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Evaluating the relationship between impervious surfaces within watersheds and coastal water quality on Virginia's Eastern Shore

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FINAL REPORT

Evaluating the Relationship between Impervious Surfaces within Watersheds and Coastal Water Quality on Virginia's Eastern Shore

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EXECUTIVE SUMMARY

Coastal water quality on the Eastern Shore of Virginia is critical in supporting the valuable shellfish aquaculture and fishing industries. In other coastal environments concentrations of fecal coliform bacteria and nutrients have been shown to increase with increasing percentages of impervious surfaces in the watershed. The Eastern Shore is undergoing rapid development that is transforming much of its traditional agricultural lands to residential and commercial development or to more intensive industrial agricultural production of tomatoes. In response to concerns over the relationship between the increasing amount of impervious surface and water quality in the region, we undertook a study to examine current water quality conditions in relation to impervious surfaces in numerous watersheds on the Eastern Shore.

We identified 18 watersheds which varied in total area, area of impervious surface from development and area of impervious surface from tomato cultivation and selected sample locations in the headwaters of creeks draining those watersheds. Aerial photography, ground truthing and GIS mapping were used to produce detailed land use maps for all 18 watersheds and estimate the amount of impervious surface within each.

Water samples were collected bi-weekly from April 9 – October 25, 2007 and analyzed for fecal coliform bacteria, suspended solids, nitrogen, phosphorus and Chl *a*. Values for each of these were expressed as mean concentrations and as loadings. We then used both regression and correlation analyses to explore the relationship between these values and watershed characteristics (total area, impervious surface area and impervious surface area from tomato cultivation).

Our results reveal few significant tends between the mean concentrations of these water quality indicators in the creek headwaters and impervious surfaces in the

watershed. They do, however, show increasing loadings (i.e., flux) of these materials from the headwaters to coastal waters in relation to increasing watershed area and area of impervious surfaces within the watershed. These results make it clear that the presence of impervious surfaces within the watershed contribute to loadings of these materials to coastal waters within the region, but they do not point to specific threshold values for the percent of impervious surface within a watershed above which critical pollution levels are observed. Further, the results from this study do not reveal significant loading of bacteria, sediment or nutrients associated with tomato cultivation within the watersheds we studied.

As development continues within the region it will be important for regional planners to consider not only the amount of impervious surfaces within each watershed, but also other factors which contribute to pollution loading. Given the close proximity of all upland in the region to valuable coastal habitats and the vulnerability of those habitats to pollution, our study makes it clear that minimizing the amount of impervious surface within a watershed should be part of an integrated approach to preserving water quality.

ACKNOWLEDGMENTS

We thank Dr. Michael Mallin for assistance in the design of the study and interpretation of results, and Dr. Peter Kingsley-Smith and Trish Wagner for assistance with field sampling. Sharon Killeen, Harry Berquist and Tom Brokenbrough provide valuable assistance with the GIS mapping. Carol Pollard and the staff at the VIMS Analytical Services Laboratory conducted the nutrient analyses. George Reiger graciously provided access to one of the sample sites. This work was supported by a grant from the Virginia Coastal Zone Management Program (NOAA Grant NA05NOS4191180).

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INTRODUCTION

Virginia ranks second in the US in production value of aquacultured shellfish, almost entirely the result of hard clam (*Mercenaria mercenaria*) aquaculture. This aquaculture predominately occurs in small tidal creeks and coastal lagoons adjacent to two counties, Accomack and Northampton, which comprise Virginia's Eastern Shore. This valuable industry is completely dependent upon good water quality. The intertidal and shallow subtidal environments that are required for this aquaculture practice are generally located within a few meters to kilometers from uplands. Thus, land use practices in the adjacent uplands are critical to the continued health of this industry. Excessive inputs of (1) sediments can bury shellfish, (2) nutrients can contribute to harmful algal blooms and, (3) perhaps most importantly, fecal coliform bacteria can lead to harvest closures.

Both Accomack and Northampton County are undergoing transformative changes in land use. Traditional grain and vegetable farming is giving way to industrial poultry production and corporate "staked tomato" farming. The latter practice, sometimes called *plasticulture*, involves covering mounded rows with impervious plastic sheeting, which serves as weed control and moisture barrier. Following rain events this impervious surface, together with extensive ditching of these fields, is often observed to result in high sediment loads in adjacent tidal creeks. Scott et al. (1990) and Arnold et al. (2004) have documented pesticide related impacts on living resources in tidal creeks downstream of tomato fields with unconstrained run-off.

Owing to its coastal location, the region is also facing tremendous residential growth pressure to its small towns and rural environments. Both counties are currently undergoing revisions to their comprehensive plans and zoning ordinances and both are looking for guidance on how to protect water quality on which the clam aquaculture and other quality of life factors depend.

Researchers in other areas have investigated the relationships between various aspects of land use water and quality in the coastal zone. Of particular interest to regional planning officials, are relationships that have been observed by two groups of researchers between the proportion of the watershed covered with impervious surfaces and water quality in the receiving tidal creeks. Mallin and colleagues (Mallin et al. 2000) in North Carolina and Holland and co-workers (Holland et al. 2004) in South Carolina have reported positive relationships between the percent of impervious surfaces and several water quality parameters, including fecal coliform bacteria.

We investigated whether a similar relationship currently exists on the Eastern Shore of Virginia, where there are two major issues which need to be clarified before this can be a truly useful tool for local planners. (1) Given that soil types, topography and specific land uses in this region differ from those where the previous studies were conducted, we need to know the specific relationships that apply between the amount of impervious surfaces in the watershed and sediment, nutrient and fecal coliform bacteria levels in the receiving tidal creeks. (2) Further, we need to determine whether or not the coverage by plastic in tomato cultivation count in this computation of impervious surface.

OBJECTIVES

The overall objective of this research is to determine the relationship between the percent of a watershed covered by impervious surfaces and water quality in tidal creeks on the Eastern Shore of Virginia in an effort to provide local governments and citizens guidance in developing zoning plans. Our specific objectives were to:

(1) Determine the relationships between percent impervious surface in a watershed and concentrations of suspended sediments, nitrogen, phosphorus, chlorophyll a and fecal coliform bacteria in tidal creek headwaters;

(2) Examine these relationships with and without the inclusion of tomato cultivation to determine whether it should be included in the determination of percent impervious surface within a watershed.

METHODS

Study Sites

We selected study sites based upon several criteria. Our primary goal was to select creek sites for which the drainage areas spanned a range of coverage by impervious surface, both traditional impervious surface (residential and commercial) and agricultural (tomato production). Where possible, we also sought sample sites upstream and downstream of significant impervious surface coverage. We also took care to select sites along north-south axis of the peninsula in both Accomack and Northampton Counties, and on both the Chesapeake Bay side and Atlantic Ocean side of the peninsula. Finally, we selected sites based upon accessibility to accommodate frequent sampling. Based upon these criteria, eighteen stations on the bayside and seaside of the Eastern Shore of Virginia were chosen for water sampling (Table 1). These stations were located in nine drainages spread between Northampton and Accomack counties (Fig. 1).

Figure 1. Location of watersheds on the Eastern Shore of Virginia. The location of the watershed name indicates the direction of drainage (coastal lagoons v. Chesapeake Bay).

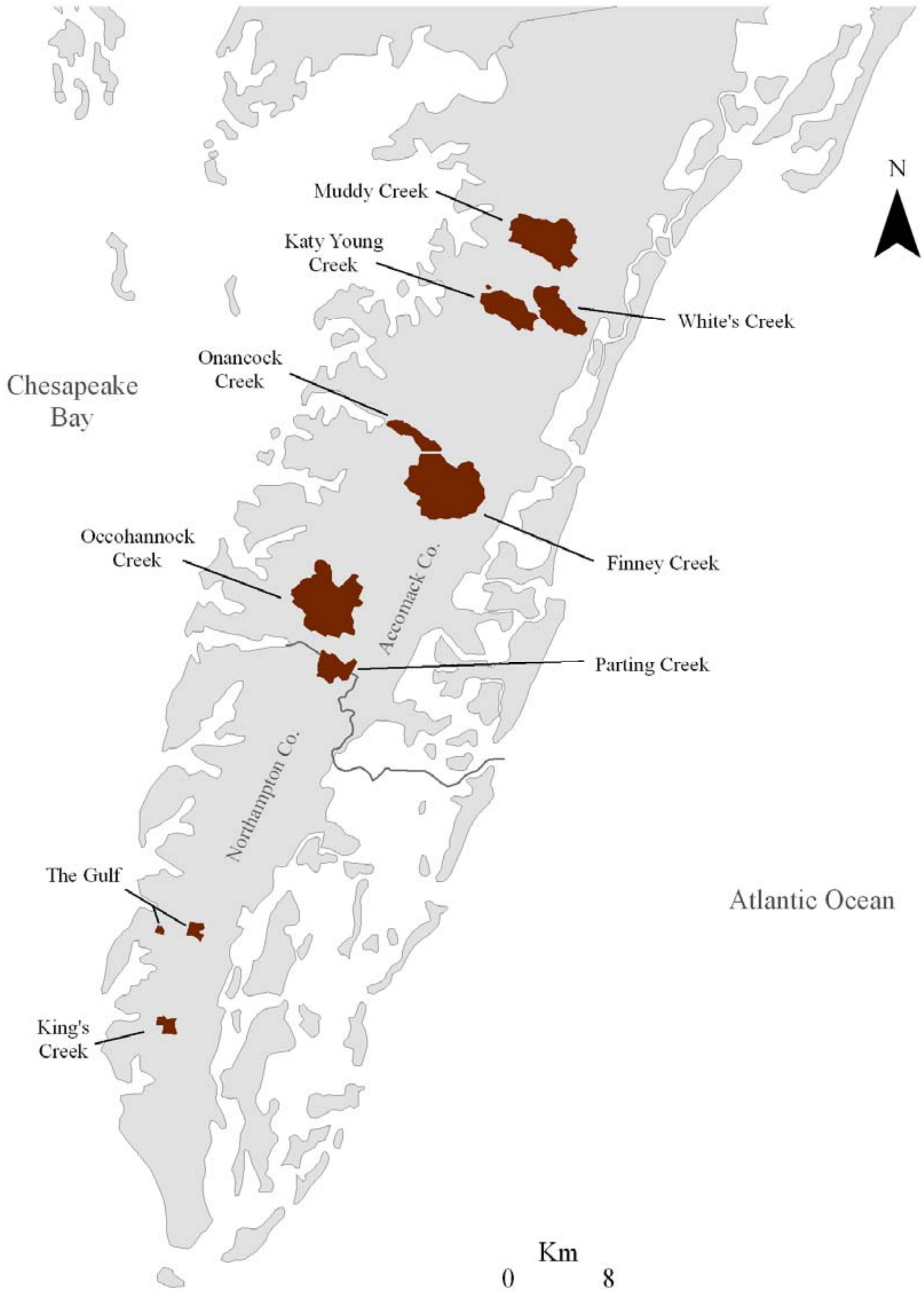


Table 1. List of eighteen water sampling stations/watersheds, general nearby geographical references and their ultimate drainage destination organized in a general south-north direction. See Figure 1 for an overall map.

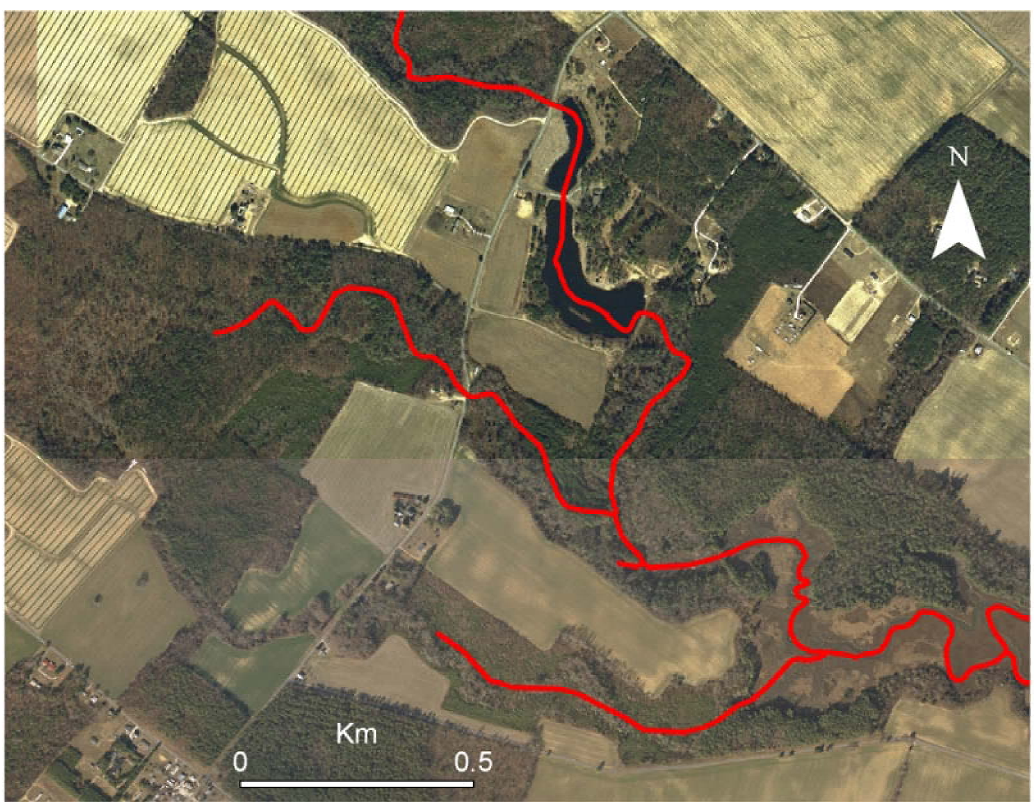
Station/Watershed Name	Nearby Geographical Reference	Ultimate Drainage Destination
South King's Creek	southern Cheriton	Chesapeake Bay
North King's Creek	northern Cheriton	Chesapeake Bay
The Gulf, Savage Neck	Savage Neck	Chesapeake Bay
The Gulf, Eastville	Eastville	Chesapeake Bay
Lower Parting Creek	Exmore	Hog Island Bay/Atlantic Ocean
Upper Parting Creek	Exmore	Hog Island Bay/Atlantic Ocean
Occohannock Creek	Belle Haven/Painter	Chesapeake Bay
Onancock Creek	Onancock	Chesapeake Bay
Lower Finney Creek	Onley/Melfa	Wachapreague Inlet/Atlantic Ocean
Upper Finney Creek	Onley	Wachapreague Inlet/Atlantic Ocean
Lower White's Creek	White's Neck/Gargatha	Gargathy Bay/Atlantic Ocean
Upper White's Creek	Gargatha	Gargathy Bay/Atlantic Ocean
Lower Katy Young Creek	Parksley	Chesapeake Bay
Upper Katy Young Creek	Parksley	Chesapeake Bay
North Katy Young Creek	Parksley/Clam	Chesapeake Bay
Lower Muddy Creek	Bloxom/Nelsonia	Chesapeake Bay
Mid Muddy Creek	Bloxom/Nelsonia	Chesapeake Bay
Upper Muddy Creek	Bloxom/Nelsonia	Chesapeake Bay

Watershed Delineation and Land Cover Mapping

We delineated a specific watershed for each water sampling location based on existing geographic information system (GIS) data combined with ground reconnaissance. Appendix I provides a brief synopsis of these external data sources. Utilizing these tools, polygons were created in ArcGIS (version 9.1) to represent watersheds, with all data projected in Virginia State Plane Feet, NAD83 (Virginia South 4502).

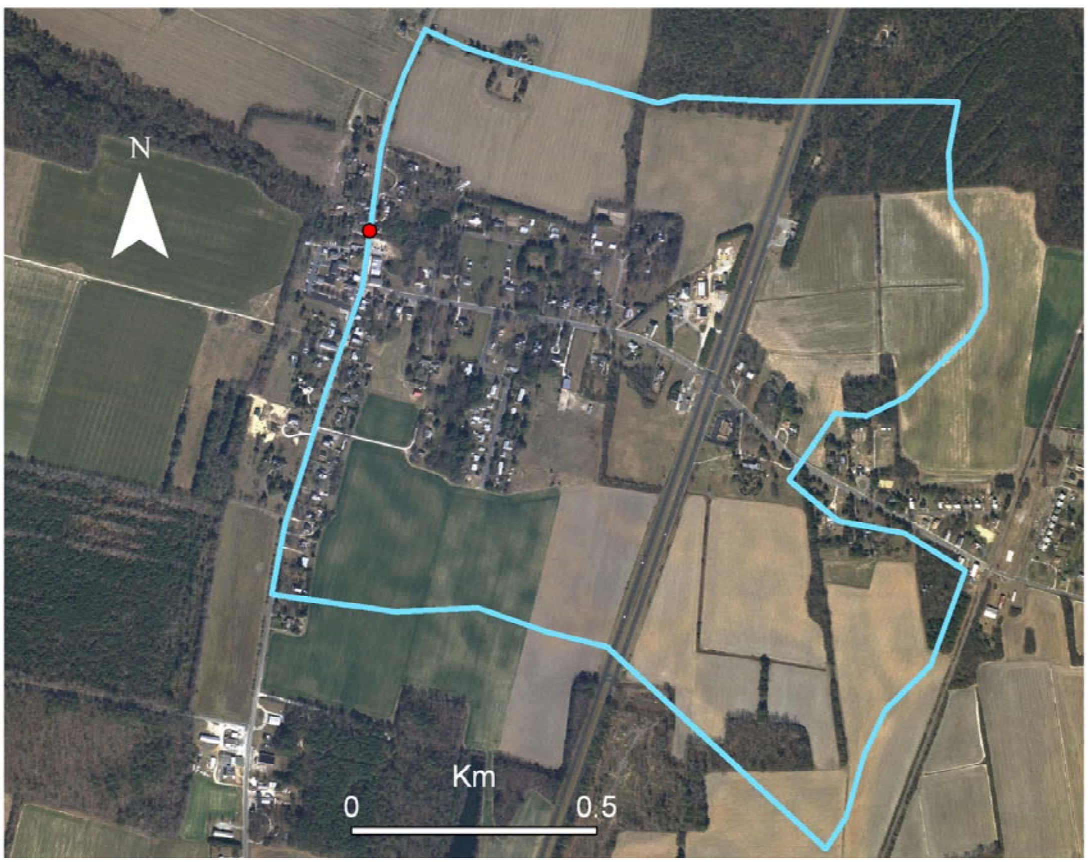
Stream/creek "Flowline" data (i.e. digitized stream centerlines) were extracted from the National Hydrography Dataset (NHD) for the study area. These line features were overlaid on high resolution aerial imagery collected in 2002 by the Virginia Base

Figure 2. Example of NHD stream centerline data (red lines) overlaid onto 2002 VBMP aerial imagery for a portion of White's Creek. Note manmade pond.



Mapping Program (VBMP) to confirm accuracy (e.g. see Fig. 2). A combination of the VBMP images and digital, geo-referenced U.S. Geological Survey topographic maps were then used to manually delineate each watershed (e.g. see Fig. 3). In some cases, these watersheds were partially adjacent to existing National Watershed Boundary Database (NWBD) hydrologic unit boundaries. In these instances, unless some overriding local features were observed, we deferred to these delineations. Where

Figure 3. Example of a delineated watershed (blue polygon) overlaid onto 2002 VBMP aerial imagery for The Gulf (Eastville) station (encompassing much of the town of Eastville, VA). Red dot is water sampling location.



drainage questions or ambiguity were encountered, ground reconnaissance was employed to make final boundary determinations. Figures 4-12 show the associated watersheds for each sampling station. Note that in some cases, the watershed of a water sampling station is nested within a larger watershed for a sampling station that is further downstream (e.g. see Fig. 6).

Figure 4. Location of water sample stations for both King's Creek watersheds. Red dots indicate sample stations. Throughout this figure sequence, the backgrounds are USGS 7.5' Topographic Quadrangle maps.

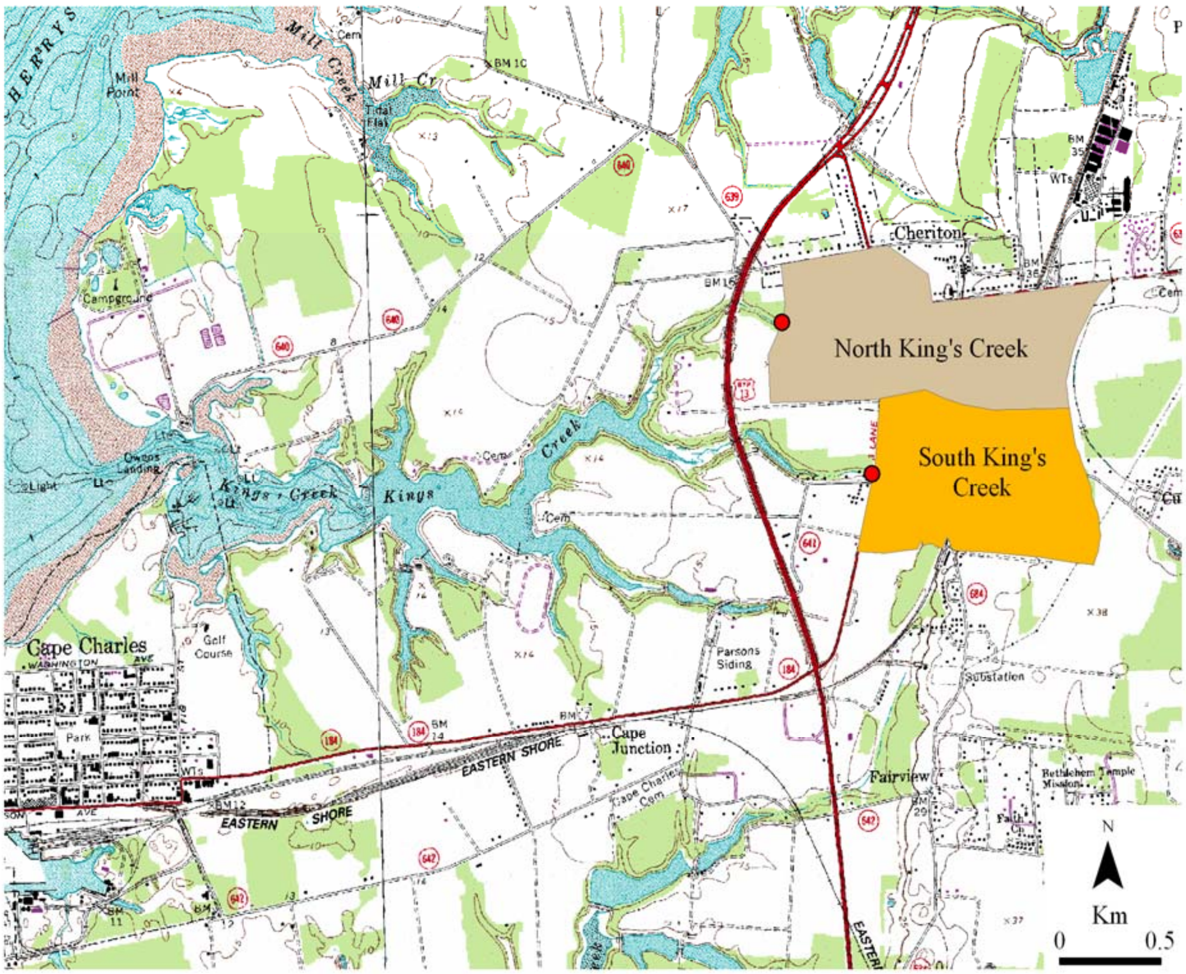


Figure 5. Location of water sample stations for both of The Gulf watersheds. Red dots indicate sample stations.

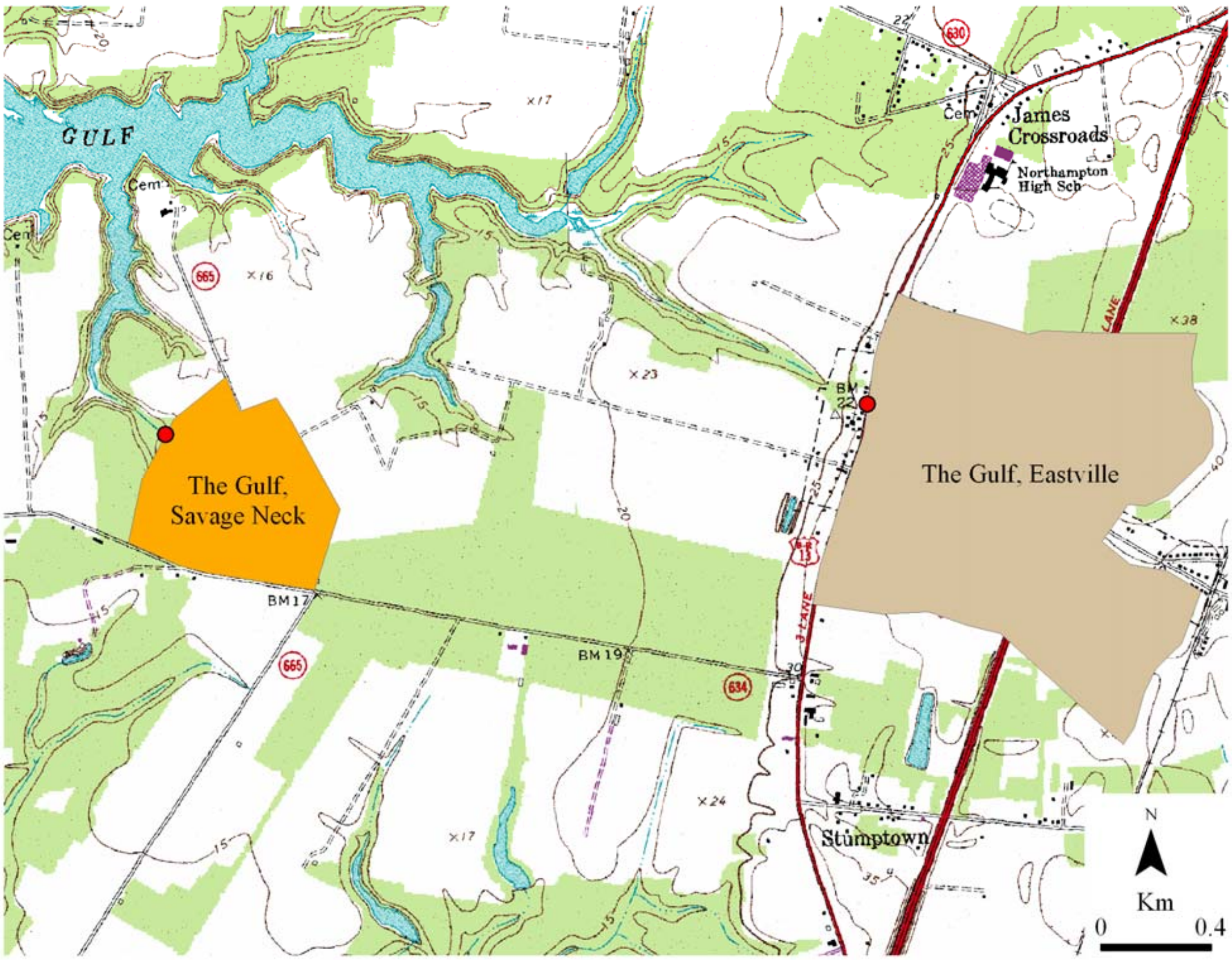


Figure 6. Location of water sample stations for the Parting Creek watersheds. The Lower Parting Creek watershed is represented by the entire highlighted area. Red dots indicate sample stations.

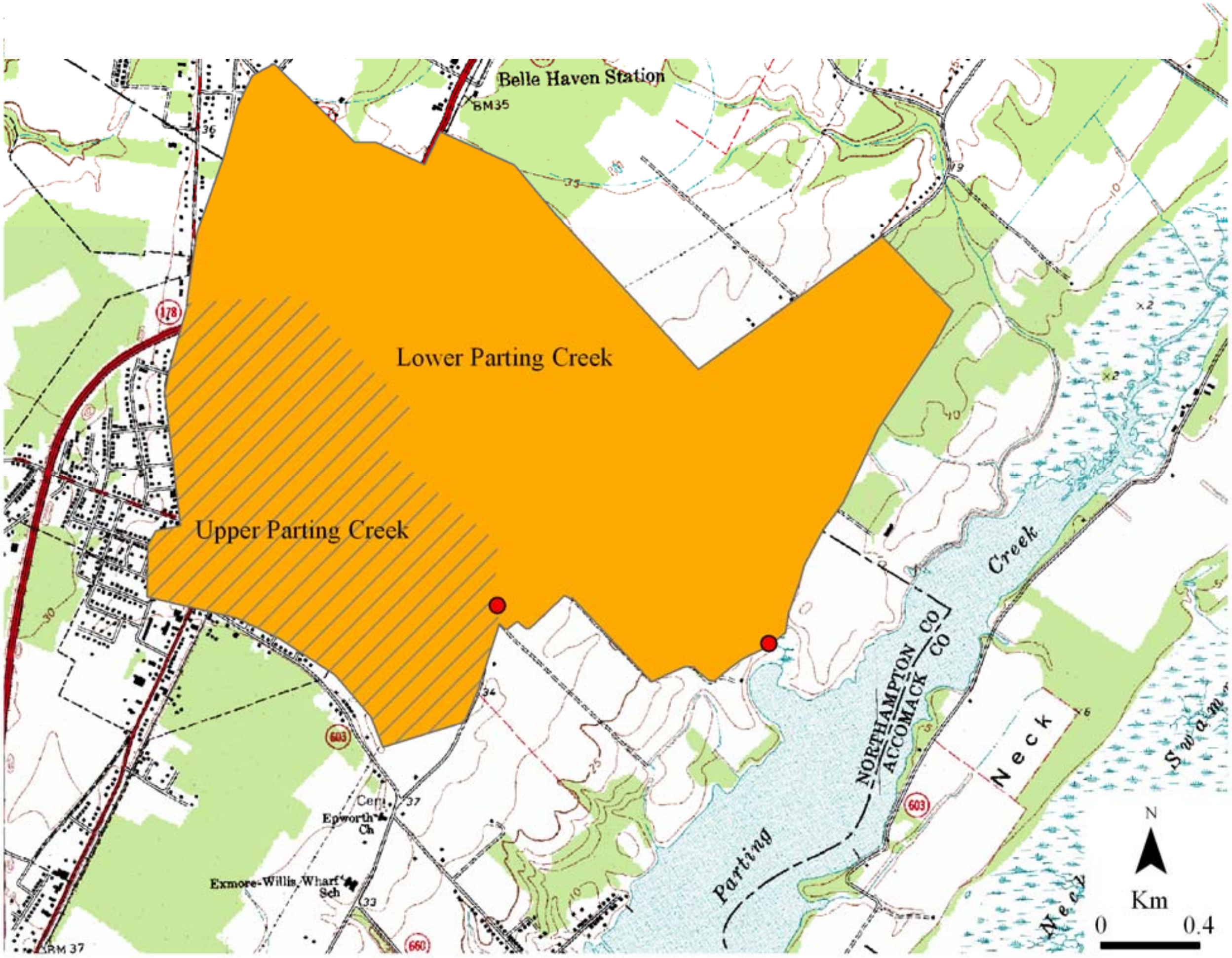


Figure 7. Location of the water sample station for the Occohannock Creek watershed. Red dot indicates sample station.

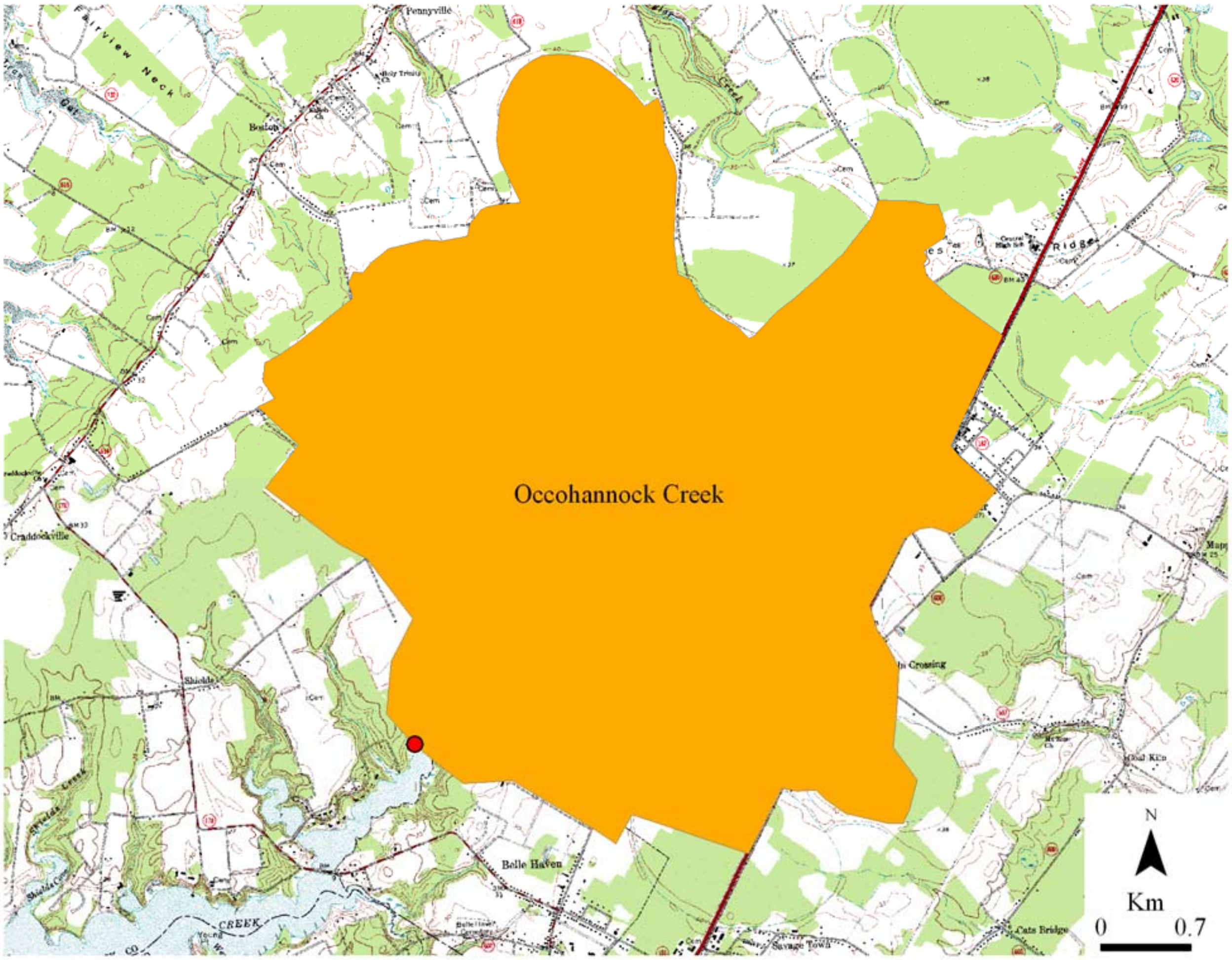


Figure 8. Location of the water sample station for the Onancock Creek watershed. Red dot indicates sample station.

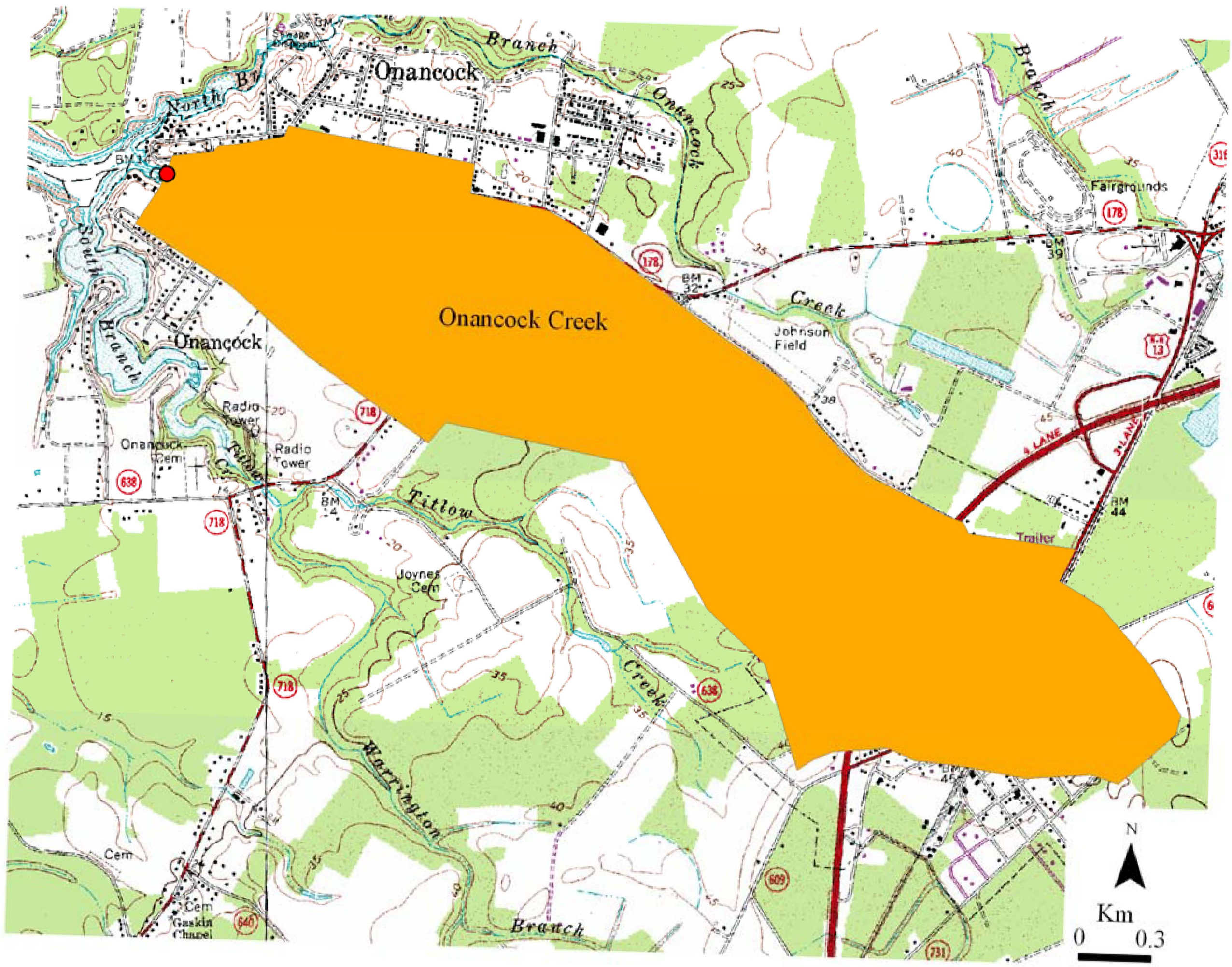


Figure 9. Location of water sample stations for the Finney Creek watersheds. The Lower Finney Creek watershed is represented by the entire highlighted area. Red dots indicate sample stations.

