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Research Letter

Small Reservoir Impact on Simulated Watershed-Scale Nutrient Yield

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The soil and water assessment tool (SWAT) is used to assess the influence of small upland reservoirs (PL566) on watershed nutrient yield. SWAT simulates the impact of collectively increasing and decreasing PL566 magnitudes (size parameters) on the watershed. Totally removing PL566 reservoirs results in a 100% increase in total phosphorus and an 82% increase in total nitrogen, while a total maximum daily load (TMDL) calling for a 50% reduction in total phosphorus can be achieved with a 500% increase in the magnitude of PL566s in the watershed. PL566 reservoirs capture agriculture pollution in surface flow, providing long-term storage of these constituents when they settle to the reservoir beds. A potential strategy to reduce future downstream nutrient loading is to enhance or construct new PL566 reservoirs in the upper basin to better capture agricultural runoff.

1. INTRODUCTION

Public Law (PL) 566 dams are flood control structures built by the United States Soil Conservation Service to mitigate the effects of increased flooding from recent land use change. Although dams are generally assumed, regardless of size, to negatively affect downstream environments, Duke et al. [1, 2] have shown that these reservoirs are a positive ecological influence, because they enhance downstream riparian growth. Of course, this downstream benefit will last only as long as the PL566s remain viable, and does not necessarily equate to the positive ecological health within the reservoirs themselves. We postulate that PL566s can likewise be a positive ecological agent by reducing downstream nutrient and sediment pollution. The Waco Lake catchment (see Figure 1) in Central Texas, USA, has been identified as an impacted watershed due to nonpoint source pollution causing noticeable eutrophication [3]. Agricultural runoff associated with dairy operations in the Upper North Bosque watershed has been identified as the probable source for much of the elevated nutrient loading into Waco Lake [4–7]. However, the same models [4–7] suggest that only dramatic and potentially infeasible management changes, such as the total removal of dairy waste from the basin, can adequately remediate the nutrient problem. However, this study illustrates that the situation would be much worse without the 81 PL566 reservoirs within the watershed.

The degradation of PL566s should be of great concern to environmental planners in the USA, because most of the PL566s are nearing the end of their design life. Under the auspices of the US Department of Agriculture, more than 10 000 of these dams have been built in the US since 1948 at a cost of 14 billion USD [8]. The cost of revitalizing these types of small reservoirs through dredging or new construction might become a heavy but necessary financial burden on local and national governments, especially if agricultural management and stream renaturation solutions are not feasible.

This study presents a comprehensive simulation of the Waco Lake catchment (see Figure 1) using the soil and water assessment tool (SWAT) [9]. The purpose of this study is to illustrate the relative impact of small upland reservoirs on simulated nutrient and sediment yields from the Waco Lake catchment.

2. MODELING METHODS

Watershed simulation utilized SWAT2000 [10]. The model is designed to use readily available GIS inputs and to be capable

