# HYDROLOGIC TRANSPORT AND FATE OF *ESCHERICHIA COLI* THROUGH A SOUTHEASTERN PIEDMONT WATERSHED

by

DEMETRIUS COX

(Under the Direction of Todd C. Rasmussen)

## ABSTRACT

*Escherichia coli* (*E. coli*) is now the preferred indicator of pathogen loading to public waters. Although Georgia ranks ninth in the nation for pathogen-impaired waters, no *E. coli* fate and transport models exist for the southeastern United States. I examined hydrologic *E. coli* transport and fate processes in a 12.9-ha watershed and downstream 1.7-ha impoundment. *Escherichia coli* (n=53) were enumerated using a commercially available defined substrate medium and by ribotyping. Base flow and storm flow samples were obtained from natural areas and from penned animals over a four-month period. Seventeen water quality parameters were also monitored. Results grouped within three distinct factors: Physical effects, primarily turbidity ($r^2 = 0.66$, $p << .001$); chemical effects, primarily dissolved oxygen ($r^2 = 0.39$, $p << .001$); and biologic effects, primarily nitrite ($r^2 = 0.53$, $p << .001$). A unified conceptual model is proposed which describes the spatial and temporal variability of *E. coli* observations.

INDEX WORDS: bacteria, bacteria source tracking, BST, coliforms, defined substrate technology, DST, *E. coli*, indicator bacteria, ponds, ribotyping, TMDL`

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## DEDICATION

*To my mother Rebecca, who fought like a tiger.*

*To my sister Angela, who also beat the odds.*

*To my surrogate father Don Berens, who gave us hope.*

*To my Uncle John Cox and Aunt Carol Carrithers, for shelter in the storm.*

*To my Aunt Barbara Ellis and Grandmother Montine Cox, for making The Stand.*

*For Jack, Adeline, Leonidas and all the others who never made it out.*

"(Life) is a severe contest between intelligence, which presses forward, and an unworthy, timid ignorance obstructing our progress." - *The Economist*

"Every time the scientists take another fort from the theologians and the politicians there is genuine human progress." - H. L. Mencken

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ALL, by protocol, the first time – EVERY time. This project would not have been possible without her efforts.

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# CHAPTER 1

# INTRODUCTION

## *1.1. Purpose of research*

*Escherichia coli* (*E. coli*) are a ubiquitous member of the coliform bacteria group, and are widely used as primary indicators of fecal pollution in water, including the presence of pathogens closely associated with the coliform family. Cholera, typhoid fever, bacterial dysentery, infectious hepatitis, *Giardia* spp., cryptosporidiosis and polio are waterborne diseases that may spread through water contaminated with fecal matter. Nationwide, coliforms and pathogens comprise 13.1% of all impairments affecting lentic and lotic waters, second only to sediment (13.9%) as the leading waterborne pollutant in the United States (USEPA 1998). The state of Georgia ranks ninth in the nation on the United States Environmental Protection Agency's (USEPA) pathogen impairment list, with 2,649 river miles in 834 water bodies classified as degraded. Pathogens and coliform bacteria also account for 35.8% of all impairments reported by the Georgia Environmental Protection Division to USEPA (USEPA 2000).

The Expert Workshop on Emerging Waterborne Pathogens recently observed, "The pathogenic strains of *E. coli* have been studied in some detail, and considerable *medical* knowledge has accumulated about the various types. However, there is little information on their occurrence and distribution in

*environmental* and treated waters" (AWWA 1996). Previous investigations (GWQCB 1969; Gorden and Fliermans 1977; Cook 1979; Buchan 1997; Gregory and Frick 2000) of bacteria sources and environmental loading in Georgia were constrained by methodology, or methods so complex as to be impractical for studies at the watershed scale. Current protocols have increased the precision and certainty of bacterial investigations, but at great financial expense vested in materials, specialized equipment, and professional labor skilled in standard methods often exceeding 40 process steps – all to obtain a single data point.

Total coliform bacteria are defined as all bacteria possessing the enzyme 4-methylumbelliferyl-*β*-D-galactosidase (MUGal), which is hydrolyzed, or cleaved, in the presence of a chromagenic substrate, resulting in the release of chromagen. *Escherichia coli* possess the enzyme 4-methylumbelliferyl-*β*-glucuronidase (MUGlu) which enables individual bacteria to cleave a fluorogenic substrate and fluoresce. Colilert™, a commercial Defined Substrate Technology (DST) media, or enzyme substrate coliform test manufactured by IDEXX Laboratories (Westbrook, Maine), has been approved for bacteria enumeration of drinking water and wastewater (Edberg et al. 1988, 1990, 1991; Elmund et al. 1999; Francy and Darner, 2000). Colilert measures total coliforms and *E. coli* and expresses the result as colony forming units (CFU) / 100 mL, which are routinely reported on a geometric ($\log_{10}$) scale. No application of this technology has been reported in hydrologic or watershed-scale field studies.

The primary goal of this thesis is to describe the hydrologic transport and fate of *E. coli* in a southeastern Piedmont watershed by using two discriminant microbiological methods. Defined Substrate Technology was selected to observe the effects of a fenced population of white-tailed deer (*Odocoileus virginianus*) on bacterial densities within the watershed. Concomitantly with describing the hydrologic transport and fate of *E. coli*, allied goals included expanding of the DST method to include bacterial source confirmation via ribotyping, a DNA-based genetic method, and evaluating the effectiveness of small impoundments in reducing *E. coli* densities.

Catfish Pond watershed, Whitehall Experimental Forest, Georgia, is a 12.9-ha watershed comprised of a first-order influent stream, stormwater flows into the stream, receiving pond, and effluent ephemeral stream. A holistic approach was undertaken to examine the transport and fate of *E. coli* in stormwater flow and from an animal confinement area, through the forested watershed and pond. While numerous published studies provide detail on fecal indicator bacteria in Southeastern U.S. surface waters, limited information is available on the effects of temperature, light, pH, dissolved oxygen, nutrients, and hydrology on *E. coli* in Southeastern Piedmont landscapes (Gorden and Fliermans 1978; Francy et al. 1993, 2000). In addition to the microbiological methods employed to monitor bacteria densities, 17 water quality parameters were observed over a five-month period to record the *in situ* interaction between biotic and abiotic variables and their possible influence on *E. coli*. Results were used to quantify and

characterize the source, transport mechanism, and fate of *E. coli* in an impounded ecosystem.

Insights from this study may be used to understand similar processes occurring in other temperate watersheds, namely the Upper Chattahoochee River Basin (UCRB), in support of the State of Georgia's transition to the USEPA *E. coli* rule and development of accurate and comprehensive Total Maximum Daily Load (TMDL) standards (USEPA 2001). Additional applications are possible, including research at larger spatial scales, implementation of Best Management Practices (BMPs), bacteria transport in soil-pore and groundwater media, sediment sequestration of bacteria, environmental fate of genetically modified bacteria, forensic and law enforcement applications, and tracking of endangered species.

### *1.2. Objectives*

The four objectives were:

- To evaluate the reliability and repeatability of a commercially available defined substrate technology (DST) medium for detecting and quantifying indicator bacteria at the watershed scale.
- To employ a DST medium in describing hydrologic transport and fate of indicator bacteria at the watershed scale.
- To pair DST with ribotyping of *E. coli* to gain inference on the bacterial source.

- To evaluate the effectiveness of a small impoundment on reducing *E. coli* densities towards the goal of recommending more efficient impoundment design, construction, and renovation.

# CHAPTER 2

# LITERATURE REVIEW

Waterborne microbial organisms or “indicators” can be classified within three recognized groups: general process indicators, fecal indicators and index / model organisms (World Health Organization 2001; Table 1). As part of the total coliform group, *Escherichia coli* (*E. coli*) are gram-negative, motile members of the Enterobacteriaceae consistent with the normal intestinal flora in humans and animals. Excreta from humans and warm-blooded animals are the main source of *E. coli* in the environment, and while rare, some pathogenic strains can cause diarrhea and death in susceptible hosts (Fewtrell et al. 1994). High levels of fecal indicator bacteria in rivers, streams, and impounded bodies of water are associated with the presence of pathogenic microorganisms (USEPA 1986, 1998, 2001; APHA 1999). Contamination sources include municipal wastewater discharges, septic leachate, runoff or ground-water seepage from livestock areas, such as pastures, concentrated animal feeding operations (CAFOs), or areas where manure and waste effluent are applied as fertilizer, and wildlife (White 1996; Easton 2000; Burton and Pitt 2002; Hartel et al. 2003).

In addition to the direct public health concerns associated with fecal contamination, fecal coliform bacteria are also commonly used for determining

water quality because they have survival rates in aquatic systems similar to other potentially more dangerous fecal-borne pathogens such as *Salmonella* spp. and *Shigella* spp. Bacteria populations in freshwater systems are generally higher within stream and lake sediments and along lake shores (Grimes 1975; Stephenson and Rychert 1982; Bergstein-Ben Dan and Koppel 1992). This is due to higher concentrations of bacteria and nutrients from land runoff, sewage and industrial discharges, storm flows, and vertical mixing. The combined effects of these forces increase the total nutrients, mineral, and organic matter within aquatic systems and can increase the life spans of normally short-lived bacterial inhabitants, possibly increasing the risk to human health. Furthermore, research has shown that fecal coliforms can persist and multiply in water laden with sediment (Schillinger 1982; Stephenson and Rychert 1982; Burton et al. 1987; Howell et al. 1996; Buckley et al. 1998).

### 2.1. Federal and State coliform standards

Codified under Federal Regulation §40 CFR 131.12 and §40 CFR 141.21, the United States Environmental Protection Agency (USEPA) has published a Final Rule establishing *Escherichia coli* -based water quality standards for the protection of public health (USEPA 1986, 1998). However, the State of Georgia currently uses fecal coliforms indices to gauge impairment of recreational water resources (GAEPD 1997). Georgia recreational water standards are less restrictive and organized under a seasonal index to highlight periods when water contact recreation is

expected to occur. From May to October, environmental fecal coliform samples cannot exceed a geometric mean of 200 CFU per 100 mL based on a minimum of four samples collected at a given site over a 30-day period at not less than 24 hour intervals. Georgia standards also include a special caveat that allows non-human fecal coliform samples exceeding the summer maximum to be considered normal at geometric readings of 300 CFU per 100 mL in lakes and reservoirs and 500 CFU per 100 mL in free-flowing freshwater streams. From November through April, fecal coliform samples cannot exceed a geometric mean of 1,000 CFU per 100 mL based on a minimum of four samples collected at a given site over a 30-day period at not less than 24-hour intervals, and cannot exceed a maximum of 4,000 CFU per 100 mL for any sample. The Georgia water quality Code also includes the following disclaimer: “The State does not encourage swimming in surface waters since a number of factors which are beyond the control of any State regulatory agency contribute to elevated levels of fecal coliform” (GAEPD 1997).

Specific coliform sampling guidelines are also set forth under Georgia Code §391-3-5.23, Coliform Sampling, and address public drinking water standards. The frequency of routine monitoring is based on the population served by public water systems and sample size can vary from one to 480 per month. Because drinking water standards are more stringent than recreational use guidelines, Georgia requires only an initial presence / absence (PA) test for total coliform bacteria. If a positive total coliform result is obtained, the State permits public water systems to choose between additional mandatory monitoring for fecal coliform or *E. coli*.

## 2.2. Previous environmental studies of *Escherichia coli*

Coliform bacteria as a major environmental pollutant was first described in the modern literature by Geldreich (1966) and Geldreich et al. (1968). Research on coliform origin and fate has been reported for rivers (Flint 1987; Davis et al. 1995; George et al. 2001), streams (Robbins et al. 1972; McDonald and Kay 1981; Turner et al. 1997), and large reservoirs (Geldreich 1972; Cook 1979; Kay and McDonald 1980; Gannon et al. 1983). The earliest official investigation on bacterial pollution of water bodies in Georgia was commissioned in 1967 in response to a formal request for information from the U.S. Department of the Interior (Georgia Water Quality Control Board 1969). Substantial numbers of coliform bacteria were recorded in streams and rivers, and were elevated near wastewater treatment plants and areas of intensive agriculture. Survey results were used by the State to establish baseline coliform criteria for recreational waters and comply with emerging Federal standards.

Gorden and Fliermans (1978) investigated *E. coli* dynamics in a thermally altered reservoir at the Savannah River Plant, and observed increased survival and natural reproduction at all sampling stations and water depths during the study. Diffusion chambers were used to assess bacteria response to changes in thermal regimes driven by operating cycles of a production nuclear reactor. While noting their results were derived from an artificial eutrophic ecosystem, the authors placed emphasis on subtle differences in temperature, pH, oxidation-reduction potential, specific

conductance, dissolved oxygen, and possibly other unmeasured parameters that could influence *E. coli* survival and propagation in warm aquatic systems.

A two-year survey completed in 1995 of fecal bacteria concentrations downstream of the city of Atlanta and the Chattahoochee River National Wildlife Area indicated observed bacteria levels exceeded the Georgia EPD maximum limit of 4,000 Most Probable Number (MPN)/100 mL in up to 25% of samples collected (Gregory and Frick 2000). In addition, the majority of fecal coliform samples analyzed during the same study exceeded the Federal standard of 400 colonies / 100 mL. The authors emphasized that such conditions are not unique to metropolitan areas and require further study to determine bacteria sources and transport pathways. They also identified genetic fingerprinting (ribotyping) as a promising tool for bacteria source tracking.

Buchan (1997) undertook a broad survey to classify *E. coli* ribotype profiles in Georgia waters by developing, testing, and evaluating ISR/DGGE, a molecular ribotype method. Two *E. coli* stream isolates were matched to source isolates across a large geospatial area, and recommendations were made to employ refined methods in less variable watersheds, which helped motivate this study. More recently, concerns over the rapid urbanization of the upper Chattahoochee River basin (UCRB) and Lake Sidney Lanier with associated increases of nutrient and bacteria loadings to the impoundment and other receiving bodies downstream has prompted researchers and the general public to become more proactive in efforts to identify and reduce inputs to the watershed by improved Best Management

Practices (BMPs) (Beck et al 2002), innovative watershed design, and development of a pathogen transport model.

### 2.3. Existing bacteria monitoring technology

Identifying and quantifying bacteria in the natural environment is not a simple task. Early techniques were rudimentary and consisted primarily of variations on the "Wurtz Method" (1912), which enumerated bacteria by streaking various media with an environmental sample and counting cell colonies after a prescribed incubation period (Hutchinson and Ridgway 1977). Later, bacteria colonies were compared in ratios to determine the degree of bacterial pollution and associated host origin (Geldreich 1969; Feachem 1975). With the advent of modern microbiology, new methods began to appear which allowed for more detailed study of bacteria: agars, baths and broths produced exclusively for enumerating selective bacteria strains, but requiring a level of technical laboratory proficiency not resident in most environmental professions. Membrane filtration methods were developed by 1960, but were not widely adapted for field deployment until circa 1980 (Spatz 1972; USEPA 1985). Portable membrane filtration devices are now commonplace and the method enjoys wide application for isolating a variety of waterborne microbes (APHA 1999; Francy and Darner 2000).

The search for a common, universal indicator bacterium, combined with a trend to standardize and streamline testing protocols for public drinking and recreational waters, led to the development of defined substrate assays

(Johnston and Pivnick 1970; Warren et al. 1978). A modification of a gas chromatographic procedure, the Eijkman Method (Eijkman 1904; Newman and O'Brien 1975), served as a foundation for a new generation of rapid colorimetric tests, which began to see commercial application in drinking water and waste treatment plants as "Presence-Absence" (PA) test kits. Based upon enzymatic hydrolysis of the substrate *o*-nitrophenyl-*β*-D-galactosidase (ONPG), the usefulness of this method rests on targeted specificity for coliforms, without excluding other bacteria which fit the fecal coliform definition (Warren et al. 1978).

While ONPG-based PA tests represented a significant advance in bacteria-specific monitoring technology and were adaptable to field application, the method was not specific for the emerging indicator bacteria of choice, *Escherichia coli*. Seminal work on defined substrates for *E. coli* by Feng and Hartman (1982) and Trepeta and Edberg (1984) yielded a fluorogenic compound, methylumbelliferyl-*β*-D-glucuronide (MUGlu), which was subsequently investigated for successful detection of total and fecal coliform and *E. coli* in water by Berg and Fiksdal (1988), Edberg and Edberg (1988), Edberg et al. (1990, 1991) and Rice et al. (1990, 1991). Encouraged by the results of these preliminary tests, a commercial application based on defined substrate technology was rapidly developed for a slightly modified substrate, 4-methylumbelliferyl-*β*-D-galactosidase (MUGal), a discrete medium that selects exclusively for total coliforms and *E. coli*. Subsequent uses of *E. coli* MUG have

been reported in laboratory settings, drinking water evaluations, and wastewater treatment (Shadix and Rice 1991; Covert et al. 1992; Fricker et al. 1997; Eckner 1998; George et al. 2001; and others). The *E. coli* MUG test was officially standardized by the American Public Health Association in Methods 9213 and 9223 for the 19th edition of *Standard Methods for the Examination of Water and Wastewater* (1995).

