocky Mountain headwaters of the Arkansas and Colorado River Basins [4]. The population in the Fountain Creek watershed has grown by about 40% in the last two decades [5], but human water-use efficiency has increased in that same timeframe. In the city of Colorado Springs, the annual per capita use of water delivered by utilities has decreased from about 0.193 megaliters (mL) per year to 0.106 mL per year between the 2000s and 2021 [6]. Therefore, each resident now uses about 55% as much water as they did about 20 years ago. Finally, the higher economic value associated with urban water use relative to agriculture has driven transfers of water rights in Fountain Creek and the Arkansas River Basin, where it resides, similarly to patterns found across the west [7].

In the Fountain Creek watershed, rapid population growth that started in the 1970s prompted concerns about water quality and quantity [8]. Early studies identified increased concentrations of nutrients and other water-quality components that reflected increasing dominance of effluent in streamflow [8,9]. Subsequent work has addressed a spectrum of issues including controlling excess sediment transport [10], finding that wildlife contributes substantially to upstream fecal contamination [11], documenting declines in some aquatic communities [12,13], and linking salinity, selenium, and uranium loading to groundwater discharge [14]. Storm-generated streamflows during the summer monsoon season have been the focus of targeted sampling efforts that showed how abrupt, rainfall-driven increases in streamflow (stormflow) increase the concentrations of suspended sediments, unfiltered trace elements, and *E. coli* in the creek [15,16]. Stormwater management has been a challenge as the watershed has urbanized, and efforts to improve it are underway [17]. Farther downstream, constituents like total dissolved solids (TDS), a measure of salinity, and selenium are substantial concerns in the Arkansas River, to which Fountain Creek is a tributary [18,19].

The primary goal of this paper is to examine trends in water-quality constituents in Fountain Creek, specifically nutrients, salinity, and selected trace elements. Trends are examined for eight streamgage monitoring locations in the watershed for the period 1999 to 2022 [20]. The timeframe is long enough to yield insights into multi-decadal trends, and the eight locations allow for a spatial analysis of the sources of water-quality constituents. The effects of stormflow sampling and suspended sediments are assessed only for their influence on overall trends across flow conditions. For context on the drivers of water-quality change, changes in water management and trends in local climate and aspects of regional hydrology in unmanaged locations are also assessed. The result is a holistic examination of water-quality change in the watershed in recent decades. An understanding of water-quality trends in Fountain Creek is important to local stakeholders. Through an examination of the trends relative to the drivers, however, Fountain Creek could also provide insights into patterns that are unfolding across the western United States.

2. Materials and Methods

2.1. Watershed Characteristics

Elevations in the Fountain Creek watershed vary from 4302 m in the northwest to about 1413 m at the creek's confluence with the Arkansas River (Figure 1). Terrain at the higher elevations is steep and mountainous with climates typical of the Rocky Mountains in Colorado, including seasonal snowpack accumulations. However, most of the watershed is within the Colorado Piedmont, a region with a semiarid climate which is located below a transition zone at around 2000 m. The major municipality in the watershed, Colorado Springs, is located at around 1800 m elevation and most of the watershed's population lives in the Piedmont region. The higher elevation terrain is underlain primarily by crystalline igneous intrusive and metamorphic rocks, and the Colorado Piedmont terrain is primarily underlain by sedimentary rocks of generally Cretaceous age [21]. Some of the sedimentary rocks, particularly the Niobrara Formation and the lower unit of the Pierre Shale, are known to negatively influence water quality via TDS and trace elements [22].

From 1991 to 2020, mean annual precipitation in Colorado Springs was 40 cm, with the heaviest precipitation being in summer due to thunderstorms (NOAA, [23]). Mean monthly temperatures in the same time period ranged from −0.2 °C in January to 22.4 °C in July (NOAA, [23]). The Köppen Climate Classification for most of the watershed is cold, arid, steppe [24].

Colorado Springs is the major municipality in the Fountain Creek watershed. The population of Colorado Springs was 356,208 in 1999 and grew to 483,953 in 2021, a 36% population increase [5]. Including the other municipalities and unincorporated communities, the population in the Fountain Creek watershed was approximately 421,000 in 1999 and grew to 590,000 by 2021, a 40% population increase [5,25]. Those population estimates excluded Pueblo residents living in the Fountain Creek corridor where it cuts through a narrow section of that municipality near the creek's mouth (Figure 1).

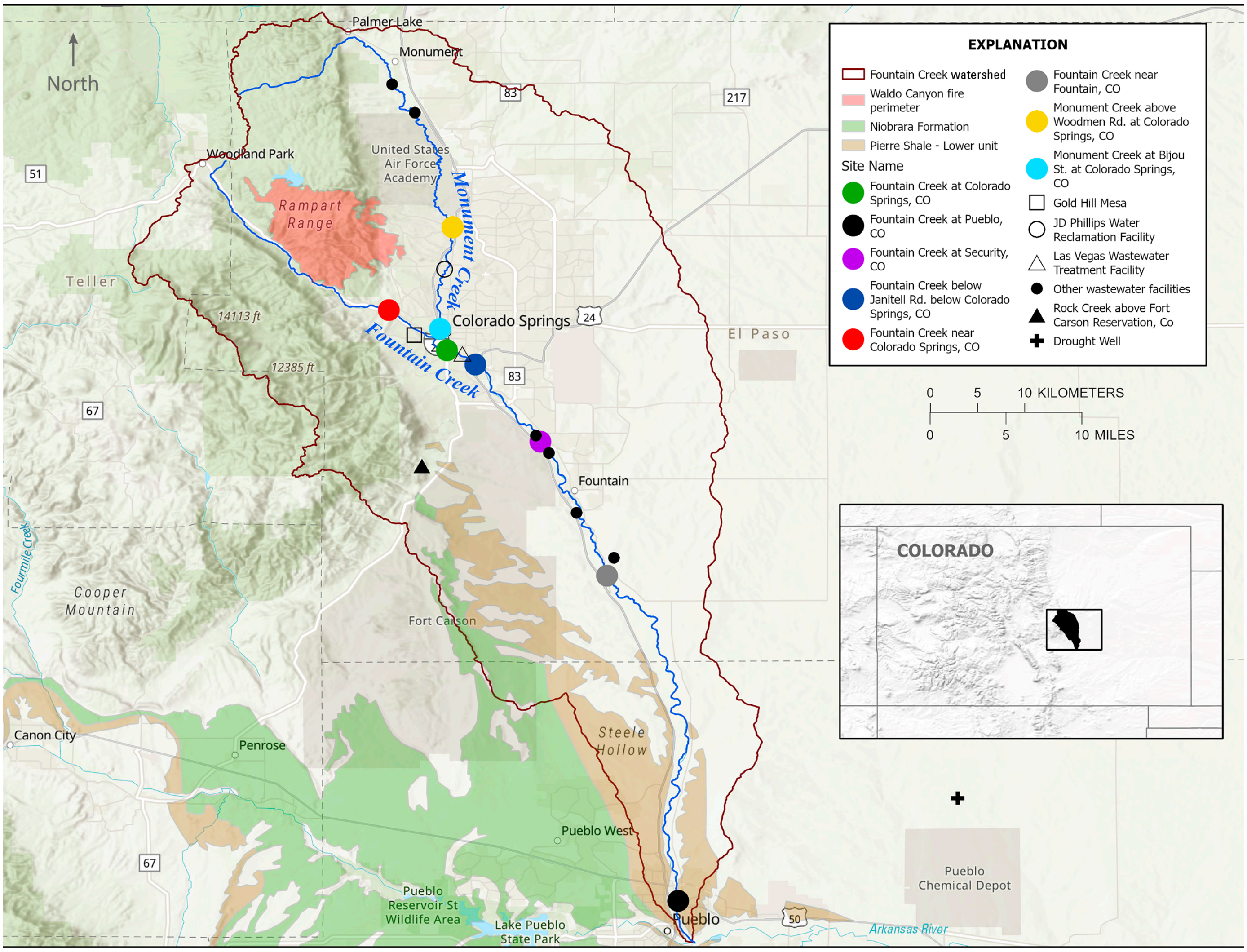

Figure 1. Map of the Fountain Creek watershed and features relevant to the study.

Because the semiarid climate limits natural local water supplies, water is imported for municipal use, and the resulting volumes and locations of treated effluent discharges to Fountain Creek are important to hydrology and water quality. Various changes in treatment processes and effluent compositions have occurred at the numerous wastewater treatment facilities across the watershed over the years (Figure 1). One major change involved the construction of the JD Phillips Water Reclamation Facility which came online in 2008 [26]. The new facility took some of the burden of wastewater treatment for the City of Colorado Springs from the Las Vegas Street Wastewater Treatment Facility, which was and remains the largest such facility in the watershed. In the process, the location of some effluent discharge for the city moved upstream to a location on Monument Creek (Figure 1). A non-potable water system is also operated in the city of Colorado Springs and as much as 5500 mL of reclaimed wastewater was distributed via that system in 2021 [6].

A major wildfire burned in the Fountain Creek watershed in 2012. The Waldo Canyon Fire burned a total of 74 km^2 of the mountainous headwaters primarily of Fountain Creek but also Monument Creek in June and July of that year (Figure 1). Burn severity was classified as 51% high, 20% moderate, and 29% low [27]. Substantial resources were deployed to mitigate runoff effects from the fire, but one flash flooding event occurred in 2012 and another four events occurred in 2013 [28,29].

Eight streamgage monitoring locations were selected to be the focus of the study (Table 1; Figure 1). The criteria for inclusion were continuous monitoring of streamflow and abundance of water-quality data across a variety of constituents. Trend analysis of water-quality constituents focused on the years 1999 to 2022 because of relative data abundance. All water-quality data used in this study are archived in the National Water Information System database and can be accessed using the USGS Station ID [20].

Table 1. U.S. Geological Survey (USGS) streamgage water-quality monitoring sites included in the study along with drainage area and gage elevation information [20].