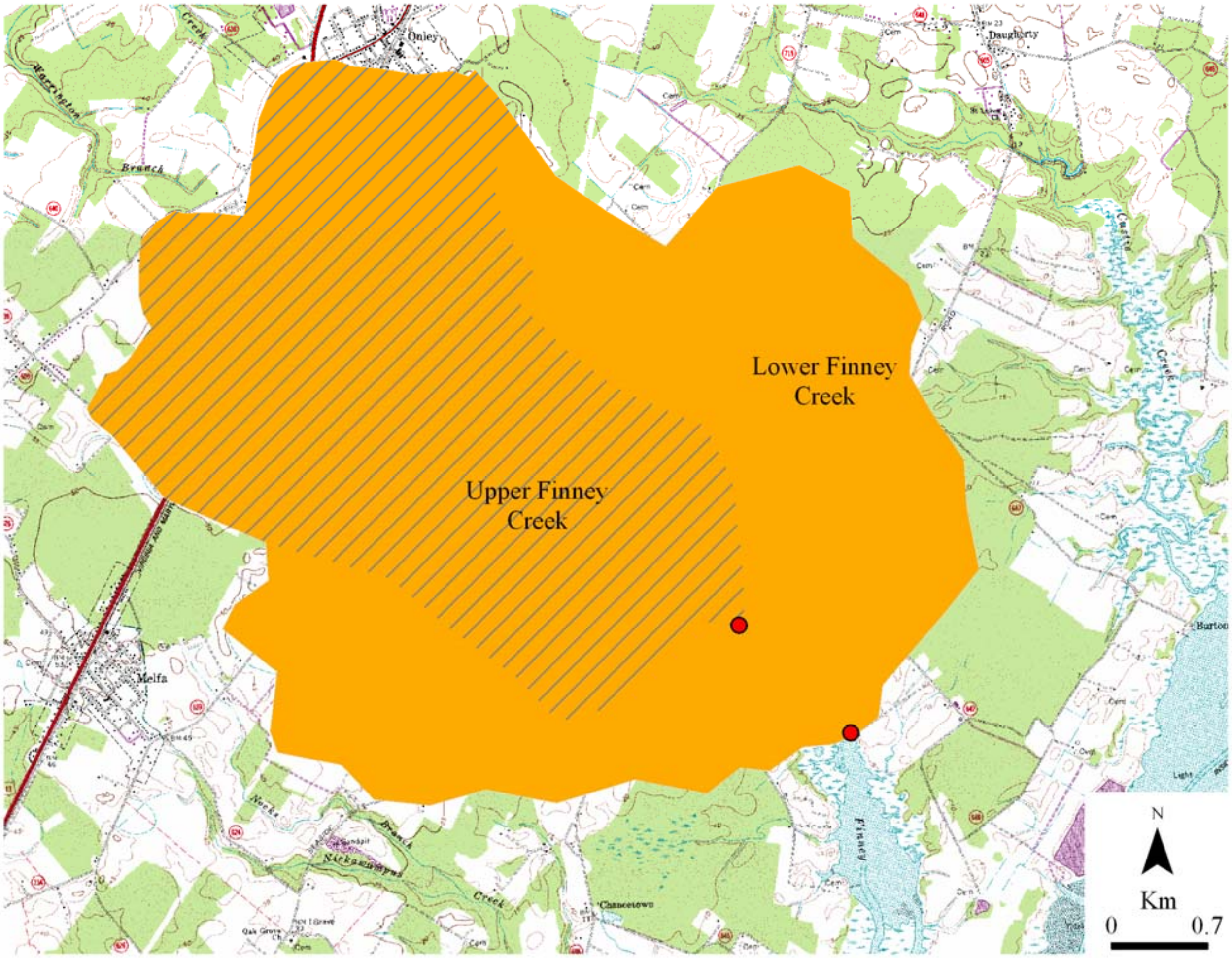


Figure 10. Location of water sample stations for the White's Creek watersheds. The Lower White's Creek watershed is represented by the entire highlighted area. Red dots indicate sample stations.

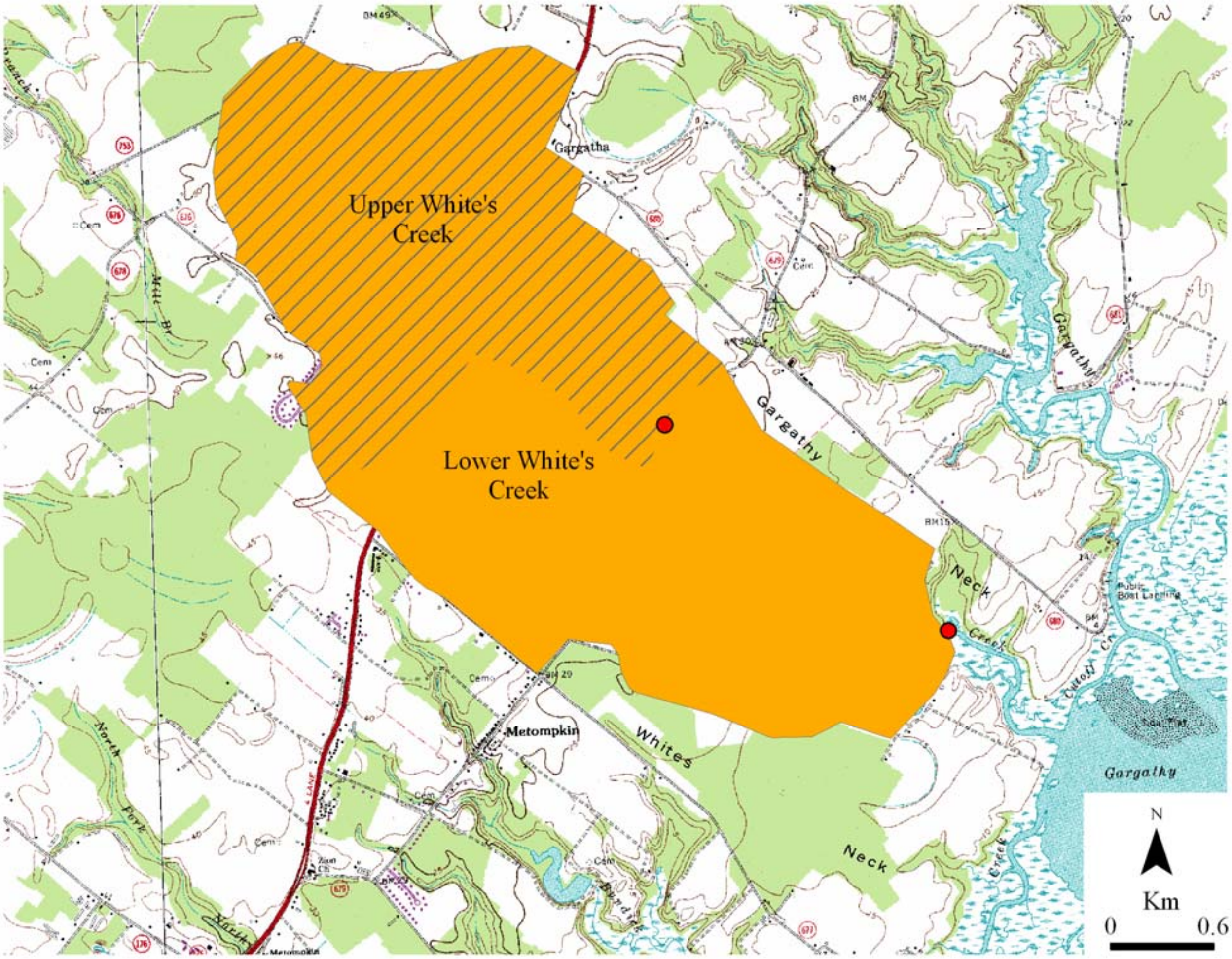


Figure 11. Location of water sample stations for the Katy Young Creek watersheds. The Lower Katy Young Creek watershed is represented by the entire orange highlighted area. Red dots indicate sample stations.

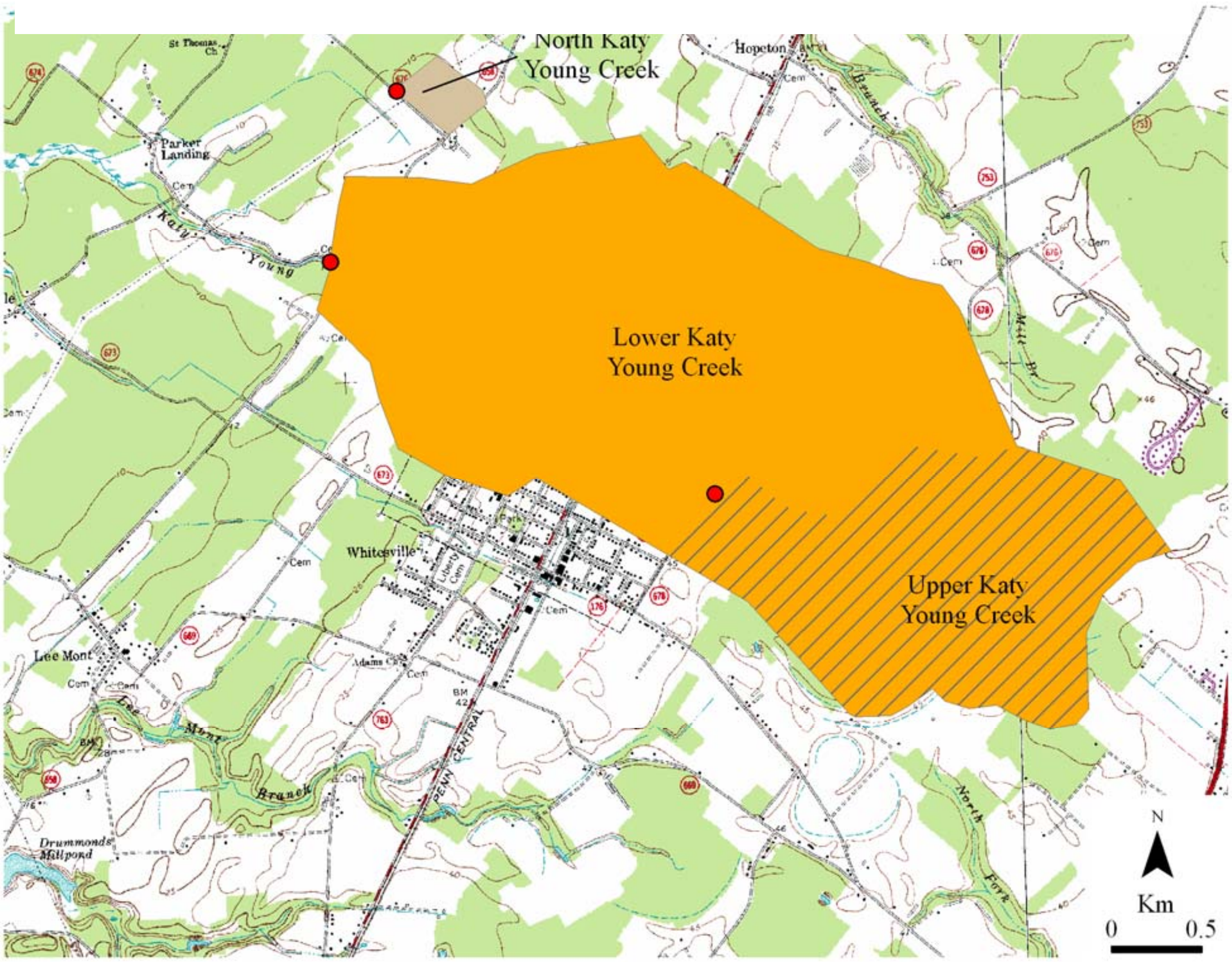
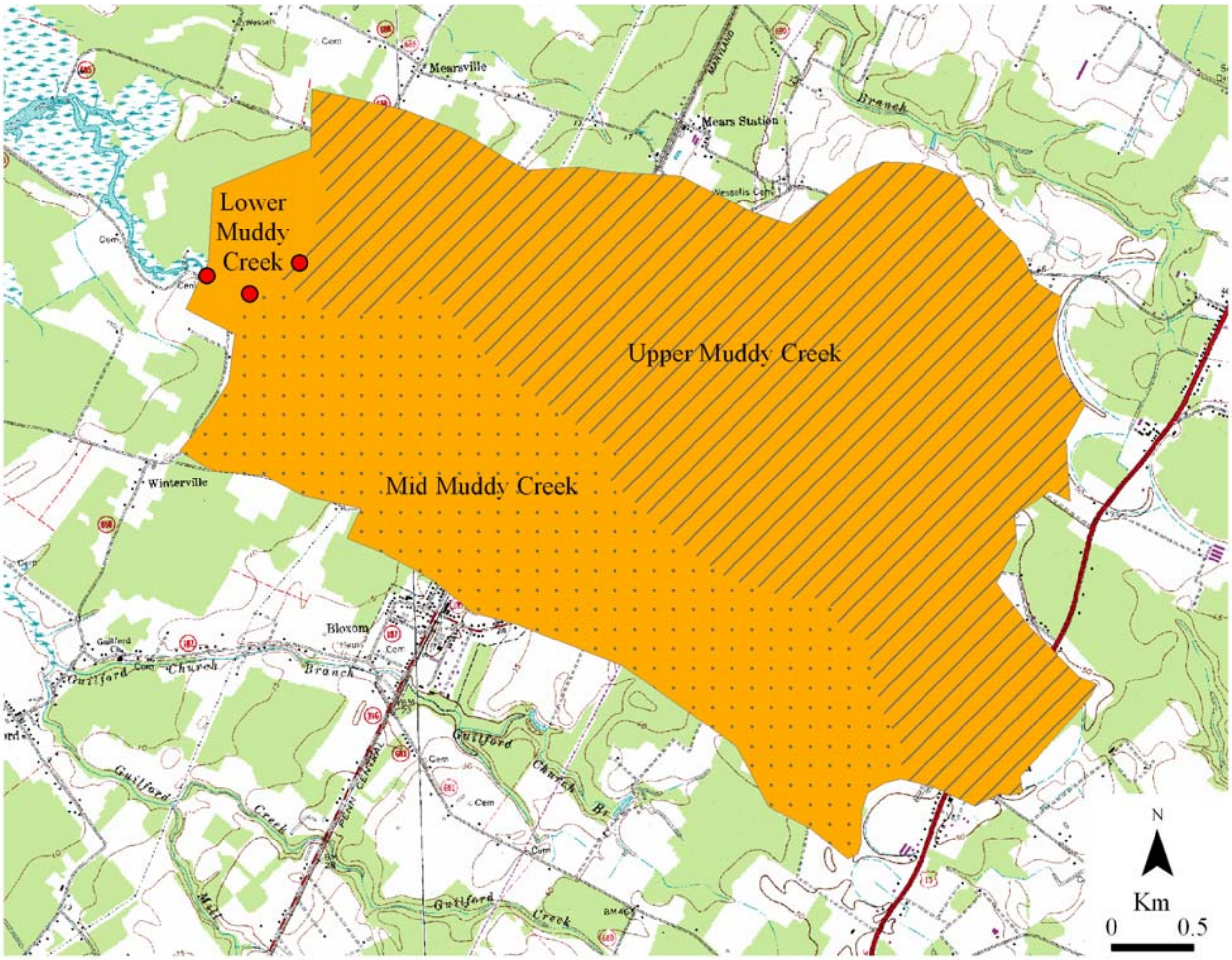


Figure 12. Location of water sample stations for the Muddy Creek watersheds. The Lower Muddy Creek watershed is represented by the entire orange highlighted area. Red dots indicate sample stations.



We did an extensive search for existing land use and/or land cover data appropriate for use in this study. The best candidate source was the 2001 National Land-Cover Database (NLCD). However, upon extraction of this data for our study area, it became obvious that much finer spatial resolution was required, especially for the smaller watersheds of this project. Therefore, we opted to manually digitize land cover polygons in ArcGIS from the 2002 VBMP aerial images, based on modified NLCD categories. In addition to modifying some of these categories, several were added that were specific to this region and the intended comparisons of this study.

Overall, 21 land cover categories were utilized (Table 2). Individual planimetric land cover polygons were digitized for each category within each watershed (e.g. see Fig. 13 and Appendix II). Since aerial images were collected in 2002, we verified these data via low level aerial surveys from a fixed-wing aircraft and land-based surveys from public roadways. Any land cover changes or discrepancies were adjusted accordingly.

Table 2. Land cover categories used in this study.

Category	Source	Brief Description
Open Water	NLCD[a]	Open water with <25% cover of vegetation or soil
Developed, Open Space	NLCD	Some constructed materials but mostly vegetation, <20% IS; large-lot single-family housing, parks, golf courses
Developed, Low Intensity	NLCD	Mixture of constructed material and vegetation, 20-49% IS
Developed, Medium Intensity	NLCD	Mixture of constructed material and vegetation, 50-79% IS
Developed, High Intensity	NLCD	People reside or work in high numbers, 80-100% IS
Barren Land	NLCD	Barren areas, <15% vegetation
Forest, Deciduous	NLCD	Trees >5m tall encompass >20% of area; >75% deciduous
Forest, Evergreen	NLCD	Trees >5m tall encompass >20% of area; >75% evergreen
Forest, Mixed	NLCD	As above, but with <75% deciduous or evergreen
Shrub/Scrub	NLCD	Shrubs <5m tall encompass >20% of area; early successional
Pasture/Hay	NLCD	Grasses/legumes for grazing or seed/hay, >20% of all vegetation
Cultivated Crops	NLCD	Annual farm crops, orchards & vineyards, >20% of all vegetation
Tomato Plasticulture	ESL[b]	Vegetable farming using plastic mulch

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Table 2 (cont.). Land cover categories used in this study.

Category	Source	Brief Description
Major 4-Lane Highway (Route 13 only)	MD/ESL[c]	U.S. Route 13, its median, shoulders and parts of intersections with other main streets
Nursery Plasticulture	ESL	Nursery operations using plastic mulch & extensive greenhouses
Wetland, Estuarine Woody	NLCD	Tidal wetland (> 0.5% salinity) dominated by woody vegetation >5m tall, >20% of all vegetation
Wetland, Estuarine Emergent	NLCD	Tidal wetland (> 0.5% salinity) dominated by erect, rooted, herbaceous hydrophytes present for most of the growing season
Wetland, Palustrine Emergent	NLCD	Tidal wetland (> 0.5% salinity) dominated by erect, rooted, herbaceous hydrophytes present for most of the growing season
Disturbed Lands	MD/ESL	Areas of significant soil disturbance: construction sites, excavation spoil, aggregate materials spread (e.g. clam shells)
Bridge	ESL	Manmade bridges spanning a waterway
Poultry Farm	ESL	Poultry farms that consist of chicken houses and associated disturbed soil for parking, access and farm activities

[a]National Land Cover Database (see Homer et al. 2004)

[b]Eastern Shore Laboratory

[c]Dougherty et al. 2004, modified by Eastern Shore Laboratory

Impervious Surface Estimation

We estimated percent impervious surface (IS) for all land cover categories based on a combination of published data and, in some cases, our own digitizing of a small sample of polygons (Table 3). Published IS data were often reported as a range of IS Coefficients, which were sometimes based on population density parameters. When population was an integral part of a model, we used the "low" or "rural" estimates unless our own observations did not support them.

Table 3. Impervious Surface Coefficients published in the literature and based on our digitized samples by land cover category (see Table 2 for category descriptions). The far right column contains the ultimate values for used for this study (in bold). Blank spaces indicate that a particular land cover category was not addressed within a specific citation.

Land Cover Category	ISAT[a]; low pop. model	Cooper (1996)[b]	Capiella & Brown (2001)	Dougherty et al. (2004)	Prisloe et al. (2003); low pop. model	ESL Sample Polygon(s) (Range)[c]	ESL Sample Polygon(s) (Mean)[c]	Values Used for this Study
Open Water	0				0.1-1.9			**1**
Developed, Open Space	10	5	8.6		8.8	3-12	8	**9**
Developed, Low Intensity	22.9	10	10.6-14.3	12	8.8-26.0	16-21	19	**20**
Developed, Medium Intensity	26	35	21.2-32.6	41	26	24-29	26	**30**
Developed, High Intensity	30	60	40.9-72.2	82-87	32.5	55-81	69	**70**
Barren Land	2.1				10.5			**10**
Forest, Deciduous	2.1			0	2.3			**2**
Forest, Evergreen	2.1			0	1.0			**2**
Forest, Mixed	2.1			0	0.7			**2**
Shrub/Scrub	2.1			0	1.0			**2**
Pasture/Hay	5.7	5	1.9	0	4.1			**4**
Cultivated Crops	3.6	5	1.9	0				**3**
Tomato Plasticulture						~40-50	50-75[c]	**50**
Nursery Plasticulture						33		**33**

Table continued on next page

Table 3 (cont.). Impervious Surface Coefficients published in the literature and based on our digitized samples by land cover category (see Table 2 for descriptions). The far right column contains the ultimate values for used for this study. Blank spaces indicate that a particular land cover category was not addressed within a specific citation.

Land Cover Category	ISAT[a]; low pop. model	Cooper (1996)[b]	Capiella & Brown (2001)	Dougherty et al. (2004)	Prisloe et al. (2002); low pop. model	ESL Sample Polygon(s) (Range)[c]	ESL Sample Polygon(s) (Mean)[c]	Values Used for this Study
Wetland, Estuarine Woody	3				0.6-1.3			**1**
Wetland, Estuarine Emergent	0				1.3-3.2			**2**
Wetland, Palustrine Emergent	0							**2**
Major 4-Lane Highway		100		66				**66**
Disturbed Lands				100				**75**
Bridge								**100**
Poultry Farm						60		**60**

[a]Impervious Surface Analysis Tool, NOAA Coastal Services Center, default EPA Land Cover impervious surface coefficients.
[b]Cooper (1996 c.f. Brabec et al. 2002)
[c]A small sample of representative polygons were analyzed for actual % Impervious Surface for several land cover category categories. Here we report the range and mean (if more than one polygon was digitized). However, for *Tomato Plasticulture* we used a range documented by Rice et al. (2001).

The coefficients ultimately used for this study were necessarily a compromise, but generally followed value ranges reported by Capiella and Brown (2001) for developed categories (Table 3). Coefficients for forest, traditional agriculture and wetlands generally followed a combination of Prisloe et al. (2003) and the Impervious Surface Analysis Tool (ISAT) default values for EPA land cover (Table 3). Overall IS estimates for each watershed were simply calculated as:

$$\sum_{21}^{i=1} \textbf{\textit{(Land Cover Category Area) * (Category-specific IS Coefficient)}}$$

<u>Water Quality Sampling</u>

We visited each site every two weeks, from April 9 through October 25 2007 (with the exception of Parting Creek lower where sampling began on April 24, 2007). For sites with tidal influence, we always sampled on ebb tides. On site, we measured water depth, surface velocity, dissolved oxygen, temperature and salinity. Water samples were collected just below the surface and placed on ice for transport to the Eastern Shore Laboratory in Wachapreague, VA, for processing.

Water samples were analyzed for total suspended solids (TSS), particulate phosphorous (P), particulate nitrogen (N), particulate carbon (C), total dissolved phosphorous (tdp), total dissolved nitrogen (tdn), chlorophyll a (chl a) and particle counts. Bacterial samples were processed within 6 hours of field collection. Nutrient samples were processed within 10 hours of field collection. Fecal coliform bacteria were processed using membrane filtration with results presented as colony forming units per 100 ml.

Analytical Methods

Chlorophyll a - The concentration of chlorophyll a (chla) was measured fluorometrically using a calibrated Turner Designs TD 700 fluorometer on samples collected on Whatman GF/F filters and extracted in 8 ml of an acetone:DMSO solution (Shoaf and Lium 1976) at room temperature in the dark for at least 24 h.

Total Suspended Solids - TSS were determined by gravimetric method (EPA method 160.2) using glass fiber filters (Whatman GF/F, nominal pore size 0.7 µm). Known volumes of sample were filtered through oven dried pre-weighed GF/F filters. Filters with retained solids were dried at 105 ºC and weighed. From the same filters, ash free dry weight (AFDW) was calculated by difference after ignition at 550 °C.

Nutrients - Particulate fractions were collected on a 0.7 µm nominal pore size GF/F filters. Particulate phosphorus was processed using the high temperature ashing oxidation method of Aspila *etal* (1976). Detection limits were 0.0012 mg P L^{-1}. Particulate phosphorus and carbon were processed using high temperature combustion (Menzel and Vaccaro 1964). Detection limits were 0.020 mg N L^{-1} for N and 0.100 mg C L^{-1} for C. Dissolved nutrients (TDP and TDN) were processed using alkaline persulfate digestion on a continuous flow analyzer (D'Elia *etal* 1977). Detection limits were 0.0084 mg L^{-1} for TDN and 0.0030 mg L^{-1} for TDP.

Coliform Bacteria - Fecal coliform bacteria were enumerated using m-FC medium (Difco broth base and Rosolic acid solution) according to standard methods

(APHA 1980). Sample volumes, adjusted to culture 20 – 500 colonies per filter, were processed through 47 mm diameter, 0.45 μm pore size, type HA with grid, membrane filters (Millipore Corp., Bedford, Mass.) Filters where placed on absorbent pads in petri plates with m-FC medium, then placed in waterproof bags (whirl pak) and incubated at 44.5 ºC for 24±1 hour, after which all blue colonies were counted as fecal coliform and reported as number of colony forming units (CFU) per 100 ml.

Loading Estimates

Each of the analyses above provided concentration estimates for the parameters being measured. Given that many of our sample locations were in upstream reaches of the creeks (a situation necessitated by the need to have some watersheds with high percent impervious surface values), we also computed loadings (or fluxes) of these materials at each sampling time. This was accomplished by first developing a cross sectional bathymetry map for each of our sample locations. Then on each sample date we measured the water depth in the channel and surface flow velocity using a hand-held mechanical flow meter (Sigma Sport, model #FP201). Water discharge was then computed as the cross-sectional area x flow velocity. Fluxes of coliform bacteria, suspended solids, nutrients and chlorophyll *a* were then computed by multiplying water discharge x concentration. All samples at tidally-influenced stations were taken during ebb tide so these values represent gross loadings to downstream areas.

RESULTS

Watershed Delineation and Land Cover Mapping

Watershed size was variable between sampling stations and ranged from 12-2,428 hectares, although 14 of the 18 were greater 100 hectares (Table 4). Overall, 2,755 individual land cover polygons were digitized and used for analysis. Across the entire study area, forest/shrub (45%), traditional agriculture (32%), developed (13%), and tomato plasticulture (8%) were the dominant broad groups of land cover encountered in this study. An example of watershed delineation and land cover mapping for one of the watersheds (Occohannock Creek) is show below (Fig. 13) and is shown for each of the watersheds in the Appendix.

Figure 13. Example of land cover mapping showing (A) a delineated watershed (blue polygon) overlaid onto 2002 VBMP aerial imagery for the Occohannock Creek station and (B) the same area with land cover polygons digitized. Detailed legends will be provided for land cover maps presented later in the *Results* and *Appendices*. Red dot is water sampling location.

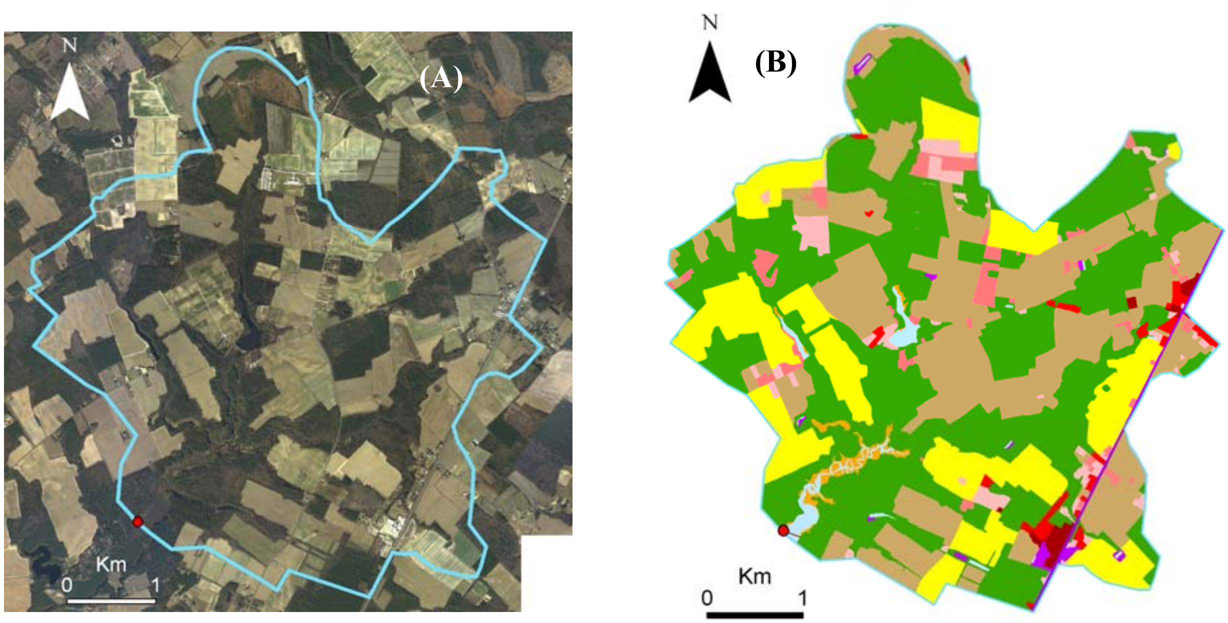


Figure 14. Percent area for grouped land cover categories (e.g. all forest/woodlands represented by the same color) for the eighteen watersheds in this study.

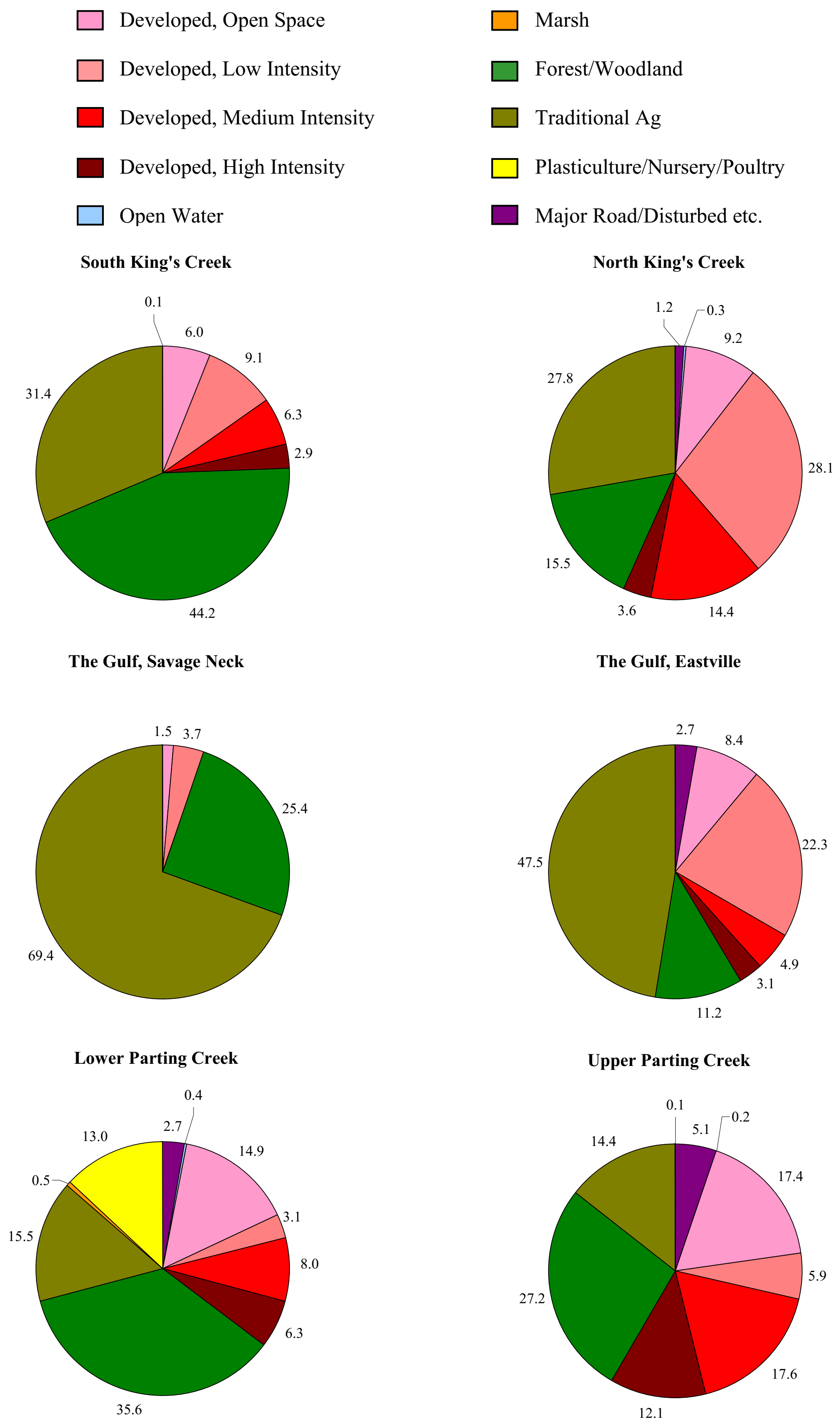


Figure 14 (cont.). Percent area for grouped land cover categories (e.g. all forest/woodlands represented by the same color) for the eighteen watersheds in this study.

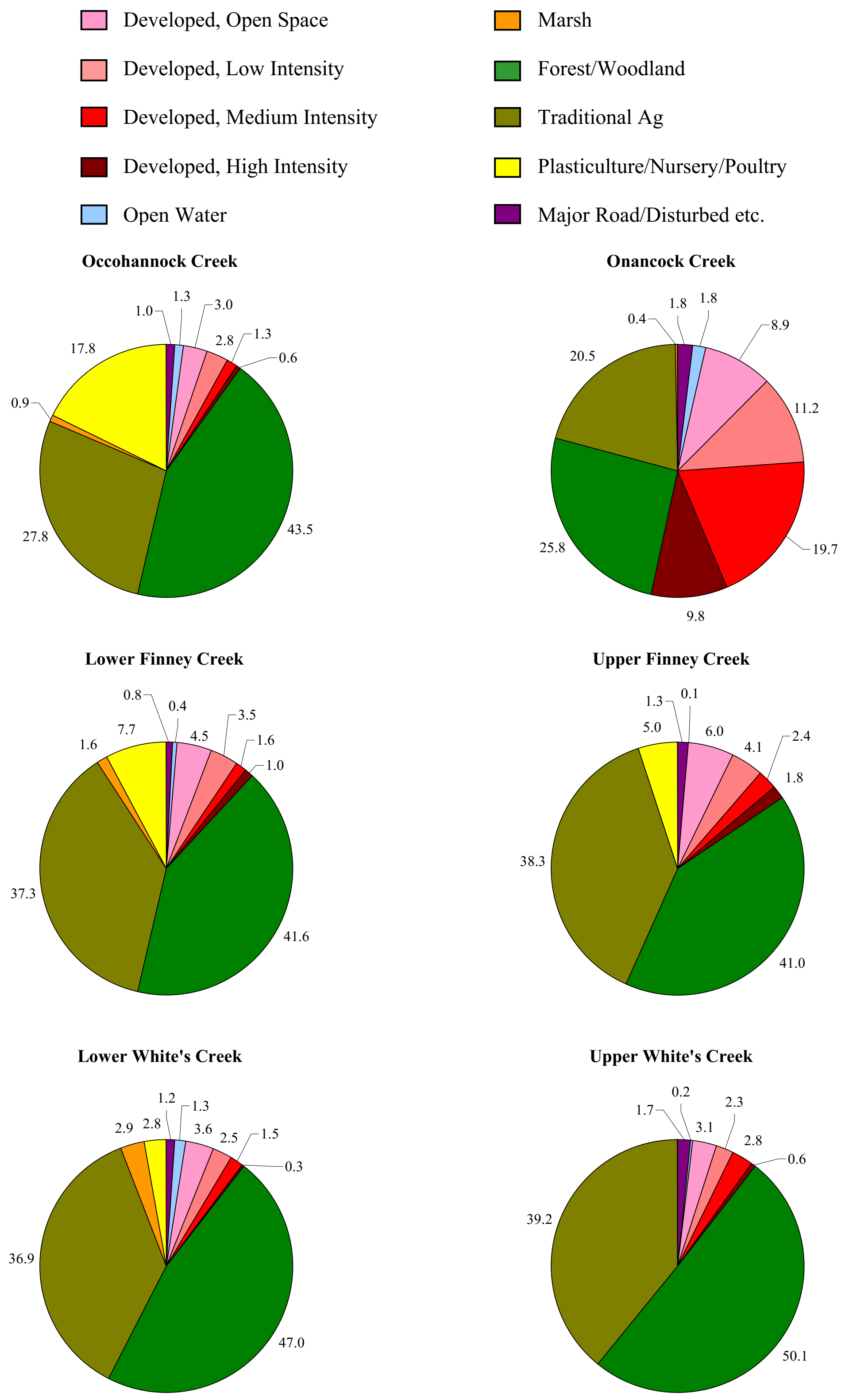
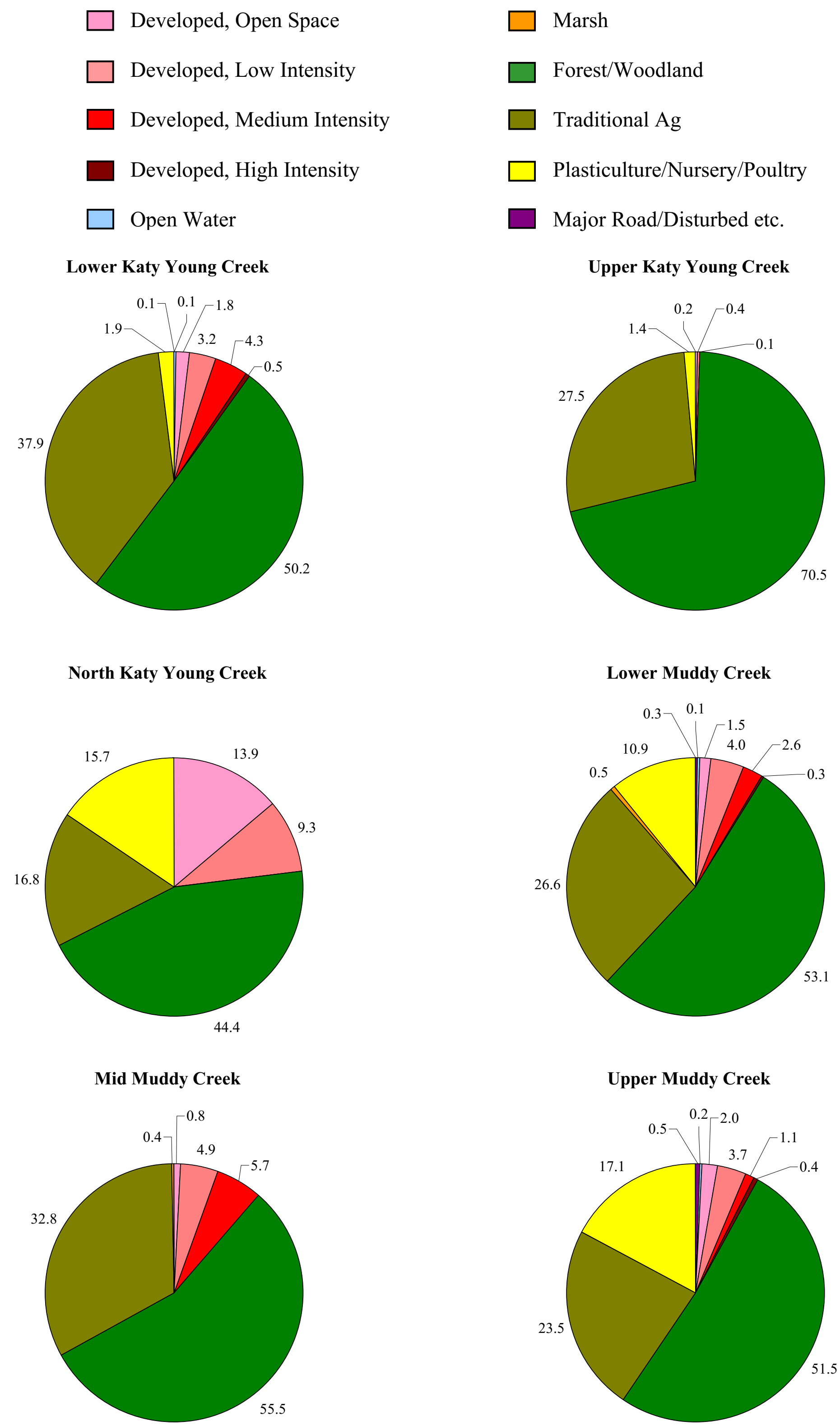


Figure 14 (cont.). Percent area for grouped land cover categories (e.g. all forest/woodlands represented by the same color) for the eighteen watersheds in this study.



Impervious Surface Estimation

Total IS was variable between watersheds for both actual area (Table 4) and percent area (Table 5). Total IS area ranged from 1 hectare in the Gulf (Savage Neck) watershed to 280 hectares in the Occohannack Creek watershed. Total percent IS ranged from 3.2% in the Upper Katy Young watershed to 21.2% in the Upper Parting Creek watershed. At least a portion of IS in every watershed came from traditional land cover, whereas a portion of IS came from tomato cultivation in seven of the watersheds (Table 5). When present, IS from tomato cultivation ranged from 13 – 192 hectares and 1.4 – 8.9% of the total watershed area.

It has previously been suggested that watersheds with >10% IS have "impaired" water quality in their waterways, whereas those with >20% have "degraded" water quality (e.g., Cappiella & Brown 2001; Mallin et al. 2000). Ten of our sample sites had <10% IS in their watersheds, seven had >10 to < 20% IS and none had >20% IS. Obtaining this range of IS required that we sample at the headwaters of several creeks and farther downstream in others, resulting in the wide range in watershed areas reported in the previous section.

Table 4. Total area, total impervious surface (IS) area, IS area from traditional land cover and IS from tomato plasticulture (hectares) for each watershed in this study. Watersheds are arranged in a general south-north direction and those closely related are grouped together.