### 2.4. Bacteria transport

Once fecal material is deposited on the land surface, associated organic complexes become subject to physical variables, or forcing functions, and random events which influence resident coliform densities and environmental persistence. Of the physical constants, duration and intensity of solar radiation (also known as photosynthetically active radiation, or PAR), ambient air temperature, and time have been identified by Crane and Moore (1986) and White (1996) as determining factors in desiccation and breakdown of fecal deposits. Random events such as rain, wind, and ice also influence environmental coliform signatures. Rain and stormwater flows act as prime movers and vectors for pollutant and bacteria transport to receiving water bodies (Williams et al. 1985, White 1996; Burton and Pitt 2002).

Surface runoff depth can be predicted using daily rainfall depths incorporating the SCS curve number equation (McCuen 1998). Understanding that surface runoff is related to soil water content, peak runoff rate can be calculated based

on the modified Rational Formula (Mulvaney 1851 *as cited in* Dooge 1973). Total and fecal coliform bacteria loading to receiving water bodies was shown by Kunkle (1970a, b), Kay and MacDonald (1980), McDonald and Kay (1981) and Bergstein-Ben Dan and Koppel (1992) to be closely related to storm hydrograph, which in turn is linked to individual watershed parameters contained in time of concentration calculations. Schillinger and Gannon (1982) demonstrated that up to 16% of inoculated *E. coli* associated with clay particles were flocculated from water columns during laboratory bench tests. Moreover, Dufour (1982) found the risk of gastro-intestinal illness correlated with *E. coli* densities associated with suspended particles exceeding 3 μm in diameter. Because bacteria densities have been shown to be closely associated with measurements of soil-induced turbidity, the Revised Universal Soil Loss Equation (RUSLE) can be employed to estimate sediment yield in surficial flows (Moore and Burch 1986; Renard et al. 1997). Based on these and other field surveys, waterborne transport of *E. coli* can be inferred to closely resemble transport dynamics exhibited by the larger coliform bacteria group.

While relatively little work has been done on the hydrology of small, non-wastewater or stormwater affiliated impoundments, Williams et al. (1985) investigated the water balance of ponds in Texas and Oklahoma as part of a national effort to develop a model (SWRRB / CREAMS) for water resources in rural basins. The authors also predicted inflow sediment yield to ponds and reservoirs using the Modified Universal Soil Loss Equation (MUSLE) to

mathematically describe an inter-storm equilibrium for suspended sediment concentrations. In addition, the SWRRB / CREAMS model incorporated a decay constant and median particle size of inflow sediment to obtain predictions on loading and sedimentation. While this model incorporated physical hydrologic constants and a mass soil wasting component, no construct was provided for bacteria loading or the influence of water quality parameters on the bacteria dynamic.

### 2.5. Bacteria fate

Comprehensive reviews on the microbiology of water, including *Escherichia coli*, have been published by Geldreich (1980, 1981) and except for those studies pertaining to bacteria or pathogen fate, will not be reviewed here. A thorough primer on bacteria survival in natural environments is contained in Roszak and Colwell (1987), which features detailed discussion of coliforms and *E. coli*. Bacteria fate in lentic and lotic systems is highly correlated to flow, turbidity, and sediment (Kunkle 1970a, b; Kay and McDonald 1980; McDonald and Kay 1981; Schillinger and Gannon 1985), and has also been shown to be influenced by a wider range of physical factors, including light (Gameson and Saxon 1967; Grigsby and Calkins 1979; Barcina et al. 1989, 1990; Curtis et al. 1992b), temperature (Verstraete and Voets 1976; Gameson 1984; Barcina et al. 1986), and predation (Enzinger and Cooper 1976; McCambridge and McMeekin 1979, 1980; Gurijala and Alexander 1990; González et al. 1992). Chemical variables

reported to influence *E. coli* variability include dissolved oxygen, oxidation-reduction potential, nutrients, and pH (Parhad and Rao 1974; Henis et al. 1988; Curtis et al. 1992a).

As noted by Gannon et al. (1983), the term “disappearance” has been used to describe bacteria sedimentation, predation, dilution, and death. Chick (1908) developed a first-order exponential decay equation which is considered a foundation for predicting bacteria fate, and this relationship has been confirmed in several variations (Crane and Moore 1986). Of these studies, two pertain to freshwater systems. Crane et al. (1973) developed a modified first-order model for fecal coliform mortality in the Great Lakes, with water temperature as the dependent variable. Kay and McDonald (1980) also proposed a first-order equation for impoundments based on distance of flow rather than time, a concept which was expanded by Auer and Niehaus (1993) to specifically include a sedimentation term. Troussellier et al. (1986) used historical data and complex partial regression to suggest direct and indirect effects of light on coliforms via inactivation (UV injury), pH, and algae. Many other hypotheses and models have been developed for marine systems and wastewater treatment, but all have lacked a unifying concept inclusive of biological, chemical, and physical processes (Crane and Moore 1986).

## 2.6. Bacteria Source Tracking

Accurately classifying sources of bacterial contamination represents one of the greatest challenges to effective remediation of non-point source pollution. Because enumeration of bacteria in environmental samples has historically been a formidable task, testing of density-dependent hypotheses has only recently become more accessible through technologic innovation and development of responsive, inexpensive, and less complex methods. The earliest method on bacteria origin was an index ratio between observations of fecal coliforms and fecal streptococcus (FC:FS) in ambient water samples (Geldreich and Kenner 1969). The narrow scope and insufficient specificity of this procedure was questioned and the method gradually gave way to presence-absence tests and the use of inference-deduction while examining contaminated stream segments (Feachem 1975; Pourcher et al. 1991).

Moreover, during this same period a heated debate arose, and continues to this day, over which bacteria and viral species should be used as universal indicators of fecal contamination. *Escherichia coli* and fecal streptococci emerged as preferred candidates and development of methods with improved sensitivity and selectivity have since permitted investigators to better describe these species, and others impacting water bodies. A seminal study of antibiotic resistance patterns in fecal streptococci by Wiggins (1996) represented a significant advance in determining the source of fecal pollution in water. While tedious and time-consuming, the method accurately identified fecal origin in up to

95% of samples and discriminated between human, cattle, poultry, and municipal wastewater inputs. These results were field tested and confirmed in a three-year study of fecal contamination in Page Brook, Virginia, where 88% of human, cattle, and wildlife isolates were correctly classified (Hagedorn et al. 1999).

Parveen et al. (1996, 1997) employed principal component analysis and ribotype profiles to also confirm Wiggins' findings and establish baseline antibiotic resistance patterns for *E. coli* in estuarine waters. Follow up work in *E. coli* ribotyping by Parveen et al. (1999) yielded an average rate of correct classification of 82%, with 97% and 67% of non-human and human sources correctly identified, respectively. Recommendations from the study advocate ribotyping over antibiotic resistance due to selective pressure on bacteria which can result in spatial and temporal variability. Ribotype profiles are a genetic characteristic and are not as easily influenced by selective pressure, and therefore provide a strong method for differentiating human source from non-human source fecal pollution (Parveen et al. 1999). Encompassed into this investigation, a novel approach using the enzymatic substrate MUGlu as a base for ribotyping *E. coli* was employed to discriminate between wild-type and confined white-tail deer (*Odocoileus virginianus*) as a primary source of fecal contamination in a forested Piedmont watershed.

# CHAPTER 3

# MATERIALS AND METHODS

## 3.1 Site description

*Catfish Pond watershed, Whitehall Experimental Forest, Athens-Clarke County, Georgia*: Catfish Pond is a 0.71-ha impoundment situated within a 12.9-ha subwatershed, completely contained within Whitehall Experimental Forest, near the campus of the University of Georgia, Athens, Georgia, USA, (83° 24'W, 33° 54'N) (Figure 1, 2). Whitehall Forest is classified warm temperate with average annual ambient air temperature average of 17 °C and precipitation of 1252 mm. Catfish Pond is situated down slope of long-term experimental timber plots and a wildlife research area of the experimental forest (deer pens, $N$ = 89), directly adjacent to the Oconee River, with all surface flow supplied by a first-order, spring-fed perennial stream. During the 2000 field season, Catfish Pond was augmented with 91 kg calcium hydroxide lime (CaOH) on 02 July, followed by three 8-L nutrient amendments in the form of ammonium polyphosphate (11-37-0) on 05 July, 27 July, and 01 October. The 01 October fertilization was by slurry of ammonium polyphosphate and soil (85% fines, 15% sand). Other system perturbations included removal of dense algal mats from the pond surface on 25 August, followed by complete removal of dense vegetative growth

from around the circumference of the pond on 27 August. A new laboratory facility was constructed atop the watershed divide during the 2000-01 sampling season; all storm runoff from the site drained away from the area of study and provided no observed inputs to bacteria densities or other water quality constituents.

### 3.2 Field instrumentation

Four water level transducers, two hydraulic flumes, a tipping bucket, solar panels, and three Campbell CR-10X dataloggers (Campbell Scientific) were installed to record rainfall and stage level in the stream and pond. Based on previous sampling efforts (1998, 1999) a significant rain event for the Catfish Pond subwatershed was established at $\geq$ 30 mm (1.2 in.) precipitation in 24 hours. One datalogger each was co-located with a flume upstream and downstream of Catfish Pond and instrumented to record stream stage, specific conductivity, and water temperature. A separate datalogger was sited on the pond levee to record precipitation, pond stage, specific conductance, water temperature, and photosynthetically active radiation (PAR).

The pond was also outfitted with two DataSonde4 water quality probes (Hydrolab Corporation) to monitor temperature, dissolved oxygen (DO), specific conductance, pH, oxidation-reduction potential (REDOX), and PAR. Automated environmental sampling was provided on site by the Environmental Process Control Laboratory (EPCL). Submersible pumps supplying constant sample flow

stream to EPCL were mounted at 0.5-m (Platform, Transect 5) and 1.5-m (Dock, Transect 14). Drain lines from EPCL returned excess sample flow to the pond via an *in situ* diffuser located in Transect 9. Water quality constituents analyzed by EPCL included suspended solids, total organic carbon (TOC), orthophosphate (ORP), nitrite ($NO_{2-}$), nitrate ($NO_{3-}$), TON (total oxidized nitrogen, or $N_{OX}$), and ammonia ($NH_3$).

Five control sites (C1–C5) and five test sites (T1–T5) were installed within a mature second generation hardwood forest to sample overland flow to the Catfish Pond headwater stream. In addition to sampling the headwater and effluent ephemeral stream, Catfish Pond was subdivided into 15 transects in order to observe bacteria spatial distribution (Figure 4). Each sampling day, the headwater stream and all pond transects were sampled on the surface. Samples were also drawn by an ISCO sampler at 0.5-m, 1-m, and 1.5-m depths from a dock centered on the pond levee (Transect 14). Although effluent flow from the pond was limited by drought conditions, a small number of observations were obtained during storm conditions in the last weeks of the study.

A total of 750 water samples were collected for bacteria analysis on 54 sampling days between June 2000 and January 2001. Between 1700 and 2100 hours, hydrologic conditions were observed and grab samples were obtained in sterilized 500-mL Nalgene bottles (Myers and Sylvester 1997). Less frequent storm sampling used deadfall and automated samplers (ISCO) to capture overland flow from control and test plots located throughout the watershed. All

samples were immediately transported to a co-located laboratory facility for processing and analysis.

### 3.3 Laboratory analysis

Each water sample was processed for Most Probable Number of total coliforms (TC) and *Escherichia coli* (EC) using a commercially available defined substrate medium, 4-methylumbelliferyl-*β*-D-glucuronide (Colilert, IDEXX Laboratories, Westbrook, ME). Samples were prepared by adding dehydrated Colilert medium to 100 ml of sample water in a sterilized dark glass bottle, gently tumbling the sample to ensure uniform mixing, then pouring the mixture into a Quanti-Tray 2000 sample tray. Trays were then fitted into a rubber seat and processed through a Quanti-Tray Sealer (IDEXX Laboratories). Samples were diluted for all fractions expected to have elevated bacterial counts (USEPA / APHA 1995).

Following incubation at 35°C for 24 to 28 hours, sample wells in each Quanti-Tray were examined under a longwave ultraviolet lamp (366 nm) for *E. coli* (fluorescence) and under ambient light for total coliform (yellow color). Sample tray wells that fluoresced or produced yellow indicator greater than or equal to the manufacturer's comparator tray were counted positive and read against a matrix to yield an estimated most probable number. To obtain turbidity values master samples were homogenized and compared against a nephelometric standard (NTU, LaMotte Corporation).

Following a storm event on 19 January 2001, a single sample collection effort was undertaken to determine the source of *E. coli* loading in the Catfish Pond watershed. Sample wells positive for *E. coli* streaked on mTEC agar (Difco, Sparks, MD) and isolated for ribotyping analysis. Ribotype patterns *of E. coli* isolated from stream water were compared with ribotype patterns of wild deer scat and feces of a confined deer herd within the watershed to determine bacteria source and dietary effects on isolated *E. coli*.

### 3.4 Controls

Data deviations caused by instrument drift and fouling were controlled for by manufacturers recommended servicing, as well as scheduled calibration and cleaning. As part of engineered upkeep, EPCL performed routine sensor calibrations daily and as part of a detailed troubleshooting menu initiated by instrument drift or failure. ISCO samplers were cleaned with hot water and flushed with 1% NaOCL solution between daily uses. Sample lines were also rinsed with deionized and strata water between individual samples to minimize bacterial cross-contamination. Bacteria data scatter and drift were monitored by duplicate samples, while laboratory quality control was tested daily with Colilert blanks used as negative controls. Except where noted, all bacteria data were $\log_{10}$ transformed prior to analysis to reduce the influence of outliers.

# CHAPTER 4

# RESULTS

Data collection was accomplished during the third year of a prolonged regional drought, which yielded fewer opportunities for storm sampling in the Catfish Pond headwater area and also resulted in decreased statistical power in the small (n=53 observation days) *E. coli* data set. Additionally, all water quality data were censured to match time series with the *E. coli* data set, reducing the overall data set from 1.2 million observations to 4293 observations. This smaller statistical matrix required greater emphasis to be placed on statistical *p*-values than on r-square values. Statistical data are often viewed with low r-square values (products of small sample size), but highly significant at ($\alpha = .05$, or $p << .001$) (*see* Tables 2.0 – 2.15).

Data presented in this study confirm the results of Kay and McDonald (1980), McDonald and Kay (1981) and Gannon et al. (1983), in that *E. coli* are transported primarily via overland flow and with the stream hydrograph (Figure 6), and conform to a basic Time, Distance, Mass (TDM) model for terrestrial transport and waterborne dispersion (Figure 26). Within the pond, 17 water quality parameters were monitored at 15-minute intervals from 11 June – 13 October 2000, producing a data set of approximately 1.2 million observations. *Escherichia. coli* sampling was conducted at 2 to 3 day intervals during the same

period and during storm events (*N* = 5), yielding approximately 750 observations. Five control sites (C1–C5) and five test sites (T1–T5) were installed within a mature second-generation hardwood forest to sample overland flow to the Catfish Pond headwater stream (Figure 1). Significant levels ($1 \times 10^2 – 10^4$) of background *E. coli* were detected at C1 and C2 during multiple storm events.

Located within the forest and under dense tree canopy, C3 and C4 received no stormwater flow. Hillslope-induced lateral flow, but no surficial flow, was observed adjacent to the headwater stream at C5. All test sites located down slope of the Whitehall Forest Whitetail Deer Research Facility registered bacteria counts up to three orders of magnitude higher than control sites. Statistics for *E. coli* and all water quality parameters are summarized in Table 1 through Table 2.15.

*Escherichia coli* concentrations in the headwater ephemeral stream ranged from 57.6 – 310,620 CFU/100 mL and consistently registered two orders of magnitude higher than bacteria densities in Catfish Pond, which registered 1.0 – 15,650 CFU/100 mL (Figure 5). Mean *E. coli* concentrations were 1,732 CFU/100 mL for the stream, and 11 CFU/100 mL for pond surface water samples. In general terms, the shallow Catfish Pond littoral nearest the headwater inflow (Transects 1 – 6, Figure 4) registered the highest mean surface bacteria concentrations, while Transects 7 – 15 ranged lower. Integrated depth surveys reflected increasing *E. coli* mean densities with depth: 11, 20, 26, and 48 CFU/100 mL at 0, 0.5, 1, and 1.5-m, respectively.

Within the headwater stream, precipitation ($r^2$ = 0.59, p << .001), turbidity ($r^2$ = 0.48, p << .001), and stage ($r^2$ = 0.40, p << .001) were most closely correlated to *E. coli* observations (Table 2). A second grouped dynamic influencing stream bacteria comprised dissolved oxygen ($r^2$ = 0.39, p << .001), oxidation-reduction potential ($r^2$ = 0.39, p << .001), pH ($r^2$ = 0.32, p << .001), and temperature ($r^2$ = 0.34, p << .001). The primary source of bacteria loading in the Catfish Pond watershed were whitetail deer, as confirmed by *Escherichia coli* ribotype profiles (n = 98) isolated from stream water on 19 January, which displayed similarity to deer in 42.9% of samples.