Short Site Name	USGS Station ID	USGS Station Name	Drainage Area (km^2)	Elevation (m)
Fountain Creek, upstream	07103700	FOUNTAIN CREEK NEAR COLORADO SPRINGS, CO	264	1862
Monument Creek, upstream	07103970	MONUMENT CR ABV WOODMEN RD AT COLORADO SPRINGS, CO	466	1911
Monument Creek at Bijou Street	07104905	MONUMENT CREEK AT BIJOU ST. AT COLO. SPRINGS, CO	609	1823
Fountain Creek at Colorado Springs	07105500	FOUNTAIN CREEK AT COLORADO SPRINGS, CO	1015	1798
Janitell Road	07105530	FOUNTAIN CR BLW JANITELL RD BLW COLO. SPRINGS, CO	1070	1780
Security	07105800	FOUNTAIN CREEK AT SECURITY, CO	1295	1719
Fountain	07106000	FOUNTAIN CREEK NEAR FOUNTAIN, CO.	1740	1632
Pueblo	07106500	FOUNTAIN CREEK AT PUEBLO, CO	2396	1434

2.2. Streamflow and Municipal Water Use Analysis

Streamflow was assessed using data downloaded from the USGS National Water Information System (NWIS) database [20]. Along with mean water year (October to September) flows, mean winter base flows for the period November to February were also calculated, as this period generally represents the base flow season. Unlike native streamflow that originates in the Fountain Creek watershed, transbasin water imports and portions of water rights transferred from irrigation are considered reusable and can be used or consumed to extinction. A transit loss accounting program has been developed to track such reusable water relative to native streamflow [30–32]. Output from this program throughout 2020 was used to assess the amount of reusable water at 6 of the 8 streamgages where output was available [33]. Trends in mean annual streamflows, base flow, and reusable flows were assessed using Kendall's nonparametric test for monotonic trend via the "kendalltrendtest" function from the "EnvStats" package in R v. 4.3.1 [20,34,35]. This same test was used for all trend assessments of non-water-quality parameters in the study.

Daily production volumes of potable water for customers covering 2000 through 2022 and daily effluent discharge volumes data covering 24 July 2010 to 30 September 2022 for the Las Vegas Street Facility and covering 5 May 2008 to 17 November 2021 for the JD Phillips Facility were provided by Annie Berlemann of Colorado Springs Utilities [26]. The proportion of the individual or combined discharges relative to measured streamflow at the appropriate streamgage downstream were calculated along with water year means (Figure 2). Trends were assessed as previously described.

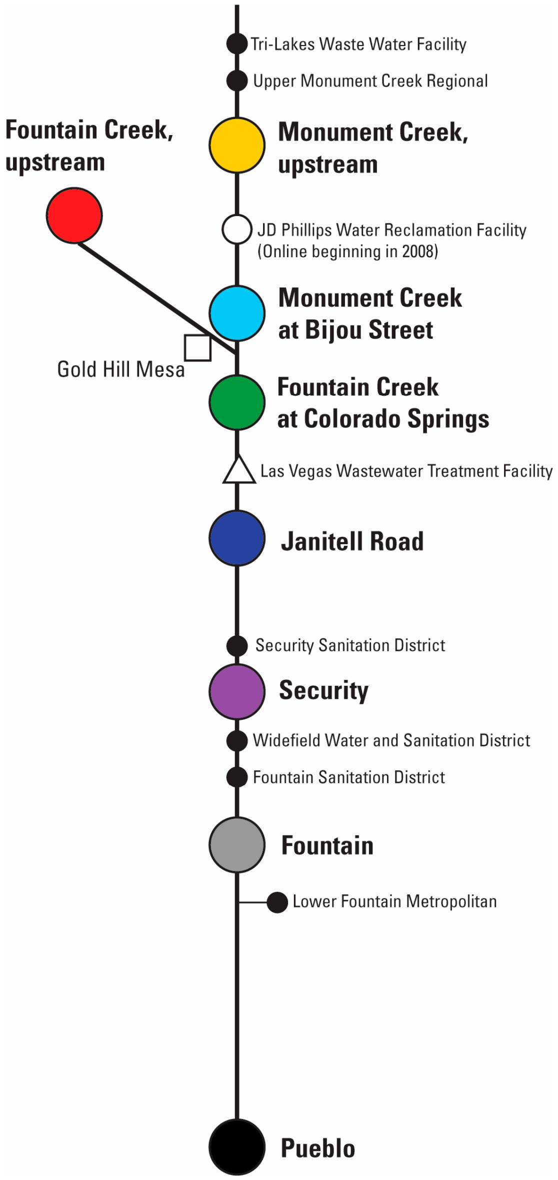

Figure 2. Diagram of the streamgage monitoring locations assessed in this paper relative to the main stems of Fountain and Monument Creeks with the same colors and symbols as Figure 1 and short names from Table 1. Locations where effluent from treatment plants enters the creeks are marked for reference.

2.3. Climate, Natural Hydrology, and Irrigation Trend Analysis

As context for water-quality trends, local climate data were analyzed. The timeframe 1980 to 2022 was selected because of the potential lag between patterns in climate and resulting effects on natural hydrology like groundwater recharge, native streamflow, and groundwater contributions to stream base flow. Precipitation totals and maximum daily temperatures were downloaded for stations at the Colorado Springs Municipal Airport and the Pueblo Memorial Airport [36]. These two stations are located in the lower elevation, Colorado Piedmont portion of the watershed where the Cretaceous age sedimentary geology is present. Precipitation was summed across years and maximum temperatures averaged by years.

To evaluate trends in local native surface water hydrology that might relate to climate and be unaffected by imported water, streamflow for the USGS streamgage 07105945 Rock Creek above Fort Carson, Reservation, Co. (Figure 1) was assessed [20]. The gage sits at

1948 m, drains 17.5 km^2, and is underlain primarily by crystalline rock. Just downstream of the streamgage, the creek infiltrates into alluvium that presumably interacts with Fountain Creek through subsurface flow paths. Mean streamflows were calculated by water year for available data which covered 1980 to 2018, and any trends were assessed.

To assess effects of regional climate on recharge of groundwater and subsequent discharge to streams, water level data were analyzed for a continuously monitored "drought well" that monitors shallow groundwater in an upland setting where climate and natural recharge are expected to be the primary controls on water levels ([37] Figure 1). The "drought well" is located outside the Fountain Creek watershed but is subject to similar climate and weather to the Colorado Piedmont in the watershed. The site is part of the USGS Water Mission Area Climate Response Network in South Central Colorado [37]. The well is used in this study because a similar well inside the watershed with a suitably long record and outside the zone affected by the augmented and managed flows in Fountain Creek could not be identified. Water level data were downloaded from the NWIS database for USGS site 382323104200701, SC01906221AAA, Drought Well near Pueblo, Colorado [20]. Water levels were averaged by water year for available data from 2004 to 2022, and the trend was assessed.

To assess how the magnitude of agricultural diversions have changed through time, diverted water volumes were downloaded by irrigation year (November–October) for 29 diversions from Fountain Creek covering the period 1980–2022 [38]. Most irrigation diversions in the watershed occur downstream of the city of Fountain (Fountain site) (Figure 2). Some individual diversions ceased during this time. For the sake of simplicity, trends were assessed using the sum of diversions by irrigation year.

2.4. Water-Quality Trend Analysis

No new water-quality data were collected for this study. Streamflow and water-quality datasets used in the trend analysis were downloaded from the NWIS database [20]. Per the long-term monitoring program, samples had been collected by integrating streamflow using standard techniques such as depth-integrated, multiple vertical profiles across stream channels [39]. Changes to and decisions about which constituents have been monitored and when have been influenced by permits and regulatory requirements. Analyses of water-quality constituents were completed at the USGS National Water Quality Laboratory in Lakewood, Colorado. The quantity of data available for trend analysis varied by site and parameter and year to year with changes in sampling schedules. The average number of annual concentration data points was 8 but ranged from 5 to 13.

The only constituent for which concentrations from NWIS were not directly used in trend analysis was TDS. Specific conductance (SC) is a commonly used proxy for TDS [19,40]. Measurement of SC was more common for site visits than collection of samples for TDS analysis, and four sites had records of continuously monitored SC. Therefore, by translating SC data into TDS concentrations, the quantity of data to support trend analysis could be substantially increased. Existing and new regressions were used to translate SC to TDS (Table S1; [19,40]).

Weighted regressions on time, discharge, and season (WRTDS) [41] were used to describe trends in concentrations and loads of nutrient, salinity, and trace metal constituents from 1999 to 2021 at the 8 selected streamgage monitoring sites. The WRTDS model was run using the default settings, which sets the period of analysis as the water year and the half-window width to 20 years [42]. The analysis was completed using the "EGRET" package in R [34,43]. WRTDS uses discrete water-quality data and daily streamflow data to make daily concentration and load predictions. The method derives coefficients for each combination of streamflow and time, from which fitted values are then calculated using a multiple linear regression model [41]. WRTDS uses time, streamflow, and seasonality as predictor variables for concentration. Because streamflow is often a dominant driver of concentration, concentration–streamflow relationships are defined daily and across the probability distribution of streamflow [44]. A primary output from the model is flow-normalized concentration smoothed by locally weighted scatterplot smoothing (lowess) which minimizes the within-year variability in streamflow and seasonality to yield a concentration estimate that reveals year-to-year trends [41]. The flow-normalization method in WRTDS that assumes stationarity was used because, as described in the results, trends in streamflow were not identified. The flow-normalized output is useful for assessing multi-year trends at individual sites and herein is compared across the 8 streamgage monitoring sites to add a spatial component to the overall analysis. The approach can make WRTDS a powerful tool for deciphering controls on water quality. Because the 2008 opening of the JD Phillips facility could have caused a potential sharp discontinuity in water quality trends, use of the "wall" option in EGRET to divide the 1999–2022 record was explored [45]. However, the "wall" resulted in two time periods that were much shorter than the 20-year minimum for which WRTDS is designed and yielded some unrealistically steep trends [41]. The option was not used in the final analysis.

Trend uncertainty for flow-normalized concentration and flow-normalized load was quantified using a 90 percent confidence interval calculated from the WRTDS Bootstrap Test via the EGRETci package in R [34,46]. The block bootstrap approach estimates Type I error probabilities—the likelihood of detecting a trend where a trend is not present [46]—using a series of Monte Carlo simulations. The bootstrap method produces a set of hypothesis tests and corresponding two-sided p-values to either reject the null hypothesis (trend is more likely than not) or fail to reject the null hypothesis (no trend is more likely than not) using an alpha threshold of 0.1. Bootstrap replicated trend results and confidence bands were obtained via the "wBT" and "ciCalculations" functions, respectively, from the EGRETci package.

The statistical likelihood of water-quality trends is presented as part of the results. The likelihood values and trend directions are computed from the two-sided p-value attained [46]. For a given trend, upward or downward, p-values from 0.95 to 1.0 are considered "highly likely", 0.90 to <0.95 is considered very likely, 0.67 to <0.90 is considered "likely", and 0.50 to <0.67 is considered "uncertain." The EGRET package can also calculate changes in load. Trends in the direction and likelihood of the load closely tracked those for concentration. The Pueblo site is the only location for which load results are presented because of local interest in that site and because mid-record concentration peaks complicate trend results at several other sites.

