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Beyond the Clean Water Rule: Impacts of a Non-Jurisdictional Ditch on Headwater Stream Discharge and Water Chemistry

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Academic Editors: Sujay Kaushal, Paul Mayer and Arthur Gold
Received: 19 September 2016; Accepted: 19 December 2016; Published: 21 December 2016

Abstract: Ephemeral drainage ditches in upland areas, such as those draining roads, are excluded from the jurisdiction of the U.S. Clean Water Act (CWA). While several studies have shown that road drainage and/or development in forested watersheds can impact water quality, the direct physical and chemical impacts of a single drainage ditch have not been identified. In this study, we measured water chemistry (silicon, calcium, and sulfate) and magnitude of discharge from one such feature and at the outlet of the catchment it is within. We found that discharge from the drainage ditch was sometimes over 10% of the larger stream into which it drains, despite the small relative size of the ditch catchment (1.1 ha) compared to the main catchment (43 ha). Furthermore, we observed sharp decreases in silicon and calcium and increases in sulfate concentrations downstream from the drainage ditch across longitudinal sampling of the stream network. This illustrates the impacts of a common feature in high relief, forested areas that when aggregated over the landscape are likely responsible for regional water quality impacts.

Keywords: runoff generation; stormwater; clean water act; clean water rule

1. Introduction

The 2015 update to the U.S. Clean Water Act (CWA) expanded the definition of "waters of the United States" to include headwater streams, including those classified as intermittent and ephemeral [1,2]. This broadened definition of waters within the jurisdiction of the CWA, however, still explicitly excludes stormwater drainage ditches in upland areas [2]. Furthermore, in the Environmental Protection Agency (EPA) document "The scientific basis for the Clean Water Act", no studies are identified that show runoff from these sources impacts the quality, quantity, or ecology of downstream waters [1].

Previous studies have shown that road runoff can impact stream water quality [3] and quantity [4] and suggested that these relatively minor impacts, when aggregated over the landscape, can impact regional water quality [5–7]. Furthermore, urbanization has been shown to negatively impact water quality and the biological function of streams [8,9]. Nationwide, these water quality problems are costly. It has been estimated that annual costs of increased sediment influx to rivers alone is in the tens of billions of dollars [10]. These costs are likely to increase for regions with continued development, such as the Southern Appalachian Mountains of North Carolina [11].

While aggregate landscape effects of road runoff and urbanization have been examined, some specific features common in forested headwater catchments in mountain areas have not. One example is stormwater drainage ditches in upland areas, which are not considered within the jurisdiction of the

CWA due to lack of evidence they impact water quality or quantity [1,2]. Therefore, examining how a single stormwater drainage ditch affects water quality and quantity downstream would demonstrate that these features can impact local water quality. This, in turn, would offer further insight into how similar settings, likely ubiquitous throughout the landscape, influence regional water quality. Therefore, we hypothesized that a small ditch draining a section of paved road surface into a forested, upland stream would have a measurable impact on water quality and quantity in a headwater stream. To test this hypothesis, we measured discharge at the outlet of a 43 ha watershed and from a drainage ditch draining 1.1 ha of the watershed, 10.4% of which was an impervious road. Additionally, we sampled stream water every 50 m along the drainage network in the 43 ha catchment while the ditch was generating runoff in order to quantify the impact it had on downstream water quality (Figure 1).