Standard linear regression and Principle Component Analysis of 17 biotic and abiotic parameters revealed three dynamics affecting *E. coli* fate in the Catfish Pond watershed: physical, chemical, and biologic components (Figure 8, 9, 10). The physical component comprised of precipitation, stream / pond stage, turbidity, temperature, and light emerged as the parameters most closely associated with *E. coli* densities in the pond (Figure 11 – 14). Turbidity ($r^2$ = 0.66, p << .001) emerged as the most influential parameter correlated to *E. coli*. Other significant parameters displayed modest spatial variation and can be grouped in two categories: nutrients and chemical. Of the nutrients, nitrite ($r^2$ = 0.53, p << .001) and total organic carbon ($r^2$ = 0.15, p << .001) reflected the strongest relationships to *E. coli*, with significant correlations at 15 and 12 of the 18 pond sampling stations, respectively (Tables 2.1 – 2.15). Phosphorus ($r^2$ = 0.22, p << .001), nitrate ($r^2$ = 0.21, p << .001) and ammonia ($r^2$ = 0.15, p << .001)

were also significant at ($\alpha = .05$), although these interactions appeared weaker than nitrite and carbon, collectively occurring in only five of 18 sampling stations. Of the physico-chemical factors, dissolved oxygen ($r^2 = 0.39$, $p << .001$) and stream / pond stage ($r^2 = 0.41$, $p << .001$) were significant at 17 and 15 of the 18 pond sampling stations, respectively. Oxidation-reduction potential ($r^2 = 0.40$, $p << .001$), pH ($r^2 = 0.36$, $p << .001$), temperature ($r^2 = 0.35$, $p << .001$), and conductivity ($r^2 = 0.56$, $p << .001$) exhibited a strong secondary dynamic, followed by PAR ($r^2 = 0.17$, $p < .001$). A weak but statistically significant relationship between *E. coli* and chlorophyll-*a* ($r^2 = 0.18$, $p << .001$) was also noted.

**Table 1. Descriptive statistics for 81 censured parameters, Catfish Pond watershed.**

| | Parameter | *N* | Mean | Std Dev | Min | Max | Range | Source |
|---|---|---|---|---|---|---|---|---|
| (Log CFU/100 mL) | E. coli, Stream | 52 | 3.23 | 0.8 | 1.76 | 5.49 | 3.73 | Colilert |
| | E. coli 0-m | 40 | 1.02 | 0.75 | 0.3 | 4.2 | 3.89 | Colilert |
| | E. coli 0.5-m | 32 | 1.3 | 0.96 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli 1-m | 32 | 1.41 | 0.92 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli 1.5-m | 31 | 1.68 | 1.07 | 0.3 | 3.63 | 3.33 | Colilert |
| | E. coli, Pond1 | 52 | 1.47 | 0.86 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond2 | 52 | 1.1 | 0.7 | 0.3 | 3.24 | 2.94 | Colilert |
| | E. coli, Pond3 | 52 | 1.07 | 0.69 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond4 | 51 | 1.01 | 0.63 | 0.3 | 3.05 | 2.75 | Colilert |
| | E. coli, Pond5 | 50 | 1.16 | 0.63 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond6 | 51 | 1.11 | 0.82 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond7 | 52 | 1.02 | 0.75 | 0.3 | 3.3 | 3 | Colilert |
| | E. coli, Pond8 | 50 | 1.11 | 0.69 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond9 | 50 | 1.03 | 0.74 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond10 | 50 | 1 | 0.69 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond11 | 52 | 0.98 | 0.64 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond12 | 52 | 0.95 | 0.68 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond13 | 50 | 0.96 | 0.73 | 0.3 | 3.38 | 3.08 | Colilert |
| | E. coli, Pond14 | 52 | 1.12 | 0.87 | 0.3 | 4.2 | 3.89 | Colilert |
| | E. coli, Pond15 | 52 | 0.95 | 0.76 | 0.3 | 3.3 | 3 | Colilert |
| (FTU) | SS Dock | 32 | 7.04 | 7.03 | 0.29 | 26.5 | 26.2 | EPCL |
| | SS Platform | 38 | 8.15 | 7.08 | 0.49 | 27.1 | 26.6 | EPCL |
| (µg/L) | TOC Dock | 38 | 14.3 | 20.6 | 3.6 | 93.5 | 90.0 | EPCL |
| | TOC Platform | 33 | 24.3 | 29.9 | 3.7 | 100.0 | 96.3 | EPCL |
| | PO4 Dock | 41 | 86.7 | 143 | 4.9 | 753 | 748 | EPCL |
| | PO4 Platform | 48 | 140 | 375 | 3.7 | 2457 | 2454 | EPCL |
| | NOx Dock | 40 | 190 | 93.5 | 14.7 | 446 | 432 | EPCL |
| | NOx Platform | 49 | 176 | 110 | 7.3 | 505 | 498 | EPCL |
| | NO2 Dock | 17 | 9.84 | 13.4 | 1.2 | 54.9 | 53.7 | EPCL |
| | NO2 Platform | 27 | 6.8 | 9.21 | 1.2 | 36.6 | 35.4 | EPCL |
| | NO3 Dock | 17 | 221 | 104 | 42.8 | 438 | 395 | EPCL |
| | NO3 Platform | 27 | 188 | 121 | 4.9 | 495 | 490 | EPCL |
| | NH3 Dock | 45 | 36.1 | 38.5 | 12.2 | 207 | 195 | EPCL |
| | NH3 Platform | 30 | 44.2 | 58.7 | 12.2 | 305 | 293 | EPCL |
| | Chl-a, Dock | 35 | 16.2 | 9.58 | 3.83 | 33.1 | 29.3 | Turner |
| | Chl-a, Platform | 49 | 36.3 | 42.8 | 4.07 | 195 | 191 | Turner |
| (°C) | Temp Dock, 0-m | 43 | 29.1 | 4.09 | 16.7 | 34.6 | 17.8 | Hydrolab |
| | Temp Dock, 1.5-m | 39 | 25.2 | 4.09 | 14.5 | 30.2 | 15.7 | Hydrolab |
| | Temp Platform, 0-m | 40 | 28.4 | 3.93 | 20.9 | 35.2 | 14.3 | Hydrolab |
| (µS/cm) | Cond Dock, 0-m | 39 | 73.3 | 20.7 | 50.8 | 110 | 59.5 | Hydrolab |
| | Cond Dock, 1.5-m | 36 | 75.0 | 16.6 | 51.7 | 102 | 50 | Hydrolab |
| | Cond Platform, 0-m | 39 | 66.0 | 19.6 | 39.8 | 117 | 77.4 | Hydrolab |

**Table 1 con't. Descriptive statistics for 81 censured parameters, Catfish Pond watershed.**

| | Parameter | *N* | Mean | Std Dev | Min | Max | Range | Source |
|---|---|---|---|---|---|---|---|---|
| | pH Dock, 0-m | 41 | 8.29 | 0.95 | 6.61 | 10.2 | 3.56 | Hydrolab |
| | pH Dock, 1.5-m | 39 | 6.93 | 0.87 | 6.12 | 9.82 | 3.7 | Hydrolab |
| | pH Platform, 0-m | 40 | 7.99 | 1.09 | 6.22 | 10.2 | 3.99 | Hydrolab |
| (mV) | ORP Dock, 0-m | 43 | 516 | 121 | 343 | 783 | 440 | Hydrolab |
| (mV) | ORP Dock, 1.5-m | 39 | 625 | 96.1 | 374 | 766 | 392 | Hydrolab |
| (mV) | ORP Platform, 0-m | 40 | 558 | 142 | 330 | 774 | 444 | Hydrolab |
| (mg/L) | DO Dock, 0-m | 43 | 7.81 | 1.73 | 3.29 | 11.4 | 8.06 | Hydrolab |
| (% sat) | DO Dock, 0-m | 43 | 103 | 25.9 | 42.3 | 151 | 109 | Hydrolab |
| (% sat) | DO Dock, 1.5-m | 39 | 52.8 | 32.6 | 2.27 | 114 | 111 | Hydrolab |
| (% sat) | DO Platform, 0-m | 40 | 102 | 31.9 | 48.4 | 169 | 120 | Hydrolab |
| ($\mu E/cm^2$) | PAR, 1.5-m | 39 | 26.1 | 77.4 | 1 | 449 | 448 | Hydrolab |
| ($\mu E/cm^2$) | PAR, 0-m | 40 | 0.99 | 1.26 | 0.01 | 4.5 | 4.49 | Hydrolab |
| (°C) | Temp, 2-m | 34 | 26.3 | 2.25 | 22.2 | 29.2 | 7.05 | Druck / CR-10X |
| (°C) | Temp, 1-m | 34 | 27.0 | 2.1 | 22.0 | 30.0 | 7.98 | Druck / CR-10X |
| (°C) | Temp, 0.5-m | 34 | 27.8 | 2.28 | 22.2 | 30.6 | 8.41 | Druck / CR-10X |
| (ft.) | Stage, Headwater | 41 | 0.055 | 0.027 | -0.007 | 0.11 | 0.12 | Druck / CR-10X |
| (ft.) | Stage, Tailwater | 33 | -0.0055 | 0.014 | -0.036 | 0.025 | 0.061 | Druck / CR-10X |
| (ft.) | Stage, Pond | 40 | -1.14 | 0.27 | -1.83 | -0.89 | 0.94 | Druck / CR-10X |
| (NTU) | Turbidity, Stream | 23 | 28.7 | 66.3 | 2.8 | 251 | 248 | LaMotte |
| (NTU) | Turbidity, Pond1 | 21 | 50.7 | 37.0 | 12.9 | 175 | 162 | LaMotte |
| (NTU) | Turbidity, Pond2 | 21 | 15.8 | 7.56 | 7.2 | 38.5 | 31.3 | LaMotte |
| (NTU) | Turbidity, Pond3 | 21 | 13.5 | 7.07 | 6.4 | 37.6 | 31.2 | LaMotte |
| (NTU) | Turbidity, Pond4 | 21 | 17.8 | 9.53 | 6 | 37.8 | 31.8 | LaMotte |
| (NTU) | Turbidity, Pond5 | 21 | 14.0 | 8.32 | 4.9 | 40.3 | 35.4 | LaMotte |
| (NTU) | Turbidity, Pond6 | 21 | 14.3 | 7.43 | 6.3 | 39.4 | 33.1 | LaMotte |
| (NTU) | Turbidity, Pond7 | 21 | 14.2 | 8.36 | 4.1 | 38.7 | 34.6 | LaMotte |
| (NTU) | Turbidity, Pond8 | 21 | 13.2 | 7.79 | 5.4 | 39.9 | 34.5 | LaMotte |
| (NTU) | Turbidity, Pond9 | 21 | 16.3 | 14.1 | 4.4 | 66.1 | 61.7 | LaMotte |
| (NTU) | Turbidity, Pond10 | 21 | 15.7 | 10.7 | 4.9 | 44 | 39.1 | LaMotte |
| (NTU) | Turbidity, Pond11 | 21 | 15.9 | 9.74 | 5.3 | 40.9 | 35.6 | LaMotte |
| (NTU) | Turbidity, Pond12 | 21 | 14.1 | 7.96 | 6.2 | 38.8 | 32.6 | LaMotte |
| (NTU) | Turbidity, Pond13 | 21 | 15.5 | 10.2 | 4.9 | 51.1 | 46.2 | LaMotte |
| (NTU) | Turbidity, Pond14 | 23 | 13.6 | 7.61 | 5.1 | 39 | 33.9 | LaMotte |
| (NTU) | Turbidity, Pond15 | 21 | 12.6 | 6.72 | 5 | 36.3 | 31.3 | LaMotte |
| (NTU) | Turbidity, 0.5-m | 21 | 20.1 | 16.4 | 7 | 83.6 | 76.6 | LaMotte |
| (NTU) | Turbidity, 1-m | 21 | 17.1 | 7.07 | 6.7 | 33 | 26.3 | LaMotte |
| (NTU) | Turbidity, 1.5-m | 21 | 30.2 | 17.8 | 11.3 | 79.7 | 68.4 | LaMotte |

**Table 2. Statistics for significant variables correlated to log-transformed *E. coli* (stream) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, P1 | 34 | 0.26 | 8.5 | 3.E-12 |
| E. coli, P3 | 34 | 0.11 | 3.1 | 6.E-05 |
| E. coli, P4 | 33 | 0.15 | 4.4 | 4.E-07 |
| E. coli, P5 | 32 | 0.08 | 2 | 9.E-03 |
| E. coli, P6 | 34 | 0.12 | 3.4 | 2.E-05 |
| E. coli, P7 | 34 | 0.27 | 9.2 | 6.E-13 |
| E. coli, P8 | 30 | 0.22 | 7.1 | 1.E-10 |
| E. coli, P9 | 31 | 0.13 | 3.6 | 9.E-06 |
| E. coli, P10 | 30 | 0.14 | 4 | 1.E-06 |
| E. coli, P12 | 31 | 0.13 | 3.7 | 6.E-06 |
| E. coli, P13 | 32 | 0.21 | 6.5 | 5.E-10 |
| E. coli, P14 | 46 | 0.31 | 11.2 | 1.E-14 |
| E. coli, P15 | 33 | 0.13 | 3.7 | 6.E-06 |
| SS, Platform | 37 | 0.15 | 4.3 | 5.E-07 |
| TOC, Dock | 37 | 0.22 | 6.9 | 1.E-10 |
| TOC, Platform | 32 | 0.19 | 5.6 | 6.E-09 |
| NO2, Platform | 26 | 0.08 | 2.2 | 3.E-03 |
| Chl-*a*, Platform | 48 | 0.10 | 2.8 | 2.E-04 |
| Temp, Dock, 0-m | 42 | 0.13 | 3.7 | 6.E-06 |
| Temp, Dock, 0.5-m | 33 | 0.17 | 5.2 | 3.E-08 |
| Temp, Dock, 1-m | 33 | 0.11 | 3 | 1.E-04 |
| Temp, Dock, 1.5-m | 38 | 0.21 | 6.4 | 6.E-10 |
| Temp, Plat, 0.5-m | 39 | 0.34 | 12.9 | 6.E-10 |
| Conductivity, Dock, 0-m | 38 | 0.09 | 2.4 | 1.E-03 |
| Conductivity, Dock, 1.5-m | 35 | 0.08 | 2.1 | 7.E-03 |
| Conductivity, Platform, 0.5-m | 38 | 0.11 | 3.1 | 7.E-05 |
| pH, Dock, 0-m | 40 | 0.13 | 3.5 | 1.E-05 |
| pH, Dock, 1.5-m | 38 | 0.17 | 4.9 | 7.E-08 |
| pH, Platform, 0.5-m | 39 | 0.32 | 11.5 | 7.E-15 |
| ORP, Dock, 0-m | 42 | 0.20 | 6.2 | 1.E-09 |
| ORP, Platform, 0.5-m | 39 | 0.39 | 15.9 | 7.E-18 |
| DO, Dock, 0-m (mg/L) | 42 | 0.21 | 6.5 | 4.E-10 |
| DO, Platform, 0.5-m (mg/L) | 39 | 0.34 | 12.9 | 6.E-16 |

**Table 2 continued. Statistics for significant variables correlated to log-transformed *E. coli* (stream) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| DO, Dock, 0-m (% sat) | 42 | 0.26 | 8.4 | 3.E-12 |
| DO, Platform, 0.5-m (% sat) | 39 | 0.39 | 15.5 | 1.E-17 |
| Stage, headwater | 40 | 0.40 | 16.5 | 3.E-18 |
| Precip | 5 | 0.59 | 35.9 | 7.E-26 |
| Cumulative precip | 51 | 0.26 | 8.6 | 2.E-12 |
| Turbidity, P3 | 21 | 0.27 | 9.2 | 6.E-13 |
| Turbidity, P5 | 21 | 0.14 | 3.9 | 2.E-06 |
| Turbidity, P6 | 21 | 0.09 | 2.4 | 1.E-03 |
| Turbidity, P7 | 21 | 0.09 | 2.5 | 1.E-03 |
| Turbidity, P8 | 21 | 0.26 | 8.4 | 4.E-12 |
| Turbidity, P10 | 21 | 0.13 | 3.6 | 8.E-06 |
| Turbidity, P11 | 21 | 0.29 | 9.8 | 2.E-13 |
| Turbidity, P12 | 21 | 0.14 | 4 | 2.E-06 |
| Turbidity, P13 | 21 | 0.11 | 3.1 | 6.E-05 |
| Turbidity, P15 | 21 | 0.16 | 4.8 | 9.E-08 |