Watershed	Total Area	Total IS Area	IS from Traditional Land Cover	IS from Tomato Plasticulture
South Kings Creek	75	6	6	0
North Kings Creek	90	14	14	0
The Gulf, Savage Neck	39	1	1	0
The Gulf, Eastville	145	18	18	0
Lower Parting Creek	513	95	61	33
Upper Parting Creek	163	35	35	0
Occohannock Creek	2,160	280	89	192
Onancock Creek	412	75	75	0
Lower Finney Creek	2,428	207	133	74
Upper Finney Creek	1,257	110	82	28
Lower Whites Creek	930	54	41	13
Upper Whites Creek	465	25	25	0
Lower Katy Young Creek	822	46	46	0
Upper Katy Young Creek	266	8	8	0
North Katy Young	12	2	2	0
Lower Muddy Creek	1,562	148	64	85
Mid Muddy Creek	522	25	25	0
Upper Muddy Creek	990	121	36	85

Table 5. Total area (hectares), % total impervious surface (IS), % IS from traditional land cover and % IS from tomato plasticulture for each watershed in this study. Arranged in order of ascending Total % IS Area.

Watershed	Total Area (hectares)	% Total IS Area	% IS from Traditional Land Cover	% IS from Tomato Plasticulture
Upper Katy Young Creek	266	3.2	3.2	0.0
The Gulf, Savage Neck	39	3.5	3.5	0.0
Mid Muddy Creek	522	4.8	4.8	0.0
Upper Whites Creek	465	5.3	5.3	0.0
Lower Katy Young Creek	822	5.6	5.6	0.0
Lower Whites Creek	930	5.8	4.4	1.4
South Kings Creek	75	8.1	8.1	0.0
Lower Finney Creek	2,428	8.5	5.5	3.1
Upper Finney Creek	1,257	8.8	6.6	2.2
Lower Muddy Creek	1,562	9.5	4.1	5.4
Upper Muddy Creek	990	12.2	3.7	8.6
The Gulf, Eastville	145	12.3	12.3	0.0
Occohannock Creek	2,160	13.0	4.1	8.9
North Katy Young	12	14.0	14.0	0.0
North Kings Creek	90	15.3	15.3	0.0
Onancock Creek	412	18.2	18.2	0.0
Lower Parting Creek	513	18.4	11.9	6.5
Upper Parting Creek	163	21.2	21.2	0.0

Coliform bacteria concentration

Fecal coliform bacteria concentrations varied over three orders of magnitude between sites and between sample dates within a site (from < 100 to > 34,000 CFU / 100 mL). Mean concentrations over the entire study period also varied widely (Fig. 15 A), but showed no trends with either the total watershed area, the total impervious surface (IS), traditional IS (w/o tomato cultivation) or with IS from tomato cultivation (Fig. 15 A-D). In these figures and ones that follow, we show watershed characteristics (total area, total impervious surface, impervious surface w/o tomatoes and impervious surface from tomatoes only) along the x-axis and the mean response variable along the y-axis. Note that the total watershed areas varies from only a few to nearly 2500 hectares and the total impervious surface from only a few to approximately 280 hectares. Despite this range in total area of the watershed and the amount impervious surface, there were no patterns between these watershed characteristics and mean coliform bacteria concentrations.

When we average the coliform bacteria counts only for those sample dates that were preceded by a 1 inch or greater rainfall within the previous 48 hrs, there is again not evident pattern with watershed area or the various impervious surface measures (Fig. 16 A – D). One site (The Gulf, Eastville) stands out as an outlier, with very high coliform bacteria concentrations. This sample site collects drainage from most of the town of Eastville.

If we consider the relationship between % impervious surface (rather than total area) within the watersheds and mean fecal coliform bacteria concentrations, there is still no significant relationship (Figs. 17 A – D). This approach is comparable to that of Mallin et al. (2000) and Holland et al. (2004), both of whom found significant relationships between mean coliform bacteria concentrations and the % impervious surface within a watershed (e.g., Fig. 17 B). Despite spanning a range from 3.2 – 21.2% of the watershed covered by impervious surface (Table 5). We did not observe such a relationship in our study.

This same lack of a relationship is observed when we consider only those sample dates that were preceded by a 1 inch or greater rainfall event (Fig. 18 A – D). As in the previous figures, the station below the town of Eastville stands out as having very high concentrations of coliform bacteria, but there is no relationship with any of the impervious surface categories. We estimate that a little over 12 % of the watershed in Eastville is covered by impervious surface (Table 5), none of which is the result of tomato cultivation.

Run-off from the town of Eastville travels via a storm water drainage system that empties into the creek just above our sample site. Though it was beyond the scope of this project to track down individual sources of coliform bacteria loading, our expectation is that bacteria from pet wastes and leaking septic systems may have been responsible for this peak in bacterial abundance following rain events.

Figure 15. Coliform bacteria concentrations in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are geometric means of Colony Forming Units (CFU) from bi-weekly samples from Apr – Oct 2007.

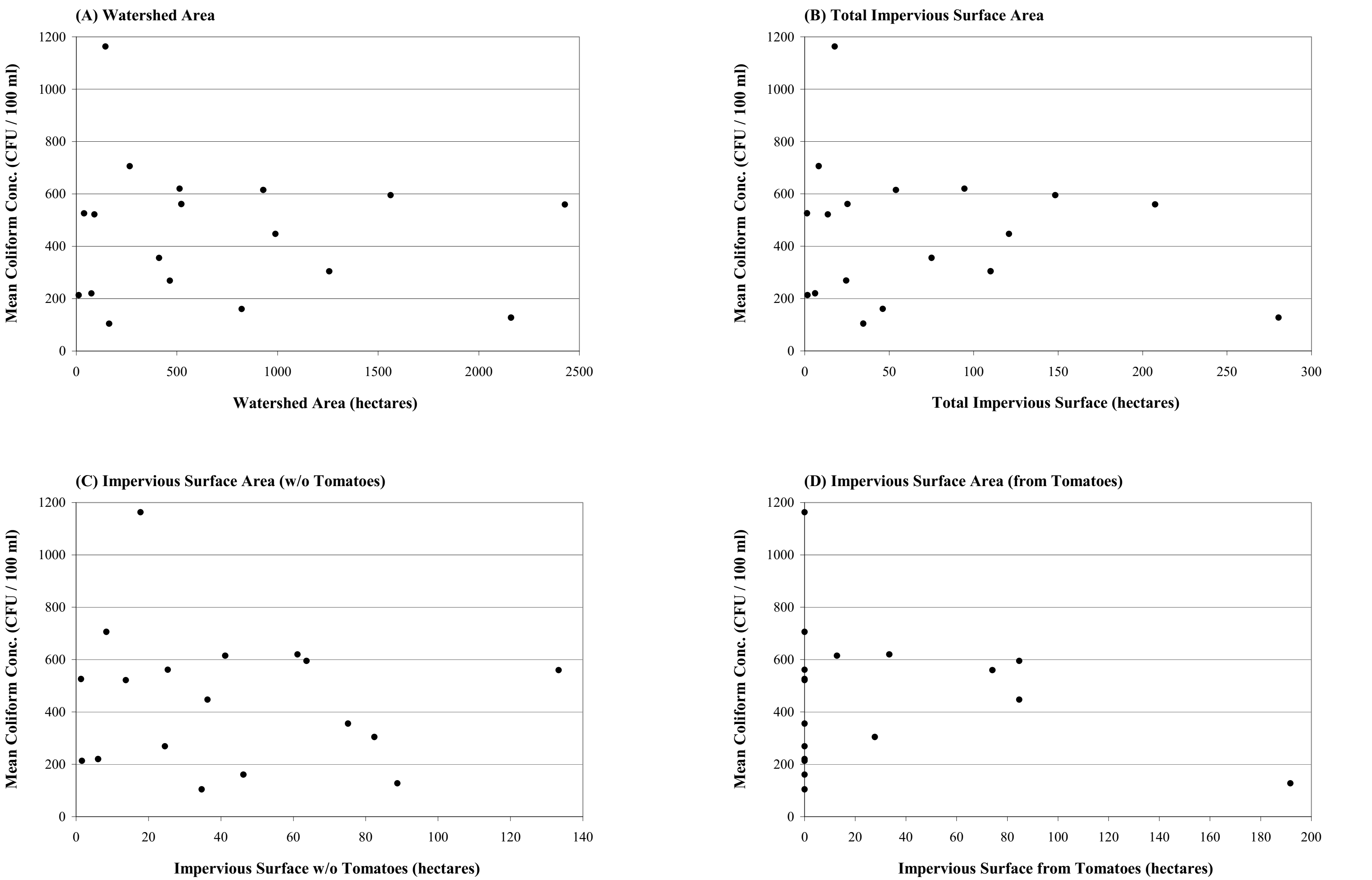


Figure 16. Coliform bacteria concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are geometric means of Colony Forming Units (CFU) from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

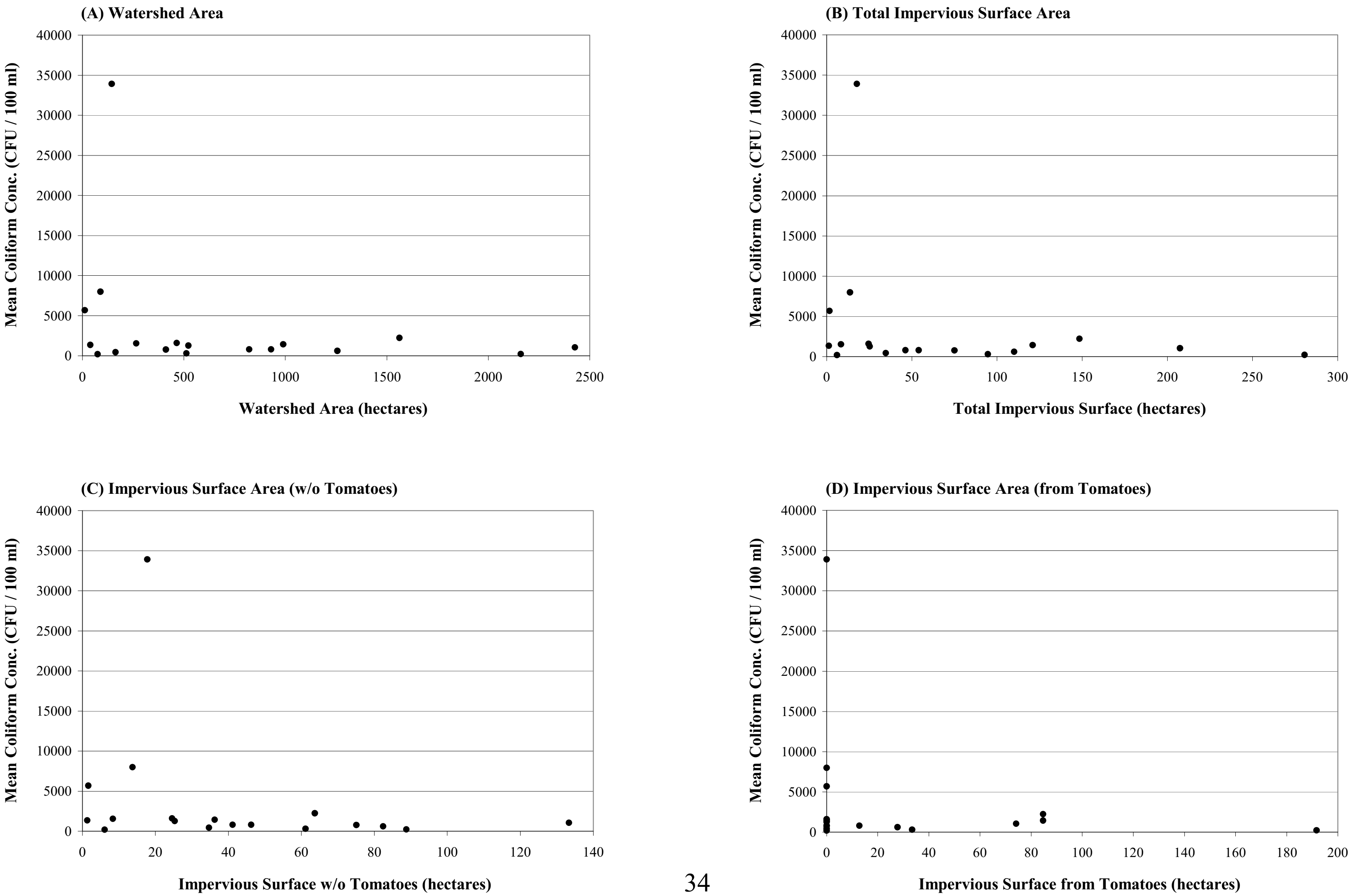


Figure 17. Coliform bacteria concentrations in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are geometric means of Colony Forming Units (CFU) per 100 mL from bi-weekly samples from Apr – Oct 2007.

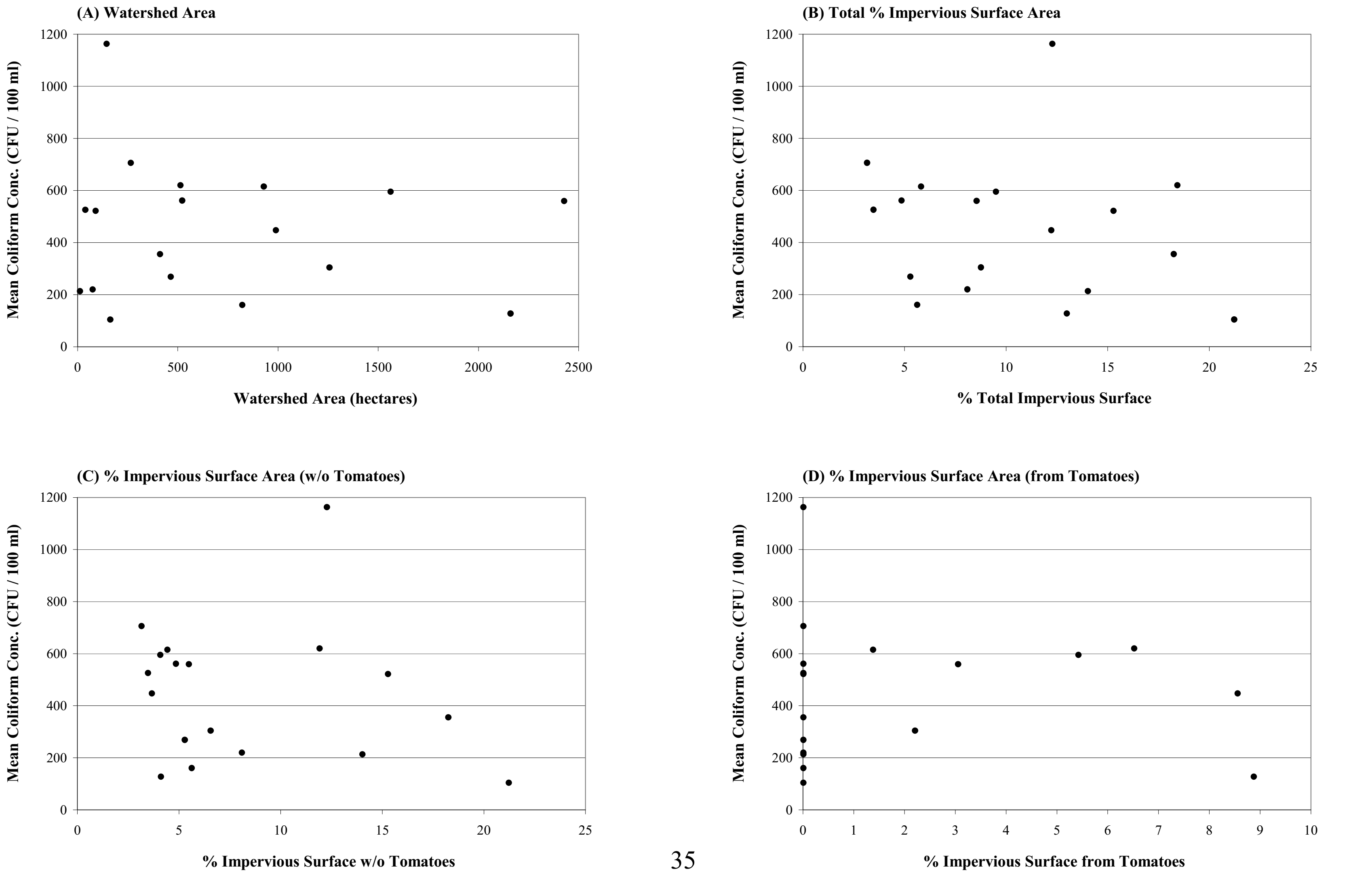
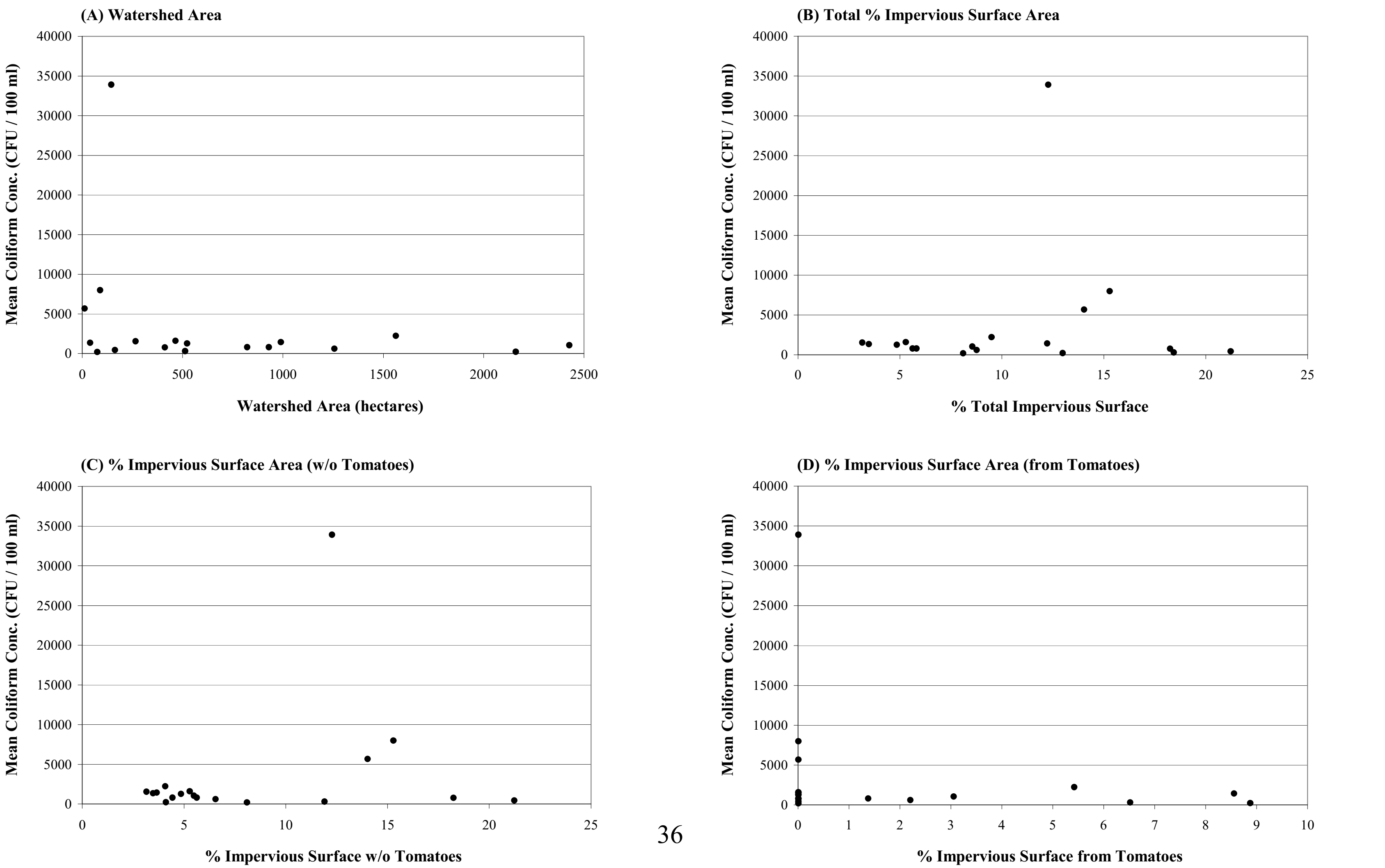


Figure 18. Coliform bacteria concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are geometric means of Colony Forming Units (CFU) from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Coliform bacteria flux

Flux of bacteria (concentrations x stream discharge rate) showed a stronger relationship with watershed characteristics (Figs. 19 - 22). Mean coliform flux over the course of the study varied over four orders of magnitude and showed a reasonable strong relationship to total watershed area (Fig. 19 A). The relationship improves when the total area of impervious surface area is considered (Fig. 19 B) and is strongest when only traditional impervious surface is considered (Fig. 19 C). No relationship was observed between the % impervious surface from tomato cultivation and coliform bacteria flux (Fig. 19 D).

The same pattern is observed when we compare the mean coliform bacteria flux following a 1 inch or greater rainfall to the various watershed characteristics, but the relationships are weaker (Fig. 20 A – D). Again, there was no relationship observed between the amount of impervious surface in a watershed from tomato cultivation and the flux of fecal coliform bacteria.

When we plot mean coliform bacteria flux versus % impervious surface measures we find that the relationships observed based upon absolute areas disappear and no pattern is evident (Figs. 21 A – D). Similarly, following a 1 inch or greater rainfall, there is no relationship between coliform bacteria flux and the % of various impervious surfaces in the watershed.

Figure 19. Coliform bacteria flux in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means of Colony Forming Units (CFU) x stream discharge from bi-weekly samples from Apr – Oct 2007.

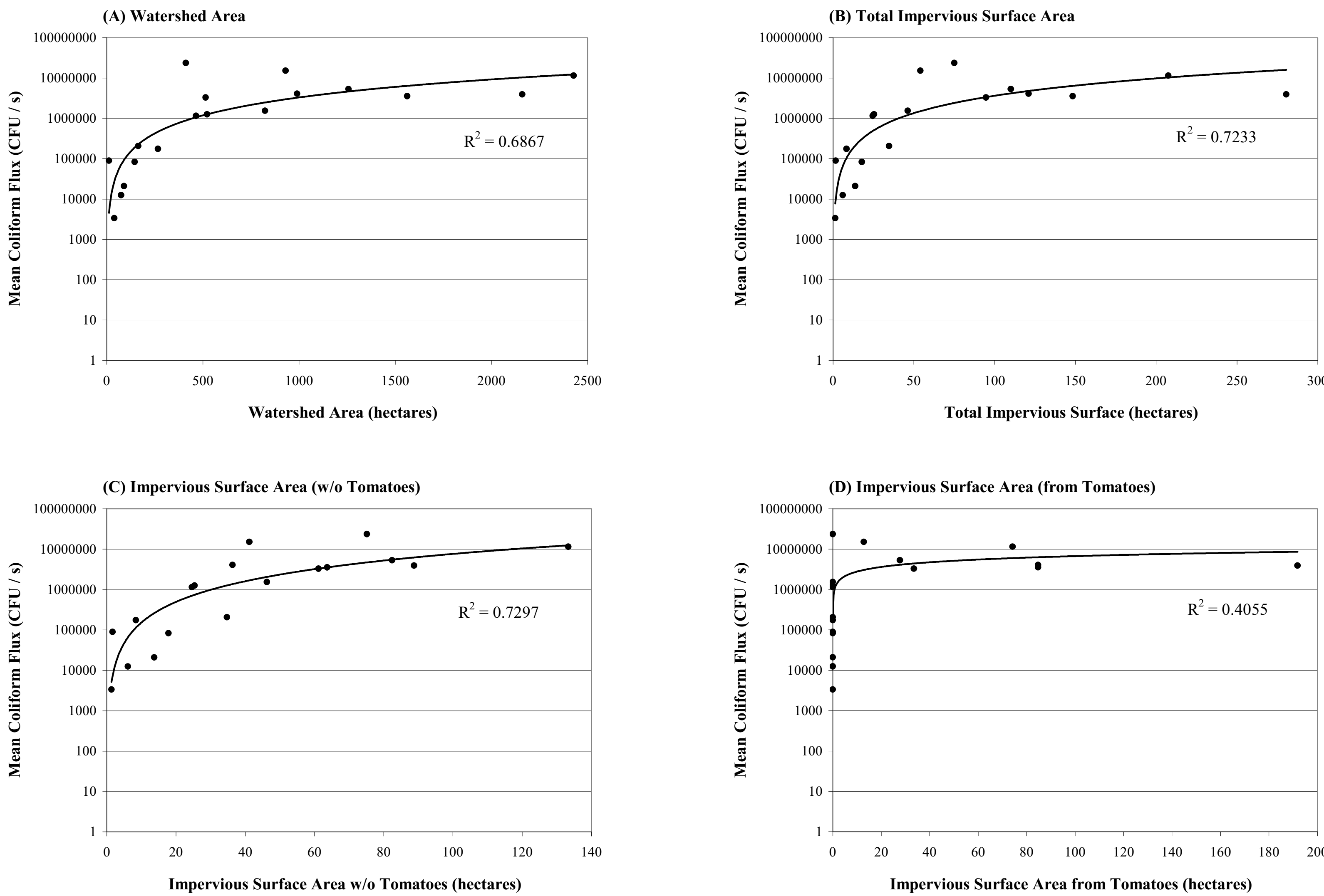


Figure 20. Coliform bacteria flux following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means of Colony Forming Units (CFU) x stream discharge from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

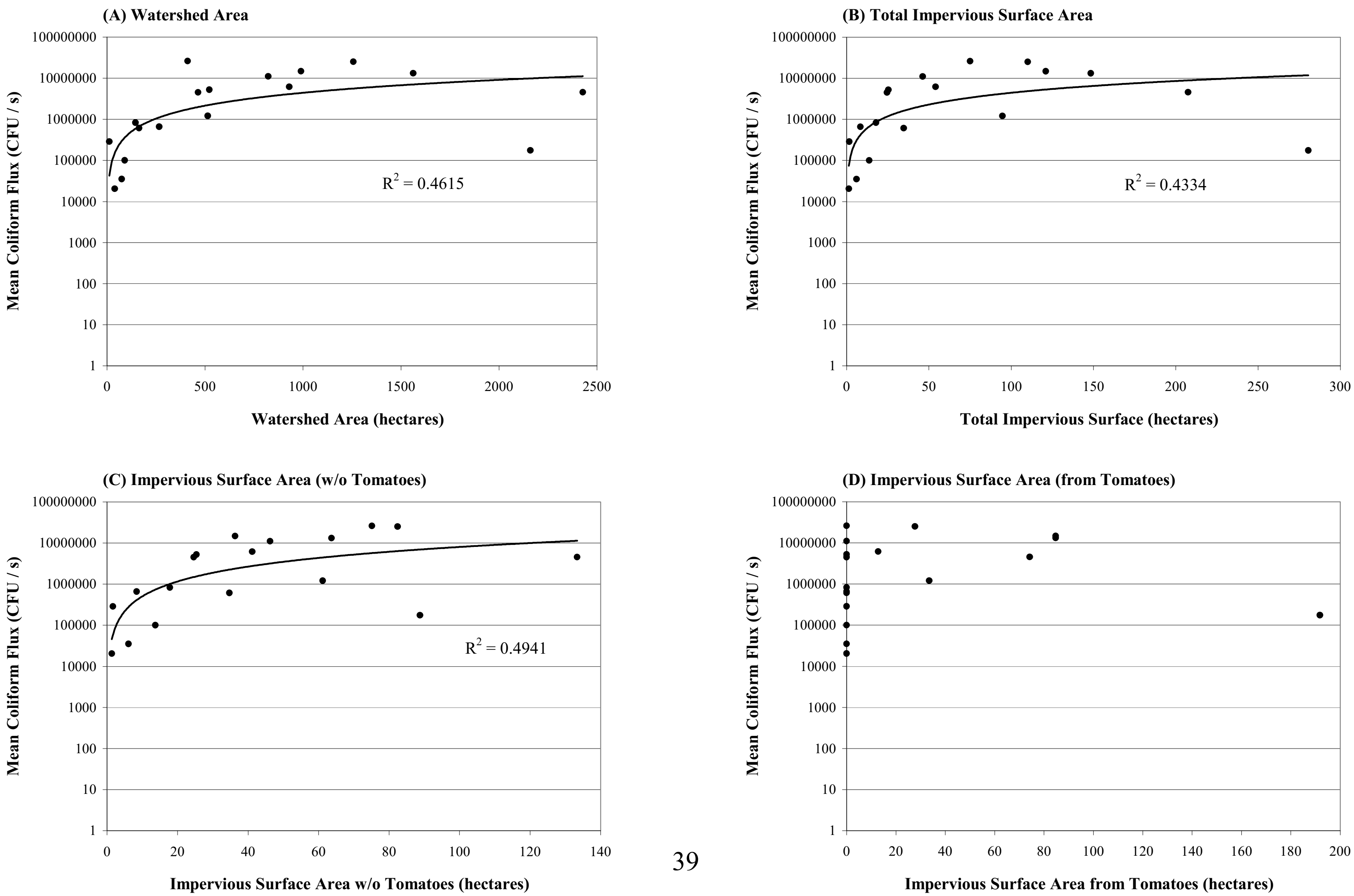


Figure 21. Coliform bacteria flux in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means of Colony Forming Units (CFU) x stream discharge from bi-weekly samples from Apr – Oct 2007.

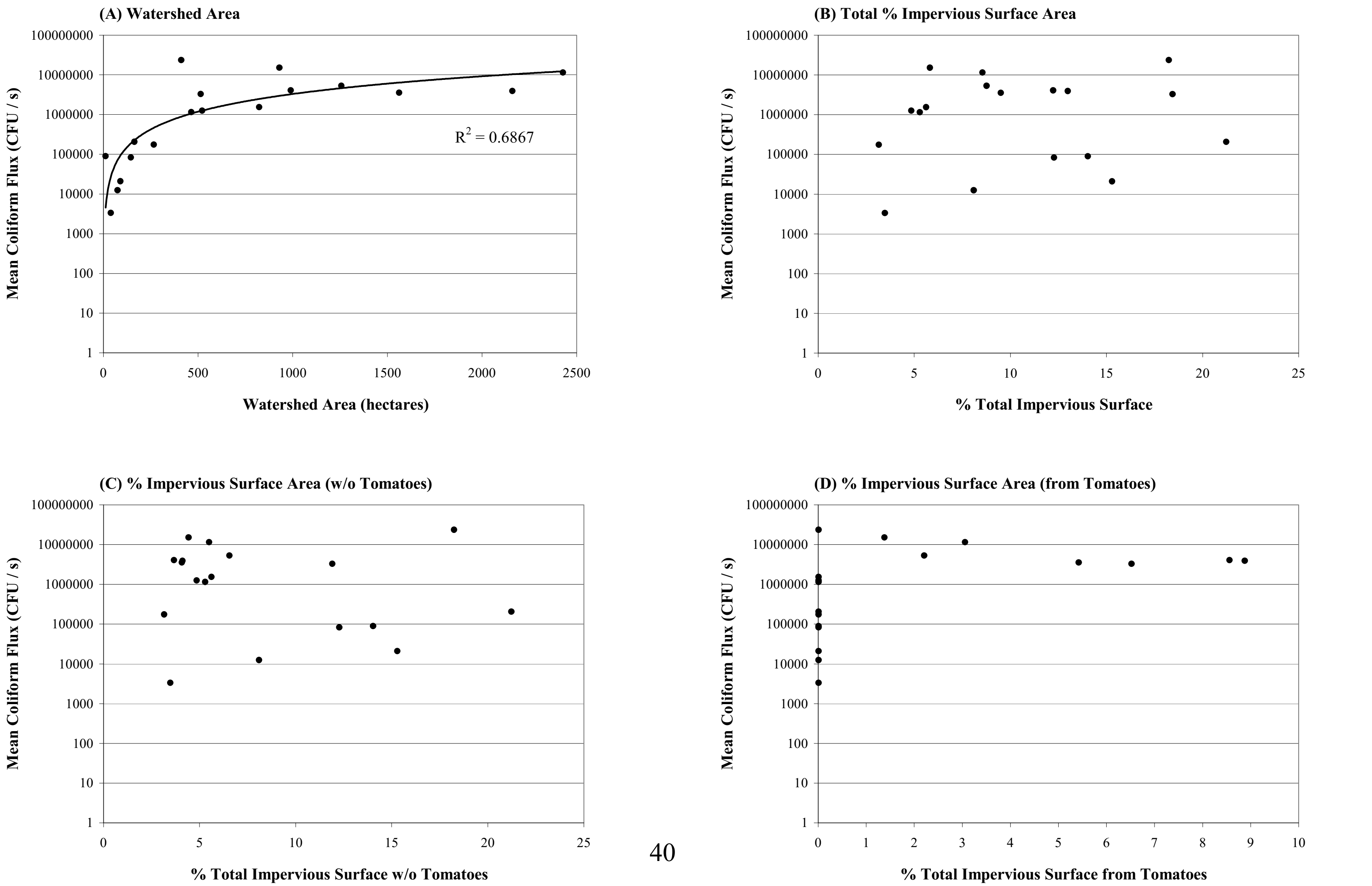
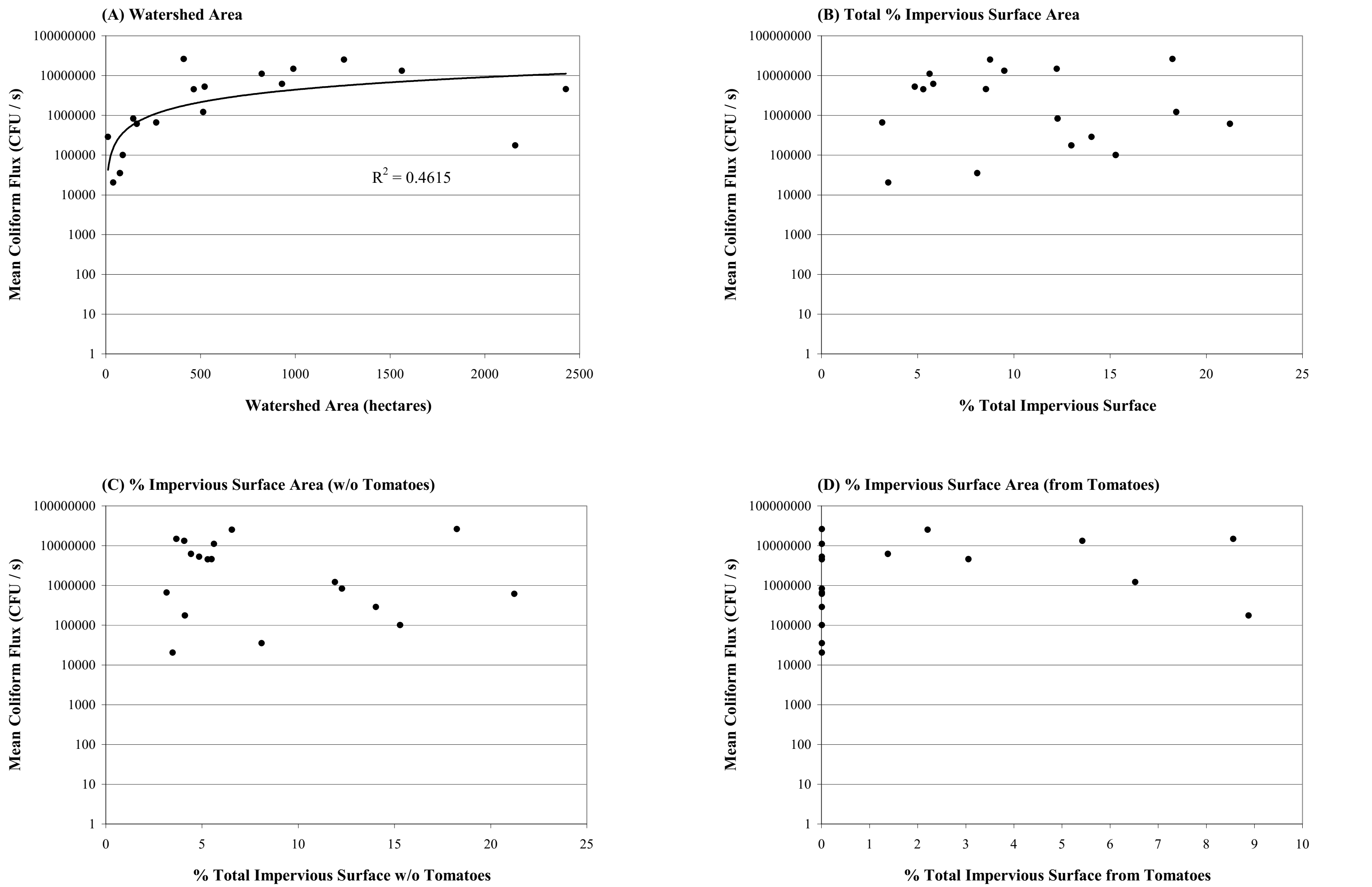


Figure 22. Coliform bacteria flux following ≥ 1" rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means of Colony Forming Units x stream discharge from samples taken within 48 hrs of a 1" or greater rain from Apr – Oct 2007.



Total Suspended Solid Concentrations

Mean total suspended solid concentrations over the study period ranged over two orders of magnitude from ~ 1 – 100 mg L^{-1}. There was, however, no significant relationship between TSS and watershed area, total IS area, IS area w/o tomato cultivation and IS area from tomato cultivation (Figs. 23 A – D). There was a slight trend for the sites with the highest mean concentrations of TSS to have greater IS area from traditional sources (Fig. 23 C), but this pattern was not significant.

Similarly, mean TSS from sample dates that were preceded by a 1 inch or greater rainfall event showed slight trends for increases in relation to watershed area and traditional IS area, but these patterns were not significant (Figs. 24 A – C). Interestingly, there is an appearance of a trend of declining TSS concentration with IS area from tomato cultivation (Fig. 24 D); however, this pattern is driven by sample site (Occohannock Creek) which has a very large area of tomato cultivation and low TSS values.

When we plot mean TSS versus the % impervious surfaces in the watershed, no relationship is evident (Figs. 25 B – D). And, when we look at similar values only for dates following inch or greater rainfall events (Figs. 26 A- D), there is even a hint of declining TSS with increasing impervious surfaces. This trend is, however, driven by three sites with relatively high TSS and low impervious surface and is not significant.