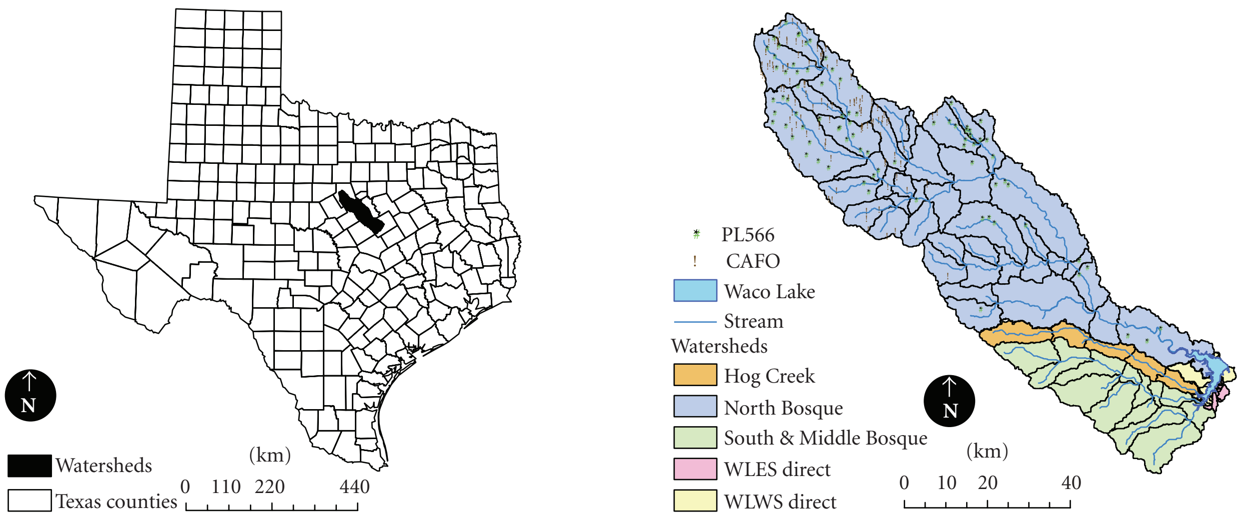

Figure 1: Maps of the Waco Lake catchment. Waco Lake is a municipal drinking water source for Waco, Texas, USA. (a) Location of study area in Texas; (b) watershed and subbasin delineation. Both confined animal feeding operations (CAFOs) and small flood control reservoirs (PL566s) are concentrated together in the Upper North Bosque watershed.

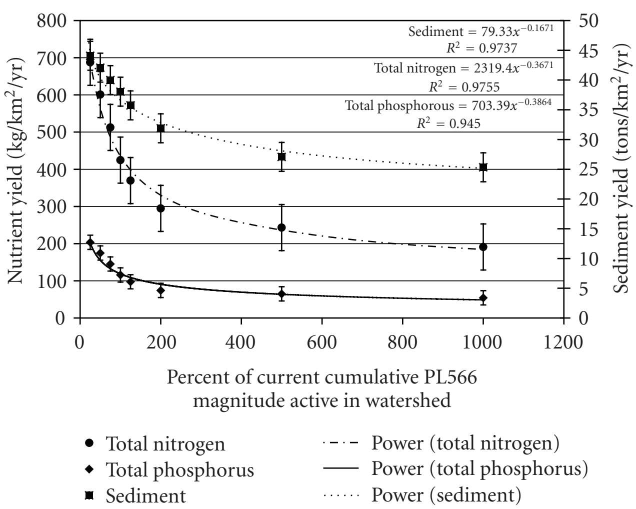

Figure 2: Predicted nutrient and sediment yield with respective estimated standard error bars from the North Bosque watershed when altering the magnitude (size) of PL566 reservoirs a constant percentage relative to the calibrated current conditions model.

of simulating long periods for computing the effects of management changes on watershed ecosystems [10, 11]. SWAT is physically based and deterministic. Calibration of the model to observed data is aimed at resolving uncertainty associated with the parameterization of physical processes. Once calibration is completed, simulations will retain the established confidence in process representation under different management scenarios. Details concerning how the processes are simulated are presented in the SWAT manuals [9, 10].

Watershed modeling for the Waco Lake catchment includes representations of concentrated animal feeding operation (CAFO) lagoons, CAFO dairy treatment fields (DTFs), eight municipal waste water treatment plants (WWTPs), and 81 PL566s (see Figure 1(b)). These features are simulated through a combination of physical parameters and management operations. CAFO lagoons are accounted for in SWAT as a "pond." The physical dimension and parameters for the CAFOs are based on the McFarland et al. [12] assessment of a lagoon in the Upper North Bosque watershed (see Figure 1(b)) that was designed for a 1000-cow dairy. DTFs are simulated using management practices and the volume of manure calculated from the CAFOs. The mass of manure from the CAFOs is applied daily to the top 10 cm of all closely grown agriculture croplands within the same subbasin. PL566 reservoirs were modeled as "wetlands" in SWAT. "Ponds" and "wetlands" are handled in the same way as in SWAT, except for water outflow. For volumes between the target (normal) storage and maximum storage, the "wetland" is hard-wired at 10 days to reach its target storage, close to what is expected for the PL566 structures. This differs from "ponds," in which the user can set the target days. The minimum 10-day residence time for surface flow contributions to PL566 storage also gives a realistic opportunity for dissolved nutrients and sediment to settle out of suspension to the bottom of the reservoirs where they can be stored. Dimensional data for the PL566s are derived from the dataset of US Army Corps of Engineers National Inventory of Dams [13]. Simulating decreases and increases in the magnitude of PL566s (PL566 size scenarios) is done by collectively multiplying all dimensional parameters for these features by selected factors. Standard error is calculated for the simulated nutrient and sediment yields to assess confidence in observed trends in the results.