The initial WRTDS analysis for unfiltered constituents yielded some unusual patterns in flow-normalized concentrations at many sites. Because only the unfiltered constituents were affected, it seems likely that the pattern was driven by high concentrations of suspended sediment in stormflow samples, as suspended sediment in Fountain Creek can commonly host nutrients and trace elements to a greater degree than water [15,16]. Based upon daily hydrographs, most of the samples with the highest concentration of unfiltered constituents came from stormflow samples. In some cases, the peak flows sampled represented one order of magnitude increases in streamflow, but others were more moderate. Daily mean streamflow, the value used as input in WRTDS, and sub-hourly changes in streamflow were separately explored for the purpose of flagging potential high concentration samples that appeared to distort the trends. Those approaches were unsuccessful, possibly because streamflow peaks and peak suspended sediment concentrations are sometimes out of sync [47]. Therefore, a different approach was tested, and a second set of WRTDS analyses were conducted for unfiltered constituents. Z-scores were calculated for all of the concentrations for a given unfiltered constituent by subtracting the mean concentration from the observed concentration and dividing by the standard deviation. A z-score greater than 4 indicated that the sample had a concentration more than 4 standard deviations greater than the mean. Such samples were omitted from the dataset, and then the process was repeated until no more datapoints with z-scores greater than 4 were found. The number of datapoints culled was recorded (Table S2), and a second round of WRTDS analysis was conducted on the remaining data. Differences between the output are discussed in the results.

As context for culling unfiltered constituent data, the relationships between streamflow and turbidity were examined for 17 and 18 June, 2018, for the upstream Fountain Creek site. Turbidity, a common proxy for suspended sediment concentrations, was monitored at this site only for a few months in 2018 [20], which prevented a broader analysis. No discrete water-quality samples overlapped with approved turbidity data. However, the patterns illustrate differences in the timing and magnitude of streamflow versus turbidity responses during stormflow events.

It is worth emphasizing that the intentional sampling of stormflow conditions to different degrees and with differing success across years introduced sampling bias into the dataset compared to regularly scheduled sampling that occurred regardless of streamflow conditions. The bias seems to be driven by the presence of more stormflow samples in the middle of the record compared to the years near the beginning and end. Assessing and attempting to decrease the effects of that bias on the timing and magnitudes of trends was the goal of the data culling procedure described. By doing so, trends during predominant non-stormflow conditions could be assessed.

3. Results

3.1. Streamflow and Municipal Water Use Patterns and Trends

The annual streamflow averages through time illustrate important aspects of Fountain Creek's hydrology. Natural interannual variability yielded coefficients of variation >0.64 at the two most upstream sites in Monument and Fountain Creek, but the coefficients were <0.55 at the Janitell site and downstream because of the moderating effects of imported water and effluent discharge (Figure 3a). The downstream sites gained little additional natural streamflow compared to the combined imported water and natural flows from upstream. Winter base flow variations were even more muted downstream because the lower elevations receive minimal winter precipitation (Figure 3b). The mean annual streamflow and winter base flow show complicated temporal patterns, and no significant trends were found (Figure 3a,b). The exception was Monument Creek at Bijou St. where the significant trends (found $p = 0.04$) may be attributable to the shorter record. The mean annual outflow from the Fountain Creek watershed at Pueblo from 1999 to 2022 was 138,000 mL.

Increased reusable flows were found for all of the sites and across all the years for which data were available (all $p \leq 0.03$) (Figure 3c). These trends illustrate both the increased presence of imported water in Fountain Creek and water rights that allow reuse to extinction. The pattern at the two most upstream sites in Figure 3c reflected the JD Phillips facility coming online in 2008. The annual percentage of reusable water at Fountain Creek at Pueblo varied substantially depending upon the native flows and ranged from 7% to 54%; the average percentage was 30%. The mean reusable flows exceeded the mean native flows from Fountain to Pueblo in 2012 and from the Janitell Road site to Pueblo in 2022. Both 2012 and 2022 were relatively low mean streamflow years (Figure 3a). No significant trends were found for native streamflow from 1999 to 2022.

There was a significant ($p = 0.013$) downward trend in annual potable water production for customers between the water years 2001 and 2022, indicating a 14% decrease (Figure S1). There was no trend in annual effluent discharge from the Las Vegas facility ($p = 0.84$) or both wastewater facilities combined ($p = 0.28$), but the JD Phillips facility ($p < 0.01$) had a 23% increase in effluent discharge between 2009 and 2021 (Figure 4a). The daily percentage of effluent from the JD Phillips facility (Figure 4b) or from both of the facilities combined (Figure 4c) could represent the fact that the streamflow downstream varied. The values >100% at Janitell Road were likely explained by losses of flow to the alluvial aquifer downstream from the JD Phillips discharge point, causing the Janitell Road streamflow to be less than the JD Phillips discharge [48]. Water year averages of the percentage of effluent could in the streamflow for Monument Creek at Bijou Street ranged from 12% to 38% (Figure 4b) and at Janitell Road it ranged from 20% to 59% (Figure 4c), but no significant trends were found (both $p > 0.3$).

3.2. Local Climate, Natural Hydrology, and Irrigation Trends

From 1980 to 2022, a significant downward trend in annual precipitation was found at Colorado Springs ($p = 0.016$, slope = −0.32) but not Pueblo ($p = 0.28$) (Figure 5a,b). Notably though, three years in which there was quite a low total precipitation in Pueblo in that time come in the latter half of the record. Significant upward trends in the annual mean of daily maximum temperature from 1980 to 2022 were found for both Colorado Springs ($p < 0.01$, slope = 0.059) and Pueblo ($p < 0.01$, slope = 0.032) (Figure 5c,d). It can be noted that no recent statewide trends in precipitation have been identified in Colorado, but the amount of precipitation in the 1980s was generally above average and in subsequent decades it was below average; statewide temperatures have trended upward over the same period [49].

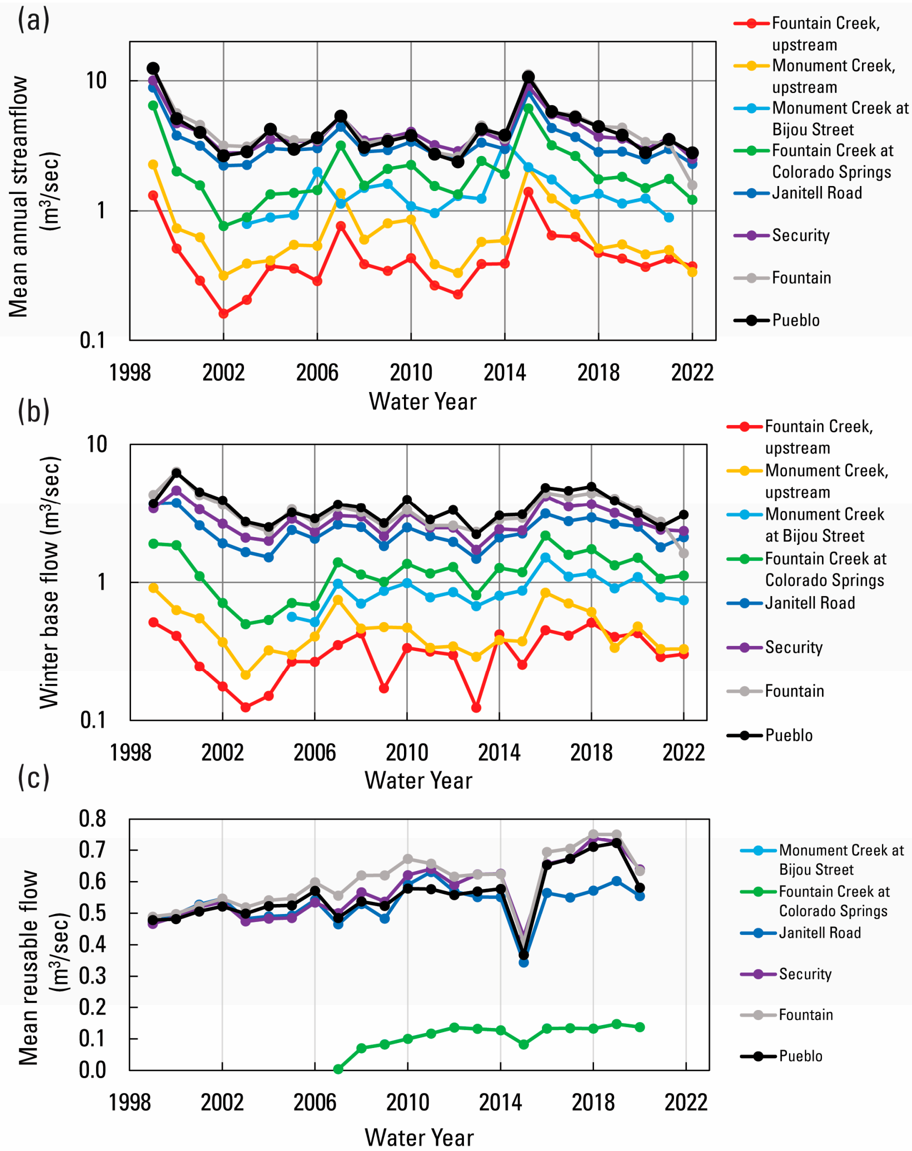

Figure 3. Metrics of streamflow at the 8 streamgages for water years 1999 to 2022: mean annual streamflow (**a**); mean streamflow for the period November to February which represents winter base flow (**b**); and mean flows of reusable water, which is a rough proxy for transbasin imported water (**c**) [20,33]. Note that the Bijou Street site data in (**c**) are overlapped by the next site downstream.

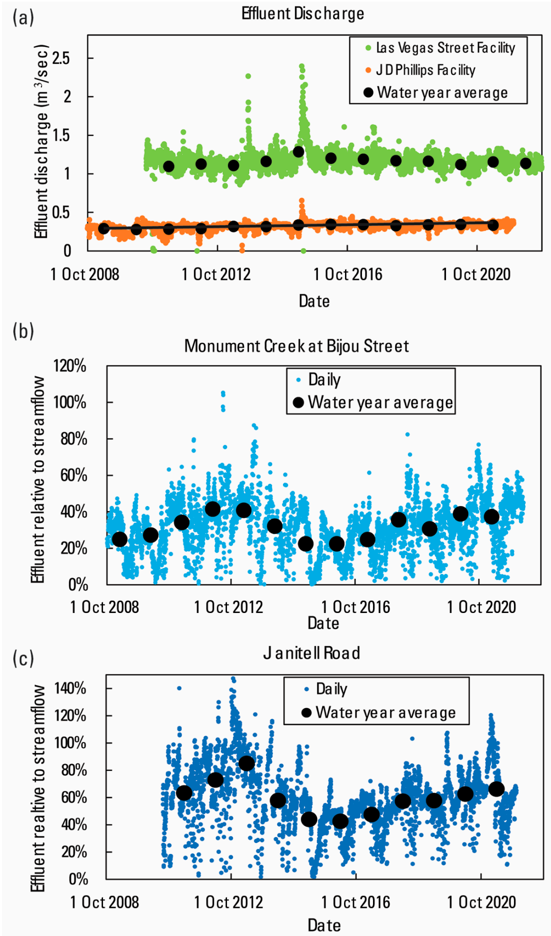

Figure 4. Details of effluent discharge from the two treatment facilities in Colorado Springs: (**a**) effluent discharge rates from the Las Vegas Street and JD Phillips facilities; (**b**) effluent discharge from the JD Phillips facility as potential percentage of streamflow at Monument Creek and Bijou Street; (**c**) and effluent discharge from both facilities as a potential percentage of streamflow at the Janitell Road site [20,26]. The trend line for effluent discharge from the JD Phillips facility is provided for reference.