**Table 2.1. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 1) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 32 | 0.26 | 8.5 | 3.E-12 |
| E. coli, 1-m | 32 | 0.07 | 3.7 | 6.E-06 |
| E. coli, P2 | 33 | 0.42 | 17.7 | 7.E-19 |
| E. coli, P3 | 34 | 0.54 | 29.2 | 8.E-24 |
| E. coli, P4 | 33 | 0.47 | 21.4 | 1.E-20 |
| E. coli, P5 | 32 | 0.40 | 16.3 | 4.E-18 |
| E. coli, P6 | 34 | 0.35 | 13.3 | 3.E-16 |
| E. coli, P7 | 34 | 0.38 | 15.3 | 2.E-17 |
| E. coli, P8 | 30 | 0.36 | 13.6 | 2.E-16 |
| E. coli, P9 | 31 | 0.49 | 23.2 | 2.E-21 |
| E. coli, P10 | 30 | 0.61 | 38.7 | 1.E-26 |
| E. coli, P11 | 33 | 0.48 | 22.5 | 3.E-21 |
| E. coli, P12 | 31 | 0.53 | 28.1 | 2.E-23 |
| E. coli, P13 | 32 | 0.51 | 25 | 3.E-22 |
| E. coli, P14 | 46 | 0.48 | 22.5 | 3.E-21 |
| E. coli, P15 | 33 | 0.52 | 26.4 | 8.E-23 |
| SS, Platform | 37 | 0.16 | 4.6 | 2.E-07 |
| TOC, Dock | 37 | 0.07 | 2.0 | 9.E-03 |
| TOC, Platform | 32 | 0.11 | 3.1 | 7.E-05 |
| NO2, Platform | 26 | 0.25 | 8.1 | 8.E-12 |
| Chlorophyll-*a* , Platform | 48 | 0.18 | 5.4 | 1.E-08 |
| Temp, Dock, 0-m | 42 | 0.07 | 1.8 | 2.E-02 |
| Temp, Dock, 0.5-m | 33 | 0.27 | 8.9 | 1.E-12 |
| Temp, Dock, 1-m | 33 | 0.21 | 6.6 | 4.E-10 |
| Temp, Dock, 1.5-m | 33 | 0.21 | 6.4 | 6.E-10 |
| Temp, Platform | 39 | 0.35 | 13.4 | 3.E-16 |
| pH, Dock, 0-m | 38 | 0.24 | 7.7 | 2.E-11 |
| pH, Dock, 1.5-m | 35 | 0.17 | 5.1 | 4.E-08 |
| pH, Platform | 38 | 0.36 | 13.6 | 2.E-16 |
| ORP, Dock, 0-m | 42 | 0.10 | 2.7 | 3.E-04 |
| ORP, Platform | 39 | 0.40 | 16.1 | 5.E-18 |
| DO, Dock, 0-m (mg/L) | 42 | 0.34 | 12.8 | 7.E-16 |
| DO, Platform (mg/L) | 39 | 0.21 | 6.5 | 5.E-10 |

**Table 2.1 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 1) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| DO, Dock, 0-m (% sat) | 42 | 0.32 | 11.5 | 6.E-15 |
| DO, Platform (% sat) | 39 | 0.27 | 8.9 | 1.E-12 |
| Stage, Headwater | 40 | 0.22 | 6.9 | 1.E-10 |
| Stage, Pond | 39 | 0.07 | 1.8 | 2.E-02 |
| Stage, Ephemeral | 32 | 0.08 | 2 | 8.E-03 |
| Precipitation, cumulative | 51 | 0.14 | 4.1 | 1.E-06 |
| Turbidity, stream | 23 | 0.11 | 2.9 | 1.E-04 |
| Turbidity, P1 | 21 | 0.33 | 12.1 | 2.E-15 |
| Turbidity, P2 | 21 | 0.15 | 4.3 | 6.E-07 |
| Turbidity, P3 | 21 | 0.30 | 10.3 | 6.E-14 |
| Turbidity, P4 | 21 | 0.21 | 6.5 | 5.E-10 |
| Turbidity, P5 | 21 | 0.16 | 4.7 | 1.E-07 |
| Turbidity, P6 | 21 | 0.09 | 2.6 | 7.E-04 |
| Turbidity, P7 | 21 | 0.17 | 4.9 | 7.E-08 |
| Turbidity, P8 | 21 | 0.17 | 5.1 | 3.E-08 |
| Turbidity, P10 | 21 | 0.13 | 3.7 | 5.E-06 |
| Turbidity, P12 | 21 | 0.37 | 14.2 | 8.E-17 |
| Turbidity, P13 | 21 | 0.21 | 6.5 | 4.E-10 |
| Turbidity, P14 | 23 | 0.29 | 10.2 | 8.E-14 |
| Turbidity, P15 | 21 | 0.35 | 13.1 | 4.E-16 |
| Turbidity, 1-m | 21 | 0.11 | 2.9 | 1.E-04 |

**Table 2.2. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 2) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, 0.5-m | 32 | 0.21 | 6.6 | 4.E-10 |
| E. coli, 1-m | 32 | 0.27 | 9.1 | 8.E-13 |
| E. coli, 1.5-m | 32 | 0.14 | 4 | 2.E-06 |
| E. coli, P1 | 33 | 0.42 | 17.7 | 7.E-19 |
| E. coli, P3 | 34 | 0.64 | 42.8 | 1.E-27 |
| E. coli, P4 | 33 | 0.45 | 20.3 | 3.E-20 |
| E. coli, P5 | 32 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P6 | 34 | 0.48 | 23 | 2.E-21 |
| E. coli, P7 | 34 | 0.31 | 10.9 | 2.E-14 |
| E. coli, P8 | 30 | 0.38 | 15.1 | 2.E-17 |
| E. coli, P9 | 31 | 0.61 | 38.8 | 1.E-26 |
| E. coli, P10 | 30 | 0.65 | 44.7 | 4.E-28 |
| E. coli, P11 | 33 | 0.53 | 28.1 | 2.E-23 |
| E. coli, P12 | 31 | 0.49 | 23.6 | 1.E-21 |
| E. coli, P13 | 32 | 0.48 | 22.4 | 3.E-21 |
| E. coli, P14 | 46 | 0.47 | 21.3 | 1.E-20 |
| E. coli, P15 | 33 | 0.28 | 9.7 | 2.E-13 |
| SS, Platform | 37 | 0.12 | 3.3 | 3.E-05 |
| TOC, Dock | 37 | 0.12 | 3.4 | 2.E-05 |
| NO2, Platform | 26 | 0.07 | 2.0 | 1.E-02 |
| ORP, Platform | 39 | 0.06 | 1.6 | 5.E-02 |
| DO, Dock, 0-m (mg/L) | 42 | 0.12 | 3.3 | 2.E-05 |
| DO, Platform (mg/L) | 39 | 0.07 | 1.8 | 2.E-02 |
| DO, Dock, 0-m (% sat) | 42 | 0.09 | 2.3 | 2.E-03 |
| Stage, Pond | 39 | 0.12 | 3.5 | 1.E-05 |
| Turbidity, stream | 23 | 0.09 | 2.4 | 1.E-03 |
| Turbidity, P2 | 21 | 0.14 | 4.0 | 1.E-06 |
| Turbidity, P3 | 21 | 0.18 | 5.3 | 2.E-08 |
| Turbidity, P4 | 21 | 0.11 | 3.2 | 5.E-05 |
| Turbidity, P5 | 21 | 0.09 | 2.5 | 9.E-04 |
| Turbidity, P7 | 21 | 0.09 | 2.6 | 7.E-04 |
| Turbidity, P10 | 21 | 0.12 | 3.2 | 4.E-05 |
| Turbidity, P12 | 21 | 0.14 | 3.9 | 3.E-06 |

**Table 2.2 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 2) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P13 | 21 | 0.07 | 1.9 | 1.E-02 |
| Turbidity, P14 | 23 | 0.15 | 4.3 | 5.E-07 |
| Turbidity, P15 | 21 | 0.19 | 5.7 | 4.E-09 |
| Turbidity, 1-m | 21 | 0.26 | 8.7 | 2.E-12 |
| Turbidity, 1.5-m | 21 | 0.09 | 2.4 | 2.E-03 |

**Table 2.3. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 3) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.11 | 3.1 | 6.E-05 |
| E. coli, 0.5-m | 32 | 0.20 | 6.1 | 2.E-09 |
| E. coli, 1-m | 32 | 0.56 | 31 | 2.E-24 |
| E. coli, 1.5-m | 32 | 0.32 | 11.5 | 7.E-15 |
| E. coli, P1 | 33 | 0.20 | 29.2 | 8.E-24 |
| E. coli, P2 | 34 | 0.33 | 42.8 | 1.E-27 |
| E. coli, P4 | 33 | 0.67 | 50.8 | 2.E-29 |
| E. coli, P5 | 32 | 0.76 | 75.6 | 2.E-33 |
| E. coli, P6 | 34 | 0.56 | 30.9 | 2.E-24 |
| E. coli, P7 | 34 | 0.55 | 29.5 | 7.E-24 |
| E. coli, P8 | 30 | 0.57 | 32.4 | 7.E-25 |
| E. coli, P9 | 31 | 0.61 | 37.7 | 2.E-26 |
| E. coli, P10 | 30 | 0.57 | 32.8 | 6.E-25 |
| E. coli, P11 | 33 | 0.71 | 59.3 | 5.E-31 |
| E. coli, P12 | 31 | 0.75 | 74.1 | 3.E-33 |
| E. coli, P13 | 32 | 0.73 | 67.5 | 2.E-32 |
| E. coli, P14 | 46 | 0.56 | 31.2 | 2.E-24 |
| E. coli, P15 | 33 | 0.35 | 13.1 | 4.E-16 |
| SS, Platform | 37 | 0.07 | 1.9 | 1.E-02 |
| TOC, Dock | 37 | 0.08 | 2.1 | 5.E-03 |
| TOC, Platform | 32 | 0.06 | 1.6 | 5.E-02 |
| NO2, Platform | 26 | 0.23 | 7.4 | 4.E-11 |
| Conductivity, Dock, 0-m | 38 | 0.14 | 4.1 | 1.E-06 |
| Conductivity, Dock, 1.5-m | 35 | 0.07 | 1.8 | 2.E-02 |
| Conductivity, Platform | 38 | 0.06 | 1.6 | 5.E-02 |
| PAR, Reference, 0-m | 39 | 0.11 | 3.1 | 5.E-05 |
| Turbidity, stream | 23 | 0.19 | 5.9 | 3.E-09 |
| Turbidity, P1 | 21 | 0.16 | 4.8 | 8.E-08 |
| Turbidity, P2 | 21 | 0.18 | 5.4 | 1.E-08 |
| Turbidity, P3 | 21 | 0.34 | 12.5 | 1.E-15 |
| Turbidity, P4 | 21 | 0.20 | 6.2 | 1.E-09 |
| Turbidity, P5 | 21 | 0.19 | 5.8 | 4.E-09 |
| Turbidity, P6 | 21 | 0.17 | 4.9 | 8.E-08 |

**Table 2.3 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 3) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P7 | 21 | 0.24 | 7.7 | 2.E-11 |
| Turbidity, P8 | 21 | 0.24 | 7.9 | 1.E-11 |
| Turbidity, P10 | 21 | 0.13 | 3.7 | 6.E-06 |
| Turbidity, P11 | 21 | 0.11 | 3.0 | 1.E-04 |
| Turbidity, P12 | 21 | 0.40 | 16.1 | 5.E-18 |
| Turbidity, P13 | 21 | 0.24 | 7.6 | 2.E-11 |
| Turbidity, P14 | 23 | 0.29 | 10.2 | 8.E-14 |
| Turbidity, P15 | 21 | 0.25 | 8.3 | 5.E-12 |
| Turbidity, 1-m | 21 | 0.19 | 5.6 | 7.E-09 |
| Turbidity, 1.5-m | 21 | 0.07 | 1.8 | 2.E-02 |

**Table 2.4. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 4) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.14 | 4.4 | 4.E-07 |
| E. coli, 1-m | 32 | 0.31 | 11.3 | 1.E-14 |
| E. coli, 1.5-m | 32 | 0.13 | 3.7 | 5.E-06 |
| E. coli, P1 | 33 | 0.47 | 21.4 | 1.E-20 |
| E. coli, P2 | 34 | 0.45 | 20.3 | 3.E-20 |
| E. coli, P3 | 33 | 0.67 | 50.8 | 2.E-29 |
| E. coli, P5 | 32 | 0.55 | 30.1 | 4.E-24 |
| E. coli, P6 | 34 | 0.68 | 51.6 | 1.E-29 |
| E. coli, P7 | 34 | 0.48 | 22.8 | 2.E-21 |
| E. coli, P8 | 30 | 0.67 | 50.8 | 2.E-29 |
| E. coli, P9 | 31 | 0.59 | 34.7 | 2.E-25 |
| E. coli, P10 | 30 | 0.37 | 14.5 | 5.E-17 |
| E. coli, P11 | 33 | 0.60 | 36.3 | 5.E-26 |
| E. coli, P12 | 31 | 0.77 | 83.7 | 1.E-34 |
| E. coli, P13 | 32 | 0.65 | 46.4 | 2.E-28 |
| E. coli, P14 | 46 | 0.51 | 25.4 | 2.E-22 |
| E. coli, P15 | 33 | 0.26 | 8.5 | 3.E-12 |
| SS, Platform | 37 | 0.07 | 1.7 | 3.E-02 |
| PO4, Dock | 37 | 0.16 | 4.7 | 1.E-07 |
| NO2, Dock | 26 | 0.08 | 2.2 | 3.E-03 |
| NO2, Platform | 26 | 0.40 | 16.4 | 3.E-18 |
| Chlorophyll-*a*, Platform | 48 | 0.07 | 1.8 | 2.E-02 |
| pH, Dock, 1.5-m | 38 | 0.08 | 2.1 | 5.E-03 |
| ORP, Platform | 39 | 0.07 | 1.9 | 1.E-02 |
| DO, Dock, 0-m (mg/L) | 42 | 0.13 | 3.7 | 6.E-06 |
| DO, Dock, 1.5-m (mg/L) | 38 | 0.06 | 1.7 | 4.E-02 |
| DO, Platform (mg/L) | 39 | 0.17 | 5.0 | 4.E-08 |
| DO, Dock, 0-m (% sat) | 42 | 0.08 | 2.2 | 3.E-03 |
| DO, Dock, 1.5-m (% sat) | 38 | 0.07 | 1.8 | 2.E-02 |
| DO, Platform (% sat) | 39 | 0.16 | 4.5 | 2.E-07 |
| PAR, Reference, 0-m | 39 | 0.12 | 3.4 | 2.E-05 |
| Stage, Headwater | 40 | 0.11 | 2.9 | 1.E-04 |
| Turbidity, stream | 23 | 0.23 | 7.5 | 3.E-11 |

**Table 2.4 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 4) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P1 | 21 | 0.15 | 4.4 | 4.E-07 |
| Turbidity, P2 | 21 | 0.08 | 2.1 | 5.E-03 |
| Turbidity, P3 | 21 | 0.30 | 10.7 | 3.E-14 |
| Turbidity, P4 | 21 | 0.44 | 19.5 | 7.E-20 |
| Turbidity, P5 | 21 | 0.24 | 7.9 | 1.E-11 |
| Turbidity, P6 | 21 | 0.13 | 3.6 | 9.E-06 |
| Turbidity, P7 | 21 | 0.30 | 10.6 | 3.E-14 |
| Turbidity, P8 | 21 | 0.19 | 5.8 | 4.E-09 |
| Turbidity, P10 | 21 | 0.19 | 5.8 | 4.E-09 |
| Turbidity, P12 | 21 | 0.43 | 18.4 | 3.E-19 |
| Turbidity, P13 | 21 | 0.37 | 14.4 | 6.E-17 |
| Turbidity, P14 | 23 | 0.33 | 12.2 | 2.E-15 |
| Turbidity, P15 | 21 | 0.23 | 7.1 | 9.E-11 |
| Turbidity, 1-m | 21 | 0.13 | 3.8 | 4.E-06 |

**Table 2.5. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 5) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 32 | 0.08 | 2 | 9.E-03 |
| E. coli, 0.5-m | 32 | 0.13 | 3.8 | 4.E-06 |
| E. coli, 1-m | 32 | 0.50 | 24.5 | 4.E-22 |
| E. coli, 1.5-m | 32 | 0.31 | 11.2 | 1.E-14 |
| E. coli, P1 | 34 | 0.40 | 16.3 | 4.E-18 |
| E. coli, P2 | 33 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P3 | 34 | 0.76 | 75.6 | 2.E-33 |
| E. coli, P4 | 33 | 0.55 | 30.1 | 4.E-24 |
| E. coli, P6 | 34 | 0.54 | 29.3 | 8.E-24 |
| E. coli, P7 | 34 | 0.43 | 18.8 | 2.E-19 |
| E. coli, P8 | 30 | 0.55 | 29.6 | 6.E-24 |
| E. coli, P9 | 31 | 0.58 | 34 | 2.E-25 |
| E. coli, P10 | 30 | 0.53 | 28.2 | 2.E-23 |
| E. coli, P11 | 33 | 0.69 | 55.5 | 3.E-30 |
| E. coli, P12 | 31 | 0.66 | 46.8 | 1.E-28 |
| E. coli, P13 | 32 | 0.72 | 63.6 | 1.E-31 |
| E. coli, P14 | 46 | 0.56 | 32 | 1.E-24 |
| E. coli, P15 | 33 | 0.25 | 8.1 | 8.E-12 |
| TOC, Dock | 37 | 0.12 | 3.3 | 2.E-05 |
| NO2, Platform | 26 | 0.23 | 7.3 | 5.E-11 |
| Conductivity, Dock, 0-m | 38 | 0.13 | 3.8 | 3.E-06 |
| Conductivity, Dock, 1.5-m | 35 | 0.12 | 3.3 | 2.E-05 |
| Conductivity, Platform, 0.5-m | 38 | 0.08 | 2.2 | 3.E-03 |
| DO, Dock, 0-m (mg/L) | 42 | 0.07 | 1.8 | 2.E-02 |
| DO, Dock, 1.5-m (mg/L) | 39 | 0.08 | 2 | 7.E-03 |
| DO, Dock, 1.5-m (% sat) | 42 | 0.07 | 1.7 | 3.E-02 |
| PAR, 1.5-m | 38 | 0.08 | 2 | 8.E-03 |
| Stage, Pond | 40 | 0.09 | 2.4 | 1.E-03 |
| Turbidity, stream | 23 | 0.16 | 4.5 | 3.E-07 |
| Turbidity, P2 | 21 | 0.20 | 6.3 | 9.E-10 |
| Turbidity, P3 | 21 | 0.31 | 10.9 | 2.E-14 |
| Turbidity, P4 | 21 | 0.41 | 17.3 | 1.E-18 |
| Turbidity, P5 | 21 | 0.21 | 6.7 | 3.E-10 |