Figure 23. Total suspended solid concentrations in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

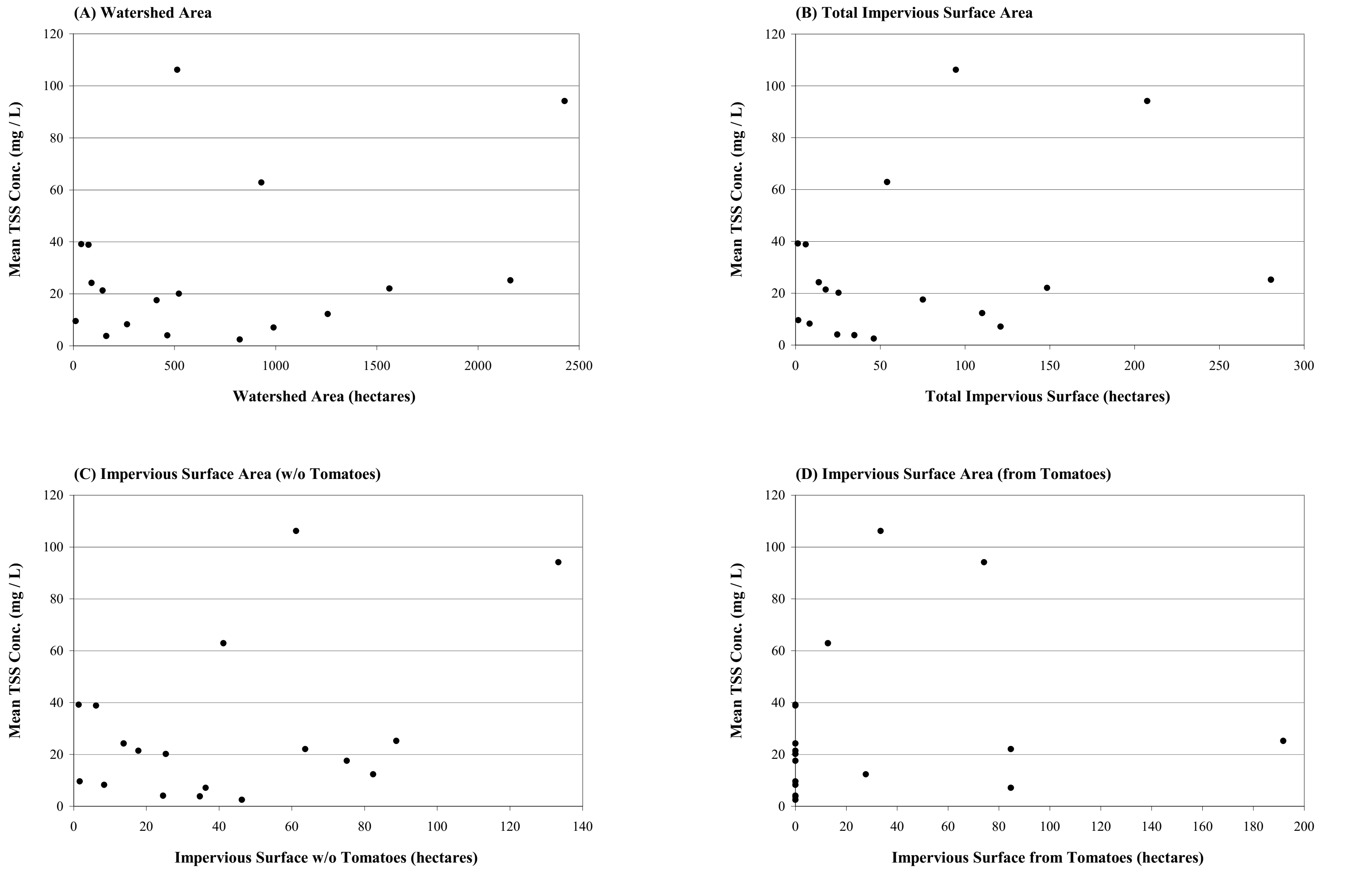


Figure 24. Total suspended solid concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

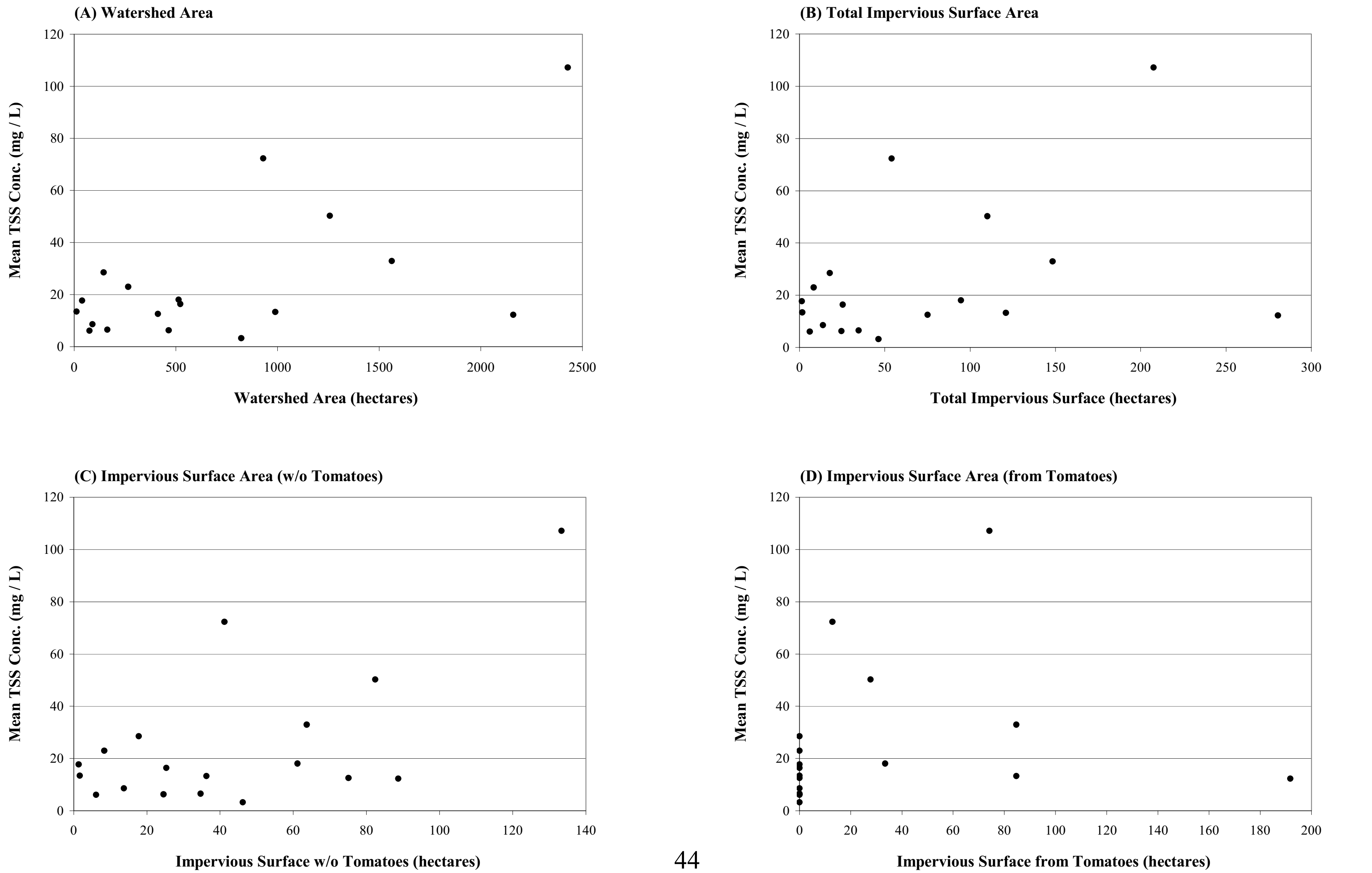


Figure 25. Total suspended solid concentrations in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

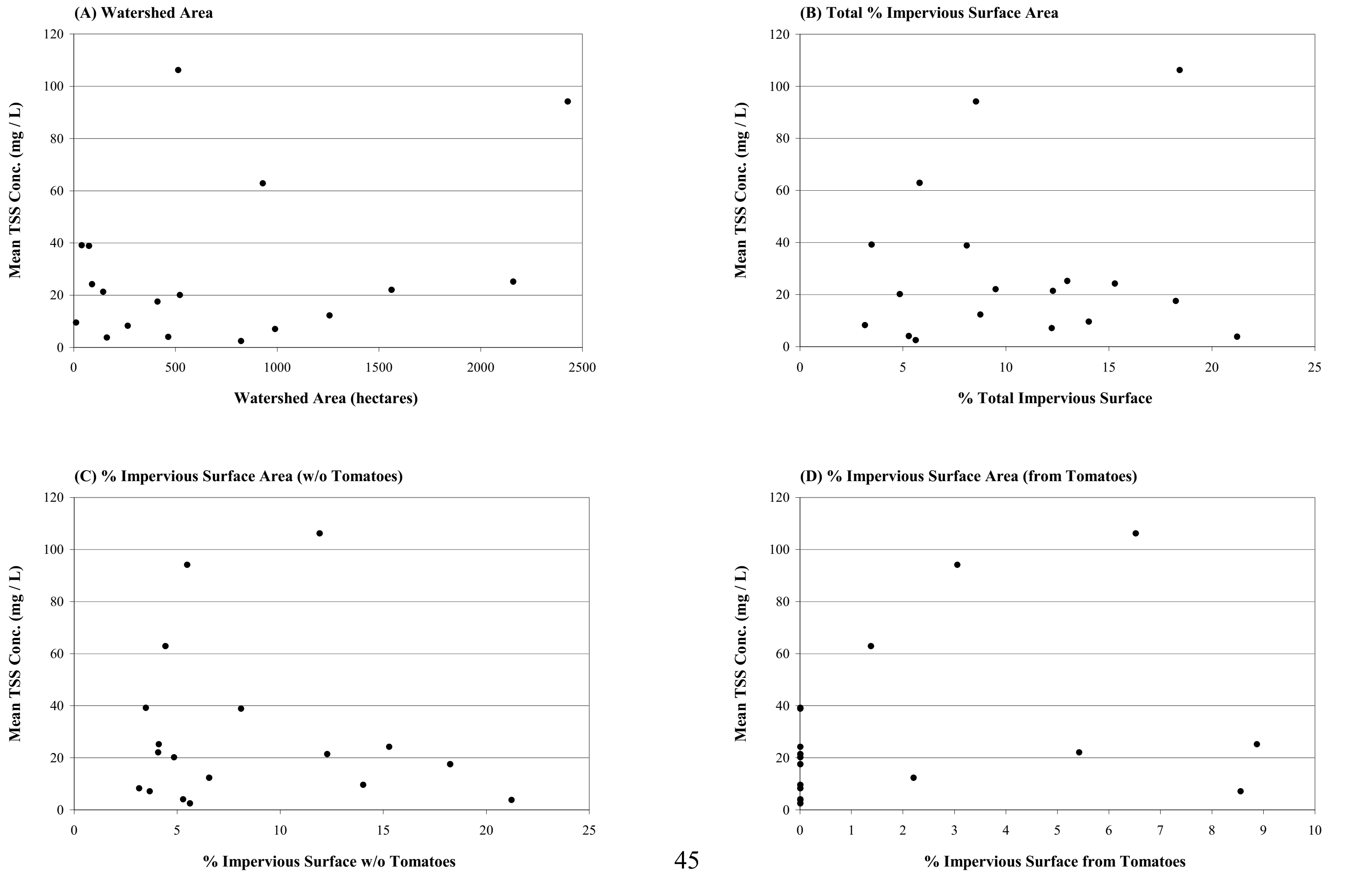
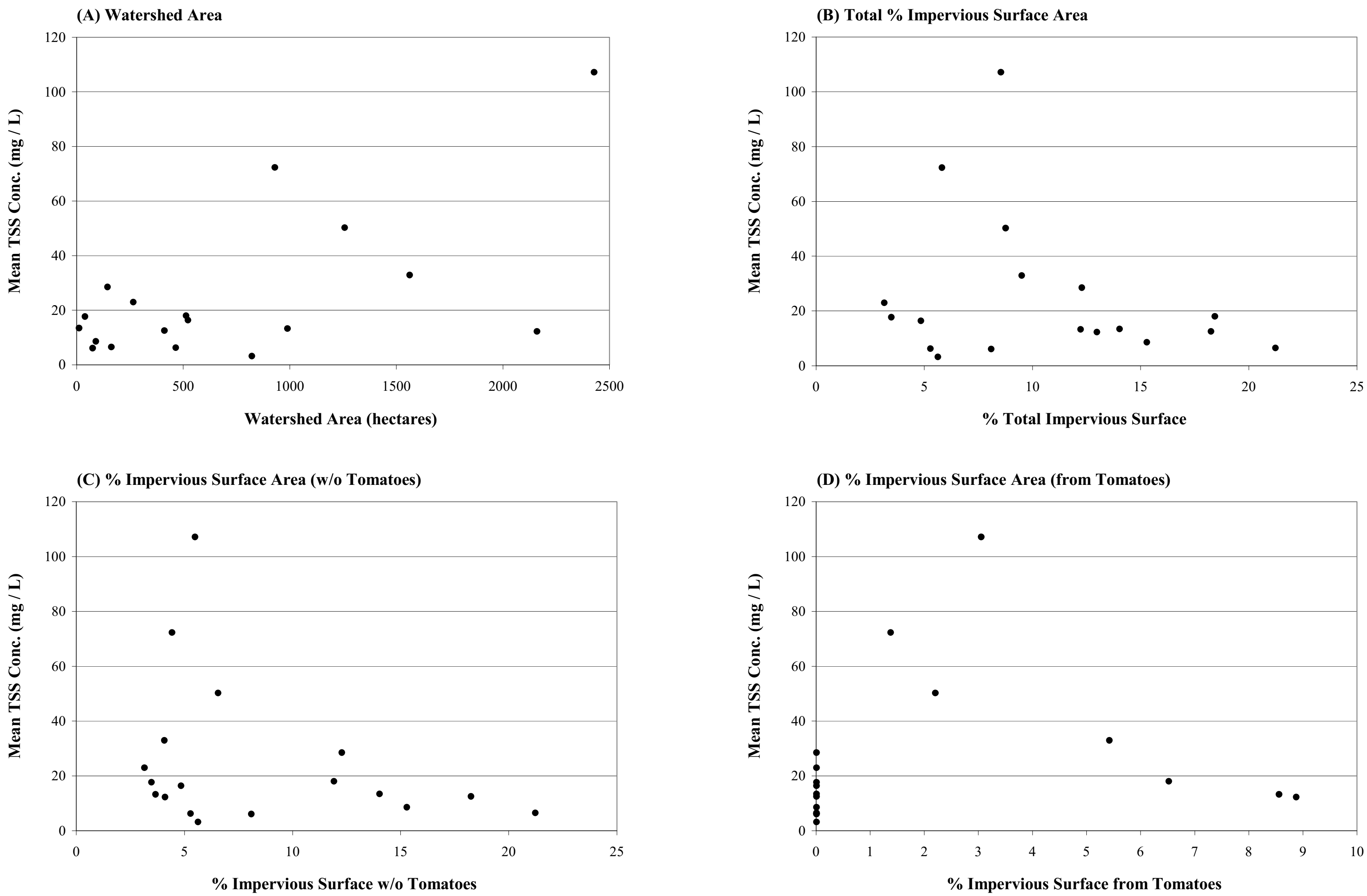


Figure 26. Total suspended solid concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Total Suspended Solid Flux

As with the coliform bacteria measurements, we find that the relationships between TSS and watershed characteristics are clearer when we look at loadings or fluxes. Driven largely by large difference in discharge rates between the creek sites, TSS fluxes vary by over four orders of magnitude (Fig. 27). Positive relationships were observed between TSS flux and watershed area, total IS area, IS area w/o tomato cultivation and IS area from tomato cultivation (Figs. 27 A – D). The strongest relationships were those with total IS area (Fig. 27 B) and IS area w/o tomato cultivation (Fig. 27 C).

Similar, but weaker, patterns were observed in TSS flux following rainfall events (Fig. 28 A – C). Perhaps surprisingly, TSS flux following rainfall events did not increase with the area of tomato cultivation in the watershed (Fig. 28 D).

When plotted against % impervious surfaces in the watershed, mean TSS flux again did not show a significant pattern with impervious surfaces (Fig. 29), nor did TSS flux following rainfall events (Fig. 30).

Figure 27. Total suspended solids flux in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L x stream discharge from samples taken from Apr. – Oct 2007.

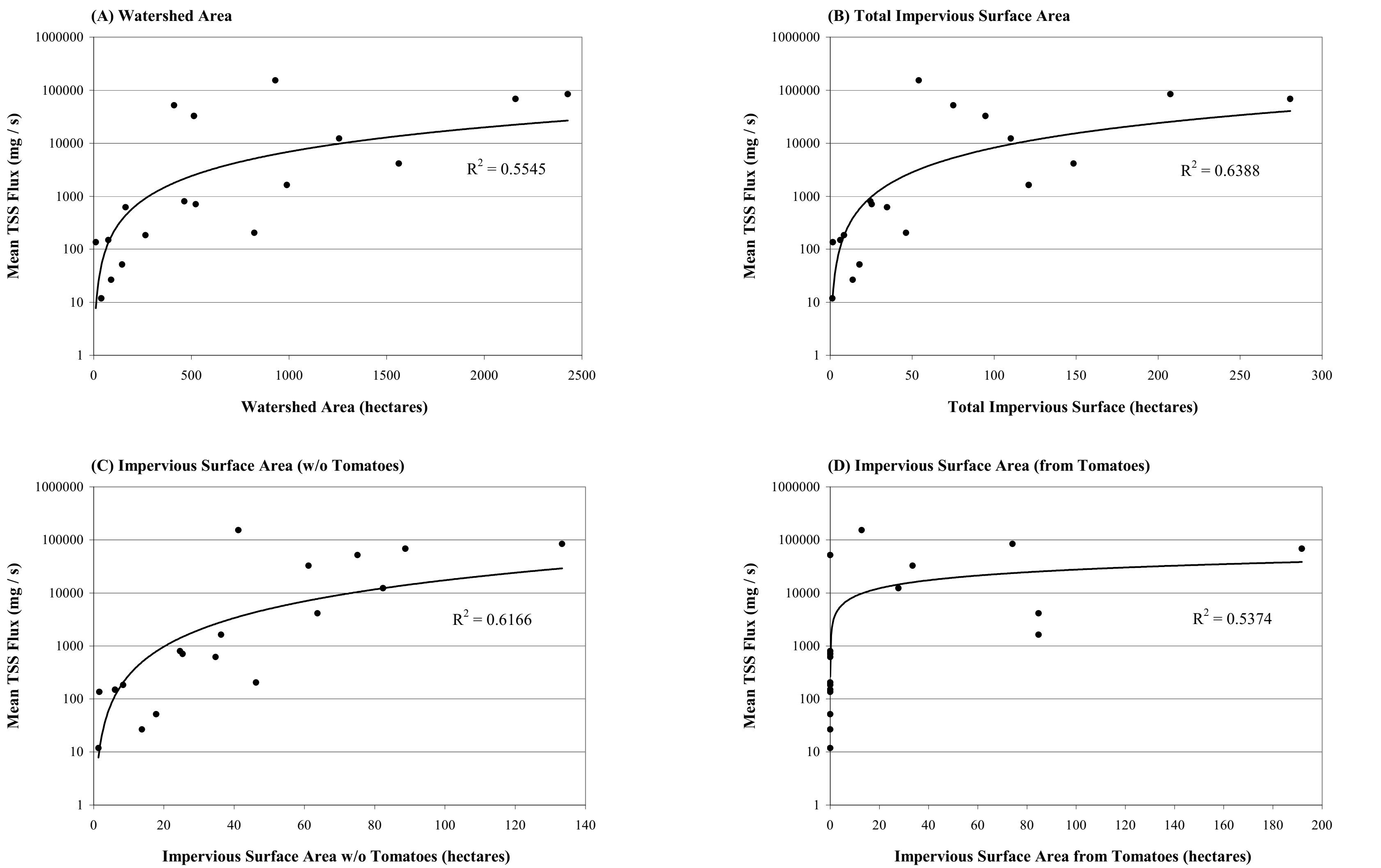


Figure 28. Total suspended solids flux following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are TSS concentrations in mg/L x stream discharge from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

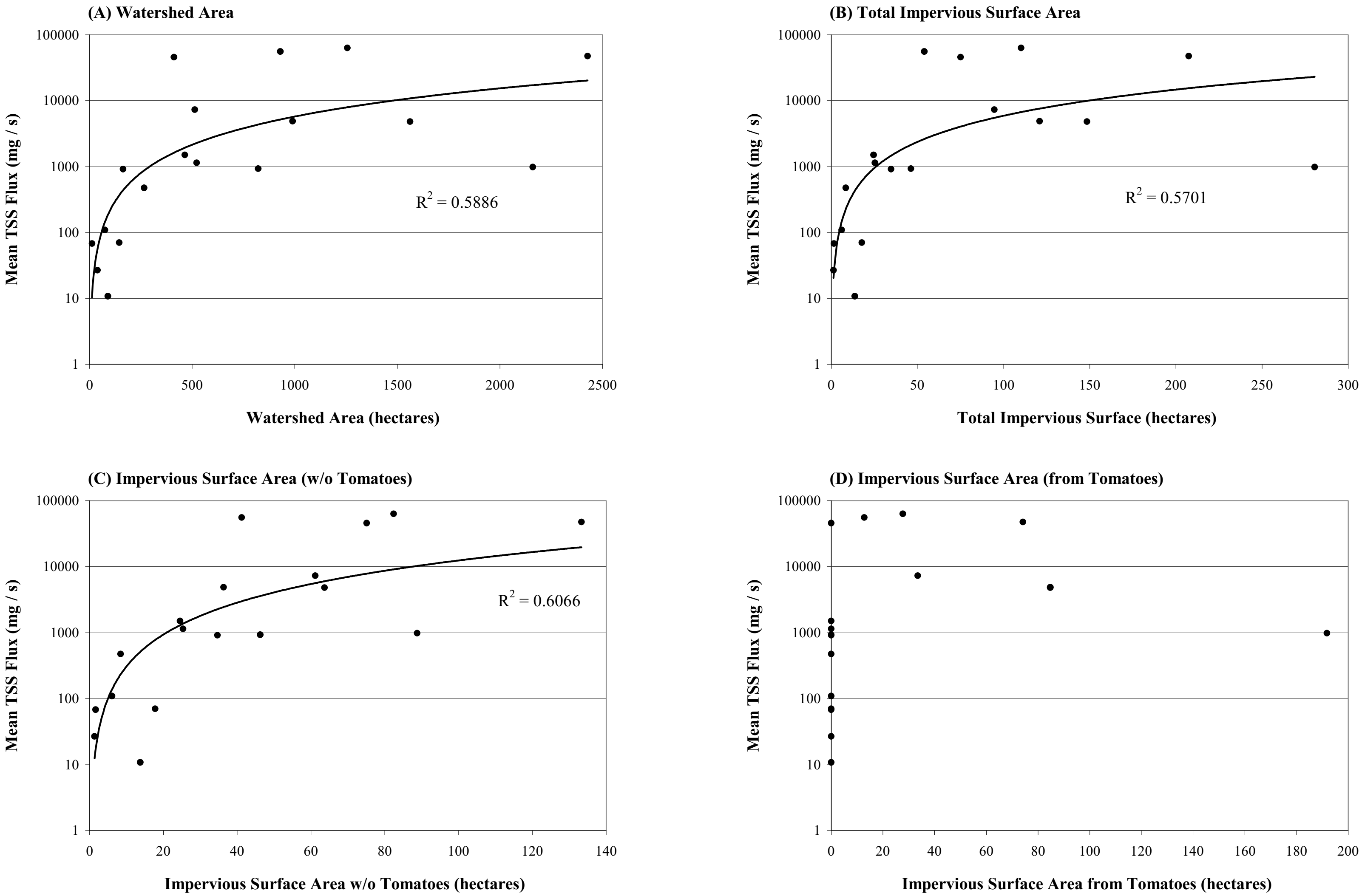


Figure 29. Total suspended solid flux in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are mean TSS concentrations in mg/L x stream discharge from bi-weekly samples taken from Apr – Oct 2007.

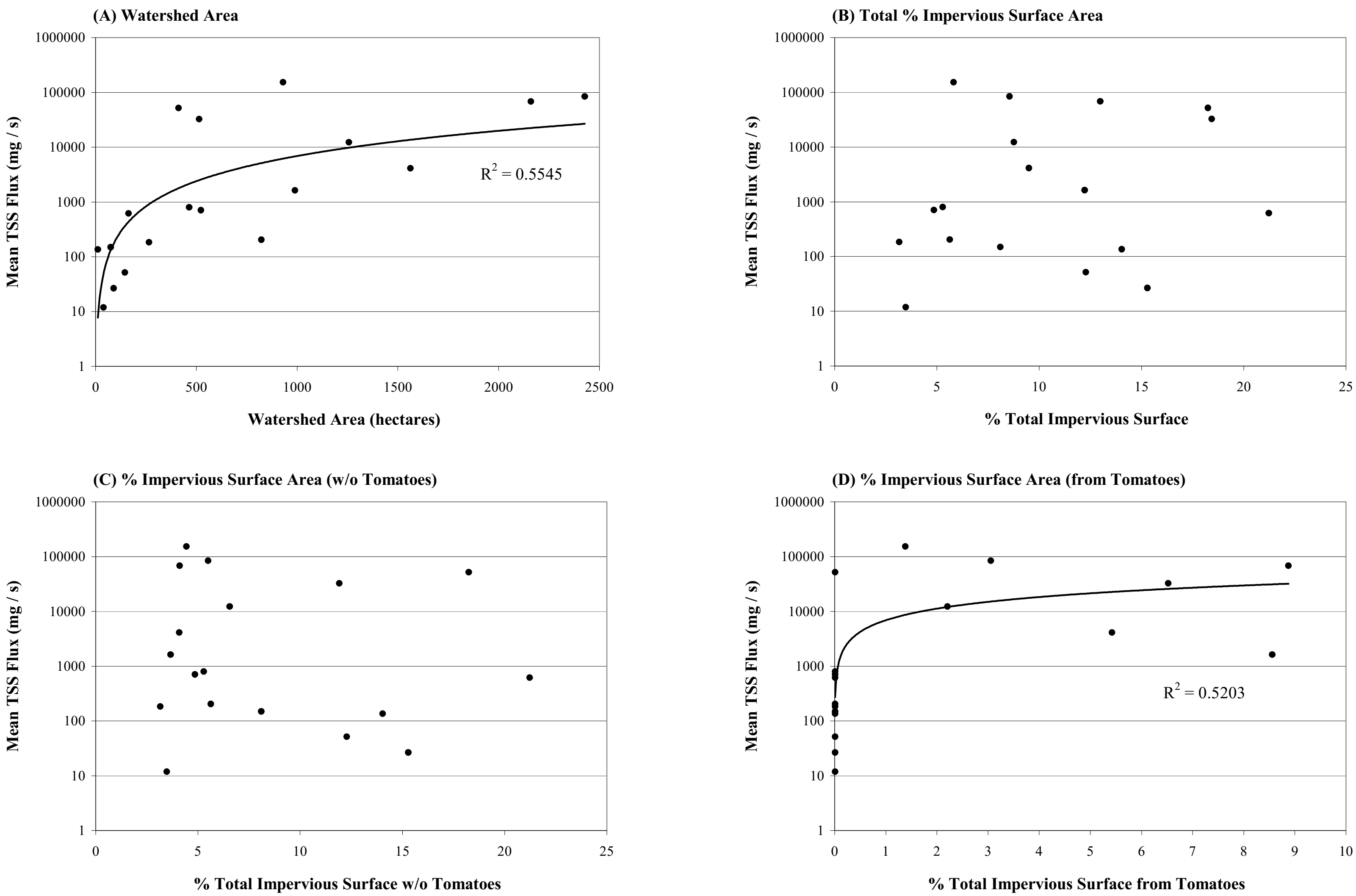
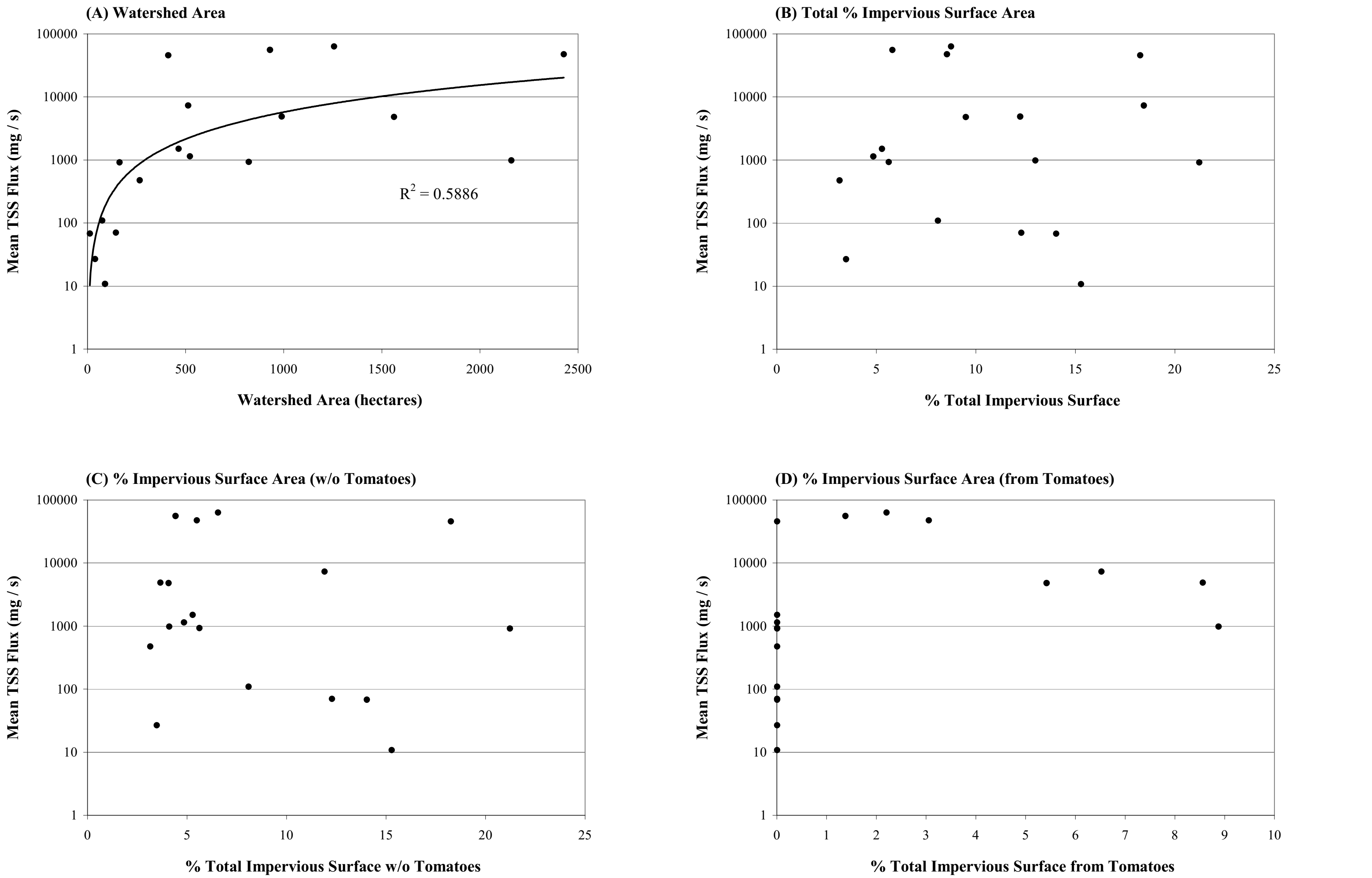


Figure 30. Total suspended solids flux following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are TSS concentrations in mg/L x stream discharge from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Nitrogen Concentration

Patterns of nitrogen concentrations across watersheds were similar for particulate nitrogen (not shown) and dissolved nitrogen (Figs. 31 – 34). Mean dissolved N concentrations over the study period varied from < 1 to > 6.5 mg L^{-1} across the 18 sites (Fig. 31 A). There was, however, no clear pattern in this variation related to watershed area, total IS area, IS area w/o tomato cultivation or IS from tomato cultivation (Fig 31 A – D).

A similar lack of pattern was observed when dissolved N concentrations are considered only sample dates following a 1 inch or greater rainfall (Fig. 32). It is worth noting that the Occohannock Creek site which had the largest area in tomato cultivation (far right point in Fig. 32 D) had among the lowest dissolved N following these rainfall events.

When impervious surfaces in the watershed are computed as % area, we once again do not observe strong relationships with impervious surface (Figs. 33 A – D). There is, however, a weak negative relationship between % Total IS, IS w/o tomato cultivation and mean TSS (Figs. 33 B & C).

Following 1 inch or greater rainfall events, a slight negative relationship persist between mean dissolved N and % Total IS (Fig, 34 B), but the relationship is not strong. The relationship is even less event for % IS w/o tomato cultivation (Fig. 34 C).

Figure 31. Dissolved nitrogen concentrations in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

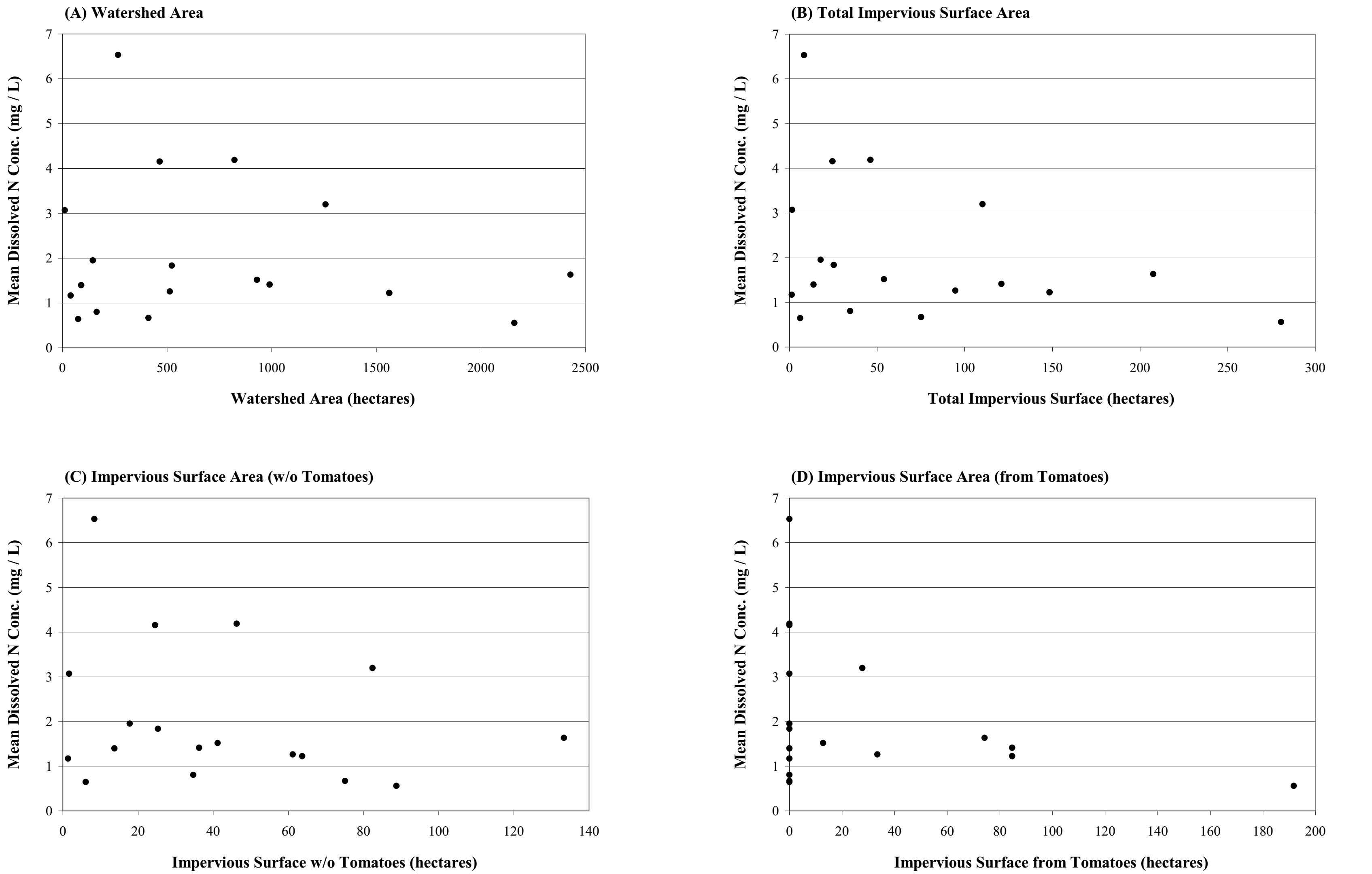


Figure 32. Dissolved nitrogen concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

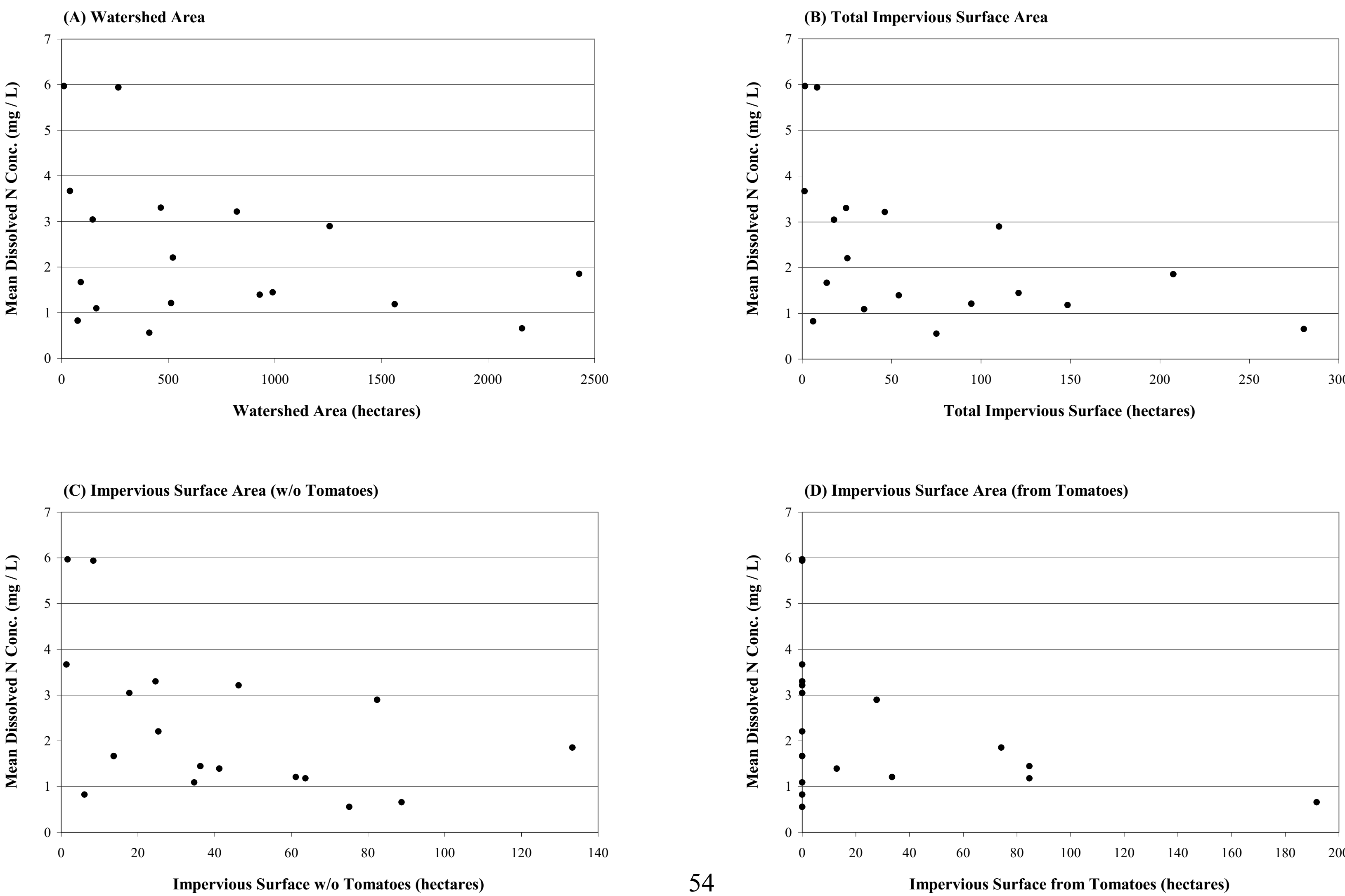


Figure 33. Dissolved nitrogen concentrations in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

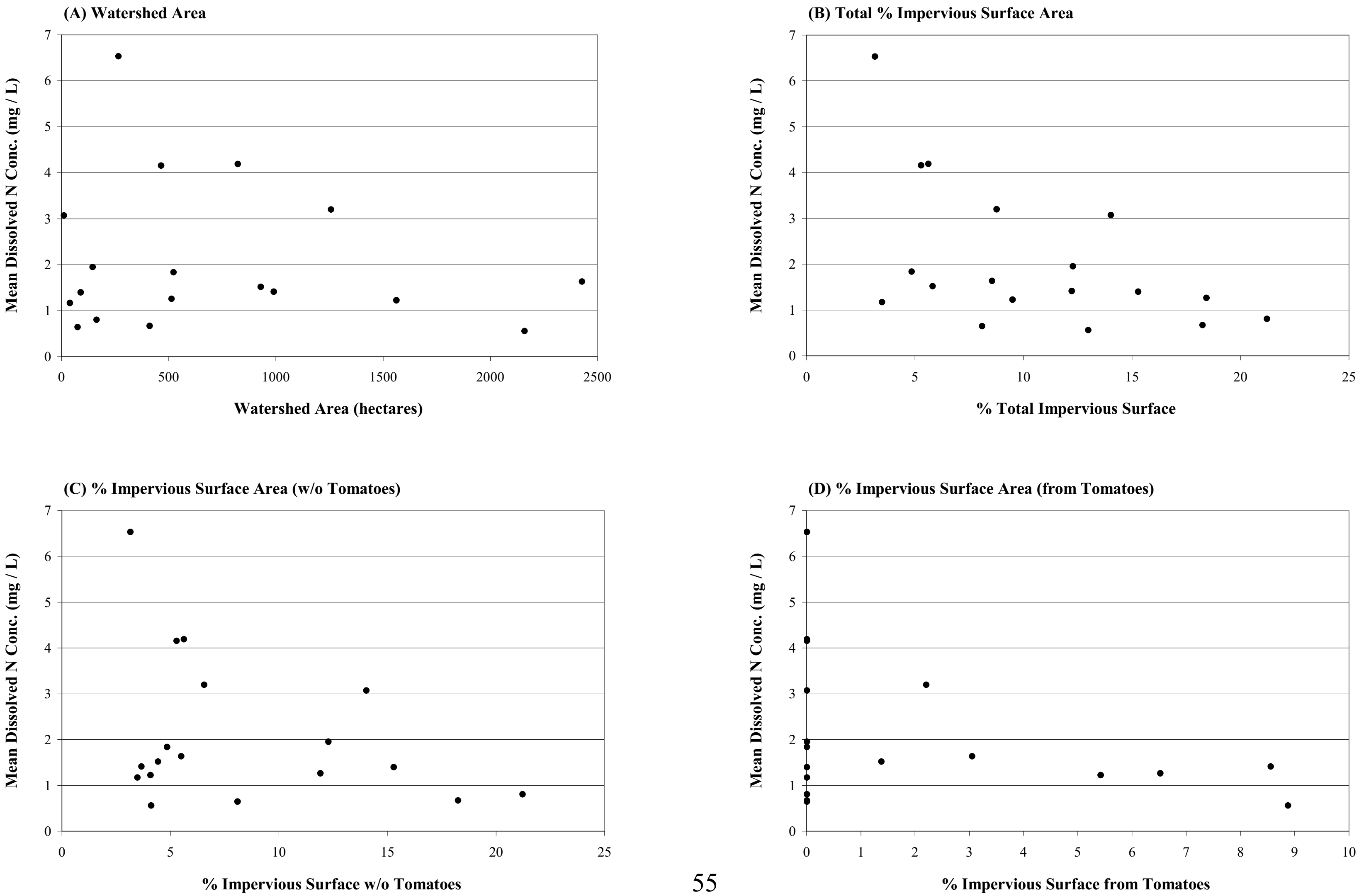
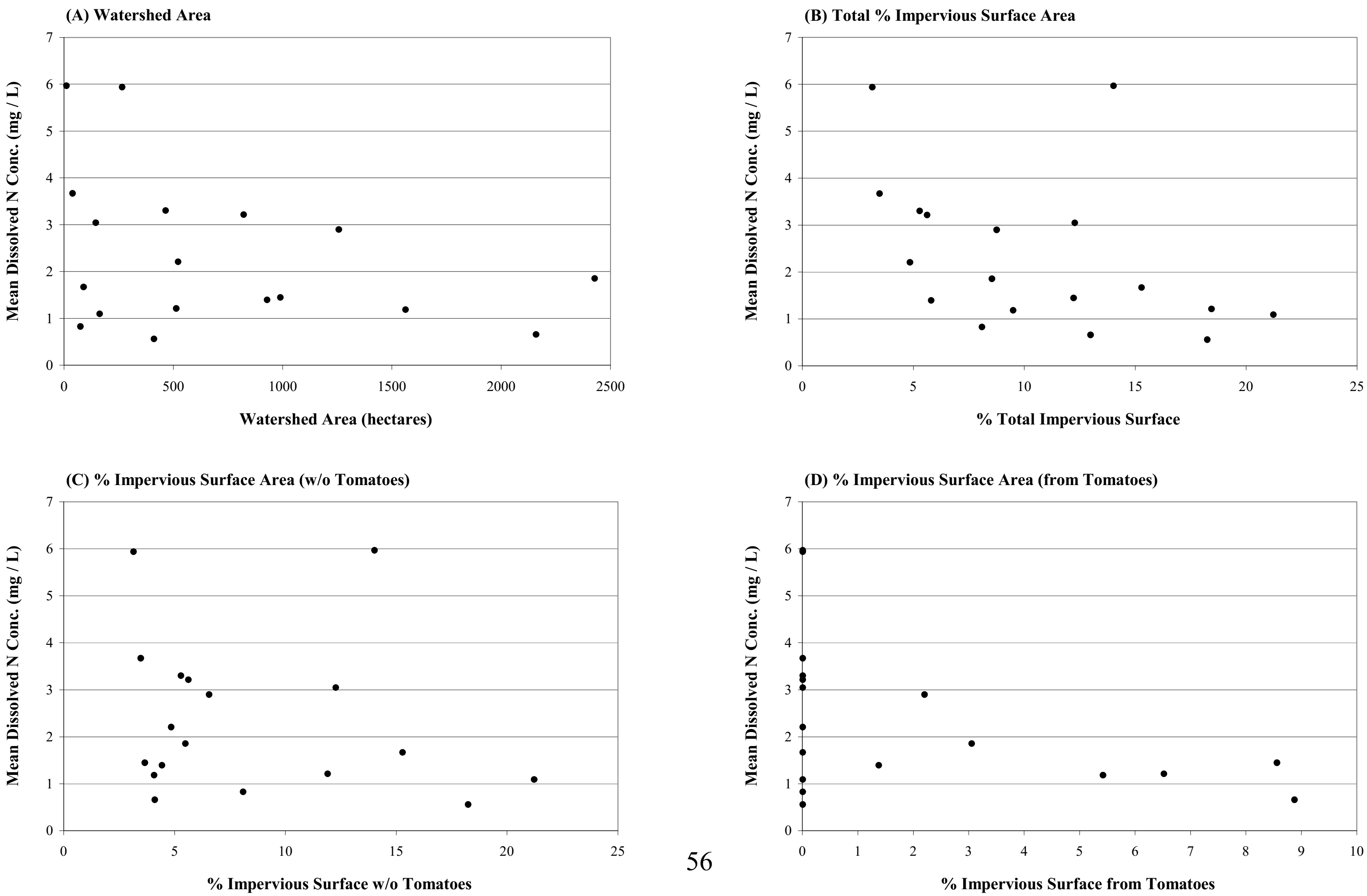


Figure 34. Dissolved nitrogen concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Nitrogen Flux

Flux of both particulate (not shown) and dissolved fractions of nitrogen varied across watersheds (Figs. 35 – 38). Total watershed area, total IS area and IS area w/o tomato cultivation explain approximately 60% of the variation in mean flux of dissolved N (Figs. 35 A – C), but no relationship was evident with IS area from tomato cultivation (Fig. 35 D).