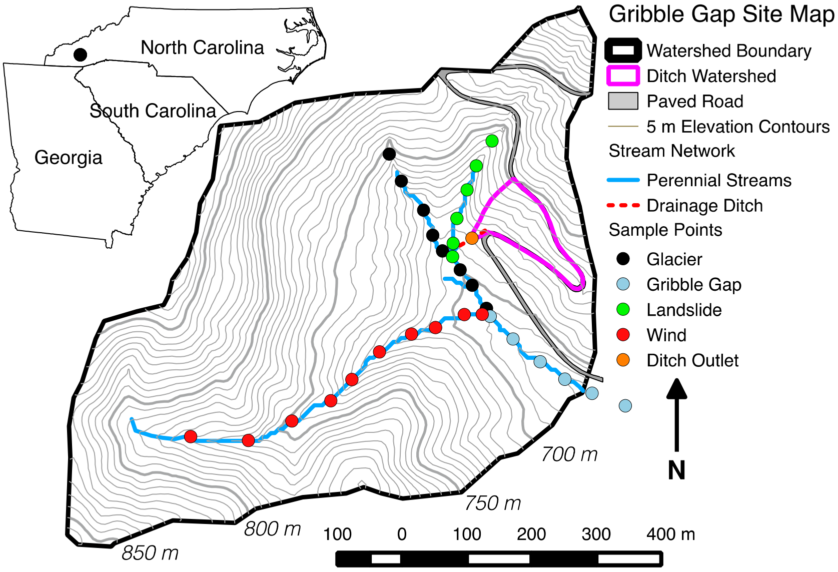

Figure 1. Map of the Gribble Gap Watershed. Sample points are shown and color-coded by stream reach. Additionally, the paved road, watershed for the ditch flume, and the path of the ditch are all shown. Contour lines were created from the 6.1 m resolution North Carolina state Digital Elevation Model.

2. Experimental

2.1. Site Description

This study was carried out within the Gribble Gap watershed of the Western Carolina Hydrological Research Station located in Cullowhee, NC. Gribble Gap is a 43 ha watershed that ranges in elevation from 681 to 871 m (Figure 1). Average annual precipitation is about 1273 mm/year; precipitation is fairly evenly distributed throughout the year [12]. Soils in the watershed are Ultisols and mapped as Evard-Cowee, Saunook, and Whiteside series [13]. The area is underlain by the felsic and mafic Cullowhee gneiss [14]. Some small bedrock exposures occur along stream beds. Forest cover is typical of a second or third generation oak-hickory montane forest. Much of the watershed was logged at least twice in the last 100 years, a portion as recently at the 1980's or 90's. Portions of the watershed were also open pasture sometime in the 1900's.

A paved, impervious road crosses the catchment on the east side, covering 1.5% (6.7 ha) of the Gribble Gap watershed (Figure 1). Two of the subwatersheds, Wind and Glacier Creeks, do not contain any impervious surfaces, as the road is located entirely within the Landslide Creek subcatchment. The road drains into the Gribble Gap stream network at two points, one near the channel head of Landslide stream and one downstream, near the confluence of Landslide with the other two tributaries. The lower of these two drainages drains into a roadside ditch which, upon leaving the roadside and entering the forest, has cut a 1.75 m wide, ~1.5 m deep gully into the hillslope that at its terminus intersects Glacier stream (Figure 1).

2.2. Instrumentation

Flumes were installed near the outlet of the Gribble Gap catchment and at the head of the erosional gully in the road ditch. The flume at Gribble Gap was a Tracom (Alpharetta, GA, USA) 2″ WSC 45 Degree Trapezoidal Flume, whereas the flume at the road ditch was a Tracom Large 60 V Trapezoidal Flume. Both flumes were instrumented with a Solinst (Georgetown, ON, Canada) Levelogger to record stage. A Solinst Barologger was installed at the Gribble Gap flume to measure barometric pressure and correct the stage readings of both flumes. Stage was converted to discharge using the manufacturer-provided stage-discharge relationship. Precipitation was recorded by an Onset (Bourne, MA, USA) Hobo RG-3 rain gage in a clearing near the outlet of the Gribble Gap watershed.

Stream water samples were collected at designated monitoring sites located every 50 m along the stream network (Figure 1). All sample sites were sampled from 11:30 a.m. to 12:30 p.m. on 2 November 2015. Peak discharge at the outlet of the Gribble Gap catchment occurred at 11:45 a.m. and peak discharge from the drainage ditch occurred at 11:35 a.m. This was the same day that peak precipitation occurred during a 3-day, 56.0 mm rainfall event (Figure 2). Streamwater samples were grab samples collected after triple rinsing a 250 mL high-density polyethelene (HDPE) bottle with streamwater. Samples were filtered through a 0.45 micron filter the same day they were collected and refrigerated until analysis.