**Table 2.5 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 5) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P6 | 21 | 0.09 | 2.4 | 2.E-03 |
| Turbidity, P7 | 21 | 0.17 | 4.9 | 7.E-08 |
| Turbidity, P8 | 21 | 0.09 | 2.3 | 2.E-03 |
| Turbidity, P11 | 21 | 0.08 | 2.3 | 3.E-03 |
| Turbidity, P12 | 21 | 0.37 | 14.7 | 4.E-17 |
| Turbidity, P13 | 21 | 0.22 | 7.0 | 1.E-10 |
| Turbidity, P14 | 23 | 0.21 | 6.7 | 3.E-10 |
| Turbidity, P15 | 21 | 0.32 | 11.6 | 6.E-15 |
| Turbidity, 1-m | 21 | 0.18 | 5.3 | 2.E-08 |
| Turbidity, 1.5-m | 21 | 0.08 | 2.2 | 3.E-03 |

**Table 2.6. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 6) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.12 | 3.4 | 2.E-05 |
| E. coli, 1-m | 32 | 0.24 | 7.5 | 3.E-11 |
| E. coli, 1.5-m | 32 | 0.13 | 3.8 | 4.E-06 |
| E. coli, P1 | 33 | 0.35 | 13.3 | 3.E-16 |
| E. coli, P2 | 34 | 0.48 | 23 | 2.E-21 |
| E. coli, P3 | 33 | 0.56 | 30.9 | 2.E-24 |
| E. coli, P4 | 33 | 0.68 | 51.6 | 1.E-29 |
| E. coli, P5 | 32 | 0.54 | 29.3 | 8.E-24 |
| E. coli, P7 | 34 | 0.60 | 37.1 | 3.E-26 |
| E. coli, P8 | 30 | 0.47 | 21.5 | 9.E-21 |
| E. coli, P9 | 31 | 0.54 | 28.2 | 2.E-23 |
| E. coli, P10 | 30 | 0.36 | 13.8 | 1.E-16 |
| E. coli, P11 | 33 | 0.47 | 21.3 | 1.E-20 |
| E. coli, P12 | 31 | 0.60 | 37.3 | 3.E-26 |
| E. coli, P13 | 32 | 0.63 | 40.9 | 3.E-27 |
| E. coli, P14 | 46 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P15 | 33 | 0.32 | 11.7 | 4.E-15 |
| NO2, Platform | 26 | 0.23 | 7.4 | 5.E-11 |
| Chlorophyll-*a*, Dock | 48 | 0.06 | 1.7 | 4.E-02 |
| ORP, Platform | 39 | 0.07 | 1.8 | 2.E-02 |
| DO, Dock, 0-m (mg/L) | 42 | 0.07 | 1.8 | 3.E-02 |
| DO, Platform (mg/L) | 39 | 0.08 | 2.1 | 5.E-03 |
| DO, Platform (% sat) | 39 | 0.09 | 2.3 | 2.E-03 |
| PAR, Reference, 0-m | 39 | 0.11 | 3.0 | 9.E-05 |
| Stage, Headwater | 40 | 0.11 | 3.1 | 7.E-05 |
| Stage, Pond | 39 | 0.07 | 1.9 | 1.E-02 |
| Turbidity, stream | 23 | 0.47 | 21.4 | 1.E-20 |
| Turbidity, P1 | 21 | 0.08 | 2.3 | 2.E-03 |
| Turbidity, P2 | 21 | 0.16 | 4.7 | 1.E-07 |
| Turbidity, P3 | 21 | 0.30 | 10.5 | 4.E-14 |
| Turbidity, P4 | 21 | 0.15 | 4.2 | 8.E-07 |
| Turbidity, P5 | 21 | 0.19 | 5.6 | 7.E-09 |
| Turbidity, P6 | 21 | 0.18 | 5.6 | 8.E-09 |

**Table 2.6 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 6) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P7 | 21 | 0.28 | 9.4 | 4.E-13 |
| Turbidity, P8 | 21 | 0.16 | 4.5 | 3.E-07 |
| Turbidity, P10 | 21 | 0.11 | 3.0 | 9.E-05 |
| Turbidity, P12 | 21 | 0.26 | 8.8 | 2.E-12 |
| Turbidity, P13 | 21 | 0.14 | 4.1 | 1.E-06 |
| Turbidity, P14 | 23 | 0.33 | 11.8 | 4.E-15 |
| Turbidity, P15 | 21 | 0.30 | 10.6 | 4.E-14 |
| Turbidity, 1-m | 21 | 0.22 | 6.8 | 2.E-10 |
| Turbidity, 1.5-m | 21 | 0.10 | 2.8 | 2.E-04 |

**Table 2.7. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 7) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.27 | 9.2 | 6.E-13 |
| E. coli, 1-m | 32 | 0.14 | 4.1 | 1.E-06 |
| E. coli, P1 | 33 | 0.38 | 15.3 | 2.E-17 |
| E. coli, P2 | 34 | 0.31 | 10.9 | 2.E-14 |
| E. coli, P3 | 33 | 0.55 | 29.5 | 7.E-24 |
| E. coli, P4 | 32 | 0.48 | 22.8 | 2.E-21 |
| E. coli, P5 | 34 | 0.43 | 18.8 | 2.E-19 |
| E. coli, P6 | 34 | 0.60 | 37.1 | 3.E-26 |
| E. coli, P8 | 30 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P9 | 31 | 0.56 | 31.6 | 1.E-24 |
| E. coli, P10 | 30 | 0.41 | 17.2 | 1.E-18 |
| E. coli, P11 | 33 | 0.44 | 19 | 1.E-19 |
| E. coli, P12 | 31 | 0.59 | 35.7 | 8.E-26 |
| E. coli, P13 | 32 | 0.61 | 38.1 | 2.E-26 |
| E. coli, P14 | 46 | 0.53 | 27.5 | 3.E-23 |
| E. coli, P15 | 33 | 0.34 | 12.5 | 1.E-15 |
| SS, Platform | 37 | 0.08 | 2.0 | 9.E-03 |
| PO4, Dock | 37 | 0.08 | 2.2 | 4.E-03 |
| NO2, Platform | 26 | 0.30 | 10.6 | 3.E-14 |
| Chlorophyll-*a*, Platform | 48 | 0.13 | 3.5 | 1.E-05 |
| Temp, Platform | 39 | 0.23 | 7.1 | 9.E-11 |
| pH, Dock, Dock, 0-m | 40 | 0.08 | 2.2 | 4.E-03 |
| pH, Dock, 1.5-m | 38 | 0.11 | 3.0 | 8.E-05 |
| pH, Platform | 39 | 0.12 | 3.4 | 2.E-05 |
| ORP, Dock, 1.5-m | 38 | 0.09 | 2.4 | 2.E-03 |
| ORP, Platform | 39 | 0.20 | 6.3 | 9.E-10 |
| DO, Dock, 0-m (mg/L) | 42 | 0.20 | 6.0 | 2.E-09 |
| DO, Platform (mg/L) | 39 | 0.13 | 3.6 | 7.E-06 |
| DO, Dock, 0-m (% sat) | 42 | 0.15 | 4.2 | 7.E-07 |
| DO, Platform (% sat) | 39 | 0.16 | 4.7 | 1.E-07 |
| Temp, Dock, 0.5-m | 33 | 0.09 | 2.3 | 2.E-03 |
| Stage, Headwater | 40 | 0.31 | 10.8 | 2.E-14 |
| Turbidity, stream | 23 | 0.40 | 16.3 | 4.E-18 |

**Table 2.7 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 7) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P2 | 21 | 0.08 | 2.0 | 8.E-03 |
| Turbidity, P3 | 21 | 0.23 | 7.3 | 5.E-11 |
| Turbidity, P4 | 21 | 0.17 | 4.9 | 7.E-08 |
| Turbidity, P5 | 21 | 0.18 | 5.4 | 1.E-08 |
| Turbidity, P6 | 21 | 0.25 | 8.0 | 9.E-12 |
| Turbidity, P7 | 21 | 0.28 | 9.5 | 4.E-13 |
| Turbidity, P8 | 21 | 0.15 | 4.5 | 3.E-07 |
| Turbidity, P12 | 21 | 0.23 | 7.3 | 5.E-11 |
| Turbidity, P13 | 21 | 0.17 | 4.9 | 7.E-08 |
| Turbidity, P14 | 23 | 0.22 | 6.8 | 2.E-10 |
| Turbidity, P15 | 21 | 0.13 | 3.8 | 4.E-06 |
| Turbidity, 1-m | 21 | 0.06 | 1.7 | 4.E-02 |

**Table 2.8. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 8) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.22 | 7.1 | 1.E-10 |
| E. coli, 1-m | 32 | 0.34 | 12.8 | 7.E-16 |
| E. coli, 1.5-m | 32 | 0.14 | 4.1 | 1.E-06 |
| E. coli, P1 | 33 | 0.36 | 13.6 | 2.E-16 |
| E. coli, P2 | 34 | 0.38 | 15.1 | 2.E-17 |
| E. coli, P3 | 33 | 0.57 | 32.4 | 7.E-25 |
| E. coli, P4 | 32 | 0.67 | 50.8 | 2.E-29 |
| E. coli, P5 | 34 | 0.55 | 29.6 | 6.E-24 |
| E. coli, P6 | 34 | 0.47 | 21.5 | 9.E-21 |
| E. coli, P7 | 30 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P9 | 31 | 0.56 | 31.5 | 1.E-24 |
| E. coli, P10 | 30 | 0.56 | 31 | 2.E-24 |
| E. coli, P11 | 33 | 0.62 | 39.6 | 7.E-27 |
| E. coli, P12 | 31 | 0.65 | 46 | 2.E-28 |
| E. coli, P13 | 32 | 0.69 | 53.7 | 6.E-30 |
| E. coli, P14 | 46 | 0.68 | 51.7 | 1.E-29 |
| E. coli, P15 | 33 | 0.14 | 3.9 | 2.E-06 |
| TOC, Dock | 37 | 0.09 | 2.3 | 2.E-03 |
| NO2, Platform | 26 | 0.52 | 26.0 | 1.E-22 |
| NO3, Dock | 16 | 0.08 | 2.2 | 4.E-03 |
| NO3, Platform | 26 | 0.17 | 5.0 | 5.E-08 |
| DO, Dock, 0-m (mg/L) | 42 | 0.13 | 3.7 | 5.E-06 |
| DO, Platform (mg/L) | 39 | 0.11 | 3.0 | 1.E-04 |
| DO, Dock, 0-m (% sat) | 42 | 0.11 | 3.0 | 1.E-04 |
| DO, Platform (% sat) | 39 | 0.11 | 2.9 | 1.E-04 |
| PAR, Reference | 39 | 0.17 | 5.1 | 3.E-08 |
| Stage, Headwater | 40 | 0.21 | 6.4 | 5.E-10 |
| Stage, Ephemeral | 32 | 0.08 | 2.3 | 2.E-03 |
| Turbidity, stream | 23 | 0.16 | 4.5 | 2.E-07 |
| Turbidity, P1 | 21 | 0.22 | 7.1 | 9.E-11 |
| Turbidity, P2 | 21 | 0.21 | 6.6 | 3.E-10 |
| Turbidity, P3 | 21 | 0.41 | 16.9 | 2.E-18 |
| Turbidity, P4 | 21 | 0.52 | 26.4 | 9.E-23 |

**Table 2.8 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 8) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P5 | 21 | 0.35 | 13.3 | 3.E-16 |
| Turbidity, P6 | 21 | 0.22 | 6.9 | 2.E-10 |
| Turbidity, P7 | 21 | 0.46 | 21.2 | 1.E-20 |
| Turbidity, P8 | 21 | 0.30 | 10.7 | 3.E-14 |
| Turbidity, P9 | 21 | 0.28 | 9.3 | 5.E-13 |
| Turbidity, P10 | 21 | 0.24 | 7.6 | 3.E-11 |
| Turbidity, P11 | 21 | 0.17 | 5.1 | 4.E-08 |
| Turbidity, P12 | 21 | 0.57 | 32.5 | 7.E-25 |
| Turbidity, P13 | 21 | 0.43 | 18.5 | 2.E-19 |
| Turbidity, P14 | 23 | 0.45 | 19.7 | 6.E-20 |
| Turbidity, P15 | 21 | 0.29 | 9.9 | 1.E-13 |
| Turbidity, 1-m | 21 | 0.08 | 2.0 | 7.E-03 |
| Turbidity, 1.5-m | 21 | 0.11 | 2.9 | 1.E-04 |

**Table 2.9. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 9) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.13 | 3.6 | 9.E-06 |
| E. coli, 1-m | 32 | 0.19 | 5.8 | 4.E-09 |
| E. coli, 1.5-m | 32 | 0.07 | 1.7 | 3.E-02 |
| E. coli, P1 | 33 | 0.49 | 23.2 | 2.E-21 |
| E. coli, P2 | 34 | 0.61 | 38.8 | 1.E-26 |
| E. coli, P3 | 33 | 0.61 | 37.7 | 2.E-26 |
| E. coli, P4 | 32 | 0.59 | 34.7 | 2.E-25 |
| E. coli, P5 | 34 | 0.58 | 34.0 | 2.E-25 |
| E. coli, P6 | 34 | 0.54 | 28.2 | 2.E-23 |
| E. coli, P7 | 30 | 0.56 | 31.6 | 1.E-24 |
| E. coli, P8 | 31 | 0.56 | 31.5 | 1.E-24 |
| E. coli, P10 | 30 | 0.71 | 60.4 | 3.E-31 |
| E. coli, P11 | 33 | 0.70 | 58.1 | 9.E-31 |
| E. coli, P12 | 31 | 0.68 | 52.2 | 1.E-29 |
| E. coli, P13 | 32 | 0.75 | 71.7 | 6.E-33 |
| E. coli, P14 | 46 | 0.70 | 56.3 | 2.E-30 |
| E. coli, P15 | 33 | 0.34 | 12.5 | 1.E-15 |
| SS, Platform | 31 | 0.14 | 4.1 | 1.E-06 |
| TOC, Dock | 37 | 0.09 | 2.5 | 7.E-04 |
| TOC, Platform | 32 | 0.06 | 1.6 | 5.E-02 |
| PO4, Dock | 40 | 0.09 | 2.3 | 2.E-03 |
| NO2, Platform | 26 | 0.53 | 27.6 | 3.E-23 |
| Chlorophyll-*a*, Platform | 48 | 0.11 | 2.9 | 2.E-04 |
| Temp, Platform | 39 | 0.10 | 2.8 | 2.E-04 |
| pH, Platform | 39 | 0.09 | 2.3 | 2.E-03 |
| ORP, Dock, 1.5-m | 38 | 0.06 | 1.7 | 4.E-02 |
| ORP, Platform | 39 | 0.14 | 4.0 | 2.E-06 |
| DO, Dock, 0-m (mg/L) | 42 | 0.24 | 7.8 | 1.E-11 |
| DO, Platform (mg/L) | 39 | 0.18 | 5.4 | 1.E-08 |
| DO, Dock, 0-m (% sat) | 42 | 0.17 | 5.0 | 4.E-08 |
| DO, Platform (% sat) | 39 | 0.18 | 5.5 | 1.E-08 |
| Stage, Headwater | 40 | 0.13 | 3.6 | 8.E-06 |
| Stage, Pond | 39 | 0.06 | 1.7 | 3.E-02 |

**Table 2.9 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 9) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, stream | 23 | 0.18 | 5.4 | 1.E-08 |
| Turbidity, P1 | 21 | 0.18 | 5.3 | 2.E-08 |
| Turbidity, P2 | 21 | 0.24 | 7.7 | 2.E-11 |
| Turbidity, P3 | 21 | 0.48 | 22.2 | 4.E-21 |
| Turbidity, P4 | 21 | 0.66 | 47.1 | 1.E-28 |
| Turbidity, P5 | 21 | 0.37 | 14.2 | 7.E-17 |
| Turbidity, P6 | 21 | 0.24 | 7.8 | 2.E-11 |
| Turbidity, P7 | 21 | 0.42 | 17.8 | 6.E-19 |
| Turbidity, P8 | 21 | 0.21 | 6.3 | 8.E-10 |
| Turbidity, P10 | 21 | 0.11 | 3.1 | 7.E-05 |
| Turbidity, P11 | 21 | 0.12 | 3.4 | 2.E-05 |
| Turbidity, P12 | 21 | 0.44 | 19.5 | 8.E-20 |
| Turbidity, P13 | 21 | 0.38 | 14.7 | 3.E-17 |
| Turbidity, P14 | 23 | 0.47 | 22.1 | 5.E-21 |
| Turbidity, P15 | 21 | 0.34 | 12.9 | 6.E-16 |
| Turbidity, 0.5-m | 21 | 0.17 | 4.9 | 5.E-08 |
| Turbidity, 1-m | 21 | 0.31 | 11.1 | 1.E-14 |
| Turbidity, 1.5-m | 21 | 0.10 | 2.6 | 5.E-04 |