3. RESULTS

Statistical covariance of simulated versus measured daily stream flow at Valley Mills (see Figure 1(b)) resulted in an

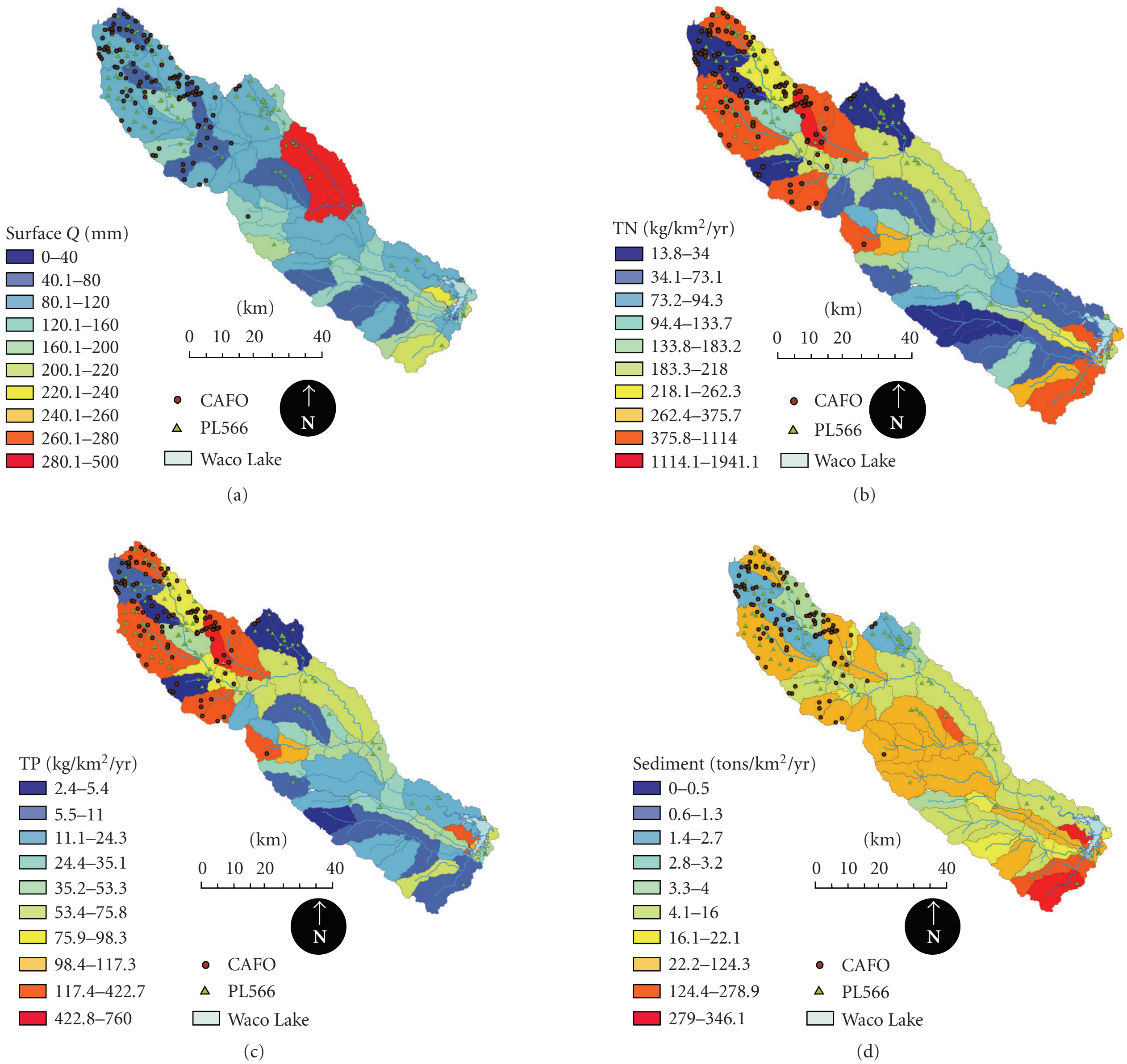

FIGURE 3: Average 25-year (1980–2004) subbasin yield of surface flow, sediment, and nutrients in the study area classified using the Jenks natural breaks methodology. The class breaks are determined statistically by finding adjacent feature pairs between which there is a relatively large difference in data value. (a) Surface flow (mm); (b) total nitrogen yield (kg/km^2/yr); (c) total phosphorus yield (kg/km^2/yr); (d) sediment yield (tons/km^2/yr).