Similar, but weaker, patterns were observed for dissolved N flux following 1 inch or greater rainfall events (Fig. 36 A – D). Once again, it is interesting to note that the station with the greatest area of tomato cultivation had very low average flux of N following rainfall events (Fig. 36 D).

When impervious surfaces are expressed as % area within the watershed, even these weak relationships with nitrogen flux disappear (Fig. 37). A similar lack of relationships are seen following rainfall events (Fig. 38)

Figure 35. Dissolved nitrogen flux in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from bi-weekly samples taken from Apr. – Oct 2007.

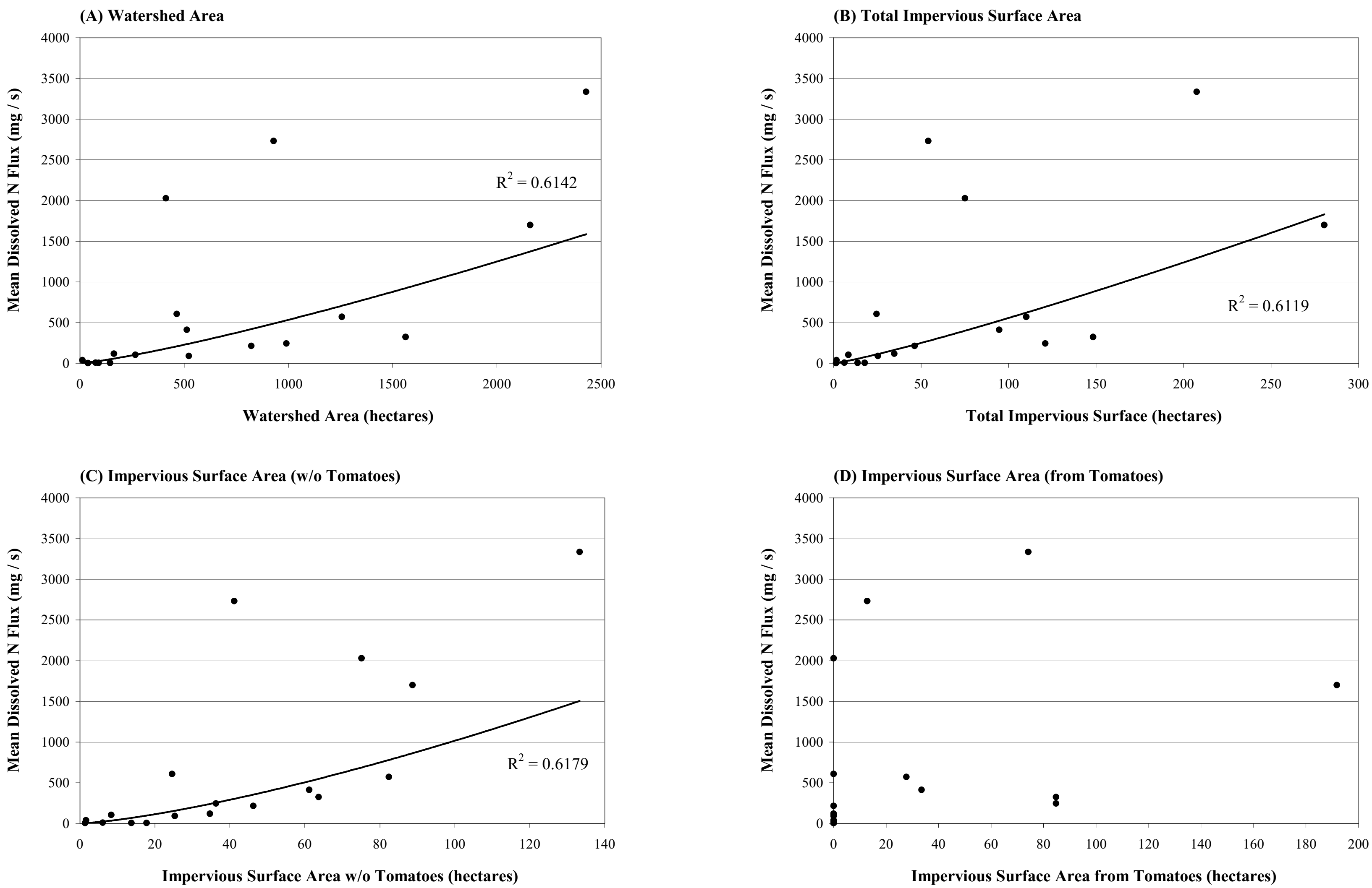


Figure 36. Dissolved nitrogen flux following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken within 48 of a 1” or greater rain from Apr. – Oct 2007.

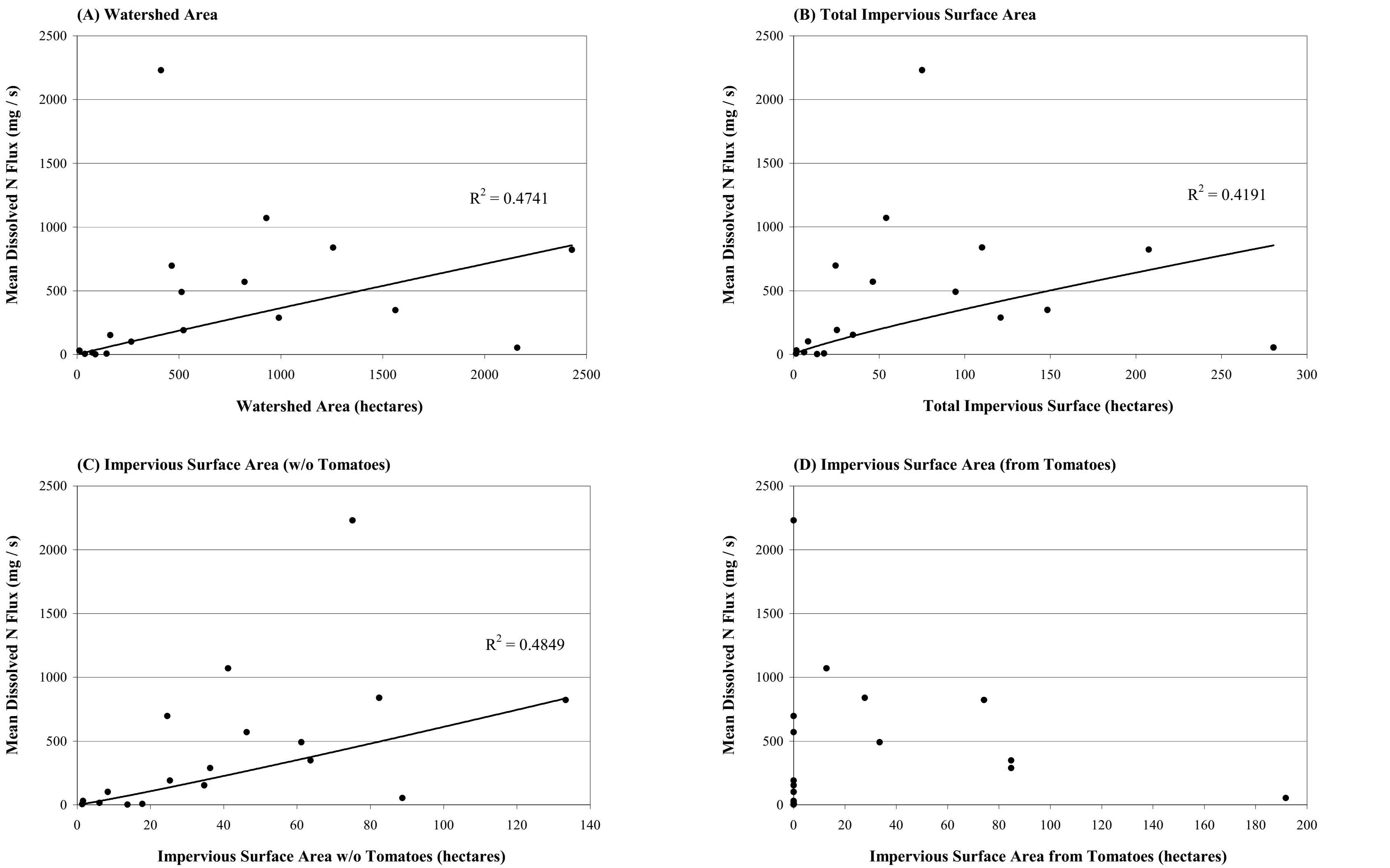


Figure 37. Dissolved nitrogen flux in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken from Apr. – Oct 2007.

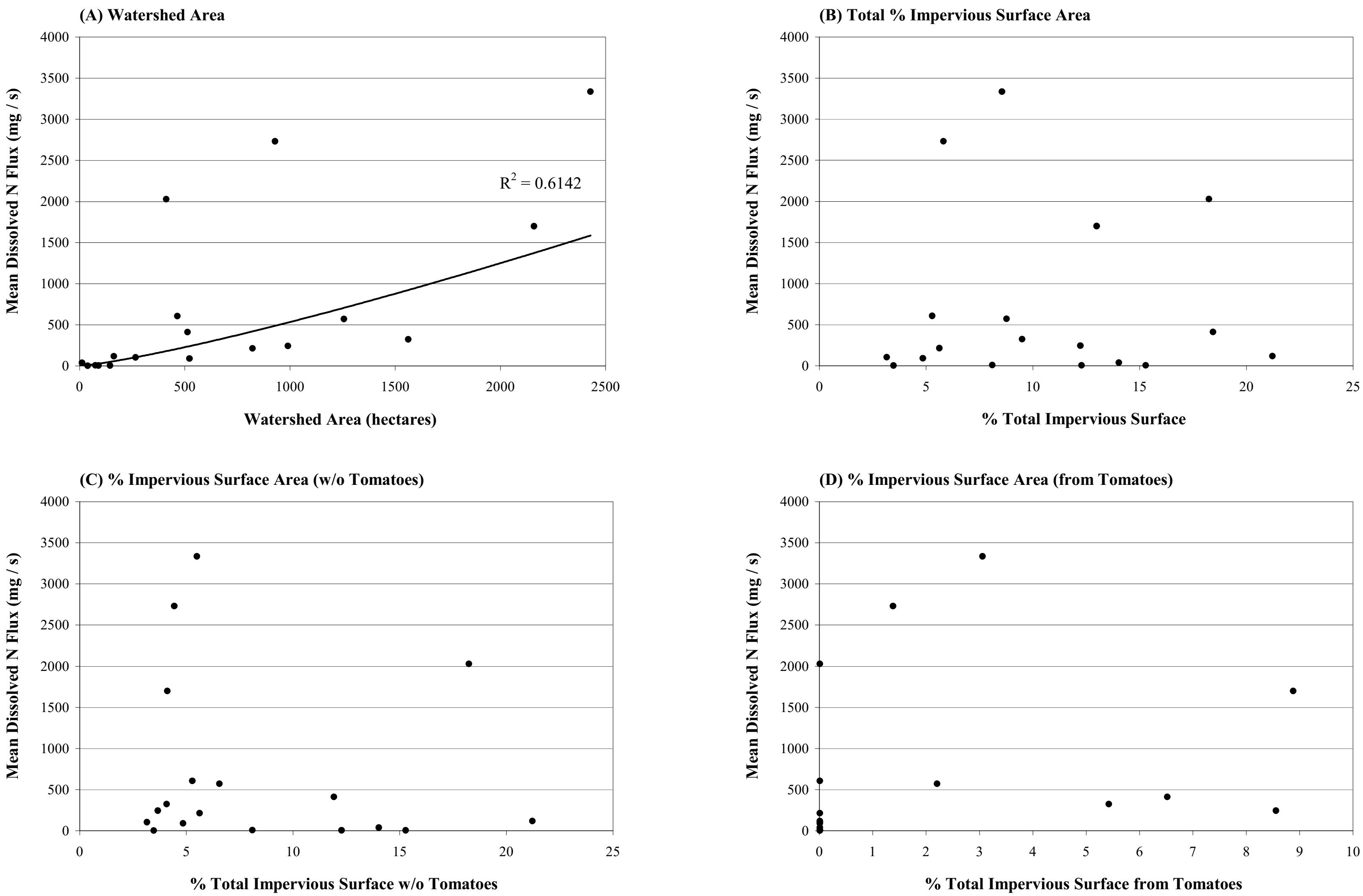
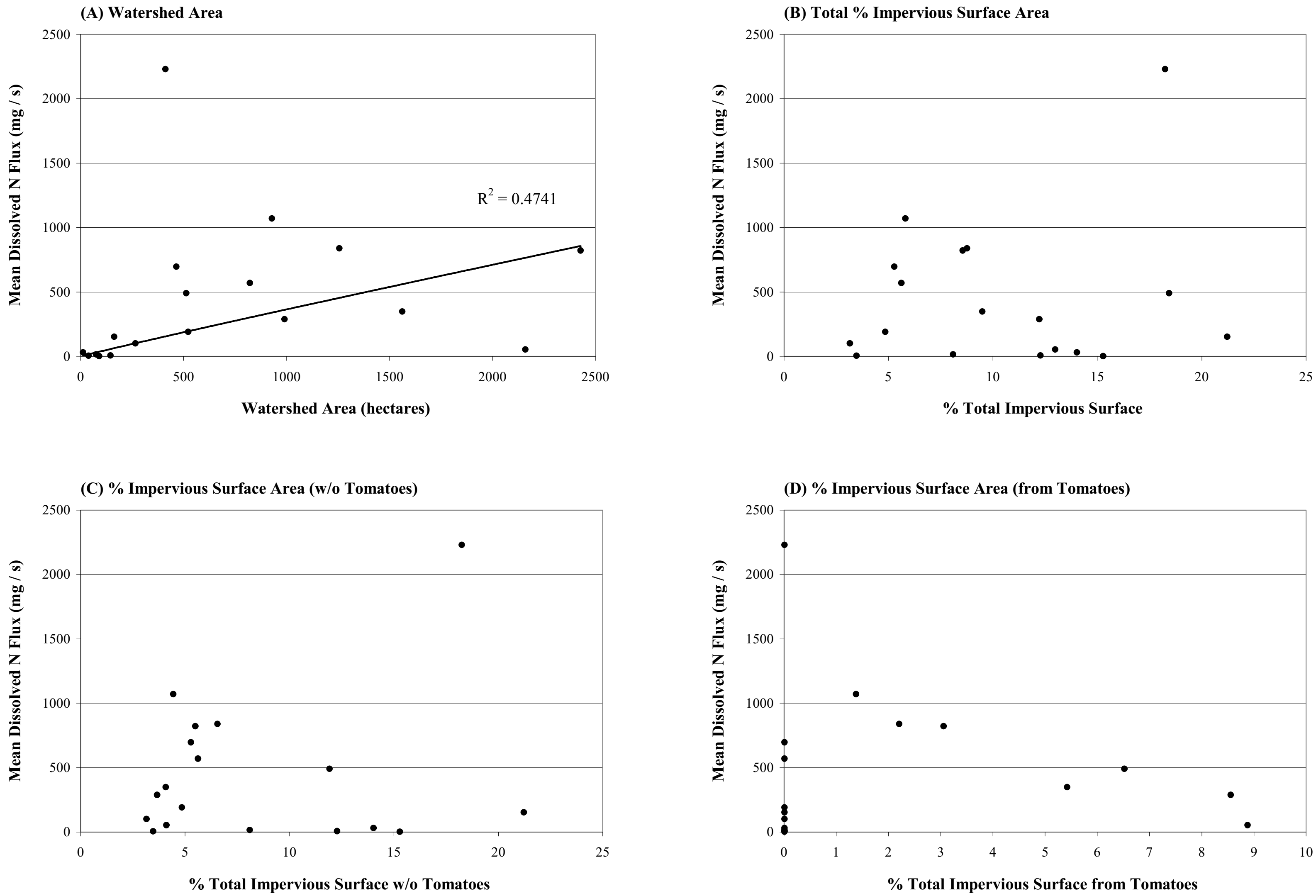


Figure 38. Dissolved nitrogen flux following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Phosphorus Concentration

As expected, most phosphorus was observed in the particulate phase. Similar patterns of concentration across watershed were observed between dissolved (not shown) and particulate phosphorus concentrations (Figs. 39 – 42). Mean particulate phosphorus concentration over the course of the study varied from a low of < 10 µg L^{-1} to ~ 180 µg L^{-1}, but there was no relationship between these mean concentrations and watershed area, total IS area, IS area w/o tomato cultivation or IS area from tomato cultivation (Figs. 39 A – D).

Following rainfall events of 1 inch or greater, mean concentration of particulate phosphorus showed weak positive relationships with watershed area, total IS area and IS area w/o tomato cultivation (Figs. 40 A – C), but not with IS area from tomato cultivation (Fig. 40 D).

When impervious surfaces are expressed as percent of the watershed area and regressed against mean particulate phosphorus concentration, no relationships are evident (Figs. 41 A – D).

Similarly, following rainfall events there were no significant relationships between mean particulate phosphorus concentration at the 18 study sites and % IS coverage (Figs. 42 B – D).

Figure 39. Particulate phosphorus concentrations in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

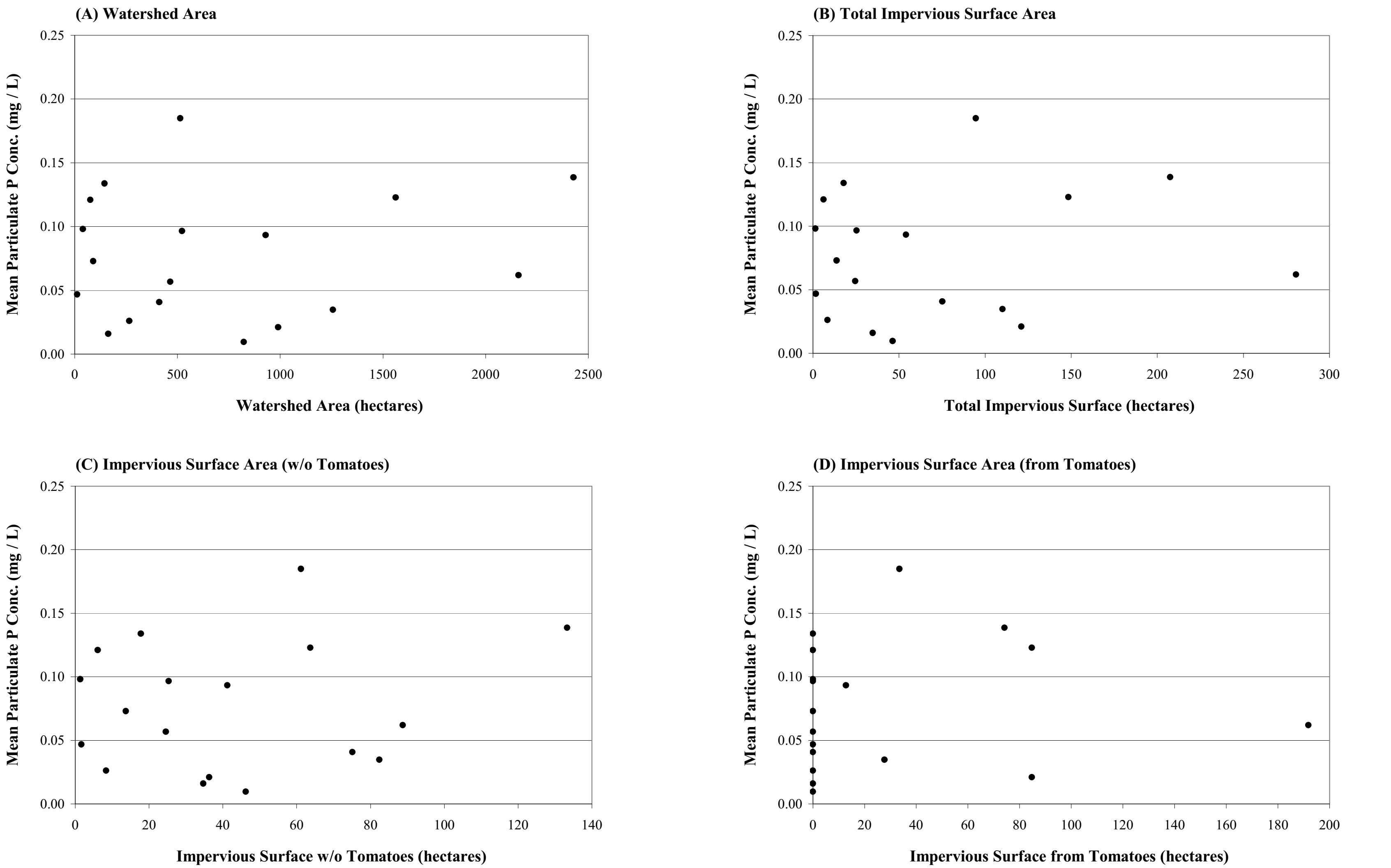


Figure 40. Particulate phosphorus concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

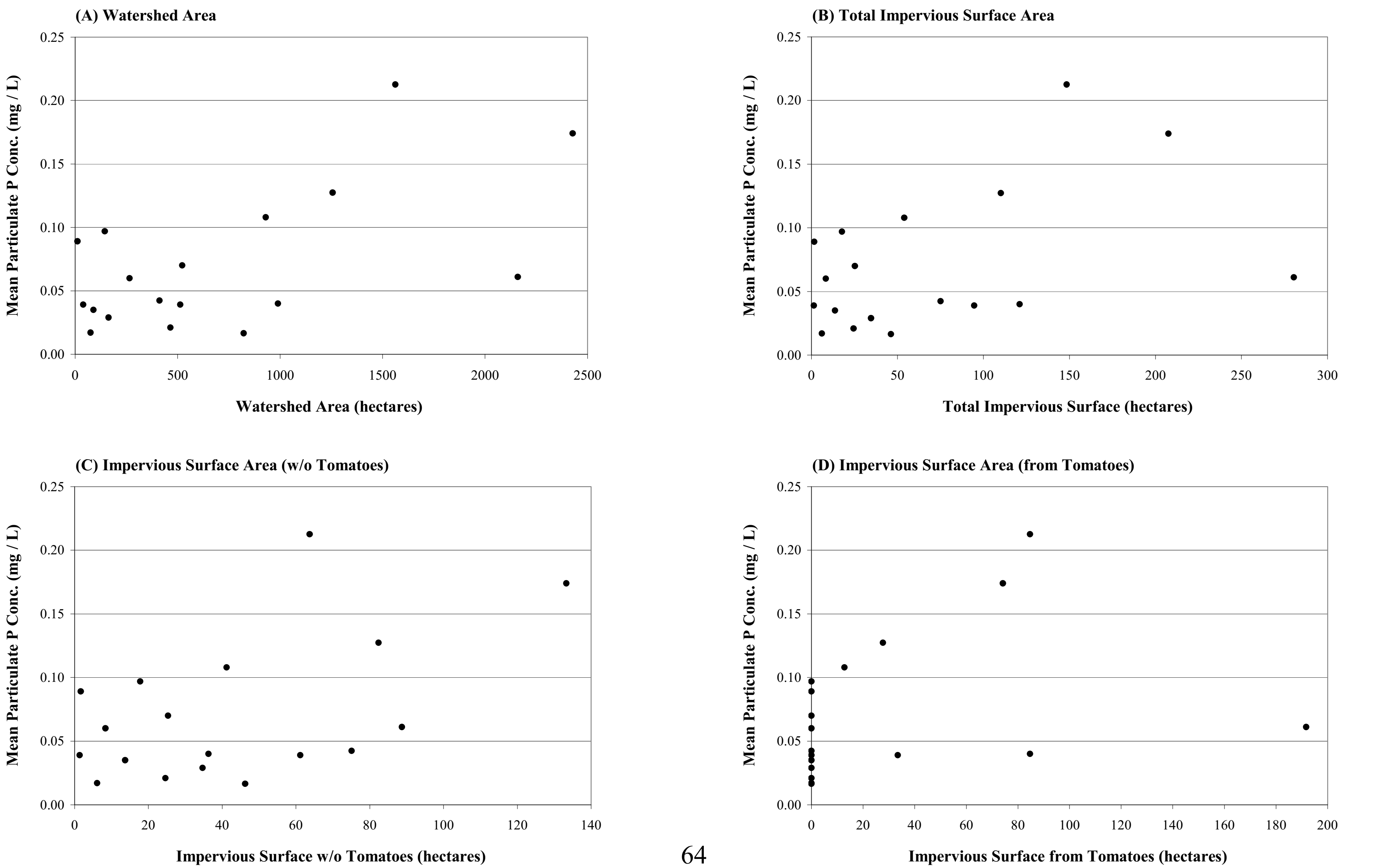


Figure 41. Particulate phosphorus concentrations in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from bi-weekly samples taken from Apr. – Oct 2007.

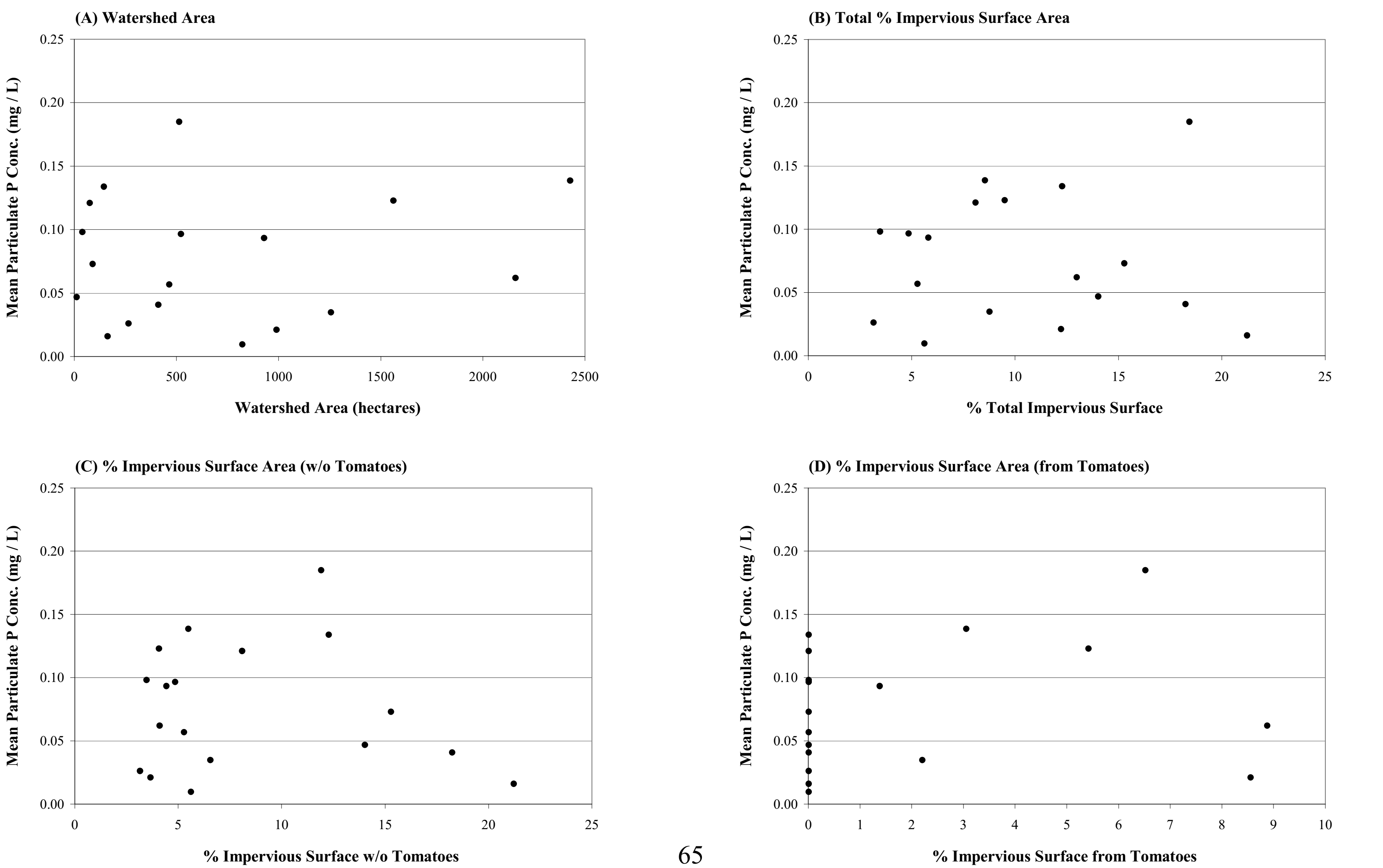
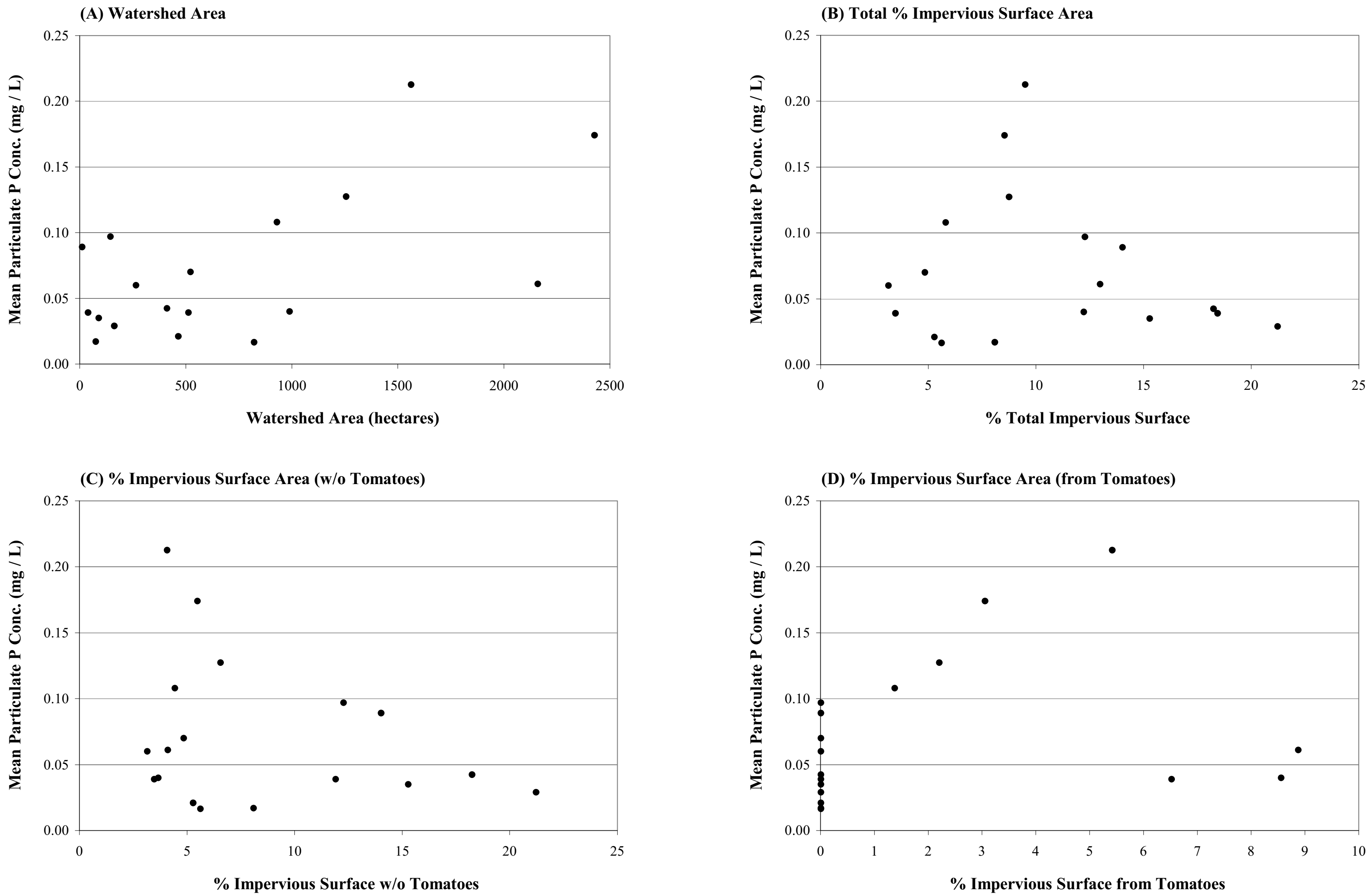


Figure 42. Particulate phosphorus concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Phosphorus Flux

Dissolved phosphorus fluxes were typically an order of magnitude below values for particulate phosphorus and are again not shown for brevity. Mean particulate phosphorus fluxes varied across watersheds from < 1 to > 200 mg s^{-1} (Figs. 43 – 46). Positive relationships were observed between the flux of particulate P and watershed area, total IS area, IS area w/o tomatoes and IS area from tomatoes (Fig. 43 A – D). Regressions between the parameters were good at explaining the variation among the majority of the study sites, but did not explain well those sites with particularly high fluxes of phosphorus Fig. 43).

Similar patterns were observed in the flux of particulate phosphorus following rainfall events (Fig. 44), but no pattern was evident with IS area from tomato cultivation (Fig. 44 D). Unexpectedly particulate phosphorus flux generally declined following rainfall events.

When impervious surfaces within the watersheds are expressed as percents of watershed area, no relationships between particulate phosphorus fluxes were observed for mean fluxes (Fig. 45) or those following significant rainfall events (Fig. 46).

Figure 43. Particulate phosphorus flux in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from bi-weekly samples taken from Apr. – Oct 2007.