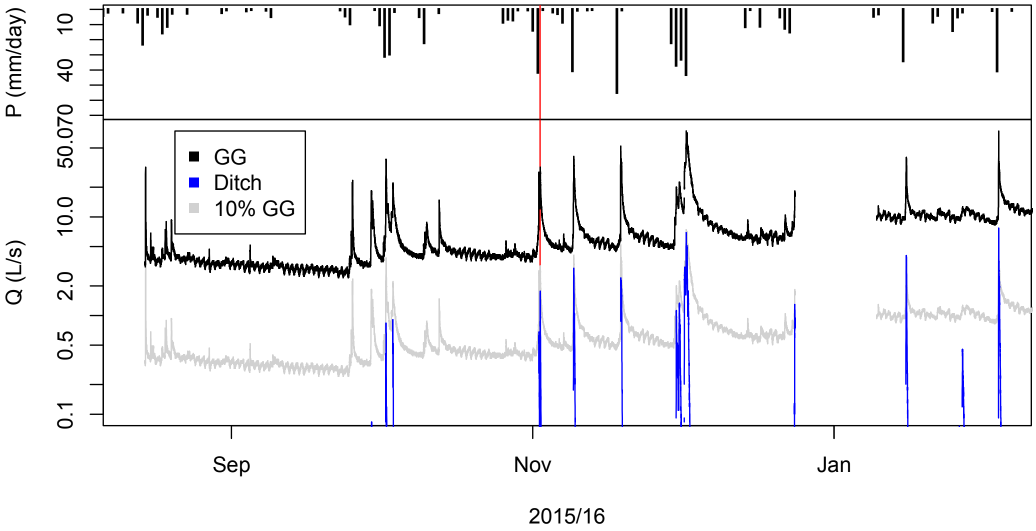

Figure 2. Discharge from the Gribble Gap (GG) and road ditch flumes are shown as black and blue lines, respectively. The grey line indicates 10% of the Gribble Gap discharge. Precipitation in mm/day is shown above. The vertical red line indicates the date and time of the sampled event. The gap in the discharge record is the result of extremely high flows on 24 December 2015, which temporarily disabled the flume at the outlet of Gribble Gap.

Silicon (Si), calcium (Ca^{2+}) and sulfate (SO_4^{2-}) were measured in the samples. Si and Ca^{2+} were chosen because they represent parameters that would be very low in precipitation running off from a road, as higher concentrations are most often associated with long flow paths through natural geologic materials and mineral weathering [15–17]. Therefore, there should be a maximum contrast between water that recently entered the system, and would therefore have low Ca^{2+} and Si concentrations, and water that had taken subsurface pathways to the stream. Conversely, SO_4^{2-} was chosen because the primary source in western North Carolina is wet and dry atmospheric deposition [16], and therefore expected concentrations are higher in precipitation draining an impervious surface, washing both wet and dry deposition into the ditch. Therefore, water recently entering the system and coming into contact with a surface such as a road, was expected to have a higher SO_4^{2-} concentration, whereas recharge in road-less portions of the catchment was expected to be low. Si and Ca^{2+} concentrations were determined using a Perkin Elmer (Waltham, MA, USA) ICP-OES. Sulfate concentrations were determined using a Dionex (Sunnyvale, CA, USA) ICS-1600 Ion Chromatograph.

Watersheds for Gribble Gap and the ditch where delineated from each flume using ESRI (Redlands, CA, USA) ArcMap and the statewide 6.1 m resolution digital elevation model (DEM) [18]. The flume watershed boundary was manually corrected to include half of the paved road. Field observations during rainfall indicated that only the downslope half of the road drains to the gully. This procedure was necessary because the available DEM did not accurately represent the slope of the road. Drainage areas for the ephemeral portions of the three tributaries were defined in order to compare to the drainage area of the ditch, which also has ephemeral flow. These drainage areas were defined as the area upslope of the first point along each tributary where a sample could not be collected during baseflow (but was collected during stormflow).