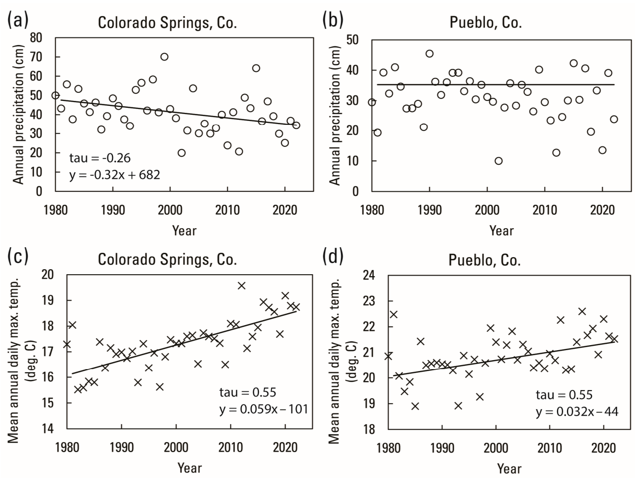

Figure 5. Annual precipitation totals by year for Colorado Springs, Co. (**a**) and Pueblo, Co. (**b**) and mean daily maximum temperatures by year for Colorado Springs, Co. (**c**) and Pueblo, Co. (**d**) [36]. Trend lines are provided for reference along with tau values and equations for significant trends.

The possible effects of warming temperatures and recent below-average precipitation on natural surface water hydrology were assessed in the small Rock Creek watershed, which contains only native flows. There, a downward trend in annual mean streamflow was significant at the 90% level (p = 0.097) (Figure 6a). That trend might have been stronger if not for the presence of high streamflows in 2015, which was a wet year overall (Figures 5a and 6a).

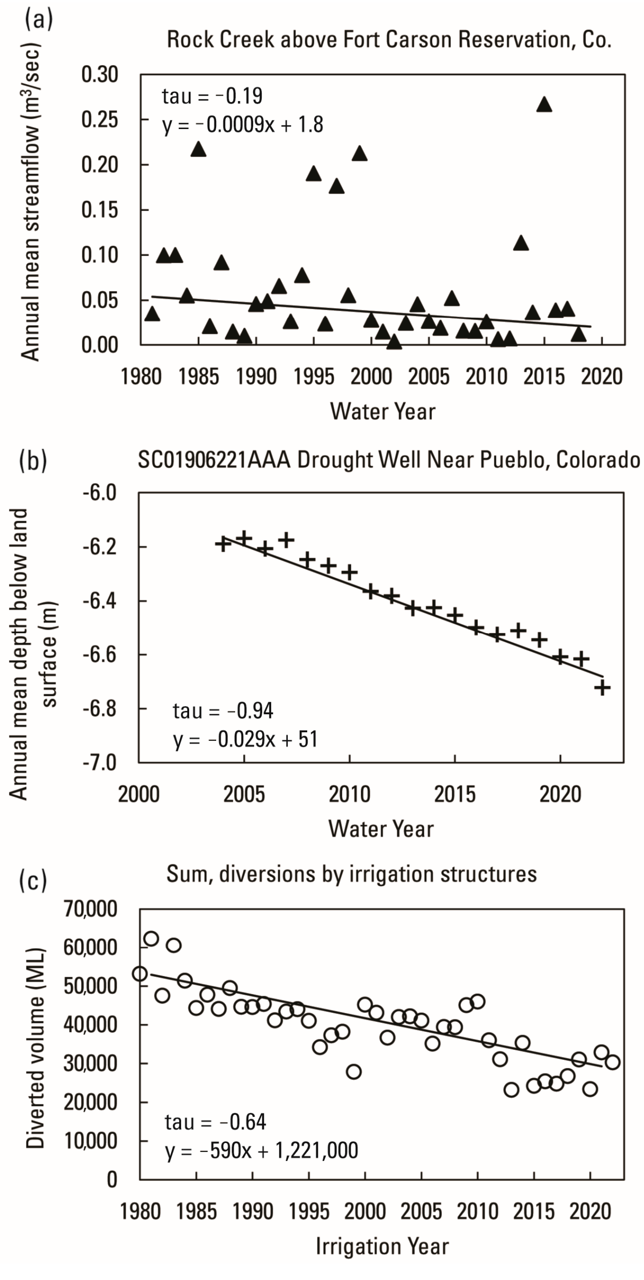

Figure 6. Hydrologic data that yield insight into potential shallow groundwater discharge to Fountain Creek: mean streamflow by year (**a**), mean depth to water below land surface by year for a monitoring well (**b**), and the sum of irrigation diversions from Fountain Creek by irrigation year (**c**) [20,38]. The stream is Rock Creek above Fort Carson Reservation, Colorado. The well is SC01906221AAA Drought Well near Pueblo, Colorado [20]. Trend lines, tau values, and equations provided for reference.

Groundwater responses to potential climate effects in the region were assessed via annual mean depths below land surface for water in SC01906221AAA, Drought Well near Pueblo, Colorado (Figure 6b) [20]. Intra-annual fluctuation was about 0.15–0.2 m per year with seasonal lows in October and highs in May or June, indicating possible natural recharge (data not shown). A significant downward trend in mean annual water levels was found for 2004–2022 ($p < 0.01$) indicating a decline of −0.029 m per year (Figure 6b).

Trends in the combined volumes of water removed from Fountain Creek by 29 irrigation-related diversions were significantly downward from 1980 to 2022 ($p < 0.01$) with a decline of −590 mL/yr/yr (Figure 6c). Diversions ceased for 15 of the ditches between 1980 and 1990. The sum of diverted water decreased by about −24,800 mL in the 42-year period, a decrease of about −46%. From 2016 to 2022, diversions averaged 28,700 mL/yr [38].

3.3. *Effects of Stormflow Sampling and Suspended Sediments on Unfiltered Constituent Trends*

As noted in the Methods Section, trends in unfiltered constituents exhibited unusual patterns at certain sites when all data were included in the WRTDS analysis. Differing priorities, strategies, and success in targeting stormflows for discrete sampling during the 22-year period analyzed appeared to be responsible, along with a transient effect from the Waldo Canyon Fire particularly at the upstream site in Fountain Creek. Suspended sediment concentrations can strongly influence concentrations of unfiltered constituents, and both suspended sediment concentrations and streamflow can change rapidly in response to stormflows. Continuously monitored turbidity from the Fountain Creek near Colorado Springs site provided an example (Figure 7). During storm events, suspended sediment concentrations, as reflected by turbidity, spiked quickly but unevenly relative to changes in streamflow. Sampling intended to target peak streamflow might have sampled or missed the peak in suspended sediments. This effect complicated the relationship between streamflow and unfiltered constituent concentration in the WRTDS and seemed to strongly influence the trend during periods when high concentrations of suspended sediments were sampled. A further complication was that the WRTDS used daily mean values as the streamflow input [42], and such daily values did not reflect instantaneous streamflow during the short-lived peaks targeted by storm sampling (Figure 7).

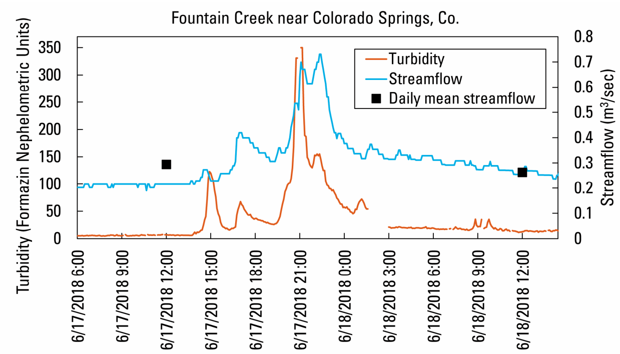

Figure 7. Continuously monitored turbidity (a proxy for suspended sediment concentration) and streamflow for 17 and 18 June, 2018 for Fountain Creek near Colorado Springs, Co. Note the differences in timing and magnitude of response between turbidity and streamflow. Also note how daily mean streamflow (the streamflow parameter used by WRTDS) compares to short duration stormflow [20].

Two examples of how such stormflow samples could have distorted trends were observed for unfiltered phosphorus in the Fountain Creek, upstream, and Pueblo sites. At the first site, the flow-normalized concentration trend was about 0.2 mg/L in 1999, which rose to a peak of about 1.3 mg/L around 2012, and then declined to about 0.2 mg/L by 2021 (Figure 8). The second site showed similar changes. Filtered constituents at these sites did not show dramatic changes in flow-normalized concentration through time.

The concentrations of unfiltered phosphorus in samples from both sites have a strongly skewed positive distribution (Figure 9), even after log transformation, which is one of the steps in WRTDS that compensates for the common situation of skewed concentration data [42]. It seemed that a few very high concentration samples collected in the middle of the period of analysis distorted the flow-normalized concentration trend. For the upstream Fountain Creek site, the few very highest concentrations were in 2013 and 2014, after the Waldo Canyon Fire, and tests removing just those samples diminished but did not remove the pronounced mid-record trend peak seen in Figure 8. The procedure of iteratively culling data points with z-scores >4 (four standard deviations greater than the mean) removed 52 of 192 unfiltered phosphorus concentrations for the Fountain Creek, upstream site (Table S2), which is a large fraction of the available data. In contrast, the z-score culling procedure only removed 12 of the 179 data points for unfiltered phosphorus for the Pueblo site (Table S2). Trends for unfiltered phosphorus at the upstream Fountain Creek site after the z-score culling procedure showed very low concentrations with little change through time (Figure 10a). Comparing the trends in unfiltered phosphorus when using all of the data (Figure 8) to those when using the z-score culled data (Figure 10a) for the Pueblo site, the flow-normalized concentrations at the mid-record peak present in both analyses decreased from almost 1.5 mg/L to less than 0.7 mg/L.