**Table 2.10. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 10) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.14 | 4 | 1.E-06 |
| E. coli, 1-m | 32 | 0.14 | 3.9 | 2.E-06 |
| E. coli, 1.5-m | 32 | 0.07 | 1.8 | 2.E-02 |
| E. coli, P1 | 33 | 0.61 | 38.7 | 1.E-26 |
| E. coli, P2 | 34 | 0.65 | 44.7 | 4.E-28 |
| E. coli, P3 | 33 | 0.57 | 32.8 | 6.E-25 |
| E. coli, P4 | 32 | 0.37 | 14.5 | 5.E-17 |
| E. coli, P5 | 34 | 0.53 | 28.2 | 2.E-23 |
| E. coli, P6 | 34 | 0.36 | 13.8 | 1.E-16 |
| E. coli, P7 | 30 | 0.41 | 17.2 | 1.E-18 |
| E. coli, P8 | 30 | 0.56 | 31 | 2.E-24 |
| E. coli, P9 | 31 | 0.71 | 60.4 | 3.E-31 |
| E. coli, P11 | 33 | 0.62 | 40.5 | 4.E-27 |
| E. coli, P12 | 31 | 0.52 | 26.8 | 6.E-23 |
| E. coli, P13 | 32 | 0.47 | 21.8 | 6.E-21 |
| E. coli, P14 | 46 | 0.69 | 54.1 | 5.E-30 |
| E. coli, P15 | 33 | 0.34 | 12.6 | 9.E-16 |
| SS, Platform | 37 | 0.07 | 1.7 | 3.E-02 |
| TOC, Dock | 37 | 0.12 | 3.4 | 2.E-05 |
| NO2, Platform | 26 | 0.10 | 2.8 | 2.E-04 |
| Chlorophyll-*a* , Dock | 48 | 0.07 | 1.8 | 2.E-02 |
| Temp, Platform | 39 | 0.10 | 2.6 | 6.E-04 |
| pH, Dock, 0-m | 40 | 0.08 | 2.2 | 3.E-03 |
| pH, Platform | 39 | 0.14 | 3.9 | 3.E-06 |
| ORP, Platform | 39 | 0.17 | 5.1 | 4.E-08 |
| DO, Dock, 0-m (mg/L) | 42 | 0.37 | 14.5 | 5.E-17 |
| DO, Platform (mg/L) | 39 | 0.21 | 6.5 | 4.E-10 |
| DO, Dock, 0-m (% sat) | 42 | 0.29 | 9.8 | 2.E-13 |
| DO, Platform (% sat) | 39 | 0.20 | 6.2 | 1.E-09 |
| Stage, Headwater | 40 | 0.09 | 2.5 | 1.E-03 |
| Stage, Pond | 39 | 0.10 | 2.8 | 2.E-04 |
| Turbidity, stream | 23 | 0.21 | 6.6 | 4.E-10 |
| Turbidity, P1 | 21 | 0.15 | 4.4 | 4.E-07 |

**Table 2.10 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 10) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P2 | 21 | 0.19 | 5.9 | 3.E-09 |
| Turbidity, P3 | 21 | 0.29 | 10.0 | 1.E-13 |
| Turbidity, P4 | 21 | 0.15 | 4.4 | 4.E-07 |
| Turbidity, P5 | 21 | 0.15 | 4.2 | 9.E-07 |
| Turbidity, P6 | 21 | 0.09 | 2.5 | 9.E-04 |
| Turbidity, P7 | 21 | 0.23 | 7.2 | 6.E-11 |
| Turbidity, P8 | 21 | 0.15 | 4.2 | 9.E-07 |
| Turbidity, P10 | 21 | 0.31 | 10.8 | 2.E-14 |
| Turbidity, P12 | 21 | 0.31 | 11.1 | 1.E-14 |
| Turbidity, P13 | 21 | 0.10 | 2.8 | 2.E-04 |
| Turbidity, P14 | 21 | 0.30 | 10.6 | 4.E-14 |
| Turbidity, P15 | 21 | 0.38 | 15.2 | 2.E-17 |
| Turbidity, 1-m | 21 | 0.19 | 5.6 | 7.E-09 |
| Turbidity, 1.5-m | 21 | 0.07 | 1.7 | 3.E-02 |

**Table 2.11. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 11) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, 0.5-m | 32 | 0.13 | 3.6 | 8.E-06 |
| E. coli, 1-m | 32 | 0.44 | 18.9 | 2.E-19 |
| E. coli, 1.5-m | 32 | 0.27 | 9.2 | 6.E-13 |
| E. coli, P1 | 33 | 0.48 | 22.5 | 3.E-21 |
| E. coli, P2 | 34 | 0.53 | 28.1 | 2.E-23 |
| E. coli, P3 | 33 | 0.71 | 59.3 | 5.E-31 |
| E. coli, P4 | 32 | 0.60 | 36.3 | 5.E-26 |
| E. coli, P5 | 34 | 0.69 | 55.5 | 3.E-30 |
| E. coli, P6 | 34 | 0.47 | 21.3 | 1.E-20 |
| E. coli, P7 | 30 | 0.44 | 19 | 1.E-19 |
| E. coli, P8 | 30 | 0.62 | 39.6 | 7.E-27 |
| E. coli, P9 | 31 | 0.70 | 58.1 | 9.E-31 |
| E. coli, P10 | 30 | 0.62 | 40.5 | 4.E-27 |
| E. coli, P12 | 31 | 0.78 | 86.8 | 6.E-35 |
| E. coli, P13 | 32 | 0.76 | 79.7 | 5.E-34 |
| E. coli, P14 | 46 | 0.72 | 62.6 | 1.E-31 |
| E. coli, P15 | 33 | 0.32 | 11.7 | 4.E-15 |
| TOC, Platform | 37 | 0.07 | 1.9 | 1.E-02 |
| NO2, Platform | 26 | 0.38 | 14.9 | 3.E-17 |
| Conductivity, Dock, 0-m | 38 | 0.17 | 4.9 | 6.E-08 |
| Conductivity, Dock, 1.5-m | 35 | 0.11 | 3.0 | 1.E-04 |
| Conductivity, Platform | 38 | 0.08 | 2.3 | 3.E-03 |
| DO, Dock, 0-m (mg/L) | 42 | 0.09 | 2.5 | 1.E-03 |
| Turbidity, stream | 23 | 0.11 | 3.0 | 9.E-05 |
| Turbidity, P1 | 21 | 0.13 | 3.8 | 4.E-06 |
| Turbidity, P2 | 21 | 0.20 | 6.0 | 2.E-09 |
| Turbidity, P3 | 21 | 0.33 | 12.0 | 3.E-15 |
| Turbidity, P4 | 21 | 0.41 | 17.3 | 1.E-18 |
| Turbidity, P5 | 21 | 0.26 | 8.6 | 2.E-12 |
| Turbidity, P6 | 21 | 0.18 | 5.3 | 2.E-08 |
| Turbidity, P7 | 21 | 0.27 | 9.0 | 9.E-13 |
| Turbidity, P8 | 21 | 0.11 | 3.2 | 5.E-05 |

**Table 2.11 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 11) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P10 | 21 | 0.09 | 2.5 | 8.E-04 |
| Turbidity, P12 | 21 | 0.46 | 21.0 | 1.E-20 |
| Turbidity, P13 | 21 | 0.26 | 8.8 | 2.E-12 |
| Turbidity, P14 | 21 | 0.32 | 11.3 | 9.E-15 |
| Turbidity, P15 | 21 | 0.36 | 13.8 | 1.E-16 |
| Turbidity, 1-m | 21 | 0.22 | 7.1 | 9.E-11 |

**Table 2.12. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 12) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 51 | 0.13 | 3.7 | 6.E-06 |
| E. coli, 0.5-m | 32 | 0.11 | 2.9 | 2.E-04 |
| E. coli, 1-m | 32 | 0.41 | 16.9 | 2.E-18 |
| E. coli, 1.5-m | 32 | 0.26 | 8.7 | 2.E-12 |
| E. coli, P1 | 33 | 0.53 | 28.1 | 2.E-23 |
| E. coli, P2 | 34 | 0.49 | 23.6 | 1.E-21 |
| E. coli, P3 | 33 | 0.75 | 74.1 | 3.E-33 |
| E. coli, P4 | 32 | 0.77 | 83.7 | 1.E-34 |
| E. coli, P5 | 34 | 0.66 | 46.8 | 1.E-28 |
| E. coli, P6 | 34 | 0.60 | 37.3 | 3.E-26 |
| E. coli, P7 | 30 | 0.59 | 35.7 | 8.E-26 |
| E. coli, P8 | 30 | 0.65 | 46 | 2.E-28 |
| E. coli, P9 | 31 | 0.68 | 52.2 | 1.E-29 |
| E. coli, P10 | 30 | 0.52 | 26.8 | 6.E-23 |
| E. coli, P11 | 33 | 0.78 | 86.8 | 6.E-35 |
| E. coli, P13 | 32 | 0.81 | 104.4 | 7.E-37 |
| E. coli, P14 | 46 | 0.75 | 72.6 | 4.E-33 |
| E. coli, P15 | 33 | 0.35 | 13.1 | 4.E-16 |
| SS, Platform | 37 | 0.11 | 2.9 | 1.E-04 |
| NO2, Platform | 26 | 0.47 | 21.5 | 8.E-21 |
| ORP, Platform | 39 | 0.08 | 2.1 | 4.E-03 |
| DO, Dock, 0-m (mg/L) | 42 | 0.13 | 3.7 | 5.E-06 |
| DO, Platform (mg/L) | 39 | 0.08 | 2.1 | 5.E-03 |
| DO, Platform (% sat) | 39 | 0.08 | 2.0 | 7.E-03 |
| Turbidity, stream | 23 | 0.19 | 5.8 | 4.E-09 |
| Turbidity, P1 | 21 | 0.19 | 5.7 | 5.E-09 |
| Turbidity, P2 | 21 | 0.24 | 7.7 | 2.E-11 |
| Turbidity, P3 | 21 | 0.39 | 15.6 | 1.E-17 |
| Turbidity, P4 | 21 | 0.23 | 7.3 | 6.E-11 |
| Turbidity, P5 | 21 | 0.23 | 7.5 | 4.E-11 |
| Turbidity, P6 | 21 | 0.24 | 7.7 | 2.E-11 |
| Turbidity, P7 | 21 | 0.23 | 7.4 | 4.E-11 |

**Table 2.12 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 12) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P8 | 21 | 0.27 | 8.9 | 1.E-12 |
| Turbidity, P10 | 21 | 0.18 | 5.3 | 2.E-08 |
| Turbidity, P12 | 21 | 0.45 | 19.8 | 6.E-20 |
| Turbidity, P13 | 21 | 0.31 | 11.0 | 2.E-14 |
| Turbidity, P14 | 21 | 0.38 | 14.8 | 3.E-17 |
| Turbidity, P15 | 21 | 0.44 | 19.3 | 1.E-19 |
| Turbidity, 1-m | 21 | 0.32 | 11.5 | 6.E-15 |
| Turbidity, 1.5-m | 21 | 0.07 | 1.9 | 1.E-02 |

**Table 2.13. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 13) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 32 | 0.21 | 6.5 | 5.E-10 |
| E. coli, 0.5-m | 32 | 0.08 | 2.1 | 6.E-03 |
| E. coli, 1-m | 32 | 0.32 | 11.3 | 9.E-15 |
| E. coli, 1.5-m | 32 | 0.13 | 3.8 | 3.E-06 |
| E. coli, P1 | 34 | 0.51 | 25 | 3.E-22 |
| E. coli, P2 | 33 | 0.48 | 22.4 | 3.E-21 |
| E. coli, P3 | 34 | 0.73 | 67.5 | 2.E-32 |
| E. coli, P4 | 33 | 0.65 | 46.4 | 2.E-28 |
| E. coli, P5 | 32 | 0.72 | 63.6 | 1.E-31 |
| E. coli, P6 | 34 | 0.63 | 40.9 | 3.E-27 |
| E. coli, P7 | 34 | 0.61 | 38.1 | 2.E-26 |
| E. coli, P8 | 30 | 0.69 | 53.7 | 6.E-30 |
| E. coli, P9 | 31 | 0.75 | 71.7 | 6.E-33 |
| E. coli, P10 | 30 | 0.47 | 21.8 | 6.E-21 |
| E. coli, P11 | 33 | 0.76 | 79.7 | 5.E-34 |
| E. coli, P12 | 31 | 0.81 | 104.4 | 7.E-37 |
| E. coli, P14 | 46 | 0.67 | 49.9 | 3.E-29 |
| E. coli, P15 | 33 | 0.35 | 13.3 | 3.E-16 |
| SS, Platform | 37 | 0.08 | 2.1 | 6.E-03 |
| TOC, Dock | 37 | 0.15 | 4.2 | 7.E-07 |
| TOC, Platform | 32 | 0.12 | 3.2 | 4.E-05 |
| NO2, Platform | 26 | 0.55 | 29.7 | 6.E-24 |
| Chlorophyll-a, Platform | 48 | 0.10 | 2.7 | 4.E-04 |
| Temp, Platform, 0.5-m | 39 | 0.11 | 2.9 | 2.E-04 |
| pH, Dock | 40 | 0.08 | 2.1 | 5.E-03 |
| pH, Platform | 39 | 0.07 | 2.0 | 1.E-02 |
| ORP, Platform | 39 | 0.12 | 3.4 | 2.E-05 |
| DO, Dock, 0-m (mg/L) | 42 | 0.11 | 3.0 | 9.E-05 |
| DO, Platform (mg/L) | 39 | 0.07 | 1.9 | 1.E-02 |
| DO, Dock, 0-m (% sat) | 42 | 0.09 | 2.3 | 2.E-03 |
| DO, Platform (% sat) | 39 | 0.08 | 2.2 | 3.E-03 |
| Stage, Headwater | 40 | 0.19 | 5.7 | 4.E-09 |
| Stage, Pond | 39 | 0.09 | 2.5 | 9.E-04 |

**Table 2.13 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 13) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Turbidity, P1 | 21 | 0.24 | 7.7 | 2.E-11 |
| Turbidity, P2 | 21 | 0.19 | 5.9 | 3.E-09 |
| Turbidity, P3 | 21 | 0.46 | 20.7 | 2.E-20 |
| Turbidity, P4 | 21 | 0.55 | 30.0 | 4.E-24 |
| Turbidity, P5 | 21 | 0.36 | 13.6 | 2.E-16 |
| Turbidity, P6 | 21 | 0.21 | 6.7 | 3.E-10 |
| Turbidity, P7 | 21 | 0.28 | 9.4 | 4.E-13 |
| Turbidity, P8 | 21 | 0.23 | 7.2 | 7.E-11 |
| Turbidity, P10 | 21 | 0.29 | 10.1 | 9.E-14 |
| Turbidity, P11 | 21 | 0.17 | 5.1 | 3.E-08 |
| Turbidity, P12 | 21 | 0.52 | 26.4 | 8.E-23 |
| Turbidity, P13 | 21 | 0.39 | 15.4 | 1.E-17 |
| Turbidity, P14 | 23 | 0.34 | 12.4 | 1.E-15 |
| Turbidity, P15 | 21 | 0.30 | 10.5 | 5.E-14 |
| Turbidity, 0.5-m | 21 | 0.12 | 3.2 | 4.E-05 |
| Turbidity, 1-m | 21 | 0.16 | 4.8 | 9.E-08 |

**Table 2.14. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| E. coli, Stream | 32 | 0.18 | 5.4 | 1.E-08 |
| E. coli, 0.5-m | 32 | 0.07 | 1.9 | 2.E-02 |
| E. coli, 1-m | 32 | 0.28 | 9.7 | 2.E-13 |
| E. coli, 1.5-m | 32 | 0.18 | 5.5 | 1.E-08 |
| E. coli, P1 | 34 | 0.48 | 22.5 | 3.E-21 |
| E. coli, P2 | 33 | 0.47 | 21.3 | 1.E-20 |
| E. coli, P3 | 34 | 0.56 | 31.2 | 2.E-24 |
| E. coli, P4 | 33 | 0.51 | 25.4 | 2.E-22 |
| E. coli, P5 | 32 | 0.57 | 32 | 1.E-24 |
| E. coli, P6 | 34 | 0.48 | 22.2 | 4.E-21 |
| E. coli, P7 | 34 | 0.53 | 27.5 | 3.E-23 |
| E. coli, P8 | 30 | 0.68 | 51.7 | 1.E-29 |
| E. coli, P9 | 31 | 0.70 | 56.3 | 2.E-30 |
| E. coli, P10 | 30 | 0.69 | 54.1 | 5.E-30 |
| E. coli, P11 | 33 | 0.72 | 62.6 | 1.E-31 |
| E. coli, P12 | 31 | 0.75 | 72.6 | 4.E-33 |
| E. coli, P13 | 32 | 0.67 | 49.9 | 3.E-29 |
| E. coli, P15 | 33 | 0.39 | 15.4 | 1.E-17 |
| SS, Platform | 37 | 0.10 | 2.6 | 5.E-04 |
| TOC, Dock | 37 | 0.14 | 4.1 | 9.E-07 |
| TOC, Platform | 32 | 0.15 | 4.3 | 5.E-07 |
| NO2, Platform | 26 | 0.14 | 3.8 | 3.E-06 |
| NO3, Dock | 16 | 0.11 | 3.1 | 7.E-05 |
| Temp, Dock, 0.5-m | 33 | 0.11 | 2.9 | 1.E-04 |
| Temp, Dock, 1-m | 33 | 0.07 | 1.7 | 3.E-02 |
| Temp, Platform, 0.5-m | 39 | 0.12 | 3.5 | 1.E-05 |
| pH, Platform | 39 | 0.08 | 2.1 | 4.E-03 |
| ORP, Platform | 39 | 0.13 | 3.8 | 4.E-06 |
| DO, Dock, 0-m (mg/L) | 42 | 0.19 | 5.6 | 6.E-09 |
| DO, Platform (mg/L) | 39 | 0.17 | 4.9 | 6.E-08 |
| DO, Dock, 0-m (% sat) | 42 | 0.14 | 3.8 | 3.E-06 |
| DO, Platform (% sat) | 39 | 0.18 | 5.2 | 2.E-08 |
| Precipitation | 5 | 0.93 | 341.2 | 2.E-49 |