3. Results

3.1. Gribble Gap and Ditch Discharge

During precipitation events, instantaneous discharge from the ditch was frequently over 10% (up to 12.4%) of discharge observed at the Gribble Gap outlet (Figure 2). Relative to the main stream, the ditch discharge was shown to activate early in precipitation events, but peak nearly simultaneously with the main Gribble Gap stream (Figure 2). For example, for the storm sampled in this study, discharge peaked at the stream outlet at 11:45 a.m. and in the ditch at 11:35 a.m. The ditch flowed for 5.75 h during the storm. The highest observed watershed area-normalized discharge for Gribble Gap was 0.6 and 2.6 mm/h for the ditch.

3.2. Upslope Areas of Natural Tributaries and Ditch

The upslope area at the ditch was 1.1 ha. The upslope areas for the Landslide, Glacier, and Wind tributaries where they transitioned from perennial to ephemeral were 3.9, 1.3, and 2.1 ha, respectively. The paved road accounts for 10.4 percent of the ditch watershed area measured at the flume. The road is also part of the upslope, headwater area of the Landslide Creek tributary catchment; however, there is no direct evidence that runoff from the road flows directly into the stream.

3.3. Water Chemistry in Streams and the Drainage Ditch

Concentrations of Si and Ca^{2+} from samples taken directly from the drainage ditch during a single storm were 3.43 and 1.47 mg/L, respectively. In contrast, the average concentration of Si and Ca^{2+} in the un-impacted Wind Creek, were 6.93 and 2.87 mg/L, respectively. The concentration of SO_4^{2-} in the drainage ditch was 1.67 mg/L compared to an average concentration of 0.95 mg/L in Wind Creek.

Differences were also observed in the general pattern of Si, Ca^{2+}, and SO_4^{2-} concentrations in streamwater between the impacted (Glacier and Landslide) and un-impacted (Wind) creeks when looked at as a whole. While mean concentrations of Si, Ca^{2+}, and SO_4^{2-} were relatively similar, standard deviations illustrate the variability of the impacted streams (Table 1). For instance, the standard deviations of Si and Ca^{2+} values in Wind Creek (un-impacted) were 0.30 and 0.08 mg/L respectively. In the impacted Glacier and Landslide Creeks standard deviation values were 2.09 and 2.68 mg/L for Si and 1.01 and 1.53 mg/L for Ca^{2+} (Table 1). Likewise, the standard deviation of SO_4^{2-} concentrations in samples in Wind Creek was 0.03 mg/L while in Glacier and Landslide Creeks it was 0.19 and 0.24 mg/L, respectively (Table 1).

Concentrations of Si, Ca^{2+}, and SO_4^{2-} also changed immediately downstream of the confluence of the drainage ditch with Landslide creek (Figure 3). Silicon decreased downstream of the confluence of the ditch with the Landslide Creek by 2.13 mg/L. Calcium also decreased below this confluence, by 2.02 mg/L. Sulfate, however, increased by 0.05 mg/L below the confluence.

Similar changes in Si, Ca^{2+}, and SO_4^{2-} were observed near the channel head of Landslide Creek. At the first sample location, the concentrations of Si and Ca^{2+} were lower than the ditch, while SO_4^{2-} was similar to the two other tributaries (Figure 3). Sulfate sharply increased by 0.65 mg/L between the channel head and the sample point located 50 m downstream (Figure 3). Silicon increased by 5.12 mg/L between the channel head and the sample point 50 m downstream as well, and Ca^{2+} increased by 3.02 mg/L.

Table 1. Mean and standard deviation (SD) of silicon (Si), calcium (Ca^{2+}) and sulfate (SO_4^{2-}) concentrations for all sample points grouped by stream reach.