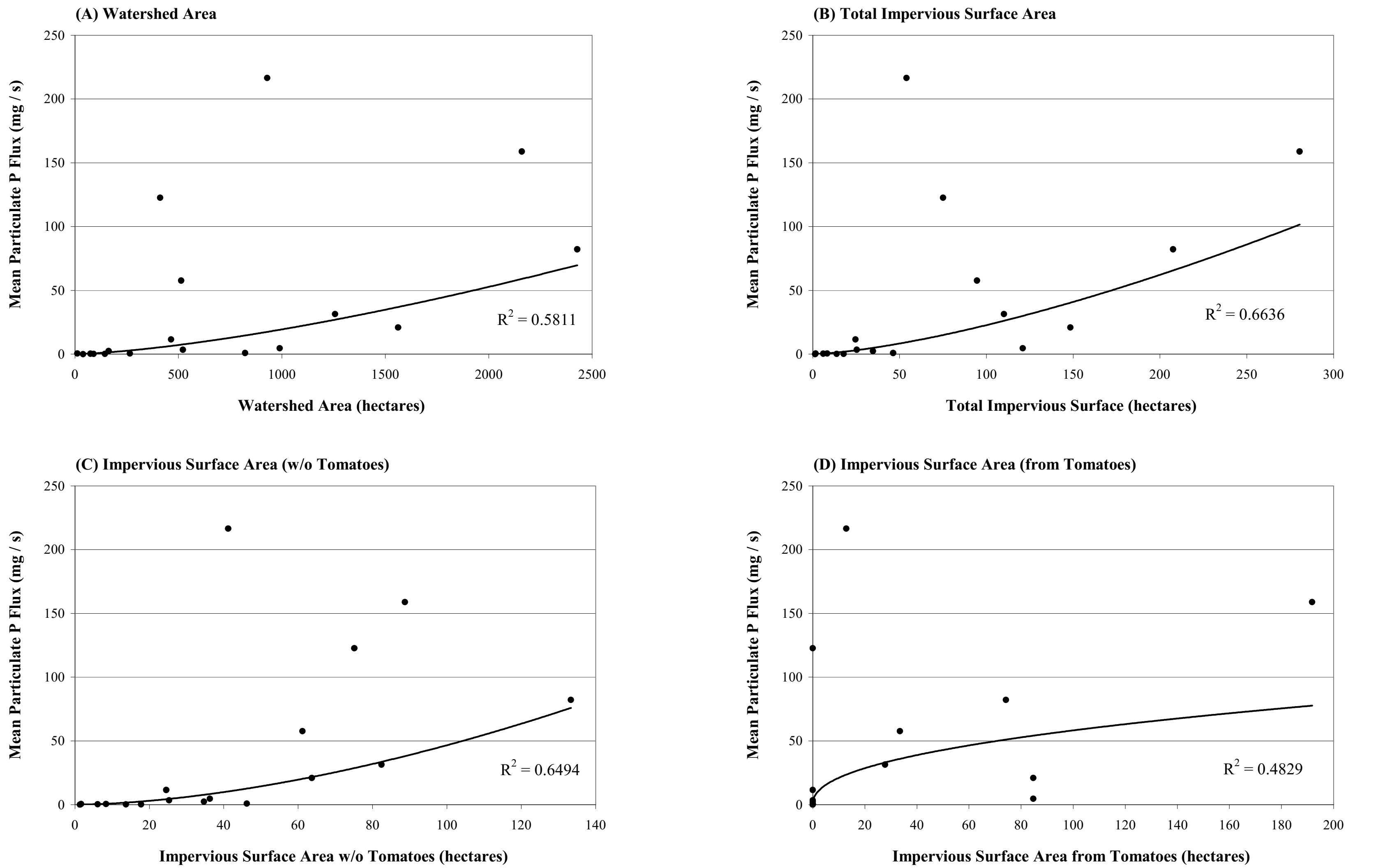


Figure 44. Particulate phosphorus flux following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken within 48 of a 1” or greater rain from Apr. – Oct 2007.

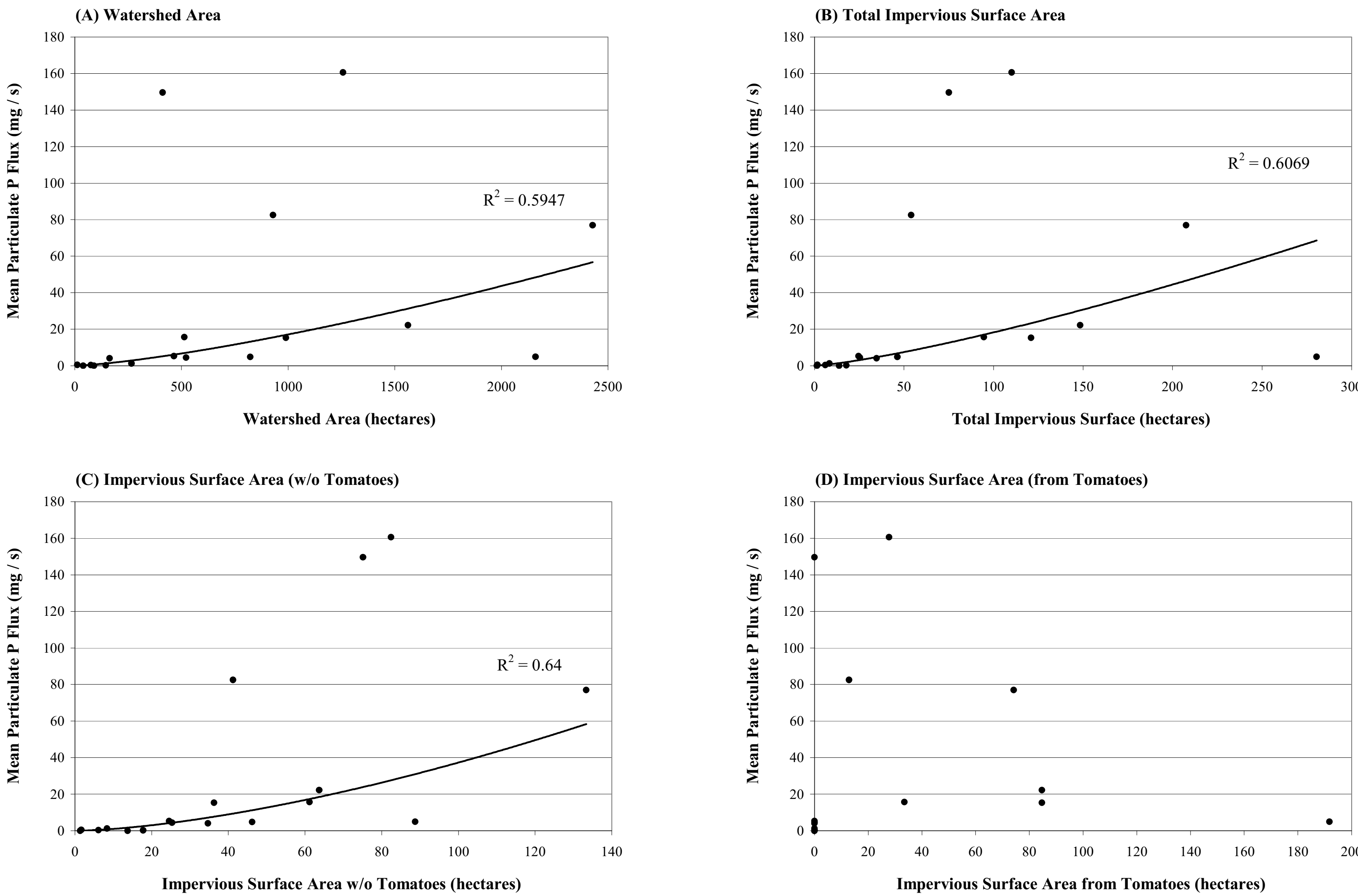


Figure 45. Particulate phosphorus flux in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken from Apr. – Oct 2007.

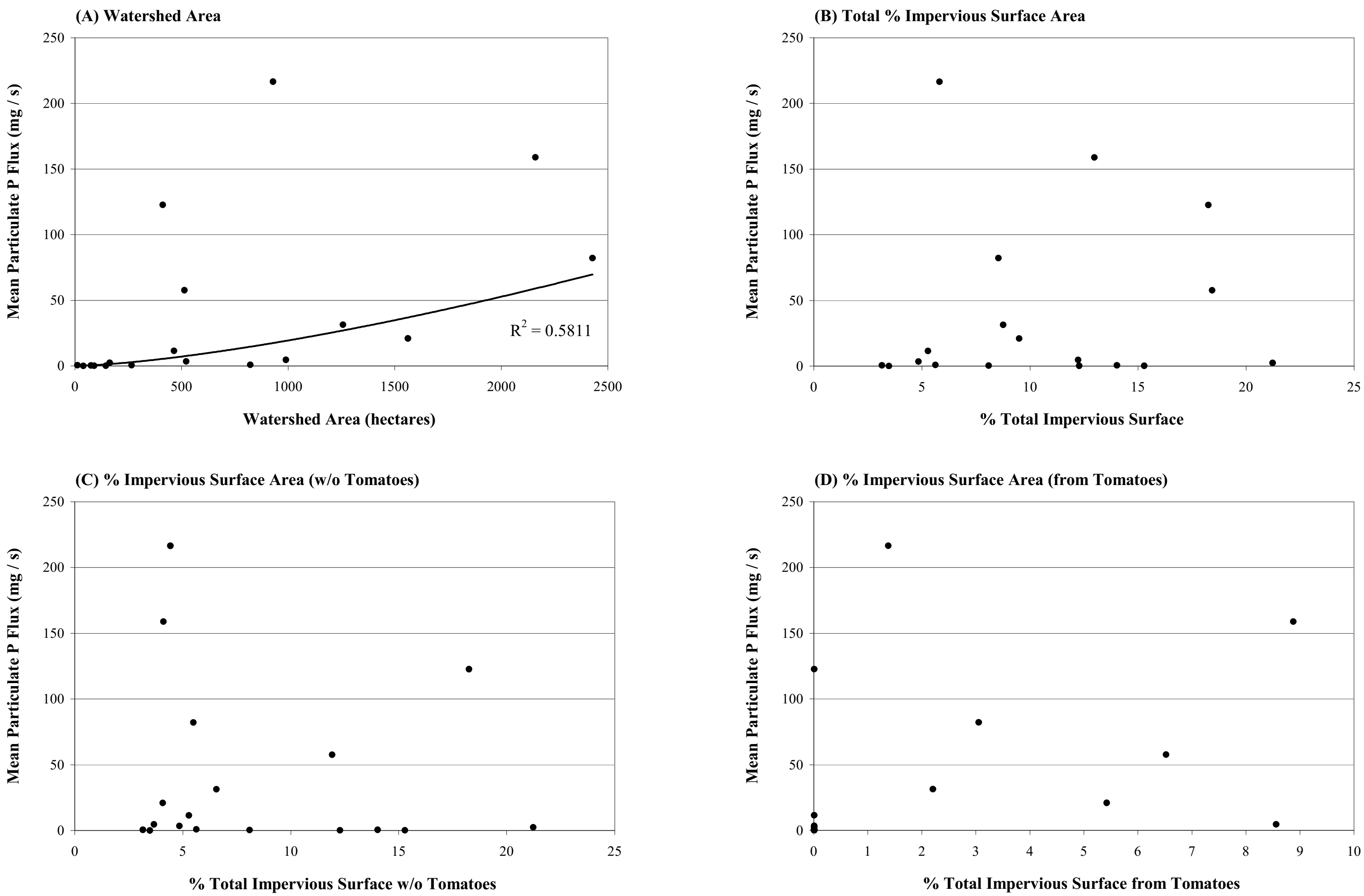
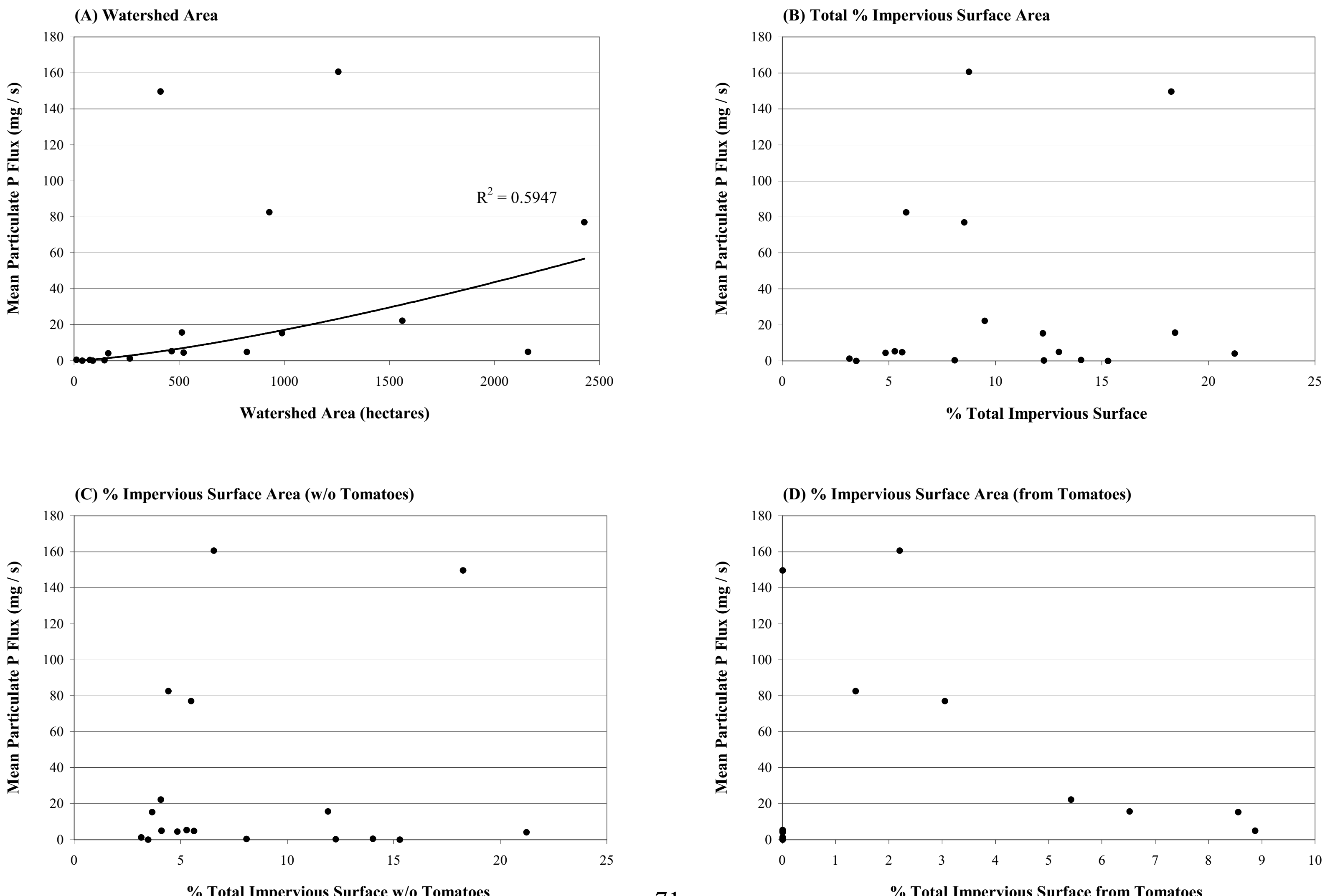


Figure 46. Particulate phosphorus flux following ≥ 1" rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in mg/L x stream discharge from samples taken within 48 hrs of a 1" or greater rain from Apr – Oct 2007.



Chlorophyll *a* Concentrations

Mean concentration of chlorophyll *a* varied across the watersheds from 1 to nearly 90 µg L^{-1} (Figs. 47 – 50). None of this variation was, however, explained by watershed area, total IS area, IS area w/o tomato cultivation or IS area from tomato cultivation (Figs. 42 A – D). Ten of the 18 study sites had mean Chl *a* concentrations below 10 90 µg L^{-1} for the duration of the study. Highest mean values of Chl *a* were found at the Lower Muddy Creek, Mid Muddy Creek and Lower Parting Creek (see Table 5 and Fig. 47).

Following 1 inch or greater rainfall events there were weak trends of increasing Chl *a* with increasing impervious surface (Figs. B – D), but none of these trends were statistically significant. As might be expected, Chl *a* concentrations in the study creeks were lower following rainfall events, presumably the result of dilution effects from freshwater.

When impervious surfaces are expressed as % of total watershed area, there are again no significant trends in mean Chl *a* concentrations (Figs. 49 B – D). Similarly, no trends were observed in mean Chl *a* concentrations following rainfall events (Figs. 50 A – D).

Figure 47. Chlorophyll *a* concentrations in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L from bi-weekly samples taken from Apr. – Oct 2007.

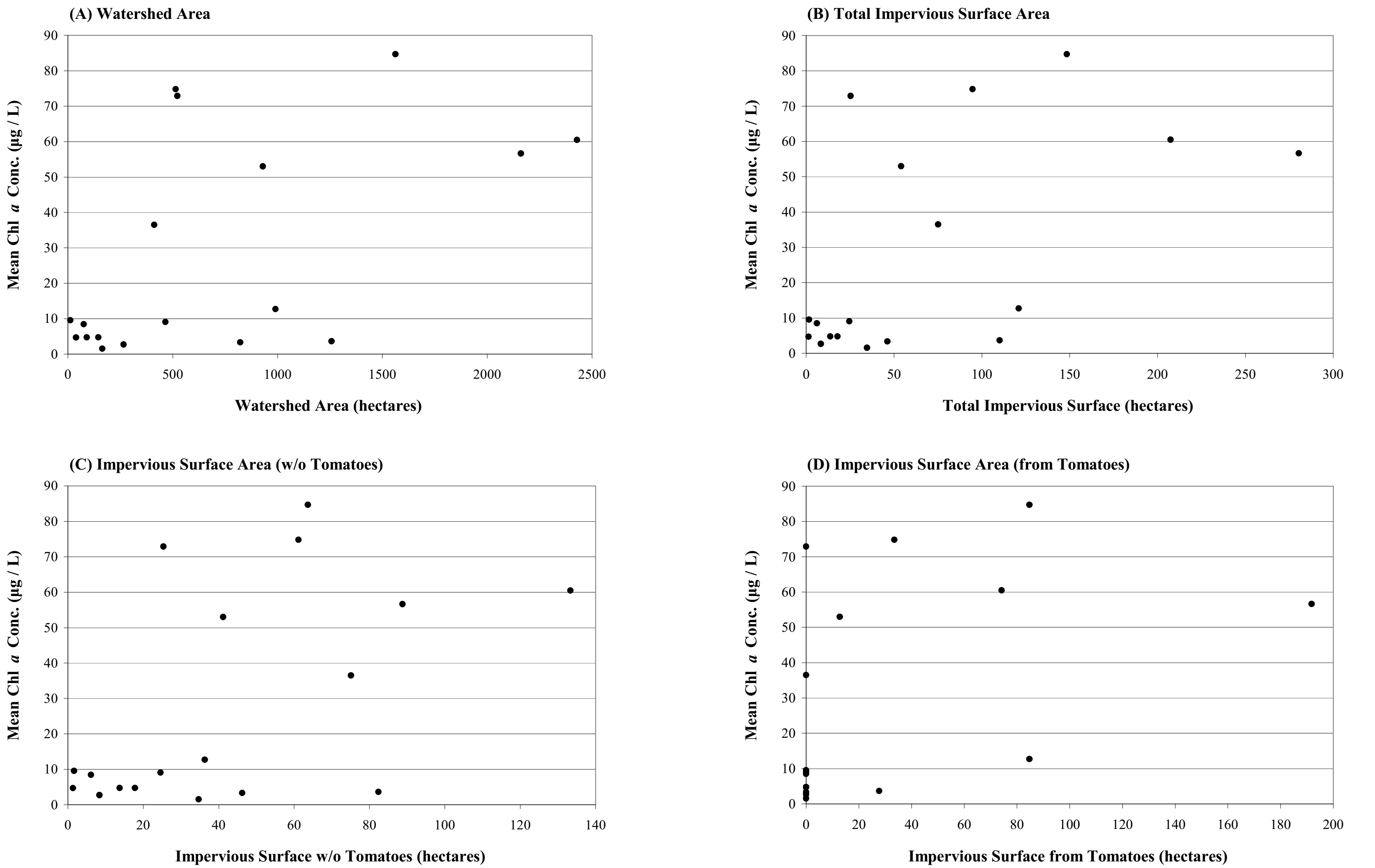


Figure 48. Chlorophyll *a* concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.

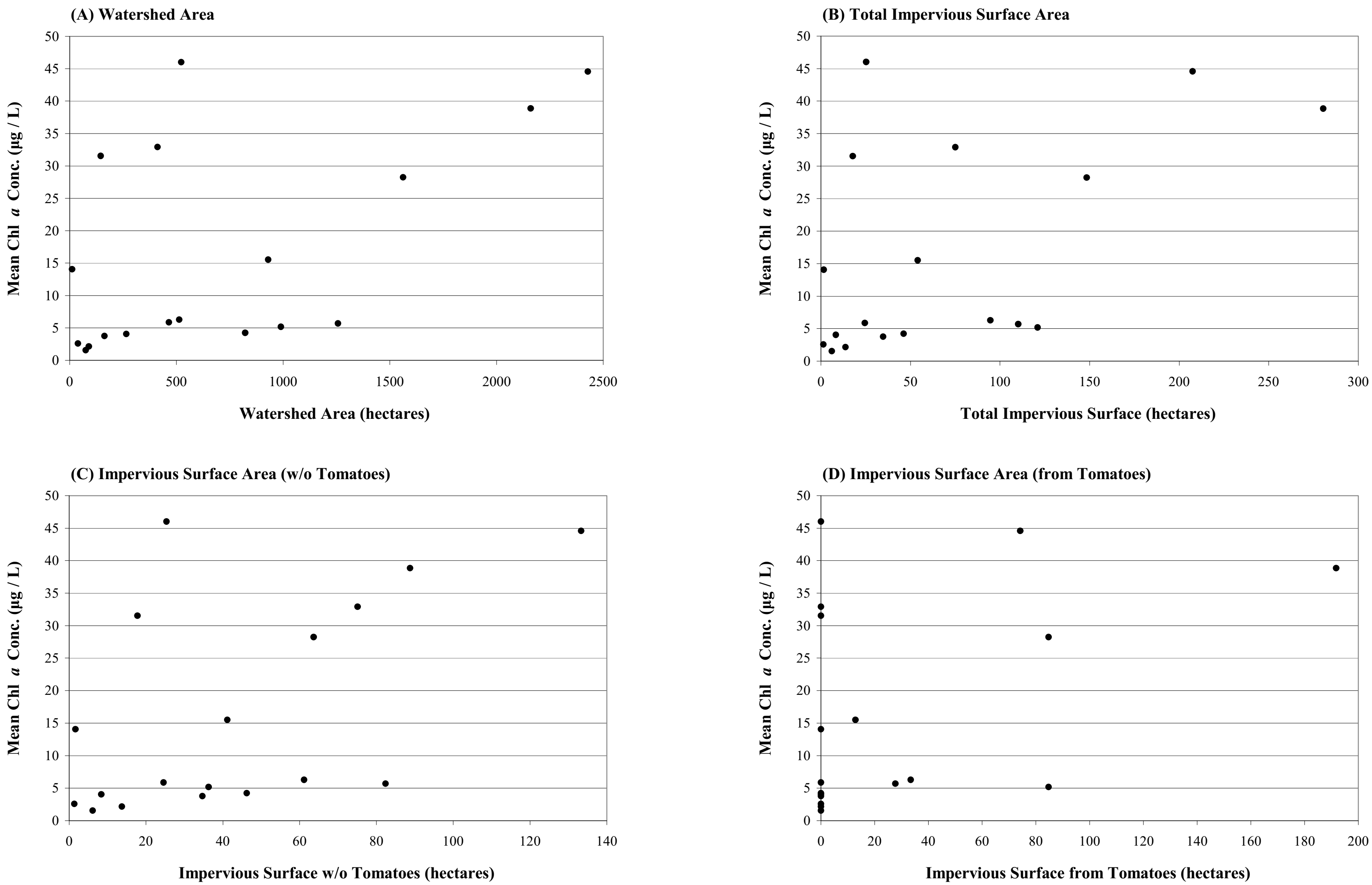


Figure 49. Chlorophyll *a* concentrations in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L from bi-weekly samples taken from Apr. – Oct 2007.

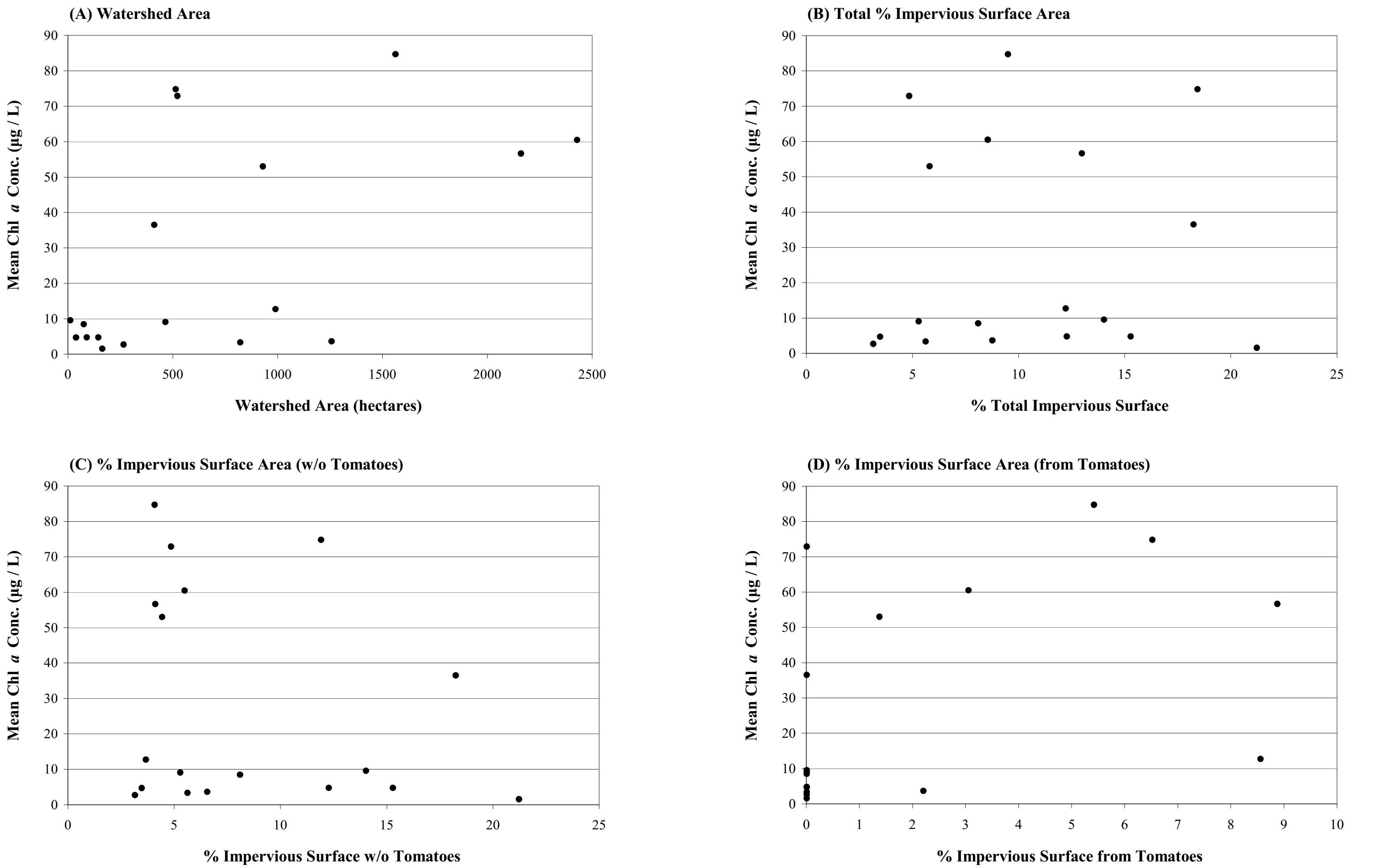
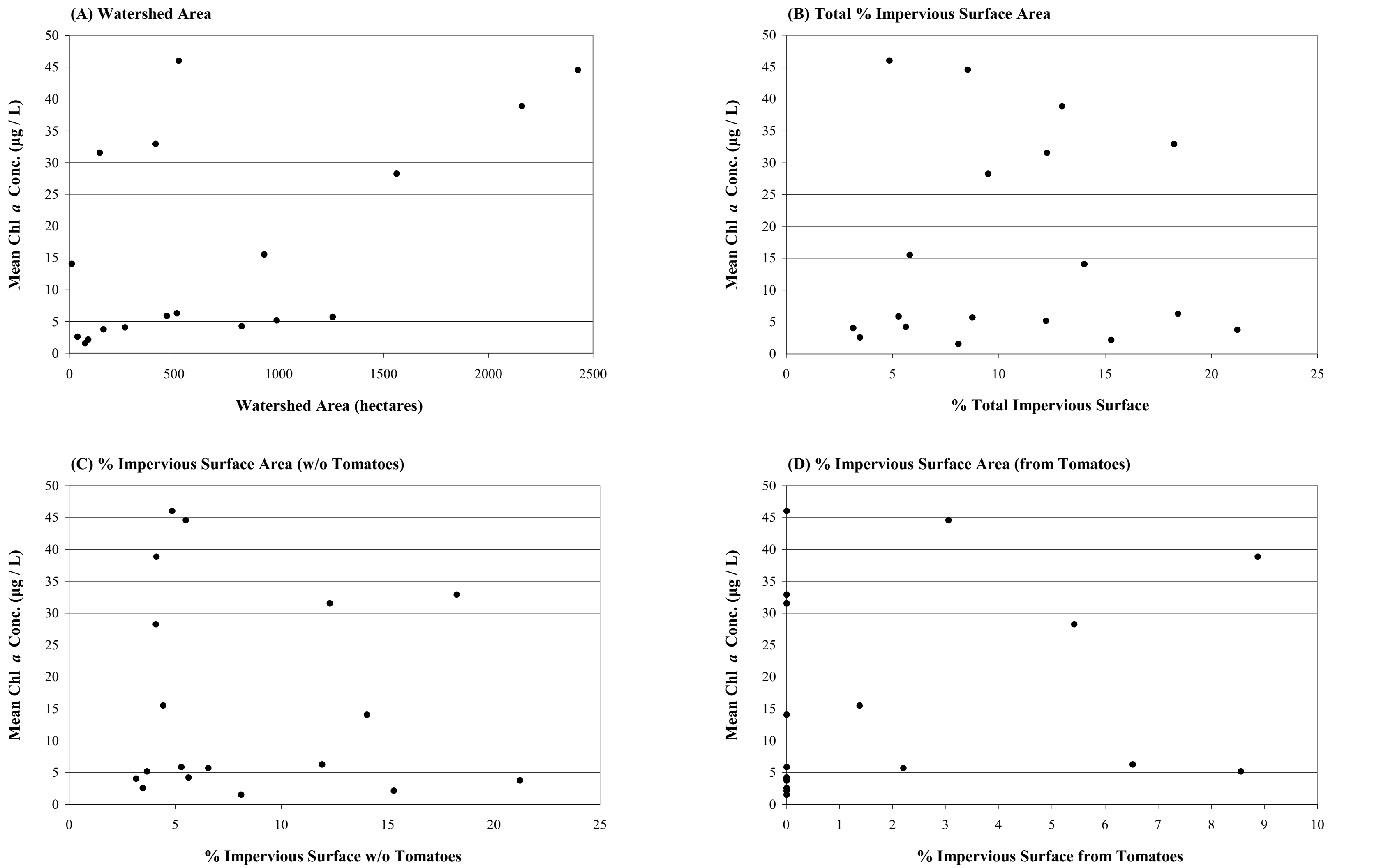


Figure 50. Chlorophyll *a* concentrations following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Chlorophyll *a* Flux

Mean flux of chlorophyll *a* varied over five orders of magnitude across sites over the period of the study (Figs. 51 – 54). Positive relationships were observed between mean flux of Chl *a* and watershed area, total IS area and IS area w/o tomato cultivation (Figs. 51 A – C), with the strongest relationship being with total IS (Fig. 51 B).

These relationships were even stronger following rainfall events of 1 inch or greater (Fig. 52 A – C). In this case 67% of the variation in mean Chl *a* flux following rainfall events across the 18 study sites was explained by the impervious surface area exclusive of tomato cultivation (Fig. 52 C).

The percentage of impervious surface within the watersheds did not explain any of the variation in Chl *a* flux, either for mean values throughout the study (Fig. 53) or following significant rainfall events (Fig. 54).

Figure 51. Chlorophyll *a* flux in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L x stream discharge from bi-weekly samples taken from Apr. – Oct 2007.

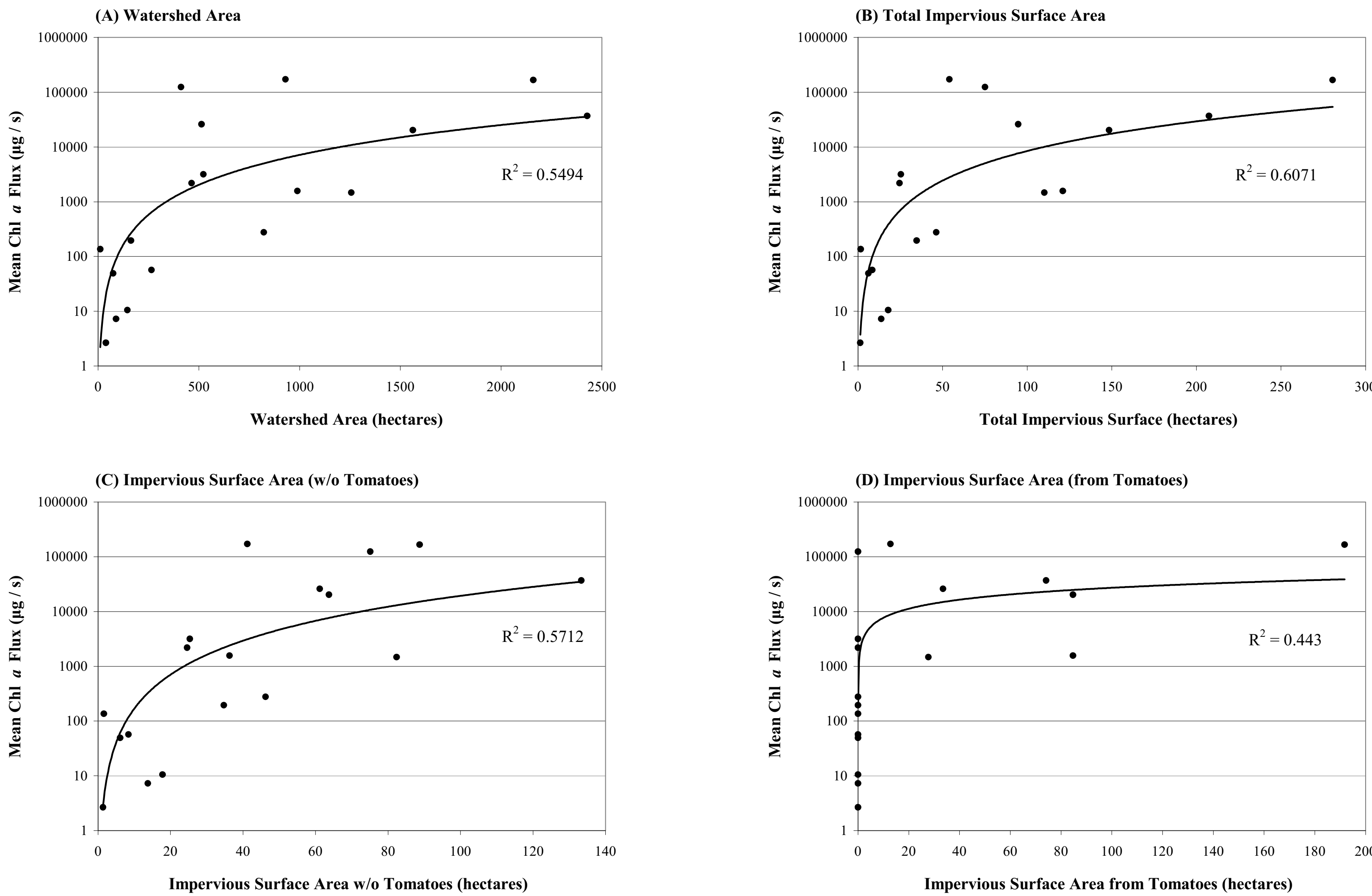


Figure 52. Chlorophyll *a* flux following ≥ 1" rain in relation to (A) total watershed area, (B) total area of the watershed covered by impervious surface, (C) area of the watershed covered by impervious surface exclusive of tomatoes and (D) area of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L x stream discharge from samples taken within 48 of a 1" or greater rain from Apr. – Oct 2007.

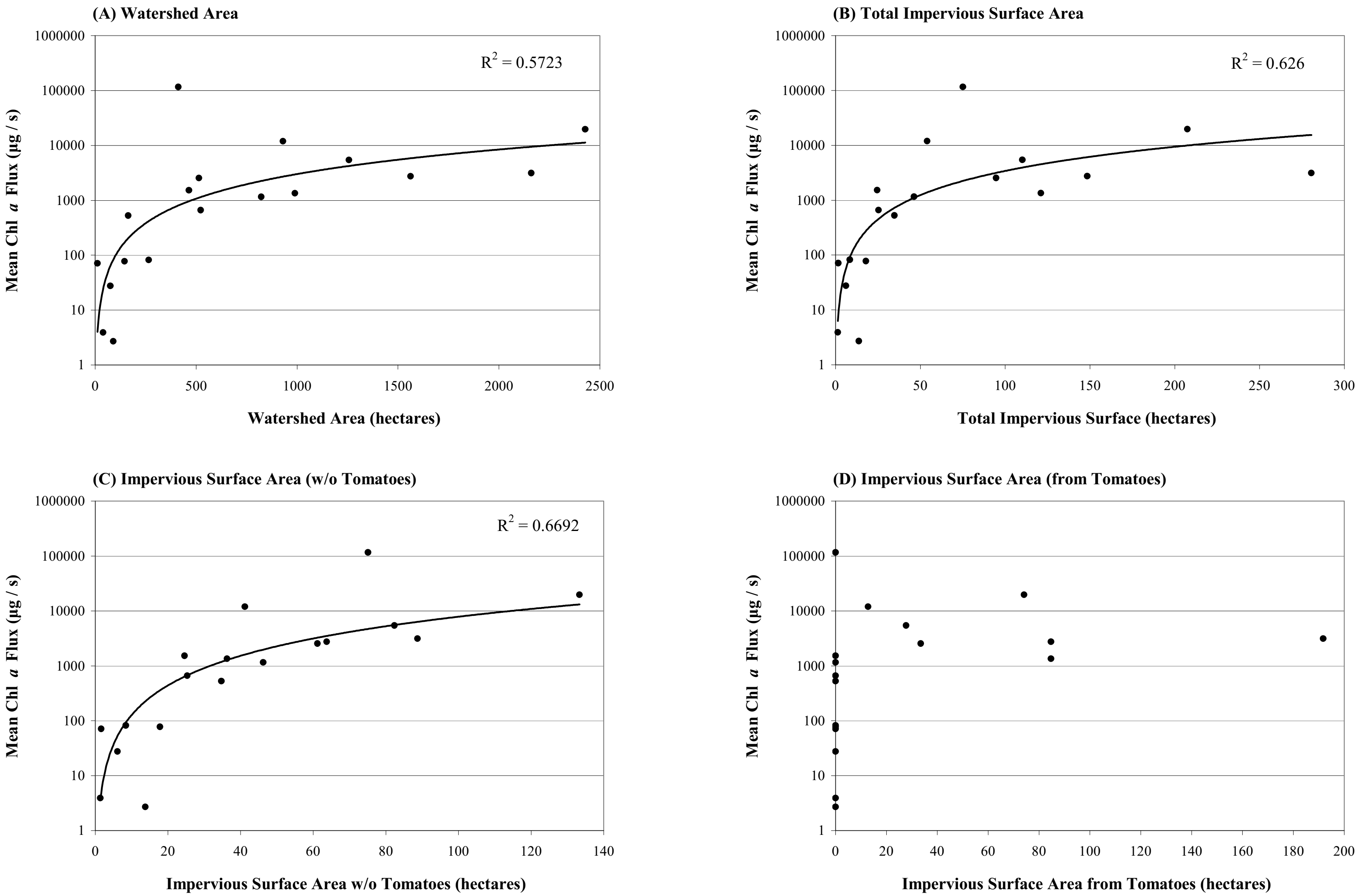


Figure 53. Chlorophyll *a* flux in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L x stream discharge from samples taken from Apr. – Oct 2007.