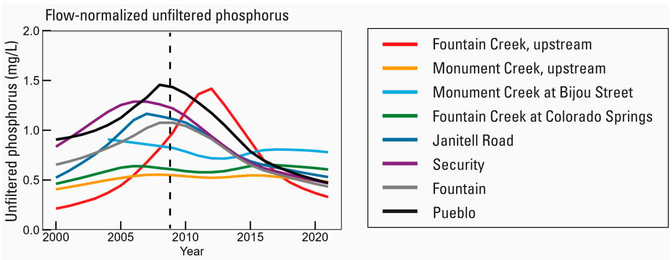

Figure 8. Trends in flow-normalized concentrations of unfiltered phosphorus for the 8 streamgage monitoring sites using all available data [20]. Lines are color coded as in Figures 1 and 2. The trends can be compared to those in Figure 10a where, as described in the text, the z-score-based culling procedure was implemented prior to the WRTDS analysis. For reference, dashed lines indicate when the JD Phillips facility began taking some of the wastewater treatment load from the Las Vegas Street facility.

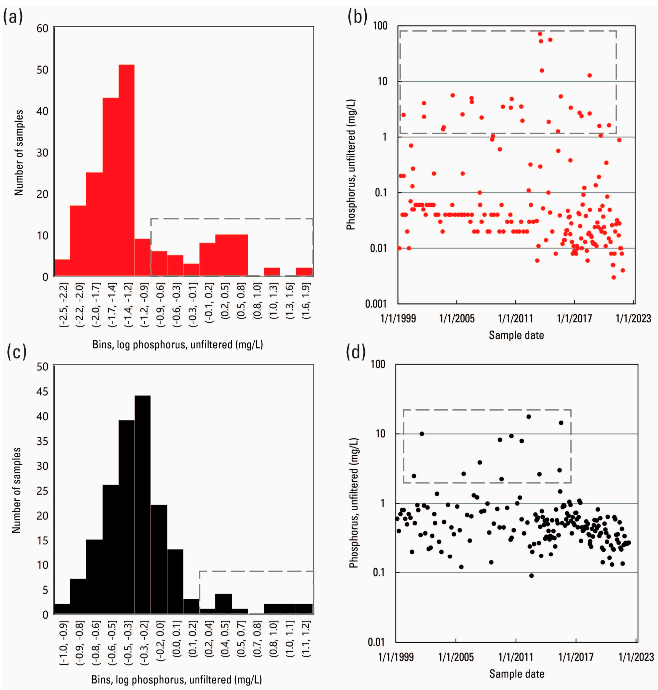

Figure 9. Histogram and all measured concentrations plotted by date of the log of unfiltered phosphorus concentrations [20] for site 07103700, Fountain Creek near Colorado Springs, CO,

(**a**,**b**) and for 07106500 Fountain Creek at Pueblo, CO (**c**,**d**). Note the skewed data distributions even after the log transformation. Also note the timing of highest concentration samples relative to trends in Figure 9. Dashed line boxes indicate the samples removed by the z-score culling procedure in all panels.

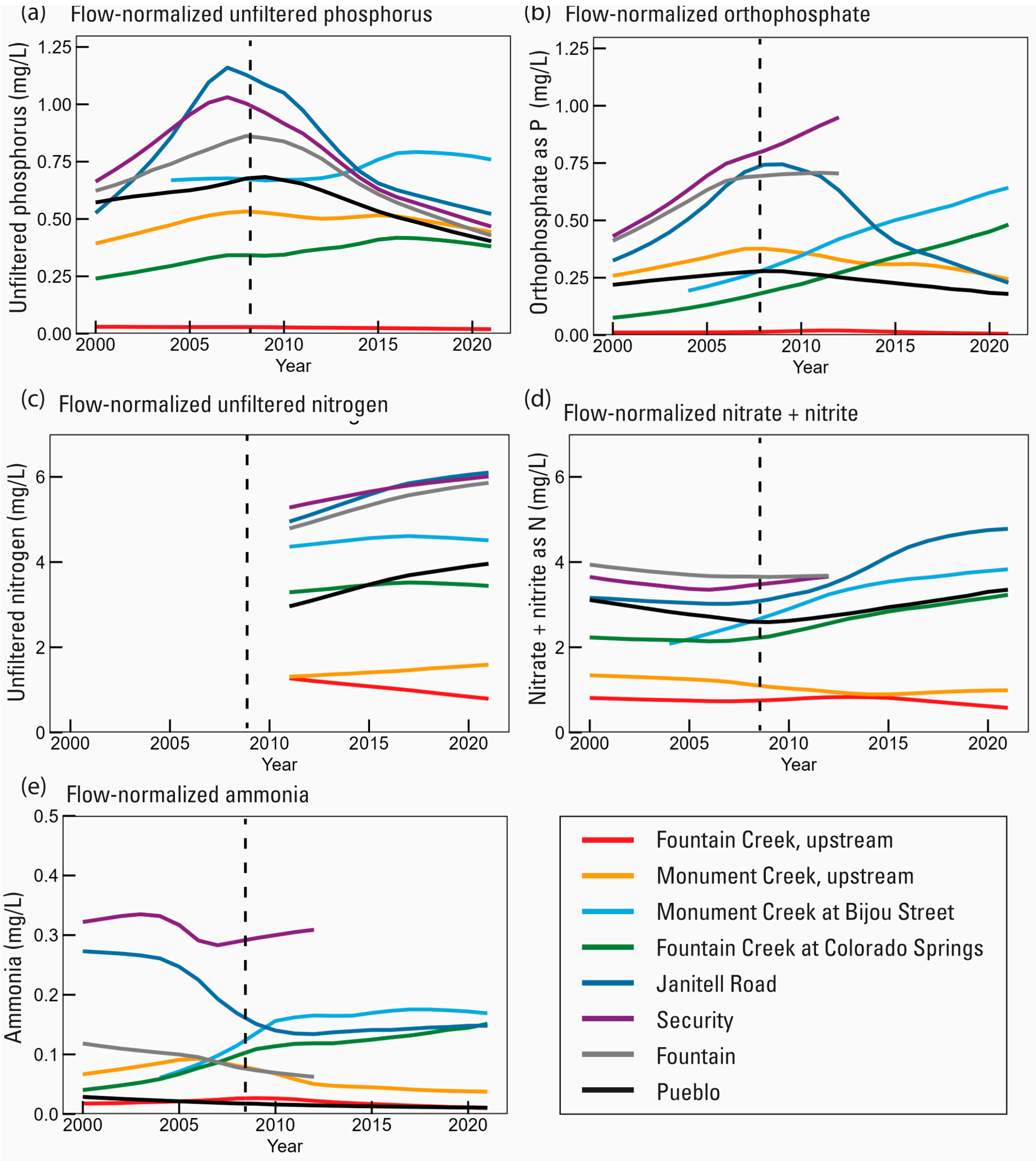

Figure 10. Flow-normalized trends in nutrient concentrations: unfiltered phosphorus as P (**a**), orthophosphate (PO_4^{3-}) as P (**b**), unfiltered nitrogen as N (**c**), nitrate (NO_3^-) and nitrite (NO_2^-) as N (**d**), ammonia (NH_3) as N (**e**) [20]. For reference, dashed lines indicate when the JD Phillips facility began taking some of the wastewater treatment load from the Las Vegas Street facility.

The z-score culling procedure was adopted for trend analysis of all the unfiltered constituents to avoid distorted trends. Data points retained versus culled are listed in Table S2. It is acknowledged that some elements of the effects of stormflows on unfiltered constituents have been omitted from the analysis. The result, however, was that water-quality trends present in the predominant, non-stormflow portion of the hydrograph could be more accurately described.

3.4. Nutrient Trends

Mid-record peaks were a feature of many of the flow-normalized, unfiltered phosphorus, and filtered orthophosphate trends (Figure 10a,b) and for that reason the statistical WRTDS trend likelihood results could be misleading (Table 2 and Table S3). The suggestion of continued increases in orthophosphate at Security and Fountain may be the product of when the monitoring stopped. Flow-normalized trends for both measures of phosphorus peaked around 2008 for the Janitell Road site and those downstream with complete records (Figure 10a,b). The timing of the declines were coincident with the 2008 opening of the JD Phillips facility which began to share the wastewater treatment load carried by the Las Vegas Street facility and shifted some treated water discharge to above the Bijou Street site (Figure 2). Concentrations of unfiltered phosphorus were generally high at Janitell Road and declined in order downstream (Figure 10a). Interestingly, unfiltered phosphorus was high for Monument Creek at Bijou Street before 2008 and no definite response to the new discharge was observed after 2008 (Figure 10a). Notable concentrations of phosphorus were present at the upstream Monument Creek site but not the upstream Fountain Creek site (Figure 10a). Pronounced strong upward trends in orthophosphate were present for the Bijou Street and Fountain Creek sites in Colorado Springs (Figure 10b, Table S3). The suggestions of those trends prior to 2008 might relate to orthophosphate being present at the upstream Monument Creek site. The steady post-2008 increases could be related to discharge from the JD Phillips facility. Distinctions between filtered and unfiltered phosphorus trends may relate to shifts in the proportions the former accounts for within the latter (Figure S2). For the Pueblo site, despite mild mid-record peaks, significant downward trends in both unfiltered phosphorus and orthophosphate were found (Table 2).

Table 2. Trend likelihoods and estimated total changes in concentration and load for Fountain Creek at Pueblo during the period examined. The 90% confidence intervals are given in parentheses. The dataset covers water years 1999 to 2022 and the bootstrap process to estimate likelihoods and changes for water years 2000 to 2021, except as noted. "*" indicates data available only from 2014 to 2022. NA indicates either trend is as likely as not.