Reach	Silicon (mg/L)		Calcium (mg/L)		Sulfate (mg/L)	
	Mean	SD	Mean	SD	Mean	SD
Gribble Gap	6.94	0.23	3.18	0.04	1.01	0.04
Wind	6.93	0.30	2.87	0.08	0.95	0.03
Glacier	7.92	2.09	4.17	1.01	1.02	0.19
Landslide	6.02	2.68	4.19	1.53	1.27	0.24

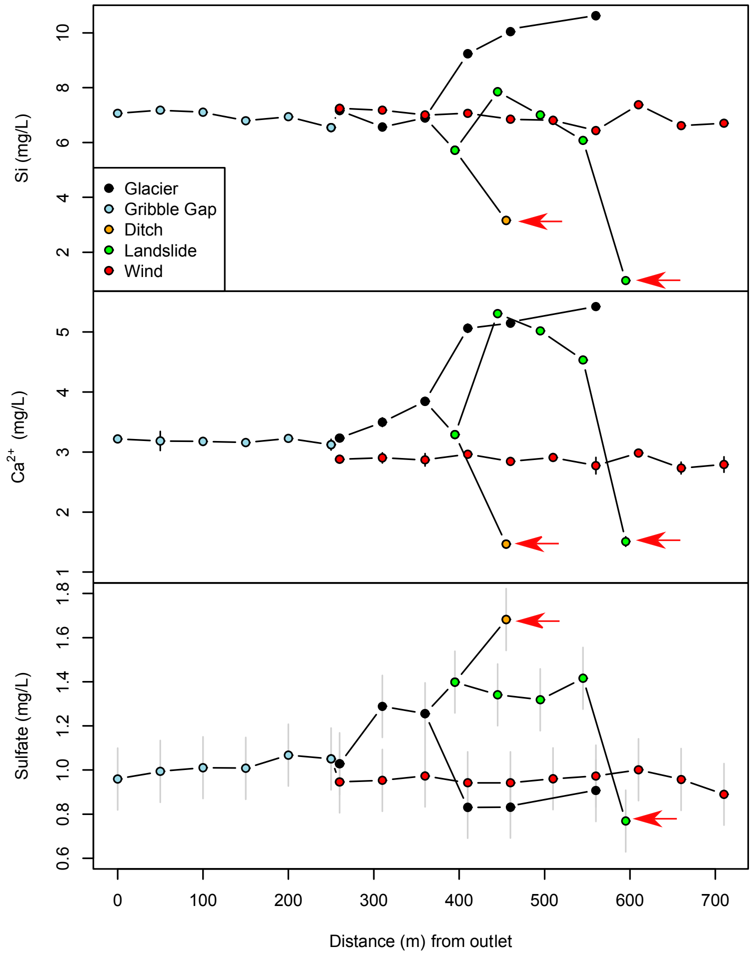

Figure 3. Silicon (Si), Calcium (Ca^{2+}), and Sulfate (SO_4^{2-}) concentrations in mg/L are shown for each sample site in the stream network and plotted against distance from the outlet. Points are colored by tributary. Lines between points identify sites connected by channelized flow. Standard error of concentrations is plotted, but for many points is smaller than the marker. Red arrows indicate locations of road runoff inputs.

Finally, at the first confluence where the impacted Landslide Creek intersected with an un-impacted creek (Glacier), changes were also observed (Figure 3). At this confluence, the concentrations of Si and Ca^{2+} both fell, by 2.34 and 1.21 mg/L, respectively. Sulfate, however, rose by 0.43 mg/L.

4. Discussion

4.1. Impacts on Water Quantity

Increased impervious cover results in higher peak discharges in watersheds [19]. Specifically, road runoff has been shown to impact stream discharge by intercepting water and diverting it to focused areas of runoff, thereby increasing watershed hydrologic connectivity [20]. The road in Gribble Gap was observed to not only intercept rainfall, but also water draining from the upslope cut bank. This expanded the contributing area of the ditch to 1.1 ha, which is nearly as large as the drainage area at the head of the perennial channel on Glacier stream (1.3 ha). Furthermore, a previous study [3] showed that when roads shed water onto hillslopes the impacts can be minimal, but if the flow channelizes, impacts can be more severe. The magnitude of discharge that can result from a section of road in a forested area, however, has not been explicitly identified.