R^2 of 0.85, residual error of 2.8%, and a COE [14] of 0.33 during a ten-year calibration interval (1986–1996). Likewise, validation of the model using a different one-year interval (1997) resulted in an R^2 of 0.86, residual error of 1.8%, and a COE of 0.77. Statistical covariance of monthly simulated versus measured nutrient data at Valley Mills (see Figure 1(b)) resulted in an R^2 of 0.81, residual error of 11.5%, and a COE of 0.78 for total nitrogen, and R^2 of 0.87, residual error of 4.9%, and COE of 0.76 for total phosphorus from 1996 to 1998.

Figure 2 illustrates the effects of adjusting the magnitude of PL566s on watershed nutrient and sediment yields over a 25-year interval from 1980 to 2004. Standard error within the three trend lines (one for each of total nitrogen, phosphorus, and sediment) is small compared to the total range of values, and it gives confidence that the trends are statistically significant (see Figure 2). Totally removing PL566 reservoirs resulted in a 100% increase in total phosphorus and an 82% increase in total nitrogen, while "total maximum daily loads" (TMDLs) calling for a 50% reduction in total phosphorus (from the 100% data point in Figure 2) can be achieved with a 500% increase in the magnitude of PL566s within the watershed (see Figure 2). Simulating the decline to complete removal of the PL566 reservoirs more rapidly increased nutrient and sediment yields than increasing the PL566 magnitude which reduced yields (see Figure 2).

The spatial distribution of surface flow, total nitrogen, total phosphorus and sediment loads are not equally distributed across the study area (see Figure 3). Subbasins in the Upper North Bosque watershed, along the South Bosque and within the direct drainage into Waco Lake (Waco Lake East Shore and Waco Lake West Shore), yield over two orders of magnitude more nutrients than subbasins in the Lower North Bosque, the Middle Bosque, and the Upper Hog Creek (see Figures 1(b) and 3(b)-3(c)). Likewise, sediment yields are of upwards of two orders of magnitude greater along the South Bosque and the direct drainage subbasins (Waco Lake East Shore and Waco Lake West Shore) than areas in the Upper North Bosque and Hog Creek (see Figures 1(b) and 3(d)). Sediment yields become greater down basin in the North Bosque, Hog Creek, and Middle Bosque watersheds (see Figures 1(b) and 3(d)). Subbasins characterized by low nutrient and sediment yields (blue hues in Figures 3(b)–3(d)) tend to also have multiple PL566 reservoirs (see Figure 3).

4. DISCUSSION AND CONCLUSIONS

Removing PL566 reservoirs from the calibrated simulation dramatically illustrates the importance of the small reservoirs for mitigating downstream nutrient and sediment pollution (see Figure 2). PL566s attenuate sediment and nutrient pollution carried with surface runoff by storing these constituents in the upper basin. Furthermore, these reservoirs may also prevent more severe downstream flooding that would increase the loading of nutrients and sediment from eroding stream banks.

Spatial analysis of the Waco Lake catchment indicates that there is a somewhat inverse relationship between nutrient and surface runoffs (mm) and sediment yields (see Figures 3(a) and 3(d)). This is especially true in the agriculturally developed Upper North Bosque watershed where CAFOs and DTFs are concentrated (see Figure 1(b)). There is a positive relationship between nutrient and surface runoffs (mm) and sediment yields (see Figures 3(a) and 3(d)) along the South Bosque, Waco Lake East Shore, and Waco Lake West Shore watersheds where there are no CAFOs or DTFs (see Figure 1(b)). This agrees with previous studies [4–7] implicating agricultural contributors, such as DTFs, as driving elevated nutrient yields as opposed to natural soil erosion or leaching in the Upper North Bosque. However, subbasins in the Upper North Bosque that route surface flow to PL566 structures have nutrient yields closer to the more natural subbasins in the Lower North Bosque and Middle Bosque (see Figure 3). This pattern indicates that PL566s can offset agricultural pollution if they are situated downstream of source areas. The rapid increase in nutrient and sediment yields with reduction in PL566 magnitude emphasizes the need to maintain these features to prevent future increases in downstream nutrient pollution. This is a critical issue since most have surpassed their design life of around 50 years, and may already be loosing much of their original storage potential.

On a watershed scale, small upland reservoirs seem to act as positive ecological features in that they store significant amounts of nutrients that can cause even more environmental problems when concentrated downstream. In fact, one possible "best management practice" (BMP) for this catchment is to strategically construct new PL566 reservoirs on subbasins in the Upper North Bosque with elevated nutrient yields (see Figure 2) [4]. This potential storage of nutrients in new PL566 structures may drastically reduce nutrient loads downstream into Waco Lake .

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