**Table 2.14 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|
| Stage, Headwater | 40 | 0.13 | 3.6 | 8.E-06 |
| Turbidity, stream | 23 | 0.44 | 19.3 | 9.E-20 |
| Turbidity, P1 | 21 | 0.25 | 8.1 | 8.E-12 |
| Turbidity, P2 | 21 | 0.23 | 7.2 | 8.E-11 |
| Turbidity, P3 | 21 | 0.40 | 16.2 | 5.E-18 |
| Turbidity, P4 | 21 | 0.33 | 11.8 | 4.E-15 |
| Turbidity, P5 | 21 | 0.37 | 14.3 | 7.E-17 |
| Turbidity, P6 | 21 | 0.23 | 7.1 | 8.E-11 |
| Turbidity, P7 | 21 | 0.34 | 12.7 | 9.E-16 |
| Turbidity, P8 | 21 | 0.17 | 5.1 | 3.E-08 |
| Turbidity, P10 | 21 | 0.14 | 4.1 | 1.E-06 |
| Turbidity, P12 | 21 | 0.48 | 22.6 | 3.E-21 |
| Turbidity, P13 | 21 | 0.30 | 10.3 | 7.E-14 |
| Turbidity, P14 | 23 | 0.13 | 3.6 | 8.E-06 |
| Turbidity, P15 | 21 | 0.52 | 26.1 | 1.E-22 |
| Turbidity, 1-m | 21 | 0.22 | 6.8 | 2.E-10 |

**Table 2.14(a). Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 0.5-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (Log CFU/100 mL) | E. coli, 0-m | 46 | 0.07 | 1.9 | 2.E-02 |
| | E. coli, 1-m | 32 | 0.36 | 13.9 | 1.E-16 |
| | E. coli, 1.5-m | 32 | 0.40 | 16.2 | 5.E-18 |
| | E. coli, P2 | 33 | 0.21 | 6.6 | 4.E-10 |
| | E. coli, P3 | 34 | 0.20 | 6.1 | 2.E-09 |
| | E. coli, P5 | 32 | 0.13 | 3.8 | 4.E-06 |
| | E. coli, P6 | 34 | 0.09 | 2.5 | 7.E-04 |
| | E. coli, P11 | 33 | 0.13 | 3.6 | 8.E-06 |
| | E. coli, P12 | 31 | 0.11 | 2.9 | 2.E-04 |
| | E. coli, P13 | 32 | 0.08 | 2.1 | 6.E-03 |
| (FTU) | SS, Dock | 37 | 0.08 | 2.1 | 5.E-03 |
| (µg/L) | TOC, Dock | 37 | 0.12 | 3.4 | 1.E-05 |
| | TOC, Platform | 32 | 0.06 | 1.7 | 4.E-02 |
| | PO4, Dock | 40 | 0.21 | 6.4 | 7.E-10 |
| | PO4, Platform | 47 | 0.22 | 6.8 | 2.E-10 |
| | NOx, Platform | 48 | 0.11 | 2.9 | 1.E-04 |
| | NH3, Dock | 44 | 0.08 | 2.2 | 4.E-03 |
| | Chlorophyll-*a*, Platform | 48 | 0.10 | 2.6 | 5.E-04 |
| (°C) | Temp, Dock, 0-m | 42 | 0.29 | 10.2 | 8.E-14 |
| | Temp, Dock, 0.5-m | 33 | 0.27 | 8.9 | 1.E-12 |
| | Temp, Dock, 1-m | 33 | 0.26 | 8.4 | 4.E-12 |
| | Temp, Dock, 1.5-m | 38 | 0.35 | 9.4 | 3.E-16 |
| | Temp, Platform, 0.5-m | 39 | 0.24 | 7.7 | 2.E-11 |
| (µS/cm) | Conductivity, Dock, 0-m | 38 | 0.31 | 11.1 | 1.E-14 |
| | Conductivity, Dock, 1.5-m | 35 | 0.56 | 31.0 | 2.E-24 |
| | Conductivity, Platform | 38 | 0.19 | 5.8 | 3.E-09 |
| | pH, Dock, 0-m | 40 | 0.09 | 2.5 | 8.E-04 |
| | pH, Dock, 1.5-m | 38 | 0.32 | 11.6 | 6.E-15 |
| | pH, Platform | 39 | 0.12 | 3.4 | 2.E-05 |
| (µS/cm) | ORP, Dock, 0-m | 42 | 0.20 | 6.2 | 1.E-09 |
| | ORP, Dock, 1.5-m | 38 | 0.20 | 5.9 | 2.E-09 |
| | ORP, Platform | 39 | 0.15 | 4.2 | 9.E-07 |

**Table 2.14(a) continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 0.5-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (mg/L) | DO, Dock, 1.5-m (mg/L) | 38 | 0.08 | 2.0 | 8.E-03 |
| | DO, Platform (mg/L) | 39 | 0.17 | 4.9 | 7.E-08 |
| (% sat) | DO, Dock, 0-m (% sat) | 42 | 0.13 | 3.6 | 9.E-06 |
| | DO, Platform (% sat) | 39 | 0.21 | 6.5 | 4.E-10 |
| (.01") | Precipitation, cumulative | 5 | 0.33 | 12.1 | 2.E-15 |
| (ft.) | Stage, Headwater | 40 | 0.23 | 7.1 | 8.E-11 |
| | Stage, Ephemeral | 32 | 0.32 | 11.7 | 5.E-15 |
| (NTU) | Turbidity, P15 | 21 | 0.07 | 1.7 | 3.E-02 |

**Table 2.14(b). Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 1-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (Log CFU/100 mL) | E. coli, 0-m | 46 | 0.28 | 9.7 | 2.E-13 |
| | E. coli, 0.5-m | 32 | 0.36 | 13.9 | 1.E-16 |
| | E. coli, 1.5-m | 32 | 0.84 | 133.2 | 2.E-39 |
| | E. coli, P1 | 34 | 0.13 | 3.7 | 6.E-06 |
| | E. coli, P2 | 33 | 0.27 | 9.1 | 8.E-13 |
| | E. coli, P3 | 34 | 0.56 | 31 | 2.E-24 |
| | E. coli, P4 | 33 | 0.31 | 11.3 | 1.E-14 |
| | E. coli, P5 | 32 | 0.50 | 24.5 | 4.E-22 |
| | E. coli, P6 | 34 | 0.24 | 7.5 | 3.E-11 |
| | E. coli, P7 | 34 | 0.14 | 4.1 | 1.E-06 |
| | E. coli, P8 | 30 | 0.34 | 12.8 | 7.E-16 |
| | E. coli, P9 | 31 | 0.19 | 5.8 | 4.E-09 |
| | E. coli, P10 | 30 | 0.14 | 3.9 | 2.E-06 |
| | E. coli, P11 | 33 | 0.44 | 18.9 | 2.E-19 |
| | E. coli, P12 | 31 | 0.41 | 16.9 | 2.E-18 |
| | E. coli, P13 | 32 | 0.32 | 11.3 | 9.E-15 |
| | E. coli, P14 | 46 | 0.28 | 9.7 | 2.E-13 |
| | E. coli, P15 | 33 | 0.10 | 2.7 | 4.E-04 |
| (µg/L) | PO4, Dock | 40 | 0.08 | 2.1 | 7.E-03 |
| | NOx, Dock | 39 | 0.09 | 2.4 | 2.E-03 |
| | NOx, Platform | 48 | 0.14 | 3.9 | 3.E-06 |
| | NO2, Dock | 44 | 0.19 | 5.7 | 5.E-09 |
| | NO2, Platform | 26 | 0.17 | 4.9 | 6.E-08 |
| | NO3, Platform | 26 | 0.08 | 2.1 | 5.E-03 |
| | NH3, Dock | 44 | 0.12 | 3.4 | 2.E-05 |
| (°C) | Temp, Dock, 0-m | 42 | 0.18 | 5.4 | 1.E-08 |
| | Temp, Dock, 0.5-m | 33 | 0.13 | 3.6 | 7.E-06 |
| | Temp, Dock, 1-m | 33 | 0.15 | 4.2 | 7.E-07 |
| | Temp, Dock, 1.5-m | 38 | 0.15 | 4.4 | 4.E-07 |
| (µS/cm) | Conductivity, Dock, 0-m | 38 | 0.26 | 8.7 | 2.E-12 |
| | Conductivity, Dock, 1.5-m | 35 | 0.31 | 10.9 | 2.E-14 |
| | Conductivity, Platform | 38 | 0.16 | 4.8 | 8.E-08 |

**Table 2.14(b) continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 1-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| | pH, Dock, 0-m | 40 | 0.09 | 2.4 | 2.E-03 |
| | pH, Dock, 1.5-m | 38 | 0.10 | 2.8 | 3.E-04 |
| | pH, Platform | 39 | 0.09 | 2.4 | 2.E-03 |
| (mV) | ORP, Dock, 0-m | 42 | 0.13 | 3.7 | 6.E-06 |
| | ORP, Dock, 1.5-m | 38 | 0.07 | 1.8 | 2.E-02 |
| (mg/L) | DO, Dock, 1.5-m | 38 | 0.14 | 3.9 | 2.E-06 |
| | DO, Platform | 39 | 0.11 | 3.0 | 1.E-04 |
| (% sat) | DO, Dock, 1.5-m | 42 | 0.11 | 3.1 | 6.E-05 |
| | DO, Platform | 39 | 0.12 | 3.2 | 4.E-05 |
| ($\mu E/cm^2$) | PAR, Reference, 0-m | 39 | 0.08 | 2.1 | 6.E-03 |
| (.01") | Precipitation, cumulative | 5 | 0.17 | 5.2 | 3.E-08 |
| (ft.) | Stage, Ephemeral | 32 | 0.19 | 5.7 | 5.E-09 |
| (NTU) | Turbidity, Stream | 23 | 0.24 | 7.8 | 1.E-11 |
| | Turbidity, P1 | 21 | 0.17 | 5.2 | 3.E-08 |
| | Turbidity, P2 | 21 | 0.13 | 3.7 | 5.E-06 |
| | Turbidity, P3 | 21 | 0.27 | 9.3 | 5.E-13 |
| | Turbidity, P4 | 21 | 0.22 | 7.0 | 1.E-10 |
| | Turbidity, P5 | 21 | 0.18 | 5.4 | 1.E-08 |
| | Turbidity, P6 | 21 | 0.14 | 4.0 | 2.E-06 |
| | Turbidity, P7 | 21 | 0.28 | 9.4 | 4.E-13 |
| | Turbidity, P8 | 21 | 0.18 | 5.3 | 2.E-08 |
| | Turbidity, P9 | 21 | 0.17 | 5.0 | 4.E-08 |
| | Turbidity, P10 | 21 | 0.13 | 3.5 | 1.E-05 |
| | Turbidity, P12 | 21 | 0.23 | 7.4 | 5.E-11 |
| | Turbidity, P13 | 21 | 0.28 | 9.7 | 2.E-13 |
| | Turbidity, P14 | 23 | 0.42 | 17.8 | 5.E-19 |
| | Turbidity, P15 | 21 | 0.22 | 6.9 | 2.E-10 |
| | Turbidity, 1-m | 21 | 0.22 | 7.0 | 1.E-10 |
| | Turbidity, 1.5-m | 21 | 0.19 | 5.9 | 3.E-09 |

**Table 2.14(c). Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 1.5-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (Log CFU/100 mL) | E. coli, 0-m | 46 | 0.18 | 5.5 | 1.E-08 |
| | E. coli, 0.5-m | 32 | 0.40 | 16.2 | 5.E-18 |
| | E. coli, 1.0-m | 32 | 0.84 | 133.2 | 2.E-39 |
| | E. coli, P2 | 33 | 0.14 | 4 | 2.E-06 |
| | E. coli, P3 | 34 | 0.32 | 11.5 | 7.E-15 |
| | E. coli, P4 | 33 | 0.13 | 3.7 | 5.E-06 |
| | E. coli, P5 | 32 | 0.31 | 11.2 | 1.E-14 |
| | E. coli, P6 | 34 | 0.13 | 3.8 | 4.E-06 |
| | E. coli, P8 | 30 | 0.14 | 4.1 | 1.E-06 |
| | E. coli, P9 | 31 | 0.07 | 1.7 | 3.E-02 |
| | E. coli, P10 | 30 | 0.07 | 1.8 | 2.E-02 |
| | E. coli, P11 | 33 | 0.27 | 9.2 | 6.E-13 |
| | E. coli, P12 | 31 | 0.26 | 8.7 | 2.E-12 |
| | E. coli, P13 | 32 | 0.13 | 3.8 | 3.E-06 |
| | E. coli, P14 | 46 | 0.18 | 5.5 | 1.E-08 |
| (µg/L) | PO4, Dock | 40 | 0.14 | 4.1 | 1.E-06 |
| | NOx, Dock | 39 | 0.10 | 2.6 | 5.E-04 |
| | NOx, Platform | 48 | 0.22 | 6.9 | 2.E-10 |
| | NO2, Dock | 44 | 0.18 | 5.3 | 2.E-08 |
| | NO2, Platform | 26 | 0.12 | 3.5 | 1.E-05 |
| | NO3, Dock | 16 | 0.06 | 1.7 | 4.E-02 |
| | NO3, Platform | 26 | 0.21 | 6.4 | 7.E-10 |
| | NH3, Dock | 44 | 0.15 | 4.3 | 6.E-07 |
| | Chlorophyll-*a* , Platform | 48 | 0.08 | 2.2 | 4.E-03 |
| (°C) | Temp, Dock, 0-m | 42 | 0.31 | 11.1 | 1.E-14 |
| | Temp, Dock, 0.5-m | 33 | 0.19 | 5.6 | 7.E-09 |
| | Temp, Dock, 1-m | 33 | 0.20 | 6.1 | 1.E-09 |
| | Temp, Dock, 1.5-m | 38 | 0.25 | 8.2 | 6.E-12 |
| | Temp, Platform | 39 | 0.21 | 6.5 | 5.E-10 |
| (µS/cm) | Conductivity, Dock, 0-m | 38 | 0.32 | 11.7 | 5.E-15 |
| | Conductivity, Dock, 1.5-m | 35 | 0.40 | 16.6 | 3.E-18 |
| | Conductivity, Platform | 38 | 0.24 | 7.7 | 2.E-11 |

**Table 2.14(c) continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 14, 1.5-m) data, Catfish Pond, Whitehall Forest, June - October, 2000 (α = .05)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| | pH, Dock, 0-m | 40 | 0.11 | 3.0 | 8.E-05 |
| | pH, Dock, 1.5-m | 38 | 0.15 | 4.4 | 3.E-07 |
| | pH, Platform | 39 | 0.16 | 4.8 | 1.E-07 |
| (mV) | ORP, Dock, 0-m | 42 | 0.14 | 3.9 | 3.E-06 |
| (mV) | ORP, Dock, 1.5-m | 38 | 0.07 | 1.7 | 3.E-02 |
| (mV) | ORP, Dock, Platform | 39 | 0.15 | 4.2 | 7.E-07 |
| (mg/L) | DO, Dock, 1.5-m | 38 | 0.09 | 2.6 | 6.E-04 |
| (mg/L) | DO, Platform | 39 | 0.25 | 8.3 | 5.E-12 |
| (% sat) | DO, Dock, 0-m | 42 | 0.14 | 4.1 | 1.E-06 |
| (% sat) | DO, Platform | 39 | 0.30 | 10.5 | 4.E-14 |
| (.01") | Precipitation, cumulative | 5 | 0.29 | 10.0 | 1.E-13 |
| (ft.) | Stage, Headwater | 40 | 0.19 | 5.7 | 4.E-09 |
| (ft.) | Stage, Ephemeral | 32 | 0.41 | 16.7 | 2.E-18 |
| (NTU) | Turbidity, Stream | 23 | 0.36 | 13.5 | 2.E-16 |
| (NTU) | Turbidity, P2 | 21 | 0.07 | 2.0 | 9.E-03 |
| (NTU) | Turbidity, P3 | 21 | 0.20 | 6.1 | 1.E-09 |
| (NTU) | Turbidity, P4 | 21 | 0.13 | 3.8 | 4.E-06 |
| (NTU) | Turbidity, P5 | 21 | 0.14 | 3.8 | 3.E-06 |
| (NTU) | Turbidity, P7 | 21 | 0.21 | 6.3 | 8.E-10 |
| (NTU) | Turbidity, P8 | 21 | 0.11 | 3.0 | 1.E-04 |
| (NTU) | Turbidity, P12 | 21 | 0.16 | 4.5 | 2.E-07 |
| (NTU) | Turbidity, P13 | 21 | 0.15 | 4.5 | 3.E-07 |
| (NTU) | Turbidity, P14 | 23 | 0.35 | 13.3 | 3.E-16 |
| (NTU) | Turbidity, P15 | 21 | 0.19 | 5.6 | 7.E-09 |
| (NTU) | Turbidity, 1-m | 21 | 0.16 | 4.6 | 2.E-07 |
| (NTU) | Turbidity, 1.5-m | 21 | 0.29 | 10.0 | 1.E-13 |