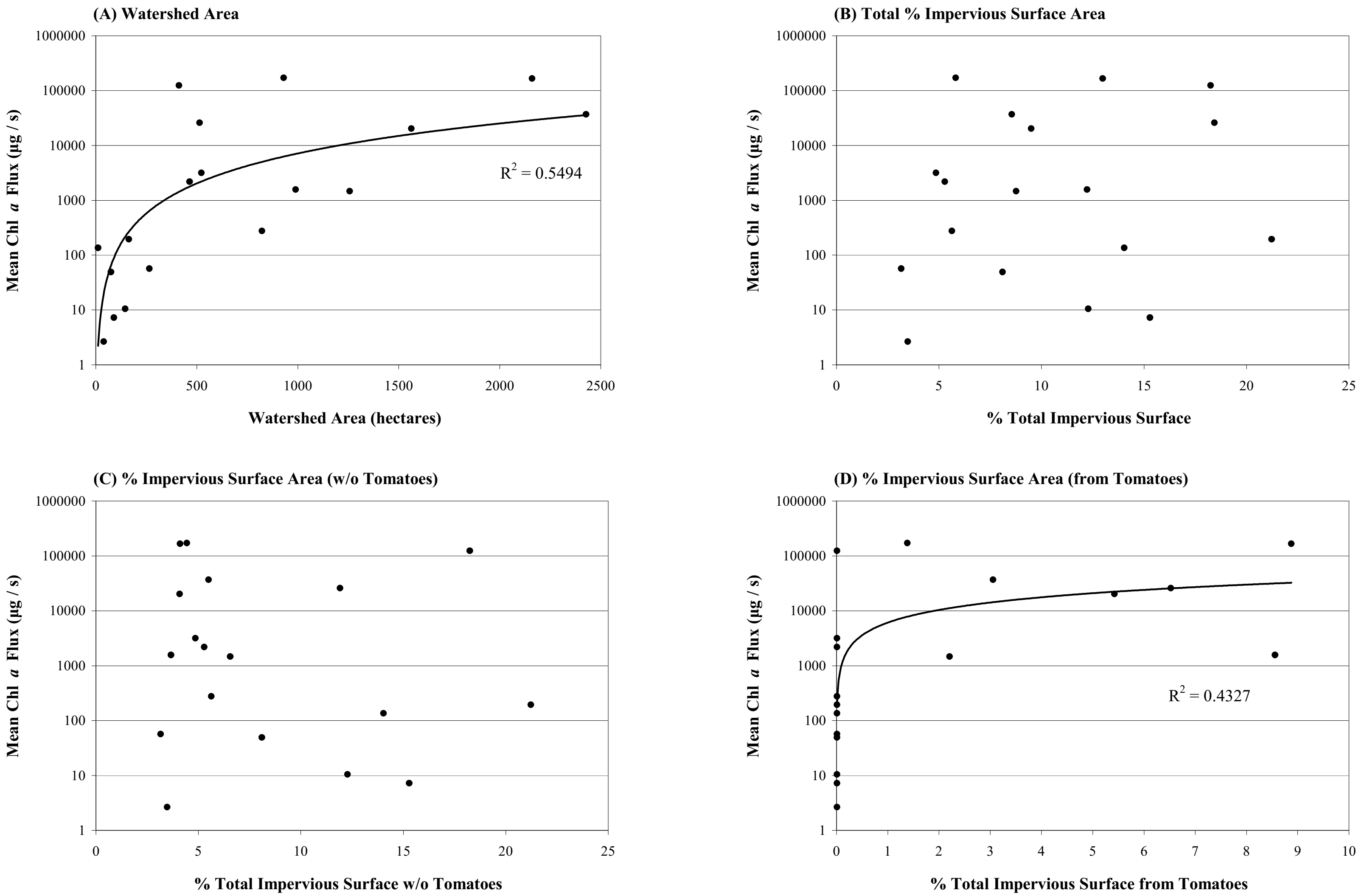
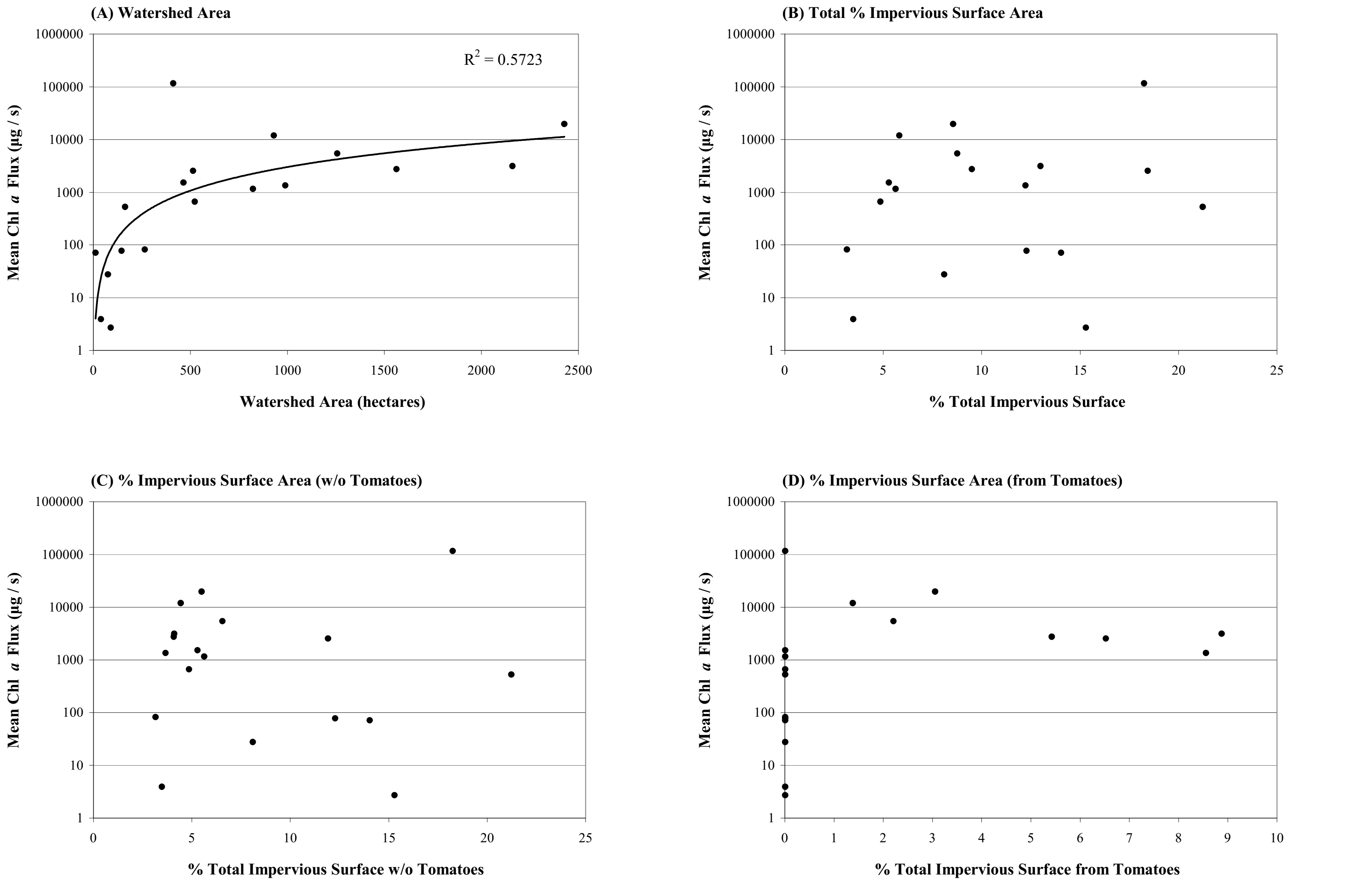


Figure 54. Chlorophyll *a* flux following ≥ 1” rain in relation to (A) total watershed area, (B) total % of the watershed covered by impervious surface, (C) % of the watershed covered by impervious surface exclusive of tomatoes and (D) % of the watershed covered by impervious surface from tomatoes only. Values are means concentrations in µg/L x stream discharge from samples taken within 48 hrs of a 1” or greater rain from Apr – Oct 2007.



Correlations Water Quality and Impervious Surfaces

The foregoing regression analyses identified numerous instances in which positive relationships between watershed area and various impervious surface measures explained greater than 50% of the variation in mean fluxes of materials (see Figs. 19, 20, 27, 28, 29, 35, 36, 43, 44, 51 & 52), but no such relationships were observed with mean concentrations of these materials. Many of the significant relationships observed in these regression analyses were based upon power functions and much of their explanatory value was the result of good fits at low values. A more conservative approach is to examine correlation coefficients between watershed parameters and material concentrations and fluxes.

We computed correlation coefficients between mean concentrations of the various water quality parameters and watershed characteristics for the duration of the study and following 1 inch or greater rainfall events (Table 6). Significant positive correlations were found between mean Chl *a* concentration throughout the study period and watershed area, total IS area, IS area w/o tomato cultivation and IS area from tomato cultivation. The same was true for Chl *a* concentration following rainfall events with the exception that the relationship with IS from tomato cultivation was marginally insignificant (Table 6). Mean concentration of Chl *a* was also positively correlated with the % IS attributable to tomato cultivation. The only other significant correlation observed for overall mean concentrations was between mean total dissolved nitrogen concentration and total % IS in the watershed. Following rainfall events, the other significant correlations were between (1) total watershed area and TSS and particulate P concentrations, (2) total IS area in the watershed and mean dissolve N and (3) total IS area exclusive of tomato cultivation and mean dissolved N and particulate P (Table 6).

The results of the correlation analyses differed when we considered fluxes of material across the study sites (Table 7). Significant positive correlations were observed between (1) total watershed area and mean flux of TSS, dissolved N and particulate P, (2) total IS area in the watershed and mean flux of dissolved N, particulate P and Chl *a*, (3) IS area exclusive of tomato cultivation and mean flux of coliform bacteria, TSS, dissolved N and particulate P, and (4) IS area attributable to tomato cultivation and mean flux of Chl *a* (Table 7). We also observed positive correlations between IS area exclusive of tomato cultivation and fluxes of TSS, dissolved N and particulate P following significant rainfall events (Table 7). No significant correlations were observed between the fluxes of any of these materials and the % coverage by impervious surfaces within the watersheds. Further, there were no significant negative correlations between any of the water quality parameters and watershed characteristics (Tables 6 & 7).

Table 6. Correlation coefficients for several watershed parameters (both in terms of actual area and % area), including impervious surface (IS), for the geometric mean of Coliform bacteria concentration, mean Total Suspended Solids (TSS) concentration, mean Total Dissolved Nitrogen (TDN) concentration, mean Particulate Phosphorus (PP) concentration and mean Chlorophyll *a* (Chl *a*) concentration. Separate correlations are reported for overall data and in cases of >1” rainfall within 48 hrs of sampling.

	Watershed Parameter	Coliform Conc. (CFU/100 ml)	TSS Conc. (mg/L)	TDN Conc. (mg/L)	PP Conc. (mg/L)	Chl *a* Conc. (µg/L)
Overall	Total Watershed Area (Hectares)	-0.101	0.313	-0.153	0.124	0.562*
	Total IS in Watershed (Hectares)	-0.159	0.303	-0.327	0.129	0.564*
	Total IS Attributable to Land Cover exclusive of Tomatoes (Hectares)	-0.115	0.427	-0.245	0.158	0.540*
	Total IS Attributable to Tomatoes Only (Hectares)	-0.163	0.164	-0.329	0.087	0.482*
	Total IS in Watershed (%)	-0.170	0.078	-0.519*	0.008	0.053
	Total IS Attributable to Land Cover exclusive of Tomatoes (%)	-0.138	-0.084	-0.316	-0.092	-0.232
	Total IS Attributable to Tomatoes Only (%)	-0.049	0.285	-0.336	0.178	0.506*
> 1” Rainfall within Previous 48 hrs.	Total Watershed Area (Hectares)	-0.270	0.613**	-0.354	0.606**	0.544*
	Total IS in Watershed (Hectares)	-0.245	0.405	-0.478*	0.453	0.523*
	Total IS Attributable to Land Cover exclusive of Tomatoes (Hectares)	-0.263	0.610	-0.470*	0.509*	0.537*
	Total IS Attributable to Tomatoes Only (Hectares)	-0.190	0.191	-0.401	0.336	0.422
	Total IS in Watershed (%)	0.122	-0.234	-0.436	-0.139	0.017
	Total IS Attributable to Land Cover exclusive of Tomatoes (%)	0.239	-0.290	-0.182	-0.268	-0.093
	Total IS Attributable to Tomatoes Only (%)	-0.215	0.110	-0.433	0.235	0.195

* Indicates significant correlation, $p<0.05$; ** Indicates significant correlation, $p<0.01$

Table 7. Correlation coefficients for several watershed parameters (both in terms of actual area and % area), including impervious surface (IS), for mean Coliform bacteria flux, mean Total Suspended Solids (TSS) flux, mean Total Dissolved Nitrogen (TDN) flux, mean Particulate Phosphorus (PP) flux and mean Chlorophyll *a* (Chl *a*) flux. Separate correlations are reported for overall data and in cases of >1" rainfall within 48 hrs of sampling.

	Watershed Parameter	Coliform Flux (CFU/s)	TSS Flux (mg/s)	TDN Flux (mg/s)	PP Flux (mg/s)	Chl *a* Flux (μg/s)
Overall	Total Watershed Area (Hectares)	0.344	0.510*	0.663**	0.502*	0.437
	Total IS in Watershed (Hectares)	0.336	0.453	0.583*	0.529*	0.514*
	Total IS Attributable to Land Cover exclusive of Tomatoes (Hectares)	0.580*	0.530*	0.740**	0.537*	0.445
	Total IS Attributable to Tomatoes Only (Hectares)	0.105	0.319	0.372	0.431	0.473*
	Total IS in Watershed (%)	0.178	-0.012	-0.003	0.091	0.128
	Total IS Attributable to Land Cover exclusive of Tomatoes (%)	0.127	-0.144	-0.122	-0.095	-0.057
	Total IS Attributable to Tomatoes Only (%)	0.082	0.236	0.213	0.328	0.325
> 1" Rainfall within Previous 48 hrs.	Total Watershed Area (Hectares)	0.267	0.427	0.210	0.335	0.030
	Total IS in Watershed (Hectares)	0.234	0.306	0.177	0.281	0.113
	Total IS Attributable to Land Cover exclusive of Tomatoes (Hectares)	0.449	0.623**	0.519*	0.601**	0.363
	Total IS Attributable to Tomatoes Only (Hectares)	0.043	0.030	-0.093	0.008	-0.082
	Total IS in Watershed (%)	0.062	-0.020	0.141	0.100	0.326
	Total IS Attributable to Land Cover exclusive of Tomatoes (%)	-0.009	-0.026	0.174	0.097	0.385
	Total IS Attributable to Tomatoes Only (%)	0.123	0.012	-0.066	0.001	-0.121

* Indicates significant correlation, p<0.05; ** Indicates significant correlation, p<0.01

CONCLUSIONS AND DISCUSSION

This study did not find significant relationships between the percent of the watersheds covered by impervious surfaces and the concentrations of coliform bacteria, suspended solids, nutrients or chlorophyll *a* observed in other studies (Mallin et al. 2000, Holland et al. 2004). We did identify numerous significant positive relationships between the flux (or loading) of these material and the total area of the watersheds and impervious surfaces. The reasons for the differences observed in this study and previous works in not entirely clear. On point of difference may be that our study was conducted during a below average rainfall year. For the period between April and November 2007 rainfall in this region was approximately 75% of average values. Despite this, our data include several sampling events taken within 48 hrs of a 1 inch or greater rainfall event at each of the study sites. Observed patterns following rainfall events were not markedly different from those observed throughout the period.

We are confident that our study design, bi-weekly sampling and 18 sample locations, provides a very robust dataset. Despite recent development, the Eastern Shore of Virginia remains largely rural and relatively few watersheds have a high percent cover by impervious surfaces. To achieve some watersheds with > 10% cover by impervious surface is was necessary in some cases to select sample locations that were upstream of tidal influences. Five of these sites—Upper Parting Creek, Onancock Creek, North Kings Creek, North Katy Young Creek and The Gulf, Eastville—receive drainage from the small towns of Exmore, Onancock, Cheriton, Parksley and Eastville, respectively. Three of the sites—Lower Parting Creek, Occohonnack Creek and Upper Muddy Creek have significant proportions of their watersheds covered by impervious surface from tomato cultivation. It is possible that the lack of strong positive relationships between water quality parameters and impervious surface in this study is related, in part, to the nature of residential development on the Eastern Shore, which contains significant green space and often lacks extensive storm drainage systems.

Most of the positive relationships that we observed between water quality parameters and watershed characteristics were for fluxes and these patterns were largely driven by water discharge rate which was positively correlated with watershed area. Since most of our sample sites were located in upstream reaches of the creeks, we feel that these fluxes, which represent loading values, are the most appropriate metrics to use in considering the effects of land use on water quality.

The fact that the observed positive relationships between water quality parameters and watershed characteristics rarely explained more than 50 – 60% of the variance in the data should not be surprising. Numerous other factors within the watershed, including point source discharges, proximity of sources to our sample sites and variations in domestic and wild animal abundances can all contribute to the observed variations. The goal of this study was not to identify specific sources of pollutants from within a watershed, but rather to identify trends across watersheds that were related to coverage by impervious surfaces. In doing so, it is abundantly clear that loadings of coliform bacteria, sediment and nutrients to the coastal waters of the Eastern Shore are related to both watershed size and the amount of traditional impervious surface in the watershed. It is not apparent from our dataset that impervious surface attributable to tomato cultivation is correlated with elevated loadings of these materials. This finding is somewhat surprising given our casual observations over the past decade of high levels of run-off from tomato fields. It is possible that this inconsistency arose as a result of low rainfall during the study period or that the particular tomato fields that comprised large areas of some watersheds had good storm water run-off measures in place. We do know from a previous study (Arnold et al. 2002) that water quality impacts from tomato cultivation can be greatly reduced through the use of storm water retention mechanisms. In the case of the watershed with the largest area under tomato cultivation during this study, Occohannack Creek, the tomato fields in that watershed have been part of a large project with the Eastern Shore Soil & Water Conservation District to minimize run-off. Further studies in watersheds with varying tomato cultivation practices would need to be conducted to further clarify this issue.

Some caution needs to be exercised in interpreting the sometimes weak or non-significant relationships observed in this study between impervious surfaces and water quality. Current development on the Eastern Shore remains low relative to many coastal environments. At high levels of development there are few mysteries about what happens to coastal water quality; degradation is inevitable. A major concern in an area undergoing rapid development, as is the Eastern Shore in some places, is that some of the undesirable effects on water quality may emerge only when thresholds are crossed and are thus not readily observed by extrapolating from earlier trends. There is little doubt that the region will continue to undergo further development and that with this development will come an increasing amount of the watersheds covered by impervious surfaces. To maintain the excellent water quality on which the valuable clam aquaculture industry, the recreational and commercial fishing industries and the quality of life on the

Shore are so dependent will require ongoing efforts to track the effects of this development on water quality and to minimize its impacts.

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APPENDICES

Appendix I. External GIS data utilized during this study.

NHD Flowline (source: U.S. Geological Survey/U.S. Environmental Protection Agency)

The National Hydrography Dataset (NHD) is a feature-based database that interconnects and uniquely identifies the stream segments or reaches that comprise the nation's surface water drainage system. Medium resolution NHD is based on the content of the U.S. Geological Survey 1:100,000-scale Digital Line Graph (DLG) hydrography data, integrated with reach-related information from the U.S. Environmental Protection Agency Reach File Version 3.0 (RF3). The stream/reach centerlines were utilized for this study. Data and details can be accessed at: http://nhd.usgs.gov/techref.html

VBMP (source: Virginia Geographic Information Network)

The Virginia Base Mapping Program (VBMP) contracted in 2002 to produce full color, leaf-off, digital orthophotography for the entire land base of Virginia. The seamless imagery for the areas used in this study were developed at 1:4,800 scale (2' resolution), which was typical for most rural areas. We utilized the images in the MrSID format. Data can be accessed at: http://www.911.virginia.gov/vbmporthophotography.shtml

Digital Quadrangle Topographic Maps (source: U.S. Geological Survey)

USGS has produced digital versions of their 7.5-minute, 1:24,000-scale quadrangle topographic map series. We utilized these rendered in raster format as GeoTiff files and stitched together seamlessly for the entire Eastern Shore of Virginia. These are simply georeferenced digital products of paper maps.

Data and details can be accessed at: http://topomaps.usgs.gov/

Appendix I (cont).

NWBD (source: U.S. Natural Resources Conservation Service)

The intent of defining hydrologic units for the National Watershed Boundary Dataset (NWBD) is to establish a base-line drainage boundary framework, accounting for all land and surface areas. Hydrologic boundaries are delineated solely upon science-based hydrologic principles. At a minimum, they are being delineated and georeferenced to the USGS 1:24,000 scale topographic base map meeting National Map Accuracy Standards (NMAS). Data and details can be accessed at:

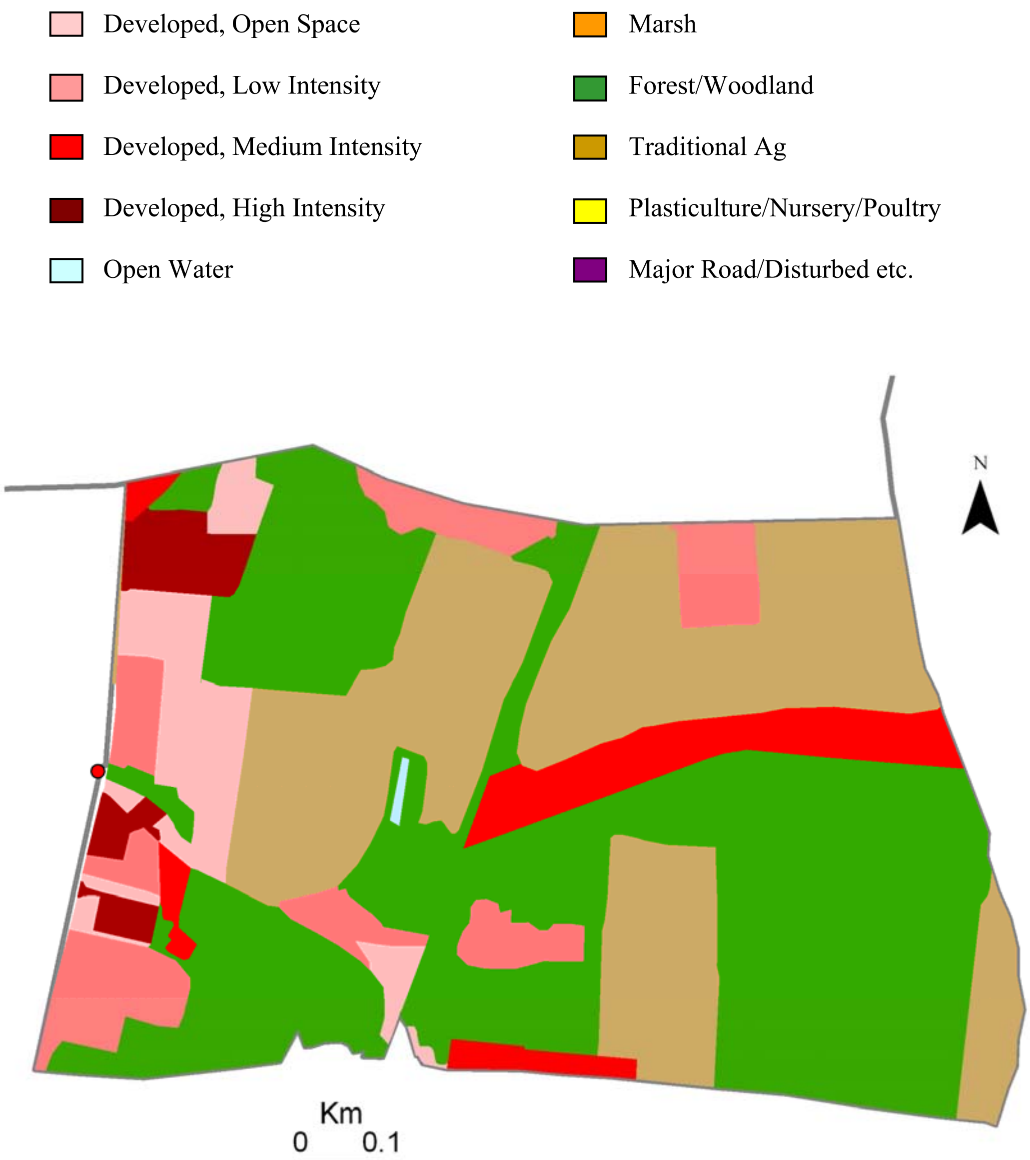
http://www.ncgc.nrcs.usda.gov/products/datasets/watershed/history.html

NLCD (source: U.S. Environmental Protection Agency)

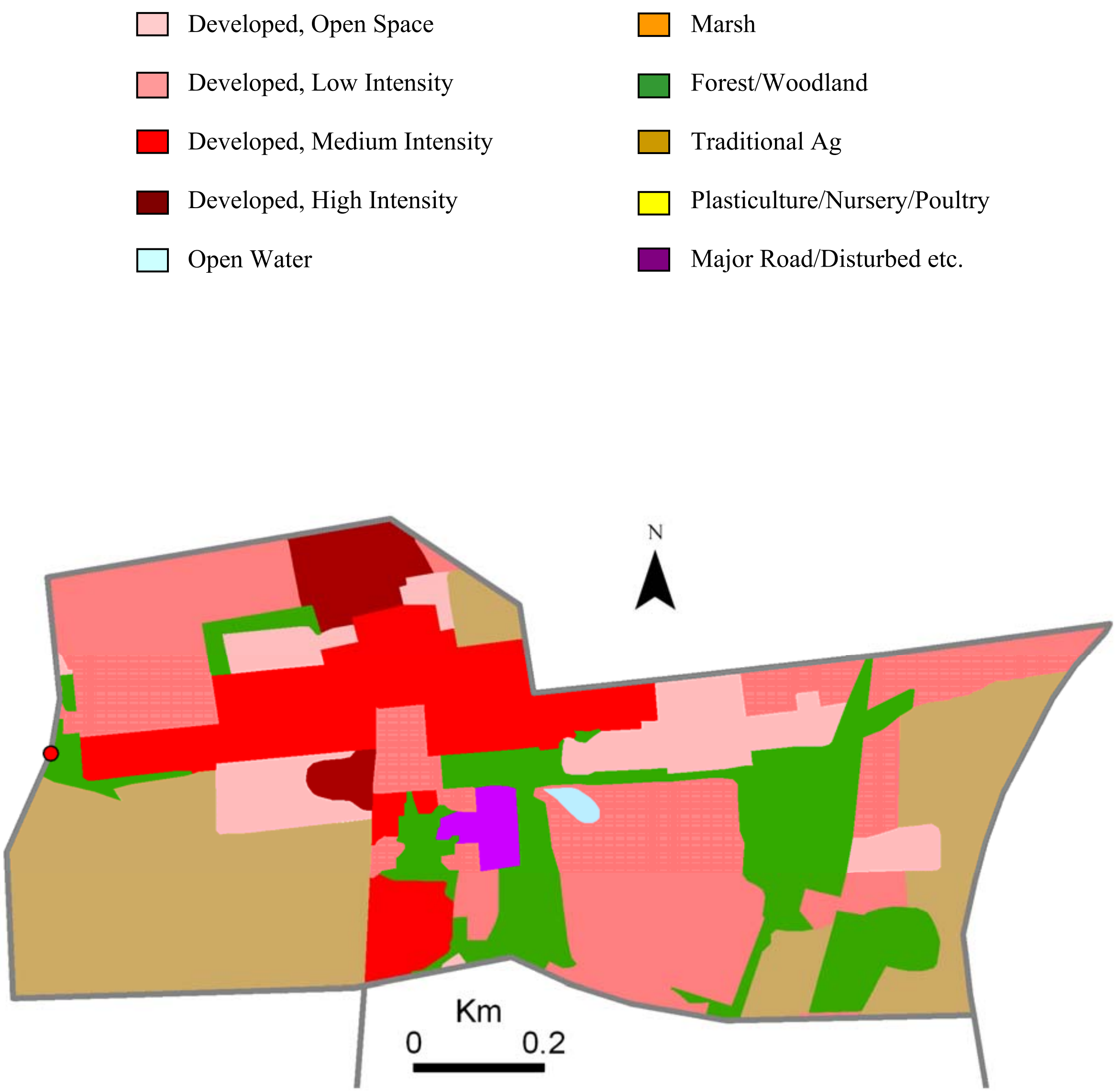
In 2001, the Multi-Resolution Land Characteristics Consortium (MRLC) produced the second iteration of National Land Cover Data (NLCD). This data uses 16 land cover classes at the native 30-meter resolution of Landsat TM for the lower 48 states. Mapping was based on algorithms utilizing clustering and logical modeling using a suite of ancillary data. NLCD 2001 is a land-cover database comprised of three elements: land cover, impervious surface and canopy density. Data and details can be accessed at:

http://www.epa.gov/mrlc/nlcd-2001.html

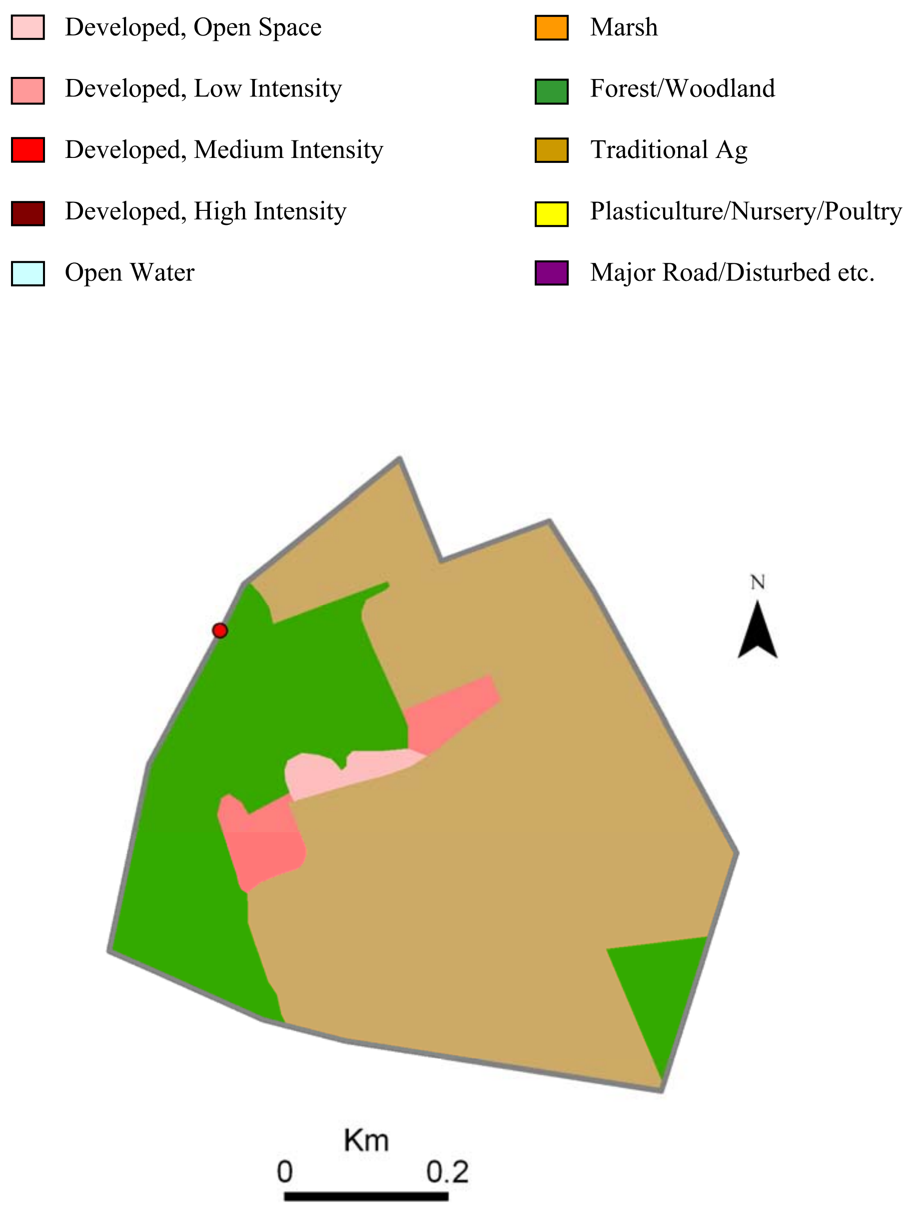
Appendix II.A. South King's Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



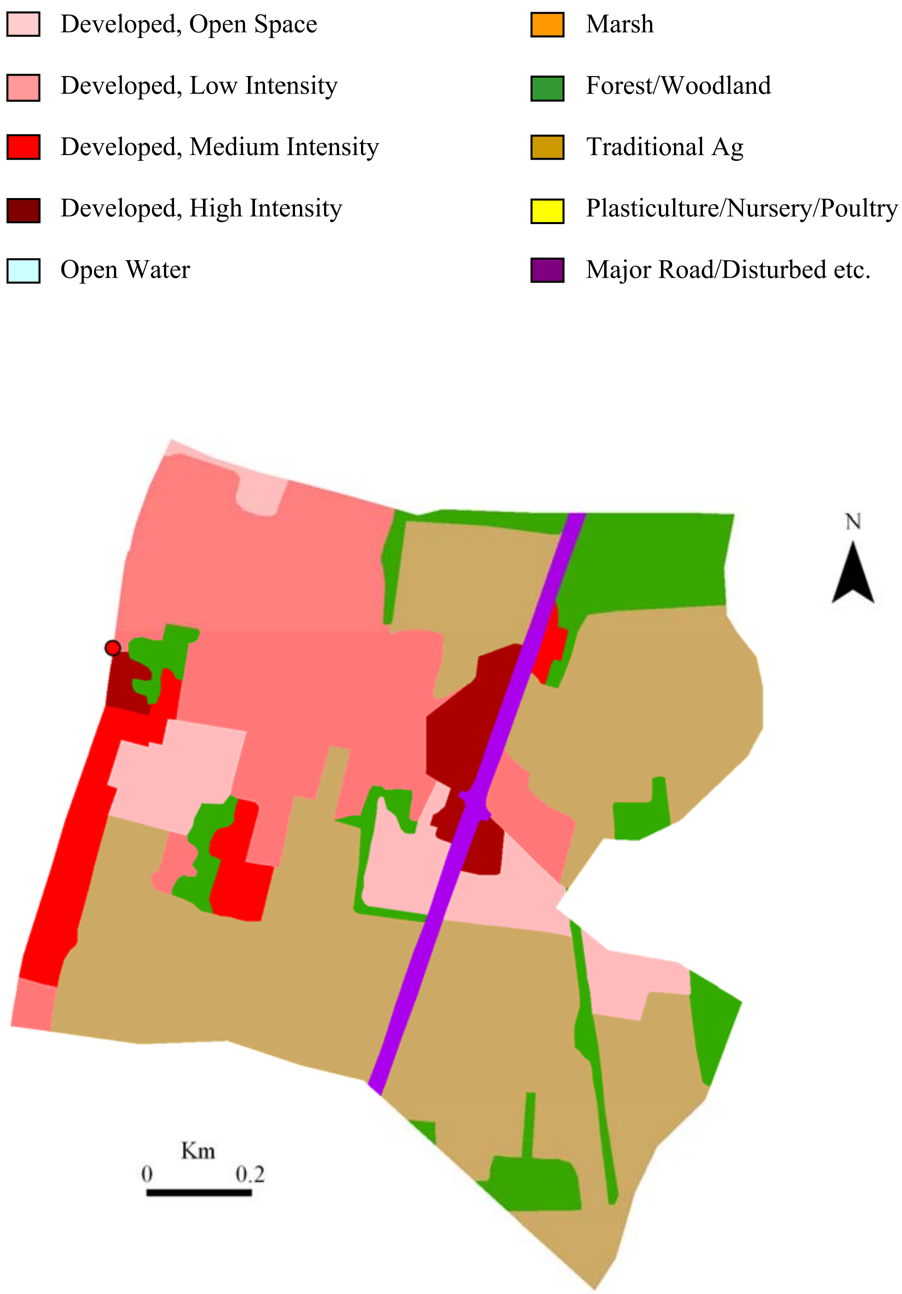
Appendix II.B. North King's Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



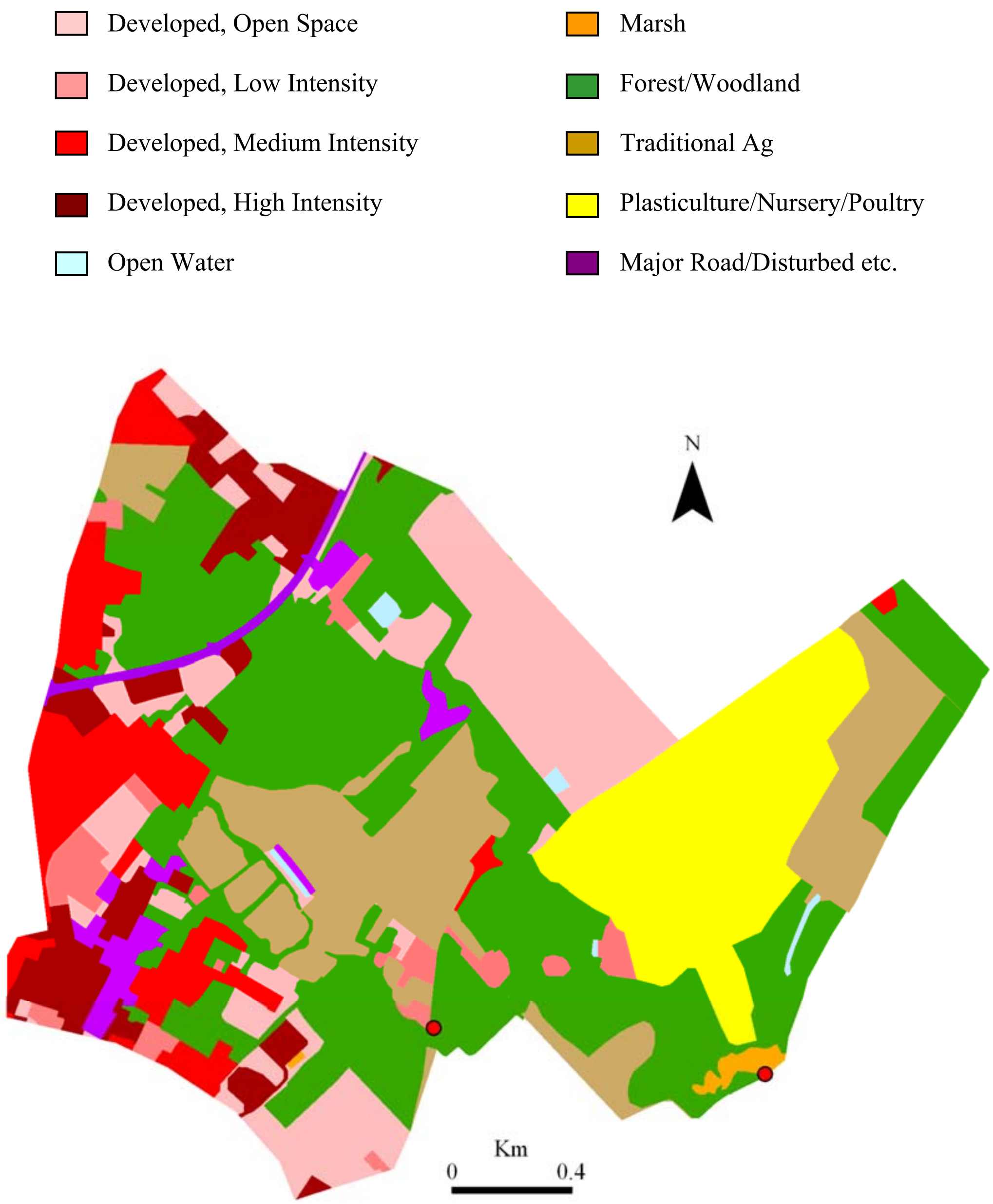
Appendix II.C. The Gulf (Savage Neck) watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



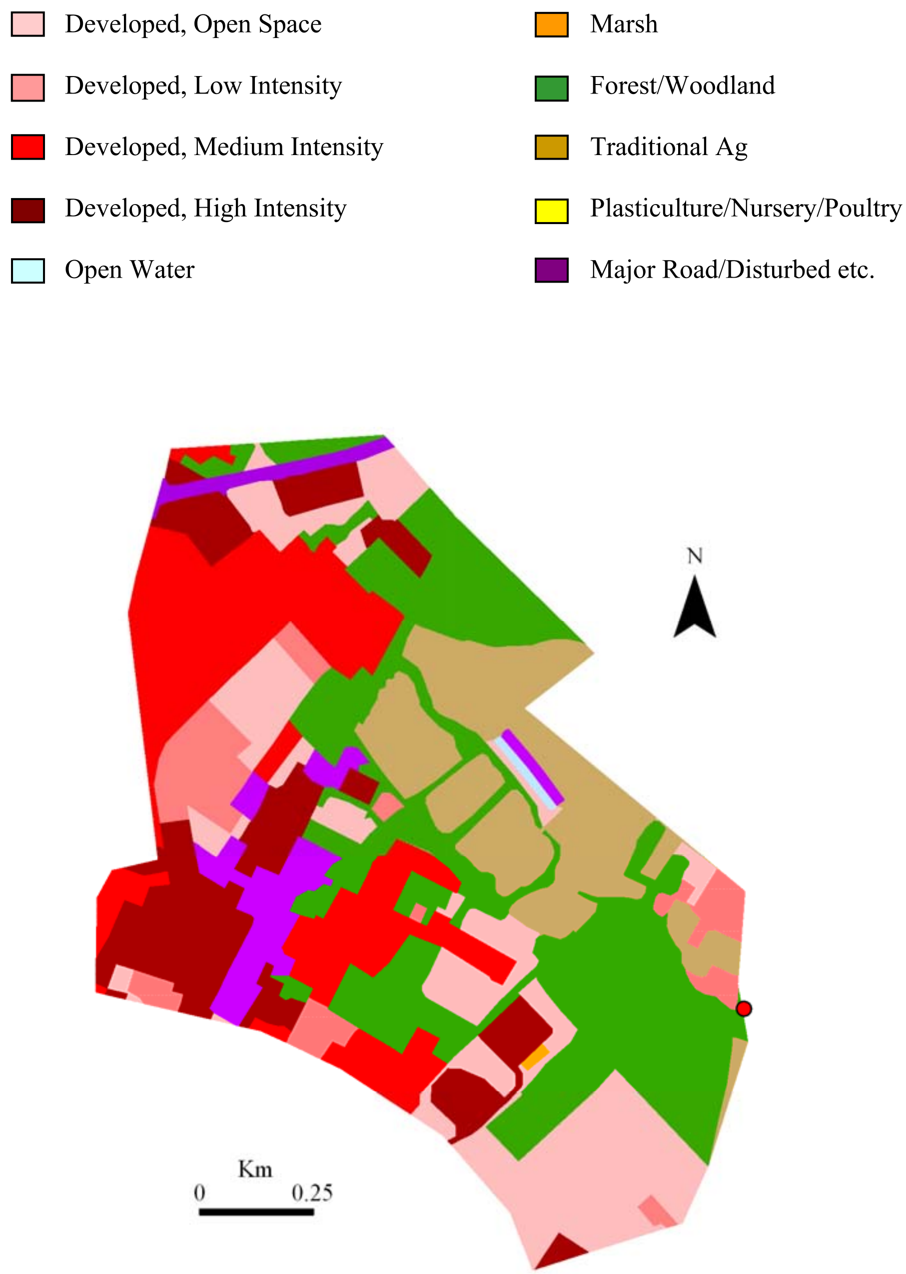
Appendix II.D. The Gulf (Eastville) watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