Our results show the impacts on catchment discharge of one drainage ditch. It should be noted that this is not the only place in the watershed where water enters the stream from road drainage (Figure 1), but based on field observations, it is the largest magnitude point discharge. The ephemeral ditch, draining a 1.1 ha watershed of which 10.1% was paved road was up to, and in some cases over, 10% of the current discharge from a 43 ha watershed at times during storms (Figure 2). Peak discharges from this ditch were frequently around 7 L/s, a magnitude greater than the summer baseflow in the entire 43 ha watershed (Figure 2). The severity of the impact from the road drainage is further illustrated by the maximum catchment area-normalized discharge, which shows the ditch produced up to 4.3 times more water per unit area. These observations indicate there is a significant impact on the quantity of discharge at the 43 ha watershed outlet from the 1.1 ha watershed with only 10.1% impervious cover.

4.2. Impacts on Water Chemistry

In addition to increased discharge from the Gribble Gap watershed, the addition of this water causes downstream impacts on water chemistry. We have shown the impact of the ditch on concentrations of Si, Ca^{2+}, and SO_4^{2-} in the Gribble Gap stream network (Figure 3).

The impacts from road drainage were detected first in the samples near the channel head of Landslide Creek, upstream of the ditch. As there is no direct evidence of point discharge to the creek, it is not possible to determine precisely where road runoff entered the stream. However, the large spike in SO_4^{2-} suggests it is between the channel head and the sample point located 50 m downslope. However, Si and Ca^{2+} were low (0.96 and 1.51 mg/L, respectively) at the channel head as well, potentially suggesting surface runoff entered the stream that was not sourced from the road (Figure 3).

Indeed, Si and Ca^{2+} concentrations were low in water sampled from the ditch, with concentrations of 3.43 and 1.47 mg/L, respectively. As a result of the ditch inflow, Si concentrations decreased after the confluence of with Landslide Creek by 2.13 mg/L (Figure 3). Ca^{2+} decreased at this position by 2.02 mg/L. Likewise, SO_4^{2-} was highest in the ditch (1.67 mg/L) and increased at the confluence of the ditch inflow and Landslide Creek by 0.05 mg/L (Figure 3). This small magnitude increase is likely due to the already elevated SO_4^{2-} concentration of Landslide Creek due to diffuse road inputs upslope. Therefore, where the ditch joins Landslide Creek, the Si and Ca^{2+} concentration was already low and the SO_4^{2-} concentration was high from other road inputs. However, the observed changes to Glacier Creek, which before the confluence with Landslide Creek is un-impacted by road runoff, illustrate the impact of the road more fully. Below the confluence of Landslide Creek with Glacier Creek, the Si concentration dropped by 2.34 mg/L (34% decrease), Ca^{2+} dropped by 1.21 mg/L (31% decrease) and SO_4^{2-} increased by 0.43 mg/L (34% increase) (Figure 3).

The impact of the drainage ditch and road runoff can also be observed in the descriptive statistics of Si, Ca^{2+}, and SO_4^{2-} for each stream reach (Table 1). Standard deviations were higher in the two impacted streams than in the un-impacted stream (Table 1). This increase in variation can also be observed when the two analytes are plotted against distance from the watershed outlet (Figure 3).

It is important to note that while we have shown that inputs from the drainage ditch impact stream chemistry at several points along the stream network, we cannot identify how much the ditch affected water chemistry the catchment outlet. Glacier Creek upstream of the confluence with the impacted Landslide Creek has higher Si and Ca^{2+} and lower sulfate than Wind Creek (Figure 3). This suggests that without the input from the drainage ditch and other road impacts, the outlet would have higher Si, Ca^{2+}, and SO_4^{2-}. However, it is not possible to tell what the concentrations of either analyte would be in an un-impacted Landslide Creek, due to the road input near the channel head. However, during several storms, the flow from the drainage ditch exceeds 10% of the discharge from the entire Gribble Gap catchment (Figure 2). This, combined with the impacts observed upstream, would suggest the drainage ditch is influencing water chemistry at the outlet of Gribble Gap Creek to some degree. Furthermore, this study clearly shows the impact on the upstream perennial reaches (Landslide and Glacier), as evidenced by water chemistry changes below confluences with flows affected by road impacts (Figure 3) and the high variability of those reaches in comparison with the entirely un-impacted Wind Creek (Table 1).