Constituent	Concentration Trend Likelihood	Load Trend Likelihood	Total Estimated Concentration Change	Total Estimated Load Change
Phosphorus, unfiltered	Downward trend is highly likely	Downward trend is likely	−0.17 mg/L (−0.27 to −0.03)	−18,810 kg/yr (−55,740 to 2073)
Orthophosphate	Downward trend is highly likely	Downward trend is highly likely	−0.14 mg/L (−0.29 to −0.04)	−15,810 kg/yr (−37,600 to −3310)
Total nitrogen	Upward trend is highly likely	Upward trend is likely	+1.02 mg/L (+0.24 to 1.64)	+96,200 kg/yr (−66,000 to +197,600)
Nitrate plus nitrite	Upward trend is likely	Upward trend is likely	+0.27 mg/L (−0.16 to +0.65)	+45,920 kg/yr (−29,400 to +97,000)
Ammonia and ammonium	Downward trend is highly likely	Downward trend is highly likely	−0.018 mg/L (−0.03 to −0.007)	−2911 kg/yr (−4935 to −622)
Total dissolved solids	Downward trend is highly likely	Downward trend is highly likely	−134 mg/L (−167 to −102)	−16,270 mg/yr (−19,400 to −11,600)
Selenium, unfiltered,	Downward trend is highly likely	Downward trend is highly likely	−16.1 µg/L (−18.5 to −13.9)	−1625 kg/yr (−1930 to −1370)
Selenium, filtered	Downward trend is highly likely	Downward trend is highly likely	−14.9 µg/L (−17.3 to −12.9)	−1362 kg/yr (−1570 to −1140)
Arsenic, unfiltered	Downward trend is highly likely	Either trend is likely as not	−1.8 µg/L (−2.3 to −0.84)	NA
Arsenic, filtered *	Downward trend is highly likely	Downward trend is highly likely	−0.4 µg/L (−0.56 to −0.14)	−67 kg/yr (−92 to −28)
Iron, unfiltered *	Downward trend is likely	Downward trend is likely	−4541 µg/L (−8097 to +2071)	−2227 mg/yr (−4300 to +7803)
Manganese, filtered	Either trend is likely as not	Either trend is likely as not	NA	NA

Data for unfiltered nitrogen only extended back to 2011. Flow-normalized concentrations were lowest at the Fountain Creek and Monument Creek upstream locations (Figure 10c). Downstream, at the two sites within the city of Colorado Springs, concentrations were higher, but trends were not discerned. The concentrations of unfiltered nitrogen were highest in the three sites downstream from the Las Vegas Street facility (Figure 2) and upward trends were likely to very likely (Figure 10c). Downstream at Pueblo, the flow-normalized concentration was lower, but an upward trend was still highly likely (Table 2). Flow-normalized nitrate plus nitrite concentrations had significant upward trends between the Bijou Street and Janitell sites (Figure 10d, Table S3). Recent trends at Fountain and Security were unknown because of a lack of recent data. For the Pueblo site, an overall upward trend in nitrate and nitrite was likely but the trend had both decreased and increased historically (Figure 10d). Pueblo was also the only site where there was an indication that nitrite plus nitrate accounted for more of the unfiltered nitrogen. The concentrations of ammonia and ammonium were comparatively low and showed trends that were localized and divergent among the different sites (Figure 10e). Inflections in many of the trends are found within a couple years of 2008 and seem to indicate effects related to effluent discharge (Figure 10e). Notably, the Security site had the highest flow-normalized concentrations, but the discontinuation of monitoring prevented an assessment of any trends in recent years.

3.5. Salinity-Related Trends

The spatial patterns in the flow-normalized concentrations of TDS showed the that concentrations increased with distance downstream (Figure 11a). One area where a substantial increase in TDS concentrations occurred was in and around the city of Colorado Springs. Additional substantial TDS increases occurred at the sites downstream from the city with a particular increase between the Fountain and Pueblo sites (Figure 11a).

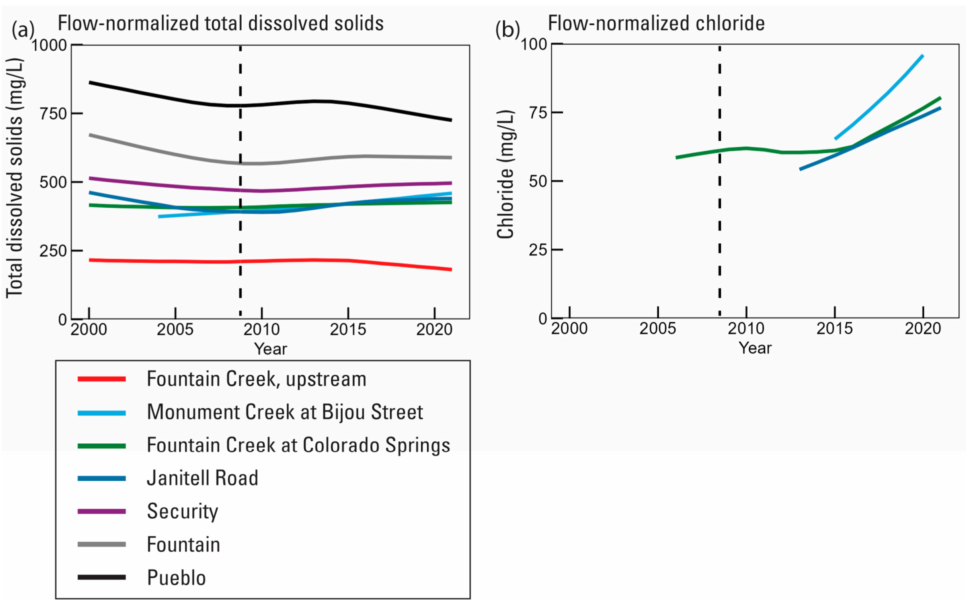

Figure 11. Flow-normalized trends in concentrations of constituents related to salinity: total dissolved solids as determined from measurements of specific conductance and regressions relating those two parameters (**a**), and chloride (**b**) [20]. For reference, dashed lines indicate when the JD Phillips facility began taking some of the wastewater treatment load from the Las Vegas Street facility.

Temporal trends in flow-normalized TDS concentration, both upward and downward, were present in the upper watershed, but the magnitudes were relatively small (Figure 11a, Table S3). Locations where trends were likely and highly likely to be upward were the Bijou Street and Fountain Creek at Colorado Springs sites, respectively. Downward trends were likely for the next two sites downstream. Downward trends were highly likely for Fountain and Pueblo. The bootstrap analysis via WRTDS indicated that flow-normalized TDS concentration at Pueblo had decreased by 134 mg/L and the 90% confidence interval (CI) in the decrease was 102 to 167 mg/L. The estimated change in annual load for TDS was a decrease of 16,000 mg with a 90% CI of 12,000 and 19,000 mg (Table 2). The changes represent approximately 16% decreases for both flow-normalized concentration and load.

Chloride concentrations were not regularly measured at most sites. Upward trends in chloride were significant or highly significant at the three sites where chloride was monitored (Figure 11b, Table S3). There was a subtle upward trend for Fountain Creek at Colorado Springs, CO, before about 2010 and a greater increase after 2015.

3.6. Trace Element Trends

Flow-normalized concentrations of filtered and unfiltered selenium in Fountain Creek show similar patterns spatially and through time (Figure 12a,b). Spatially, there is one marked increase in flow-normalized concentrations of selenium starting around the city of Colorado Springs and another larger increase somewhere between the two most downstream sites (Figure 12a,b). Notably though, trends in the flow-normalized concentrations of unfiltered and filtered selenium were likely or highly likely to be downward at all sites where data were available for 1999 to 2022 (Table S3). At Pueblo, the decreases in unfiltered selenium concentration and load during the period of analysis were 16.1 μg/L (90% CI 13.9 to 18.5 μg/L) and 1625 kg/yr (90% CI 1370 to 1930 kg) (Table S3). The decreases in filtered selenium concentration and load during the period of analysis were 14.9 μg/L (90% CI 12.9 to 17.3 μg/L) and 1362 kg/yr (90% CI 1140 to 1570 kg/yr) (Table S3). The changes represent decreases in the range of 61 to 67%.

The flow-normalized concentrations of filtered and unfiltered arsenic, along with unfiltered iron, showed spatial and temporal patterns that were broadly similar to those for selenium (Figure 12c–e). The concentrations were greater with distance downstream, and there was a marked increase in concentrations between Fountain and Pueblo. Trends were likely to highly likely to be downward at all sites (Table S3). Flow-normalized concentrations of unfiltered lead were distinctly higher at Monument Creek at Bijou St and Security but lower at intervening sites (Figure 12f). Trends for unfiltered lead were likely or highly likely to be downward at all sites except for at upstream Fountain Creek for which either trend was as likely as it was not likely (Table S3). The flow-normalized concentrations of filtered manganese indicated that there were higher concentrations in the upper watershed compared to the lower watershed (Figure 12g). Trends were mixed for filtered manganese, with significant upward trends for both Monument Creek sites and Fountain Creek in Colorado Springs. Many of the trend lines for filtered manganese had an undulating pattern (Figure 12g).