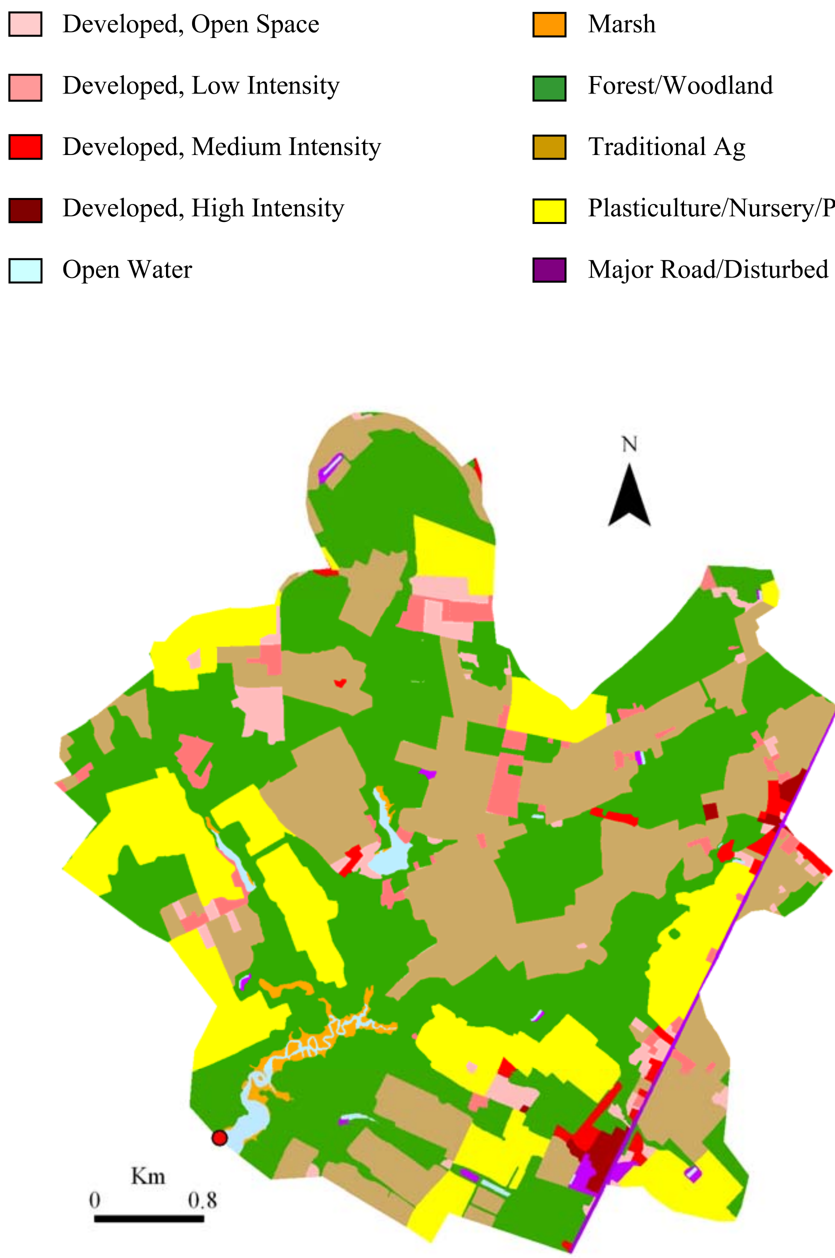
Appendix II.E. Lower Parting Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



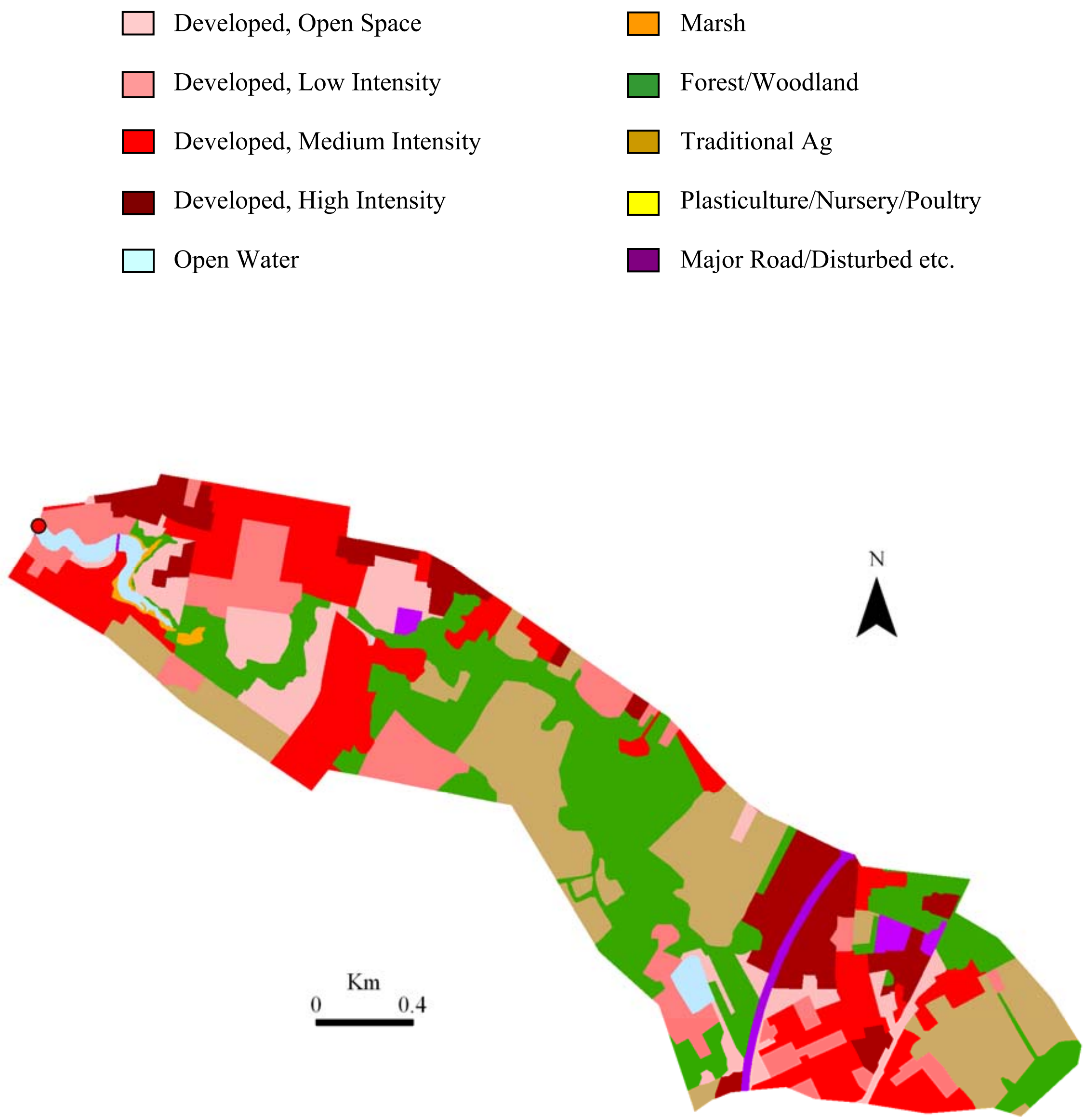
Appendix II.F. Upper Parting Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



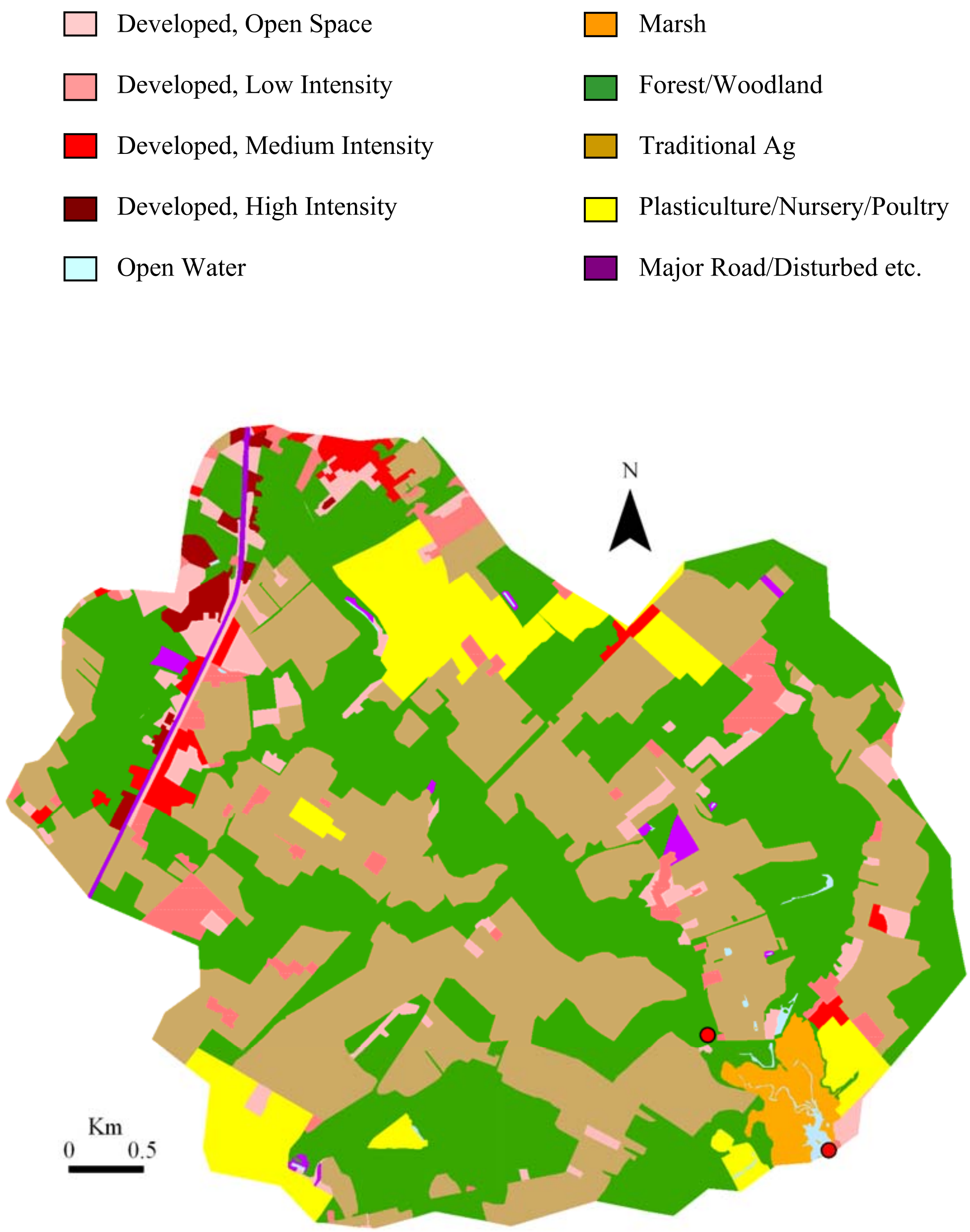
Appendix II.G. Occohannock Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



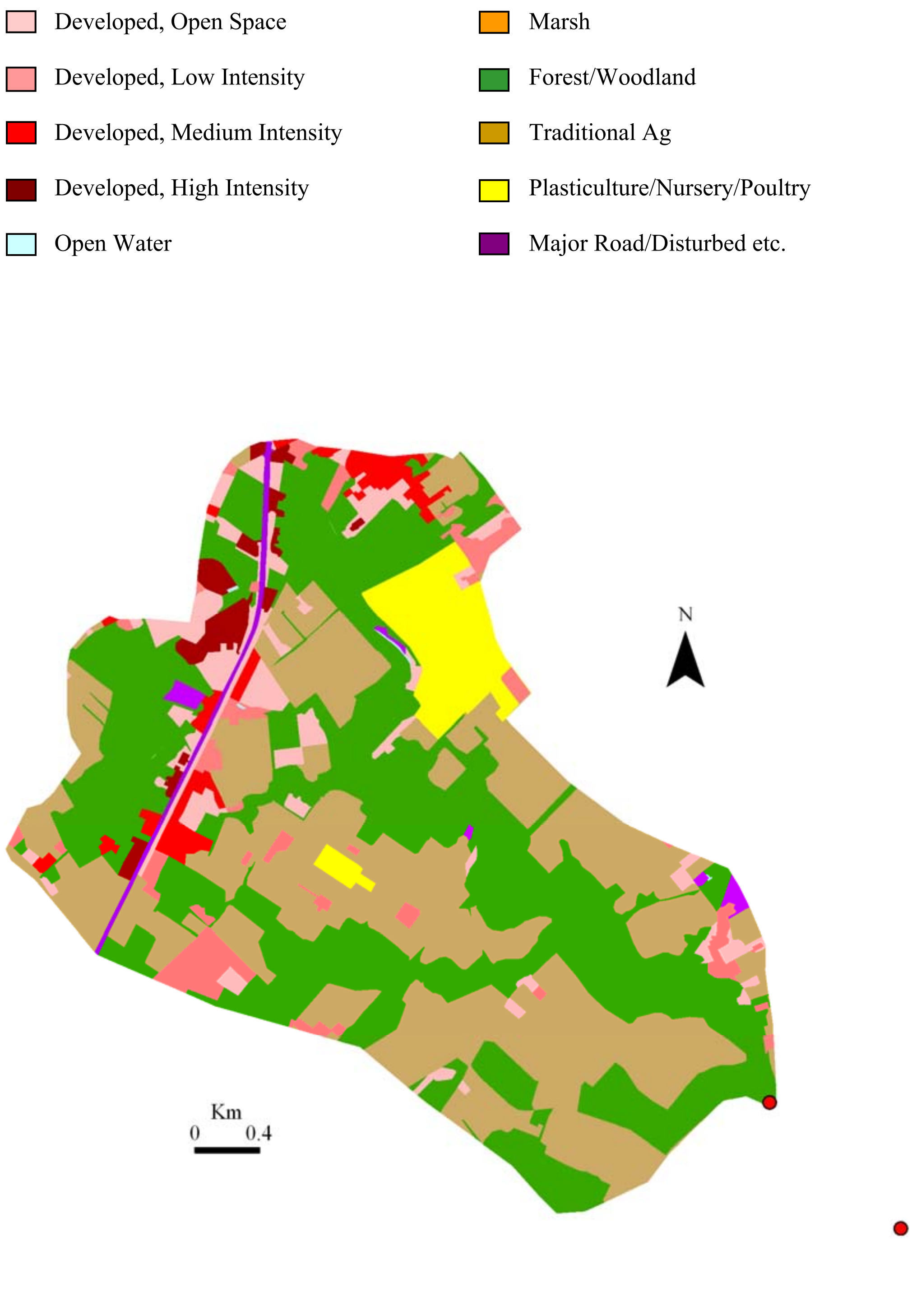
Appendix II.H. Onancock Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



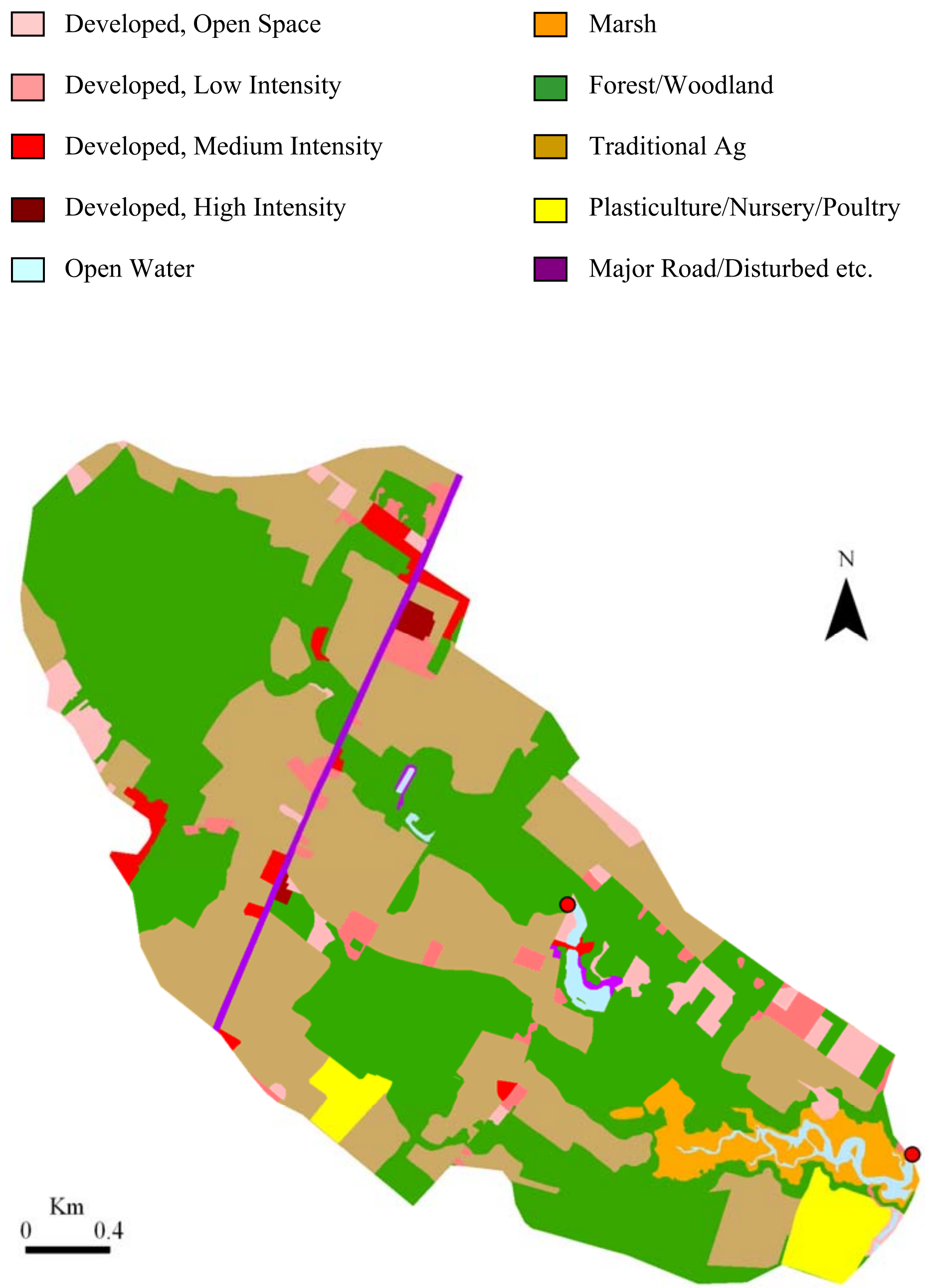
Appendix II.I. Lower Finney Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



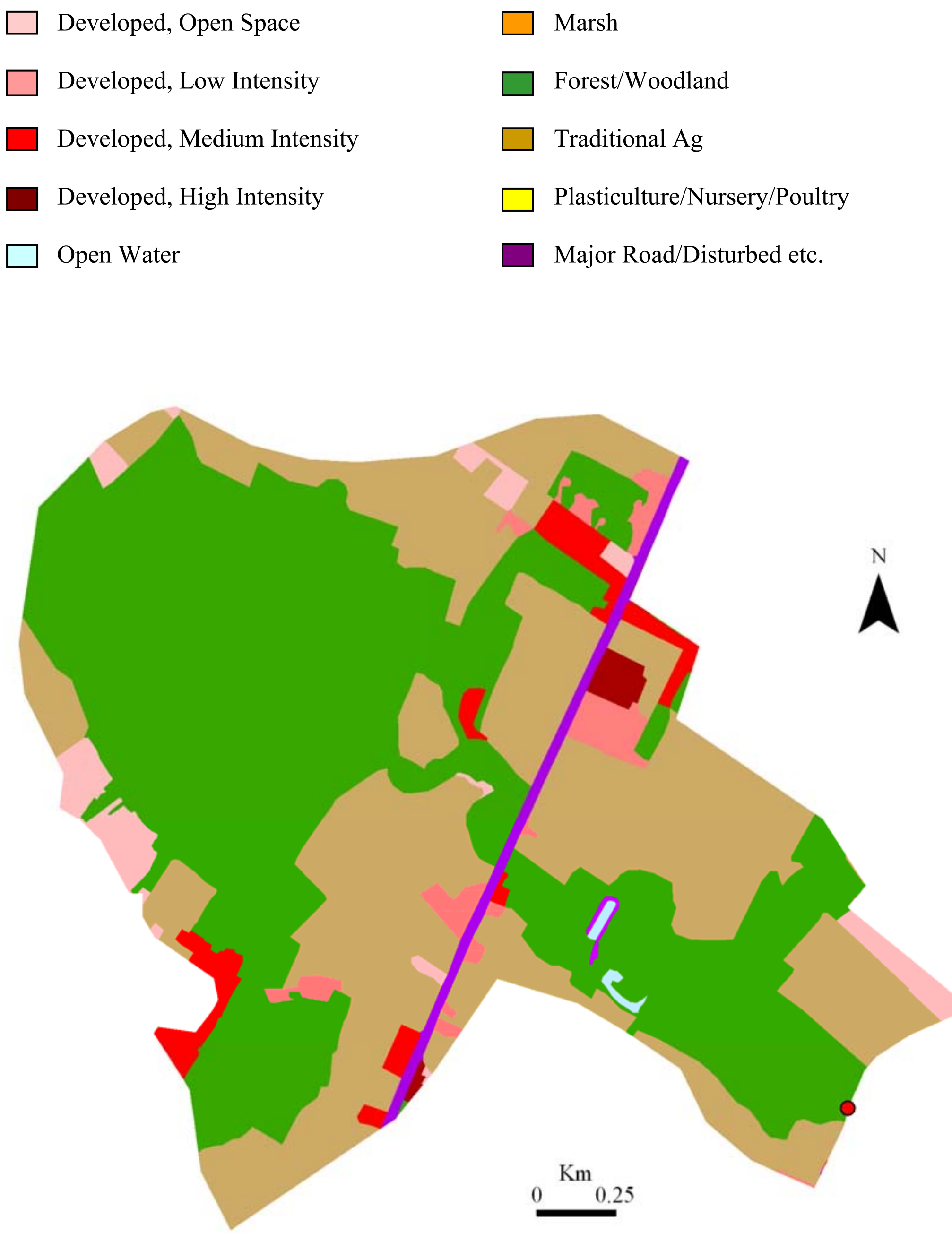
Appendix II.J. Upper Finney Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



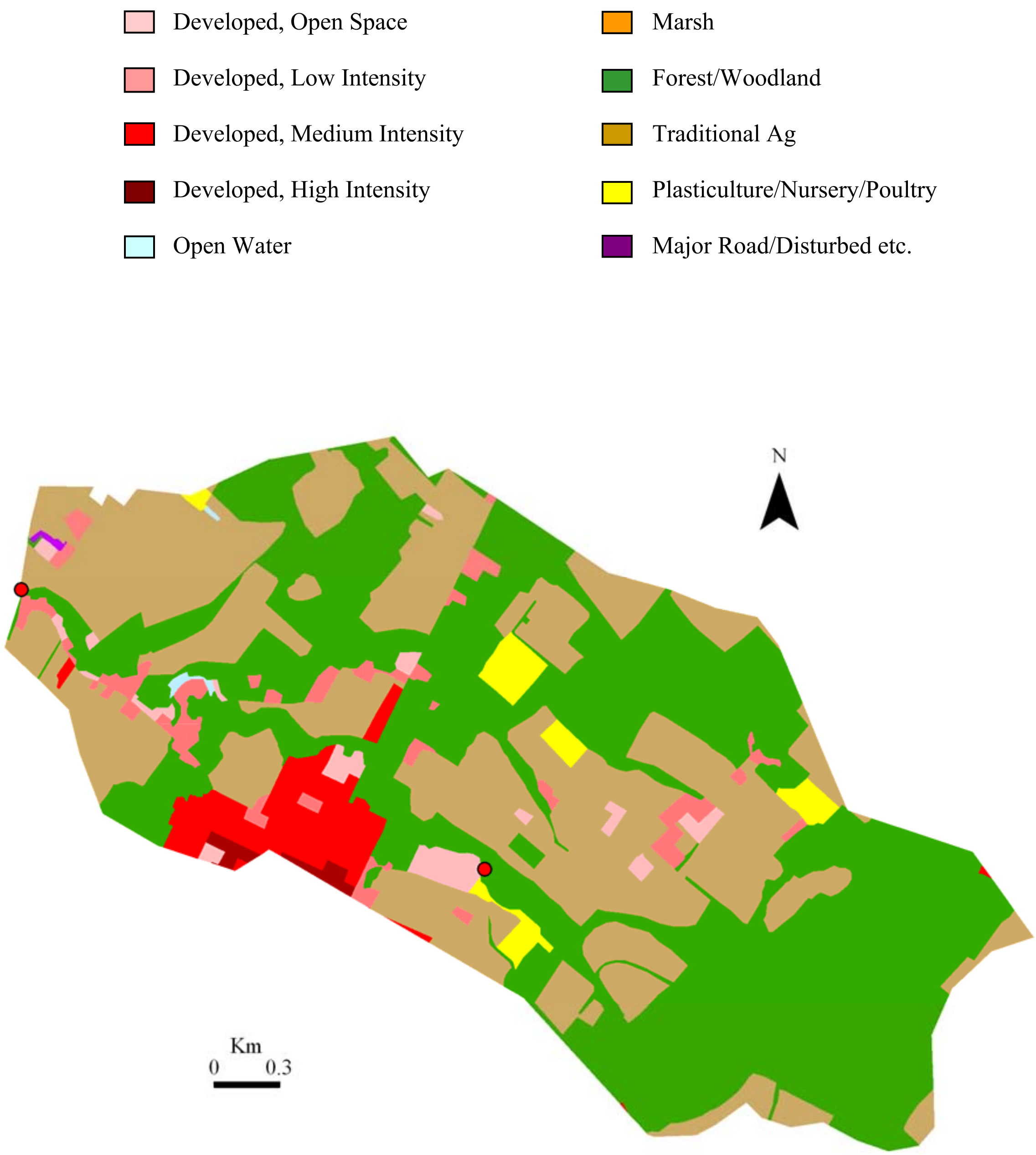
Appendix II.K. Lower White's Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



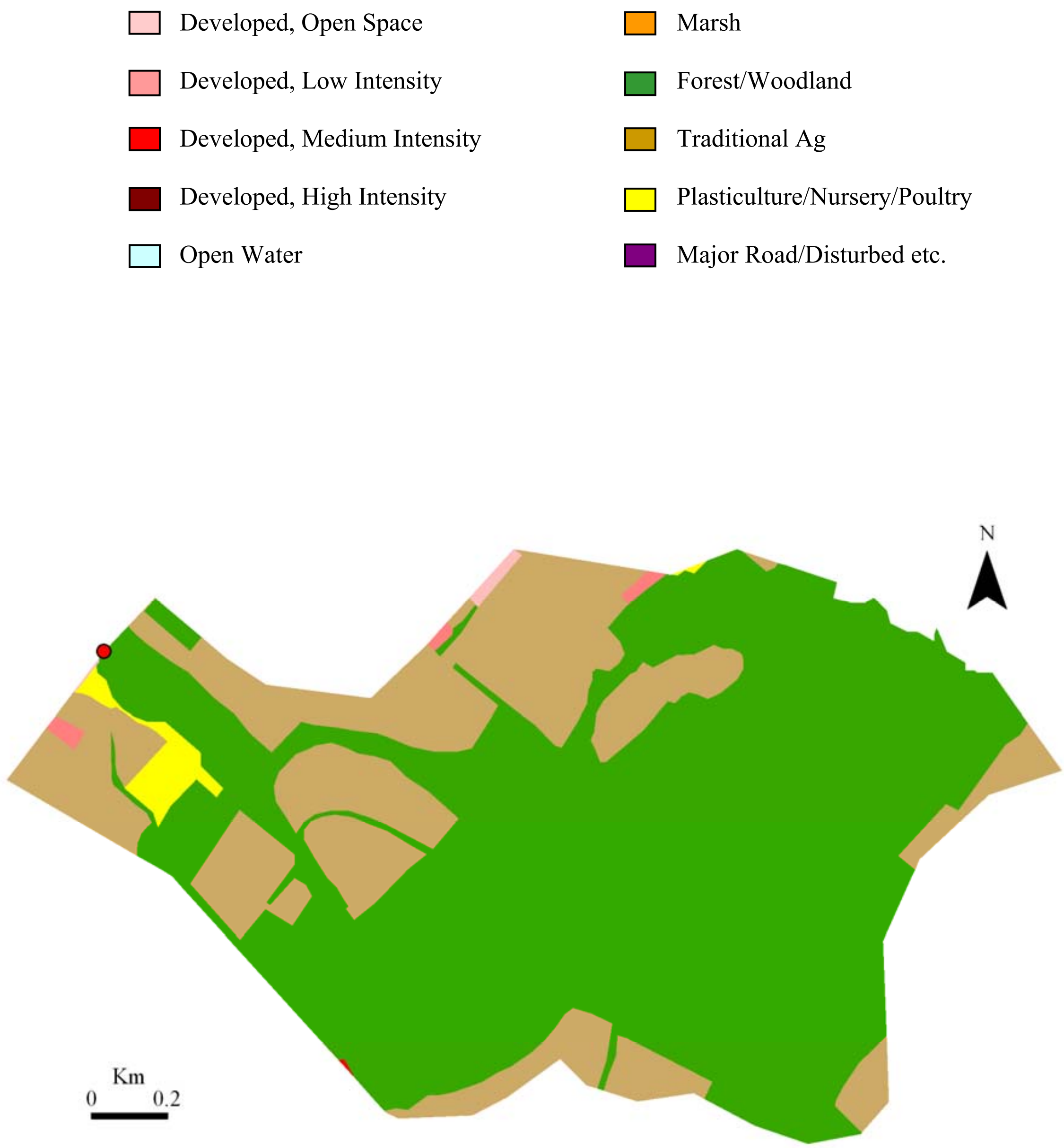
Appendix II.L. Upper White's Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.



Appendix II.M. Lower Katy Young Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.

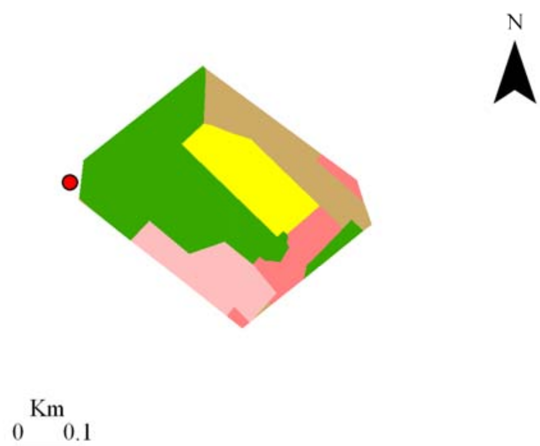


Appendix II.N. Upper Katy Young Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.

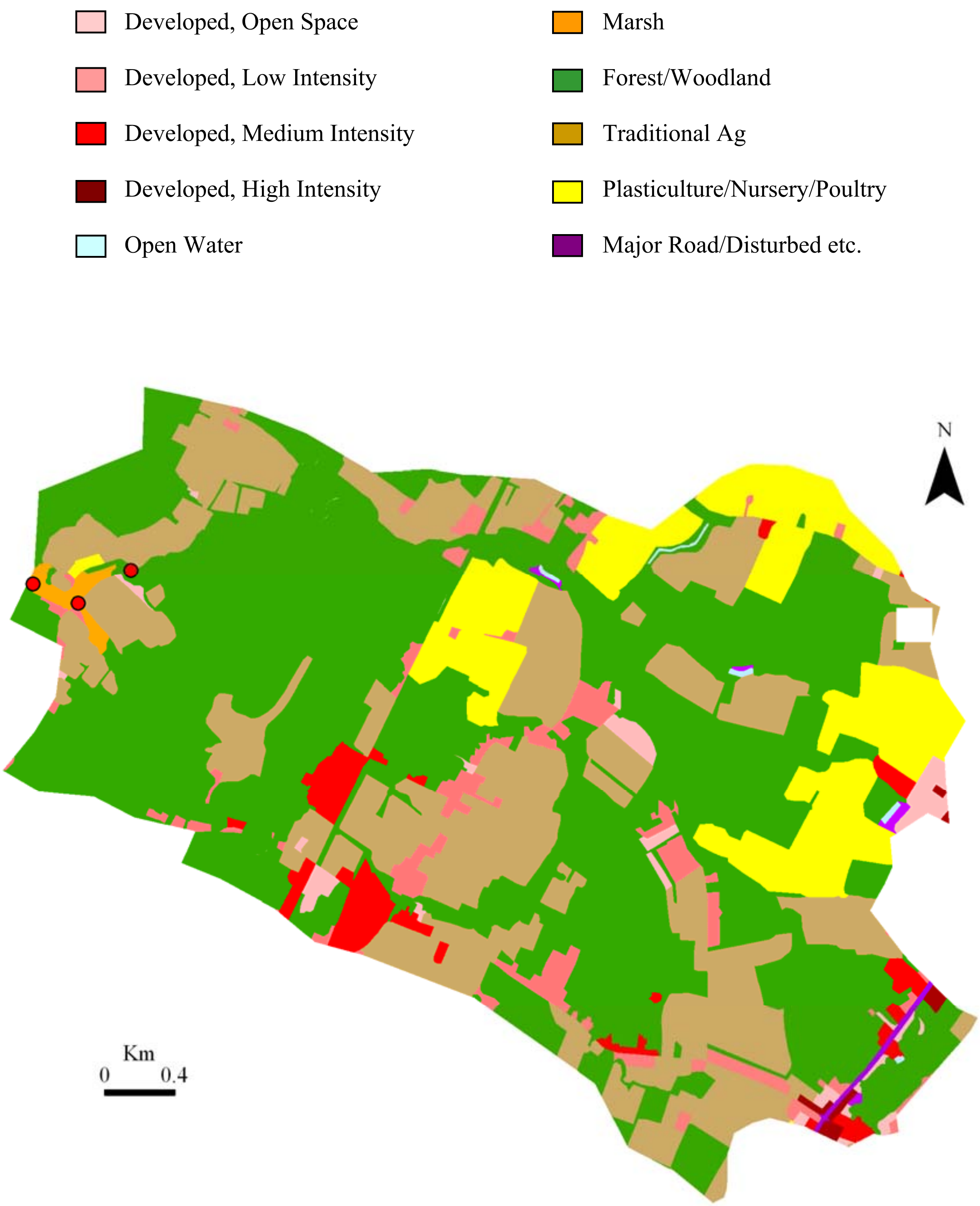


Appendix II.O. North Katy Young Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dot indicates sample station.

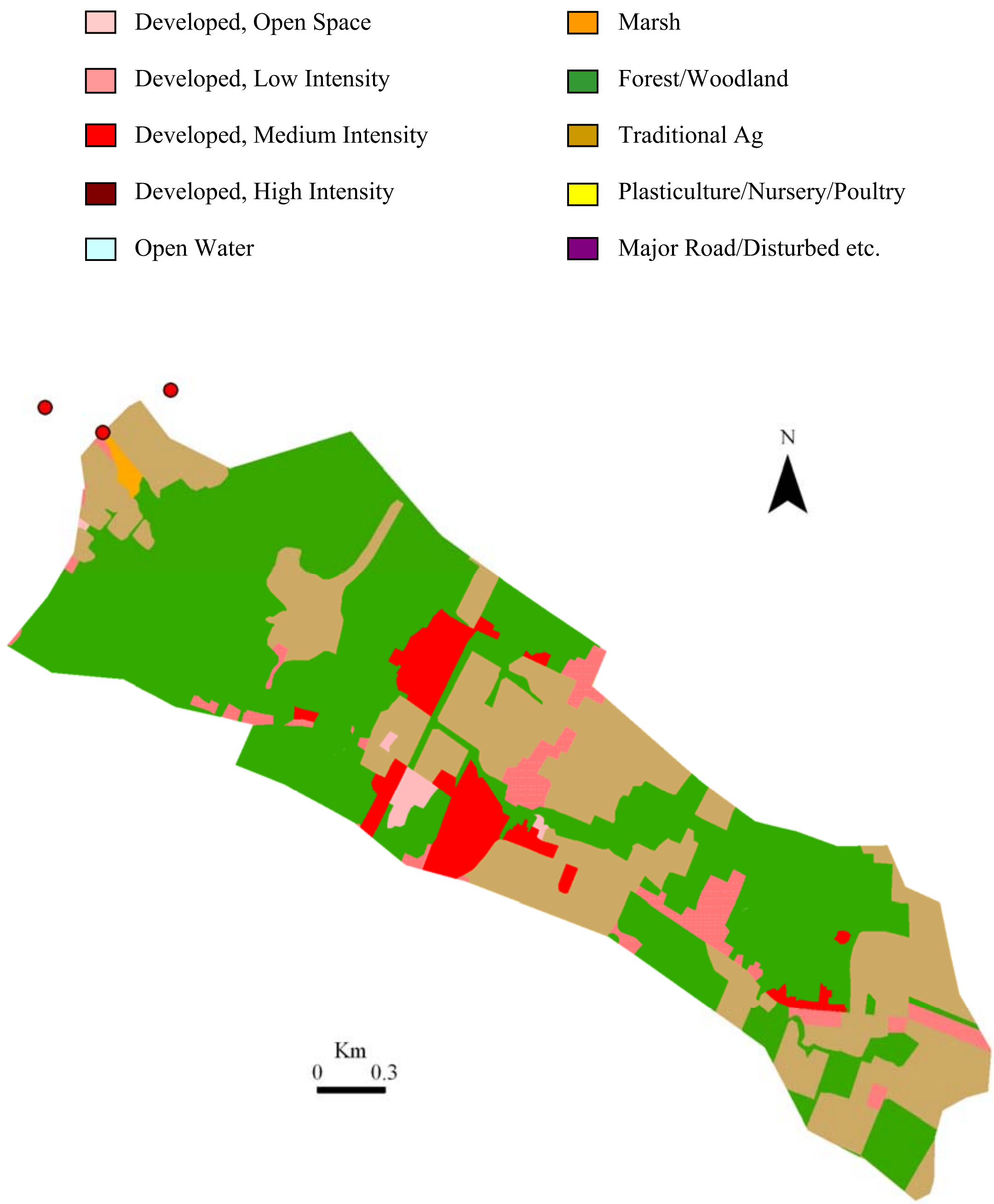
- Developed, Open Space
- Developed, Low Intensity
- Developed, Medium Intensity
- Developed, High Intensity
- Open Water
- Marsh
- Forest/Woodland
- Traditional Ag
- Plasticulture/Nursery/Poultry
- Major Road/Disturbed etc.



Appendix II.P. Lower Muddy Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



Appendix II.Q. Mid Muddy Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.



Appendix II.R. Upper Muddy Creek watershed land cover. Similar land covers are grouped together for this Appendix (e.g. all forest/woodlands represented by the same color). Red dots indicate sample stations.