Previous studies have shown that development and/or urbanization affect water chemistry and the biological functioning of headwater streams [21] and identified the need to work towards understanding the transition from forested to urban areas [6]. Effects of different land-cover and runoff generation processes on water quantity and quality have also been identified [16,19]. However, these studies have either been conducted to identify larger, spatially aggregated effects [16,19] or on far more urbanized watersheds [7,21]. For instance, previous work at the watershed level at the Coweeta Hydrologic Laboratory in western North Carolina suggested SO_4^{2-} was higher in watersheds with more quick-flow [16]. This study also shows that surface flow does indeed contain more SO_4^{2-} and can lead to increases in concentration downstream. Similarly, we highlight a specific source that leads to lower Si and Ca^{2+} concentrations in the stream network.

This study therefore provides insight into processes that have been identified at larger scales or more urbanized environments by identifying a road drainage ditch as a source downstream water quality impacts in a forested upland area. Furthermore, the results suggest that even small-scale changes in land cover can result in water quality impacts in a headwater stream with the potential for those effects to continue to propagate downstream. However, even absent direct evidence of impacts further downstream, we highlight the ability of the ditch to transport material/contaminants from the road to sensitive headwater streams.

4.3. Regional Implications

While the impacts of this individual ditch draining a road are not particularly severe, the aggregate impacts of numerous similar and/or more severe settings must be considered. Several authors have proposed that small headwater streams exert a strong control over regional water quality [5,22,23]. For example, higher SO_4^{2-} concentrations have been observed in surface waters in areas with more development [16]. These aggregate effects have been attributed to the majority of stream length being headwaters or by larger scale analyses of landscapes and water quality. We have shown a specific flow path and source that is responsible for impacts on water quality and quantity. Furthermore, the conditions leading to this impact are common throughout at least the Appalachian region of the United States and not identified as a proven source of surface water impacts in the CWA or scientific literature [1].

Previous studies have shown that road runoff can source water directly to streams if it channelizes rather than dissipates on hillslopes and that such a connection was common (24% of road-draining culverts in the Deschutes river basin in Oregon were connected) [4]. Our study shows the impacts of an individual case of road runoff channelizing and delivering water to a stream network, which points to a need to identify where this happens throughout the landscape. Furthermore, the road runoff in this instance is actively eroding a ditch into a hillslope, suggesting there is a resultant landscape feature that could potentially be mapped remotely or by extensive field surveys. A more regionalized approach, such as this, may help elucidate the processes leading to the larger scale impacts on streamflow from development previously identified in the region [24] as well as identify sites at which to further investigate water quality impacts.

5. Conclusions

In this study we show that a drainage ditch draining a paved road in an otherwise forested upland catchment in western North Carolina affects water chemistry in the stream network and contributes disproportionally high discharge to the system. Decreases in Si and Ca^{2+} concentrations were observed below the confluence of the drainage ditch and the stream network, as well as an increase in SO_4^{2-}. During storms, the drainage ditch episodically contributed over 10% of the total instantaneous catchment discharge despite only accounting for 2.6% of total catchment area.

Features such as this drainage ditch are excluded from the jurisdiction of the Clean Water Act (CWA) [2]. The results of this study suggest that features such as this are indeed important to perennial stream water quality, especially if their aggregate affect over the landscape is considered. We therefore suggest this study points to the need to further quantify the effects of these features across the landscape to better understand their impacts on regional water quality.

Acknowledgments: This study was funded by the Western Carolina University Provost's Internal Funding Support Grant. The authors would also like to thank the many undergraduate students who helped with data collection. Finally, we would like to thank Jerry Miller for a very helpful early review of this manuscript.

Author Contributions: John P. Gannon, David A. Kinner and Mark L. Lord conceived and designed the experimental set up. John P. Gannon, David A. Kinner and Mark L. Lord also installed the infrastructure and collected the samples/data. John P. Gannon analyzed the data. John P. Gannon wrote the paper with considerable input and assistance from David A. Kinner and Mark L. Lord.

Conflicts of Interest: The authors declare no conflict of interest.

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