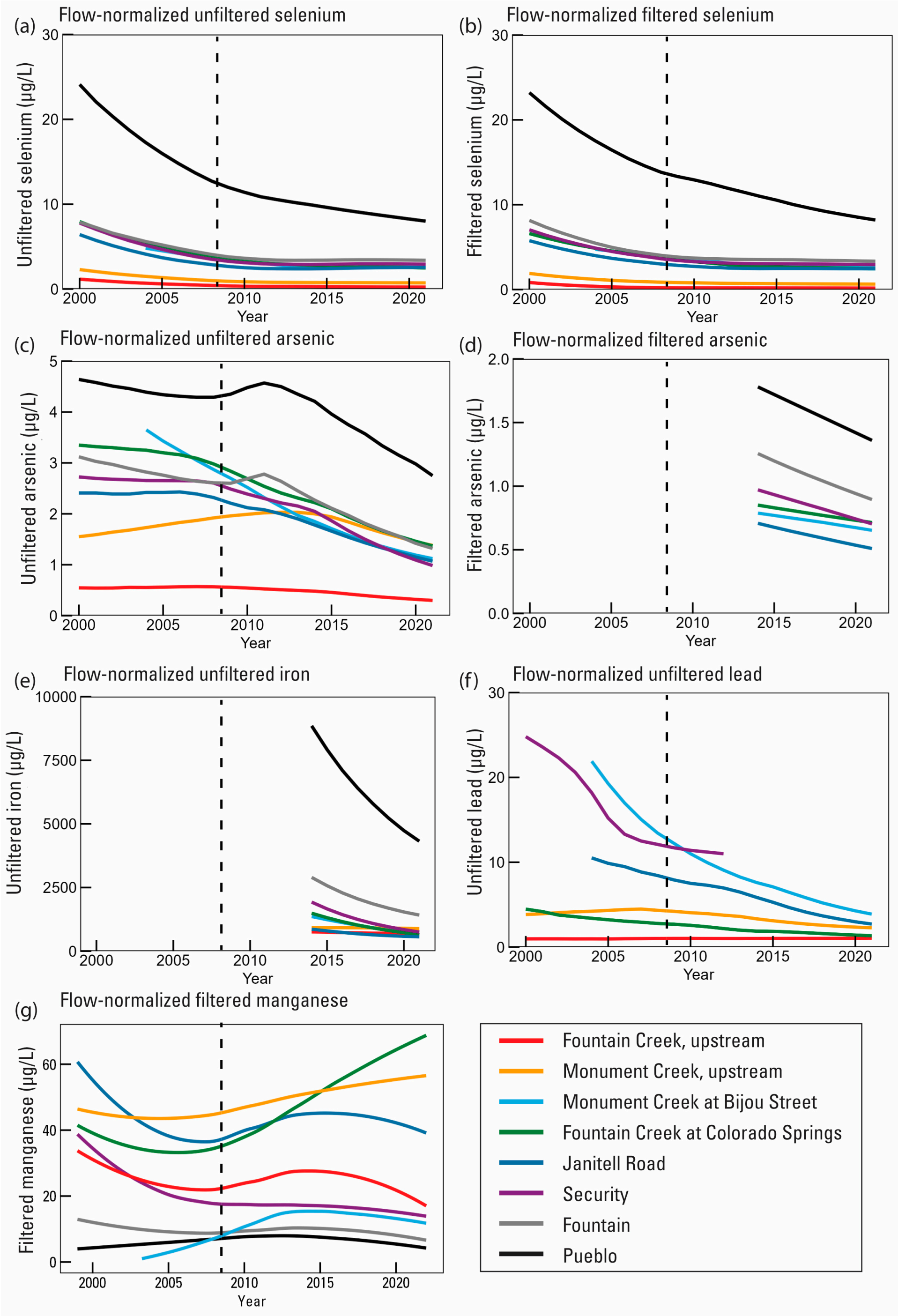

Figure 12. Flow normalized trends in trace element concentrations: unfiltered selenium (**a**), filtered selenium (**b**), unfiltered arsenic (**c**), filtered arsenic (**d**), unfiltered iron (**e**), unfiltered lead (**f**), filtered manganese (**g**) [20]. For reference, dashed lines indicate when the JD Phillips facility began taking some of the wastewater treatment load from the Las Vegas Street facility.

4. Discussion

4.1. Streamflow and Municipal Water-Use Patterns and Trends

The managed nature of streamflow in Fountain Creek was apparent through the decreases in interannual streamflow variability with distance downstream, by the low amount of variability in the winter base flow, which was partially sustained by effluent, and by the substantial volumes of reusable water relative to the total streamflow (Figure 3).

The presence of reusable water, much of it transbasin imports, moderated the inter-annual streamflow variability (Figure 3) compared to a local stream with only native flow (Figure 6). Effluent may have accounted for as much as 59% of streamflow at some locations in some years (Figure 4). Such predominance and flow-moderating effects of effluent in streamflow (Figure 4) are a common occurrence in urban streams in semiarid to arid regions [50,51].

The artificial component of Fountain Creek streamflow is important to consider relative to the human population and water use in the watershed. Historically, across the United States, increases in wastewater generation have closely tracked increases in population [52], but in recent years, the trend has been towards efficiency [53]. The 14% decline in potable water production from 2001 to 2022 (Figure S1), despite a 30% increase in the population of Colorado Springs [5], reflects such a trend. The negligible increase in combined effluent discharge from the Las Vegas Street and JD Phillips facilities (Figure 3c) between 2010 and 2021, despite a roughly 15% increase in the population of Colorado Springs in that time [5], could also reflect increased efficiency. A greater reclamation of water for non-potable uses rather than effluent discharge could account for some of the decrease, but could have only accounted for at most 8% of the potential discharge in 2021 [6]. Per capita effluent discharge in Colorado Springs was about 0.16 mL/yr in 2008 and decreased to 0.12 mL/yr by 2021. For reference, the average urban wastewater generation in North America in 2015 was about 0.23 mL/yr per person [54]. The decline in potable water production in Colorado Springs and the negligible change in effluent discharge might reflect changes in the delivery or sewer systems, but it could also reflect decreases in uses like residential irrigation, with implications for artificial groundwater recharge.

An assessment of per capita outflow from the whole watershed indicates increased water-use efficiency at that scale also. That assessment was made using mean streamflow exiting the watershed at Pueblo of 138,000 mL relative to the watershed population increase from approximately 421,000 in 1999 to approximately 590,000 in 2021. In 1999, outflow was 0.33 mL/yr per capita and it had decreased to 0.23 mL/yr by 2021. That was about a 30% decrease in streamflow per person carrying the sum of human-related water-quality constituents produced in the watershed. These intensifications of human water-use efficiency at the municipal and watershed scales provide context for the water-quality trends.

4.2. Local Climate, Natural Hydrology, and Irrigation Patterns and Trends

Warming and drying trends were apparent in the assessment of local climate and natural hydrology. Significant decreases in precipitation were found around Colorado Springs and increases in daily maximum temperatures for both Colorado Springs and Pueblo occurred between 1980 and 2022 (Figure 6). In Rock Creek, a small stream within the watershed that carries only native flows, a significant decrease in streamflow was found over the same period (Figure 6a). The Rock Creek trend was more notable because it and other creeks sink into and recharge the alluvial aquifer along Fountain Creek. At the drought monitoring well slightly outside the study watershed (Figure 1), the shallow groundwater levels had declined significantly which indicated a possible broader pattern of decreased recharge to shallow aquifers in the region (Figure 6b). Drying trends indicate potentially decreased groundwater and resulted in a decreased shallow groundwater discharge to Fountain Creek. Such links between climate, recharge, and groundwater discharge are becoming more commonly identified [55].

The groundwater age near Fountain Creek suggests how quickly groundwater discharge to the creek might respond to the climate trends. The maximum apparent age of groundwater in the alluvium aquifer just south of Colorado Springs was 21.5 years, but most ages were <10 years [48]. Assuming similar ages for general groundwater discharge to Fountain Creek, a response to climate forcing could be possible within a decade [56]. Decreased groundwater discharge has been suggested as driving water-quality trends in other settings [57].

Diversions of water for agricultural irrigation can affect water quality as water is partially consumed by evapotranspiration, mobilizes soluble constituents beneath fields, and re-enters the creek via return flows. Recent irrigation diversions of around 28,700 mL/yr were notable, as the total streamflow out of the watershed at Pueblo is 138,000 mL/yr. Perhaps more important to understanding trends in water quality was the 46% decrease in annual irrigation diversion volume (−24,800 mL) between 1980 and 2022.

4.3. Nutrient Patterns and Trends

The focus of the study was on effluent discharge, but urban nonpoint sources can also contribute substantially to nutrients [58]. Distinguishing between the two was beyond the scope of this study [50]. The most pronounced trends in nutrients in Fountain Creek appeared to be related to the two largest effluent discharges in the watershed (Figure 10). Based upon timing, opening of the JD Phillips facility reduced flow-normalized phosphorus concentrations in much of the watershed (Figure 10a,b), reversing previous upward trends. In more recent years, the Bijou Street site had the highest phosphorus concentrations, but contributions from the upstream Monument Creek site appear to have contributed to that pattern (Figure 10a,b). However, the increasing trends in orthophosphate at the two sites immediately downstream from JD Phillips suggested that this facility is a major driver (Figure 10b). Despite those increases, orthophosphate decreased at Janitell Road later in the record, which may indicate decreased contributions from the Las Vegas Street facility or instream processes consuming the increased orthophosphate from upstream. Instream processes such as uptake by biota like algae, binding to sediments, and other processes serve to remove nutrients from the water column and decrease concentrations with distance downstream [52]. Ratios of filtered nitrogen to filtered phosphorus at Janitell Road have increased in recent years, indicating preferential phosphorus removal (Figure S4). Similar removal may have contributed to the likely to highly likely downward trends at Pueblo that indicated a decreased export of phosphorus from Fountain Creek (Figure S4, Table 2).

Of the nitrogen parameters, trends in ammonia were the most complex and localized (Figure 10e), possibly due to low concentrations, oxidation to nitrate by nitrifying bacteria, and/or rapid uptake by algae and plants during the daytime [59,60]. A notable ammonia source may exist between Janitell Road and Security, a pattern that has been noted previously [16]. In contrast, the other nitrogen constituents showed more straightforward patterns. The highest flow-normalized concentrations of unfiltered nitrogen had a spatial relationship that indicated that the Las Vegas Street facility was a notable source (Figure 10c). Interestingly, concentrations did not decline with distance downstream until somewhere between Fountain and Pueblo, which potentially indicated either minimal instream removal or additional sources between Colorado Springs and Fountain. The highest recent concentrations of nitrate plus nitrite at Bijou Street and Janitell Road, immediately downstream from the two largest effluent discharges, suggested that they were potential sources. However, lower concentrations downstream of those sites at Fountain Creek in Colorado Springs and Pueblo, respectively, pointed to some instream removal (Figure 10d), though not as great as that for phosphorus (Figure S4). The significant or highly significant upward trends for both measures of nitrogen at Pueblo indicated increasing export from the Fountain Creek watershed (Table 2).

The recent downward trends in many phosphorus concentrations and upward trends in many nitrogen concentrations may presumably be attributed to changes in how wastewater was treated prior to effluent discharge. The overall fraction of effluent accounted for in the streamflow changed little (Figure 4b,c). One potential explanation for the upward trends in nutrients is more highly concentrated wastewater entering treatment facilities. Per capita effluent discharge decreased 23% just between 2008 and 2021, from 0.16 mL/yr to 0.12 mL/yr. As domestic water-use efficiency improves, the diluting effect of low-efficiency devices is removed, and wastewater reaching treatment facilities can see dramatic increases in nutrient concentrations [61,62]. A second possible influence could be diminished dilution of effluent in the watershed by urban return flows related to decreased lawn watering and fixing leaking infrastructure. Around Denver, Colorado, the north of Colorado Springs, development greatly influences recharge to groundwater [63] and water from municipal systems accounted for 80% of urban base flow there during the summer [64]. Efficiency-driven reductions in artificial recharge and runoff in the Colorado Springs area may have influenced the water quality patterns observed in Fountain Creek.

4.4. Salinity Related Trends

The decreases in flow-normalized TDS concentration of 134 mg/L and load of about 16,000 mg/yr at Pueblo (Table 2) were important because they indicated decreased TDS contributions from Fountain Creek to the Arkansas River, where TDS presents a major concern [18,19]. The upward trends in TDS concentrations for Monument Creek at Bijou Street and Fountain Creek at Colorado Springs (Table S3) may have been related to effluent discharge from the JD Phillips facility. The increases in TDS in the City of Colorado Springs, compared to sites upstream, were presumably driven by effluent and non-point urban sources. Interestingly, the increased municipal water-use efficiency that may have increased some nutrient concentrations via effluent apparently did not similarly increase TDS, as TDS had a significant downward trend for the Janitell Road site (Table S3; Figure 12a). The pattern could indicate reduced urban return flows.

Spatially, major additional increases in TDS occurred at the three sites farther downstream. As effluent contributions in the lower watershed were small, those increases were presumably driven by either TDS-rich return flows from irrigation or gains from natural geologic sources delivered via groundwater discharge. Both potential sources could enter the creek through similar, diffuse subsurface flow paths.

The 46% decrease in irrigation diversions between 1980 and 2022 could have driven decreased TDS-bearing return flow in the lower watershed. Irrigation-driven flushing of salts from soils in the Arkansas River Valley, downstream from Fountain Creek, mobilizes substantial fractions of TDS [18]. However, unlike the Arkansas River Valley, much of the irrigated agriculture along Fountain Creek occurs on modern alluvium that may contain less salt than upland soils due to recent fluvial re-working [21,65]. An argument against decreased irrigation being a major factor in downward TDS trends is that most irrigation diversions from Fountain Creek are located south of the Fountain site and downward trends in TDS exist at Fountain and the two sites immediately upstream (Table S3). Therefore, decreased agricultural irrigation likely played some role in the downward TDS trends but may not have been the primary driver.

Perhaps a more likely driver of the TDS concentration decreases was decreases in natural discharge of high-TDS shallow groundwater. Such discharges to Fountain Creek may be volumetrically small under the semiarid climate, but concentrations of TDS in shallow groundwater can be substantially greater than those in Fountain Creek [14]. A perspective on the TDS concentrations in shallow groundwater can be gleaned from surface water flows into Fountain Creek south of the Fountain site, which are generally intermittent but may be more perennially connected to Fountain Creek in the subsurface via alluvium. The concentrations of TDS for two streams in the area (07105940 Little Fountain Creek near Fountain, CO; median = 1150 mg/L; range 161–4070 mg/L; n = 10 and 383325104424801 Sand Creek below Fort Carson near Wigwam, CO; median = 740 mg/L; range 301–1980 mg/L; n = 4) indicate that natural water entering Fountain Creek via surface or subsurface flow paths in that region could have high TDS concentrations [20]

Elsewhere in the region, the Niobrara Formation is known to be a disproportionate source of TDS to surface water [22]. Niobrara Formation outcrops are present in the lower watershed, suggesting a role in the substantial TDS gains there (Figure 1). Even where the Niobrara Formation does not outcrop at the surface, it is commonly overlain only by the lower units of the Pierre Shale (Figure 1). Both the Niobrara Formation and the lower units of the Pierre Shale (particularly the Sharon Springs Member) contain abundant pyrite which oxidizes to yield components of TDS [22] and sources therein. Near Pueblo, shallow emplacement of the Niobrara Formation along Fountain Creek indicates that it could be influencing the composition of groundwater that enters the creek (see Figures 4 and 5 in [14]).

The above evidence points to substantial geologic sources of TDS and high TDS concentrations in shallow groundwater in the Fountain Creek watershed. A drier climate, due to reduced recharge, may have played a role in decreasing the discharge of such high-TDS groundwater to the creek. (Figures 6 and 7). Elsewhere in the western United States, in the Upper Colorado River Basin, downward trends for TDS in base flow, in excess of those expected from salinity control projects, have been attributed to climate, landscape changes, or other unidentified processes [57]. Recent drying-driven decreases in groundwater-supported base flow could play a role, but making definitive links between cause and effect can be difficult [57,66,67]. It can be noted that reductions in base flow have been observed in the Upper Rio Grande Basin, roughly 150 km southwest of Fountain Creek and perhaps responding to similar climate forcings as Fountain Creek [68].

The recent subtle increases in TDS concentration at the Bijou Street, Fountain Creek in Colorado Springs, and Janitell sites within Colorado Springs may be influenced by chloride concentrations, which contributes to TDS and saw steep concentration increases (Figure 11a,b). Across the United States, deicing salts have driven steep upward trends in stream chloride concentrations [69]. Effluent can also be a substantial source of chloride and concentrations from the JD Phillips and Las Vegas Street facilities are in the 50 to 60 mg/L range (A. Berlemann, Colorado Springs Utilities, written commun., 2023), quite similar to those in Fountain Creek (Figure 11b). Broader monitoring of chloride along Fountain Creek could help explain these patterns.

4.5. Trace Element Trends

The Colorado chronic wildlife toxicity standard for dissolved selenium is 4.6 μg/L [70]. Flow-normalized concentrations of both filtered and unfiltered selenium were generally above that value (Figure 12a,b). However, the likely downward trends in unfiltered and filtered selenium concentrations and loads were important because of the issues selenium presents downstream [18,19,71].

A volumetrically small groundwater discharge with high selenium concentrations contributes much of the selenium observed in regional surface waters, with geologic units like the Niobrara Formation being the primary source [14,22]. In Fountain Creek, the spatial pattern of larger selenium concentration increases at the southern end of the watershed supports that idea because that is where the Niobrara Formation outcrops (Figures 1 and 12a,b). The lower units of the Pierre Shale (particularly the Sharon Springs Member) also contain abundant selenium and may also be another notable source, as with TDS ([22] Figure 1).

Spatially, filtered and unfiltered selenium, filtered and unfiltered arsenic, and unfiltered iron all increased in concentration in the lower, southern end of Fountain Creek (Figure 12a–e). Like selenium, arsenic and iron are mobilized to surface waters from geologic sources by complex redox processes [72,73]. Similar downstream concentration increases for all three elements appeared to link them and TDS together via shared geologic sources and processes in the lower reaches of Fountain Creek.

Regarding trends through time, selenium, arsenic, and iron all showed downward trends in concentration (Figure 12a–e). Such patterns were similar to those for TDS although TDS can be assumed to have a broader collection of notable sources, including effluent (Figure 12a). In contrast to TDS, the trace elements showed similar downward trends in flow-normalized concentrations across essentially all eight sites. The same effect of drying climate that may have driven downward TDS trends at Pueblo may have driven the trace element trends across the watershed. Climate seems to be a likely driver capable of affecting all trace elements similarly across all 8 sites by decreasing recharge and subsequent discharge of groundwater that heavily influences their concentrations in Fountain Creek.

In a contrasting example, a drier climate was linked to increases in sulfate, manganese, and zinc concentrations in a river in the snow-dominated North Fork of the Snake River elsewhere in Colorado [74]. However, bedrock in that watershed is highly mineralized, and drying was understood to expose more pyrite to oxidation, liberating more trace elements and sulfate through mineral weathering [75]. In Fountain Creek, by contrast, both the trace elements and TDS would seem to exist in forms ready for mobilization, as precipitated salts in the unsaturated zone, ions sorbed on surfaces, or already dissolved in groundwater, and so annual fluxes of natural recharge could be a strong influence on mobilization [18].

Unfiltered lead concentrations in Fountain Creek were generally either low (Fountain Creek, upstream) or significantly trending downward (Figure 12f). Importantly, the higher lead concentrations did not appear to be spatially linked to Gold Hill Mesa (Figures 1 and 2), where a mill that processed ore for gold and silver and generated between 12 and 14 million tons of tailings [76]. Gold Hill Mesa does have a localized influence on the concentrations of arsenic, copper, lead, manganese, selenium, and zinc at a monitoring site on Fountain Creek just before its confluence with Monument Creek [16], a site that was excluded from the present study due to lack of a streamgage. In the present study, the site that had the highest flow-normalized concentrations of filtered manganese and with the steepest upward trend is Fountain Creek in Colorado Springs, which is downstream from Gold Hill Mesa (Figures 1, 2 and 12g). That pattern might indicate increased mobilization of manganese from the tailings, like the drying-induced mineralized-bedrock watershed patterns observed in the Snake River [74]. In other parts of the Fountain Creek watershed, flow-normalized trends of filtered manganese show somewhat undulating patterns (Figure 12g). The cause of those patterns remains unclear. The spatial pattern of lower concentrations downstream may be driven by larger contributions in the upper watershed and removal by oxidation and precipitation with distance downstream [77].

5. Conclusions

Streamflow in Fountain Creek is highly managed, with large fractions of transbasin water and treated wastewater effluent being present. Depending upon location and year, effluent may have accounted for up to 59% of the streamflow. Certain trends in nutrient concentrations between 1999 and 2021 appear to be related to effluent management and major discharges in the city of Colorado Springs. In several cases, phosphorus concentrations have declined substantially from peaks in the middle of the record. Upward trends in orthophosphate are localized and instream processing appears to cause lower concentrations with distance downstream. In contrast, unfiltered nitrogen and nitrate plus nitrite concentrations have significant to highly significant upward trends below major effluent discharge points and towards the mouth of the creek. Upward trends in nutrients may be related to increased human water use efficiency, as deliveries of potable water have been declined and overall effluent discharge has remained essentially flat even as population in Colorado Springs and the larger watershed have increased by about 36% and 40%, respectively. Diminishment of diluting return flows from lawn and park watering and leaking infrastructure could also play a role in nutrient trends.

Salinity, evaluated as TDS, significantly trended slightly upward in parts of the watershed possibly due to chloride from deicing salts or the shift of some effluent discharge to a location farther upstream. However, TDS concentration significantly trends downward at a point downstream from the two major effluent discharges, suggesting that water conservation has not driven increased salinity. Farther downstream, sources of TDS appear related to geology. Significant downward trends in TDS at the mouth of the creek indicate decreases in concentration of 134 mg/L and decreases in load of 16,000 mg/yr, from 1999 to 2021, both representing approximately 16% decreases. The trends might be related to either decreases in agricultural irrigation or decreases in recharge because of recent drying, both of which could decrease the discharge of high-TDS groundwater to the creek. Unfiltered selenium showed highly likely downward trends in concentration and load of 16.1 μg/L and 1625 kg/yr. Selenium, arsenic, and iron concentrations all show significant to highly significant downward trends in streamflow across the watershed. The existence of similar, spatially widespread trends points to a spatially widespread driver, like recent drying-driven decreases in groundwater discharge, but this cannot be confirmed. Nevertheless, downward trends in TDS and selenium are notable because of the challenges these constituents can pose downstream of Fountain Creek in the Arkansas River.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16101343/s1, Table S1 (TDS regressions), Table S2 (data retained after z-score culling), and Table S3 (concentration trend likelihood output from the WRTDS analysis); Figure S1 (potable water production), Figure S2 (ratios of filtered, orthophosphate as P to unfiltered phosphorus), Figure S3 (ratios of filtered nitrate plus nitrite as N to unfiltered nitrogen as P), and S4 (ratios of reactive nitrogen (nitrate plus nitrite) to reactive phosphorus (orthophosphate)).

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Data Availability Statement: Data used in this article regarding potable water deliveries and effluent discharge are available at https://doi.org/10.5066/P97BJ1KK [26]. Data regarding the transit-loss accounting program for streamflow are available at https://doi.org/10.5066/P90J3L5S [33]. All other data used in this article are available from the USGS National Water Information System database at https://doi.org/10.5066/F7P55KJN [20].

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