**Table 2.15. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 15) data, Catfish Pond, Whitehall Forest, June - October, 2000 ($\alpha = .05$)**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (Log CFU/100 mL) | E. coli, Stream | 32 | 0.13 | 3.7 | 6.E-06 |
| | E. coli, 1-m | 32 | 0.10 | 2.7 | 4.E-04 |
| | E. coli, P1 | 34 | 0.52 | 26.4 | 8.E-23 |
| | E. coli, P2 | 33 | 0.28 | 9.7 | 2.E-13 |
| | E. coli, P3 | 34 | 0.35 | 13.1 | 4.E-16 |
| | E. coli, P4 | 33 | 0.26 | 8.5 | 3.E-12 |
| | E. coli, P5 | 32 | 0.25 | 8.1 | 8.E-12 |
| | E. coli, P6 | 34 | 0.32 | 11.7 | 4.E-15 |
| | E. coli, P7 | 34 | 0.34 | 12.5 | 1.E-15 |
| | E. coli, P8 | 30 | 0.14 | 3.9 | 2.E-06 |
| | E. coli, P9 | 31 | 0.34 | 12.5 | 1.E-15 |
| | E. coli, P10 | 30 | 0.34 | 12.6 | 9.E-16 |
| | E. coli, P11 | 33 | 0.32 | 11.7 | 4.E-15 |
| | E. coli, P12 | 31 | 0.35 | 13.1 | 4.E-16 |
| | E. coli, P13 | 32 | 0.35 | 13.3 | 3.E-16 |
| | E. coli, P14 | 46 | 0.39 | 15.4 | 1.E-17 |
| (µg/L) | TOC, Dock | 37 | 0.08 | 2.3 | 3.E-03 |
| | NO2, Platform | 26 | 0.20 | 6.3 | 9.E-10 |
| | Chlorophyll-*a* , Platform | 48 | 0.15 | 4.5 | 3.E-07 |
| (°C) | Temp, Dock, 0-m | 33 | 0.08 | 2.2 | 3.E-03 |
| | Temp, Dock, 0.5-m | 33 | 0.31 | 10.9 | 2.E-14 |
| | Temp, Dock, 1-m | 33 | 0.30 | 10.6 | 4.E-14 |
| | Temp, Dock, 1.5-m | 33 | 0.24 | 7.8 | 2.E-11 |
| | Temp, Platform, 0.5-m | 39 | 0.23 | 7.4 | 4.E-11 |
| | pH, Dock, 0-m | 40 | 0.25 | 8.0 | 9.E-12 |
| | pH, Platform | 39 | 0.22 | 6.7 | 3.E-10 |
| (mV) | ORP, Dock, 0-m | 38 | 0.13 | 3.7 | 5.E-06 |
| | ORP, Dock, 1.5-m | 42 | 0.07 | 1.9 | 1.E-02 |
| | ORP, Platform | 39 | 0.25 | 8.1 | 8.E-12 |
| (mg/L) | DO, Dock, 0-m | 42 | 0.27 | 9.1 | 7.E-13 |
| | DO, Platform | 39 | 0.15 | 4.2 | 7.E-07 |

**Table 2.15 continued. Statistics for significant variables correlated to log-transformed *E. coli* (Pond 15) data, Catfish Pond, Whitehall Forest, June - October, 2000**

| | Variable | *N* | $R^2$ | F | p |
|---|---|---|---|---|---|
| (% sat) | DO, Dock, 0-m | 42 | 0.26 | 8.6 | 2.E-12 |
| | DO, Platform | 39 | 0.18 | 5.3 | 2.E-08 |
| (.01") | Precipitation, cumulative | 5 | 0.10 | 2.9 | 2.E-04 |
| (ft.) | Stage, Headwater | 40 | 0.08 | 2.0 | 7.E-03 |
| | Stage, Pond | 39 | 0.12 | 3.2 | 3.E-05 |
| (NTU) | Turbidity, P1 | 21 | 0.22 | 6.8 | 2.E-10 |

# CHAPTER 5

# DISCUSSION

## 5.1 Hydrologic transport of *Escherichia coli*

Conventional transport and fate models such as the Time, Distance, Mass (TDM) model (Figure 26) hold that *E. coli* and other enteric bacteria are rapidly attenuated by environmental conditions upon leaving their hosts of origin. Once exposed to ambient conditions, bacteria display limited ability to reproduce or propagate across large geospatial scales when physical transport vectors and favorable environmental conditions are absent (White 1996; Easton 2000). When such vectors form, usually with rainfall, bacteria are mobilized and begin defacto propagation. Exactly where bacteria such as *E. coli* eventually come to rest, or zero momentum, has been previously determined to be a function of three distinct factors. Time, usually from initial rainfall moment, or $t_0$; Distance, usually a function of topography, rainfall intensity, and stream power; and Mass, assumed here to be the mass of individual bacterium, or as may frequently be the case when bacteria form biofilms upon organic and inorganic matter, the combined mass of the bacteria(um) and their affiliated substrate, such as leaf litter or soil particles (Robbins et al. 1972; Kay and McDonald 1980; McDonald and Kay 1981; Schillinger and Gannon 1982, 1985; Gannon et al. 1983; Baxter-

Potter and Gilliland 1988; White 1996; Burton and Pitt 2002; and others). From initial rainfall moment, or $t_0$, bacteria movement can be extremely rapid. Small rivulets of water form across the landscape and scour the ground surface collecting soil, detritus, and fecal matter (with associated bacteria) into streams of increasing hydraulic power, flowing into ephemeral streams, rivers, and eventually into an aquifer, impoundment or ocean (Crane and Moore 1986). Once mobilized into a torrent of water, bacteria are generally transported some distance beyond their origin, such that their movement is linear and one-dimensional. As the stream or small body of flowing water reaches a confluence with slow-moving bodies of water (e.g. large river, lake, impoundment, or ocean), the physics of both water and bacteria change. Per the TDM model, forward momentum of water and all mass contained therein will decrease, resulting in the settling (or downward motion) of all objects of mass over a finite distance, as related to decreasing forward momentum and associated Reynold's Number for each individual bacterium, soil or detritus particle, or aggregate mass (Purcell 1977, 1997).

Data presented in this study confirm the results of Kay and McDonald (1980), McDonald and Kay (1981), and Gannon et al. (1983), in that *E. coli* are transported primarily via overland flow and with the stream hydrograph (Figure 6). Precipitation (pond: $r^2 = .93$, $p << .001$; headwater stream: $r^2 = .59$, $p << .001$) and headwater stage ($r^2 = .40$, $p << .001$) were correlated to *E. coli* and conform to a basic TDM model for terrestrial transport and waterborne dispersion (Table

2; Figure 12, 26). A holistic approach is used here to explain the TDM concept and how DST and ribotyping can accurately describe bacteria transport and fate. Fluid mechanics articulated in the following series equations adapted from Williams et al. (1985), Maidment (1993) and Burton and Pitt (2002) describe bacteria transport within the TDM model. First, precipitation acts as a kinetic vector and surface runoff forms. Both can be predicted for daily rainfall with the SCS curve number equation:

$$Q = \frac{(R - 0.2s)^2}{R + 0.8S} \quad (1)$$

where Q = daily runoff; $R$ = daily rainfall; and $s$ = a retention parameter, which is related to soil water content:

$$S = s_x \left\{ 1 - \frac{SW}{SW + \exp[\omega_1 - \omega_2(SW)]} \right\} \quad (2)$$

where $SW$ = soil water content in root zone; $\omega_1$ and $\omega_2$ = shape parameters; and $\boldsymbol{s_x}$ = value of $\boldsymbol{S}$ corresponding to the dry moisture condition curve number ($CN_x$).

Understanding that surface runoff is related to soil water content, peak runoff rate can be calculated based on the modified Rational Formula:

$$q_p = \frac{(\alpha)(Q)(A)}{360(t_c)} \tag{3}$$

where $q_p$ = peak runoff rate ($m^3 \cdot s^{-1}$); α = a dimensionless parameter representing a fraction of total rainfall which occurs during the watershed time of concentration, $t_c$ in hours; and $A$ = watershed area in $km^2$.

Storm hydrographs are linked to individual watershed parameters contained in time of concentration ($t_c$) calculations. Time of concentration can be estimated by adding the surface ($t_{cs}$) and channel ($t_{cc}$) flow times:

$$t_{cc} = \frac{0.62(L)(n)^{0.75}}{(A)^{0.125}(\sigma)^{0.375}} \tag{4}$$

where $t_{cc}$ = time of concentration for channel flow in hours; $L$ = channel length from the most distant point to the watershed outlet in kilometers; $n$ = Manning's roughness factor; and σ = average channel slope in $m \cdot m^{-1}$.

$$t_{cs} = \frac{(\lambda \cdot n)^{0.6}}{18(S)^{0.3}} \tag{5}$$

where $t_{cs}$ = time of concentration for surface flow in hours; $\lambda$ = surface slope length in meters; and $S$ = land surface slope in $m \cdot m^{-1}$. Thus, topography, land

cover and the kinetic energy contained in rainfall combine to mobilize fecal material deposited across space and time (White 1996).

Schillinger and Gannon (1982, 1985) and Auer and Niehaus (1993) demonstrated that coliform bacteria densities can be closely associated with measurements of soil erosion-induced turbidity. Results from this project confirm earlier findings, and support a strong turbidity-*E. coli* link ($r^2$ = .66, p<< .001). Recognizing the significance of turbidity, which is a function of soil loss, the Revised Universal Soil Loss Equation (RUSLE) can be employed to estimate sediment yield in surficial flows (Moore and Burch 1986; Renard et al. 1997):

$$Y = 11.8(V \cdot q_p)^{0.56}(K)(C)(PE)(LS) \qquad (6)$$

where $Y$ = sediment yield in tons; $V$ = surface runoff volume for the sub-basin in $m^3$; $q_p$ = peak flow rate for the sub-basin in $m^3 \cdot s^{-1}$; $K$ = soil erodibility factor; $C$ = crop management factor; $PE$ = erosion control practice factor; and $LS$ = slope length and steepness factor. The RUSLE accounts for mass landscape wasting, however does not adequately describe transport of sediment suspended in streams, rivers, lakes, or impoundments. While the equation includes a parameter for runoff flow rates, a time component for sediment transport rate is absent and can be described by the Von Kármán equation. Based on the concept of continuity of mass, this integral holds:

$$q_s = \int C_o V dz \quad (7)$$

where $q_s$ = total sediment transport rate; $V$ = velocity; and $C_0$ = sediment concentration in vertical section. Channel flow rates for sediment usually differ from runoff calculations based on sediment particle mass suspended in the stream cross-section, which is primarily a function of stream power. Data from the DST method confirm turbidity as a correlating factor in bacteria transport within the headwater stream ($r^2$ = .47, p<< .001) and correspond to previous findings in streams by Kunkle (1970a, b) and Stephenson and Rychert (1982), who found *E. coli* concentrations up to 750 times greater in resuspended sediment and storm flows than under base flow conditions.

Although drought conditions precluded collection of a large stormwater data set, which resulted in decreased statistical power in the *E. coli* data component, hydrographs (Figure 11, 12, 13a) clearly demonstrated sediment and bacteria delivery to Catfish Pond via turbid stormwater flow (Table 2.0 – 2.15; Figure 5, 6, 8). Williams et al. (1985) proposed a series of equations describing the physical factors affecting small ponds, and focused on water balance and sediment delivery rate as dependent variables. Derived from field data located at approximately the same latitude as the state of Georgia, the proposed lotic water balance equation is:

$$VM = VM_0 + QI - QO - EV - SP \quad (8)$$

where $VM_0$ = volume of water stored in all ponds within a sub-basin at the beginning of the day; $VM$ = volume at the end of the day; $QI$ = inflow during the day; $QO$ = outflow; $EV$ = evaporation; $SP$ = seepage; all units in $m^3$. Pond inflow, $QI$, includes all surface runoff from headwater drainage and rainfall on the actual impoundment surface. The outflow condition is reached when pond volume exceeds permanent pool storage capacity:

$$QO = VM - VM_{\max}; \quad VM \; \phi \; VM_{\max}$$

And

$$QO = 0; \quad VM \leq VM_{\max} \tag{9}$$

where $VM_{max}$ = maximum permanent pool storage of all ponds in the sub-basin in $m^3$. Surface area (SA), evaporation (EV), and seepage (SP) were calculated as:

$$SA = \omega_1 (VM)^{\omega_2} \tag{10}$$

where $\omega_1$ = a parameter (~0.3); and $\omega_2$ = a fairly constant parameter (~0.9);

And

$$EV = 10(\eta)(E_0)(SA) \tag{11}$$

where η = evaporation coefficient (~0.6); and $SA$ = surface area of all ponds in the sub-basin in hectares;

And

$$SP = 240(SC)(SA) \tag{12}$$

where $SC$ = saturated conductivity of the pond bed in mm · $h^{-1}$.

Recognizing that final impoundment suspended sediment concentration decreases to an equilibrium during inter-storm periods, the authors described the process as:

$$c_s = (c_{s_2} - c_{se})\exp(-k_s \cdot t \cdot D50) + c_{se} \tag{13}$$

Where $c_s$ = impoundment concentration $t$ days after the value of $c_{s2}$ is obtained; $c_{s2}$ = impoundment sediment concentration at the end of the day in t · $m^{-3}$; $k_s$ = a decay constant; $D50$ = median particle size of inflow sediment in μm; and $c_{se}$ = equilibrium impoundment sediment concentration. $k_s$ is evaluated by assuming that 99% of the 1 μm particles are settled within 25 days ($k_s$ = 0.184). During storm flows sediment delivery to impoundments can be represented by:

$$c_{s_2} = \frac{VM_i c_{s_1} + QIc_I - \frac{QO}{2} c_{s_1}}{VM_2 + \frac{QO}{2}} \tag{14}$$

Where $c_{s1}$ = impoundment sediment concentration at the beginning of the day in t · $m^{-3}$; $VM_1$ and $VM_2$ = impoundment storage volumes at the beginning and end of a day in $m^3$; $QI$ = inflow volume in $m^3$; and $c_I$ = inflow concentration in t · $m^{-3}$.

Because impoundments function as bioreactors, generally diluting or sequestering toxic elements and organisms until they are broken down, important considerations for impoundment and watershed management are those instances when permanent pool storage capacity will be exceeded. Small impoundments may be short-circuited by storm flows, with reduced residence times for bacteria; such conditions could result in greater risk of exposure to pathogens by the general public (USEPA 1986, 1998; WHO 2001).

Analysis of spatial data indicates bacteria loading in the watershed emanated primarily from captive deer and that *E. coli* are transported via overland flow in rain events measuring greater than 0.75-cm (0.3") precipitation ($t_C$ = 20 min). This hypothesis was independently confirmed ($p$ = 0.05), absent supporting hydrologic data, by ribotyping scat from wild (n = 100 isolates) and captive (n = 100 isolates) animals during a DST-sampled storm event on 19 January 2001 (Figure 7). Isolates (n = 98) drawn from stream sampled Colilert-positive wells reflected normal animal diversity in the watershed, with 42.9% demonstrating similarity to whitetail deer (Hartel et al. 2003). Results support DST as a suitable and economical method for *E. coli* enumeration in natural waters.

### 5.2 Biotic and abiotic effects on *Escherichia coli*

Commenting on the dynamic environment in which bacteria exist, Stevenson (1978) observed:

*"The posture of bacteria in natural aquatic systems is definitely not the plush* [artificial, favorably regulated] *existence typified by laboratory cultures."*

Standard linear regression and Principle Component Analysis of 17 biotic and abiotic parameters revealed three separate dynamics affecting *E. coli* fate in the Catfish Pond watershed: physical, chemical, and biologic components (Table 1 – 2.15; Figure 8, 9, 10). The physical component comprised of precipitation ($r^2$ = .93, p<< .001), stream / pond stage ($r^2$ = .40, p<< .001), turbidity ($r^2$ = .66, p<< .001), temperature ($r^2$ = .35, p<< .001), and light ($r^2$ = .31, p<< .001) emerged as the parameters most closely associated with *E. coli* densities in the pond (Figure 11 – 14).

During this reconnaissance, the physical relationship articulated by Williams et al. (1985) became uncoupled across space and time as suggested by Kay and McDonald (1980) and Gannon et al. (1983), who advocated the significance of distance decay relationships in reducing bacteria densities in reservoirs. In Catfish Pond (Figure 4), turbidity at the stream-pond confluence (50.74 NTU, Transect 1) gradually attenuated with linear distance (12.63 NTU, Transect 14), and was strongly influenced by precipitation ($r^2$ = 0.93, p << .001) and stream stage ($r^2$ = 0.40, p << .001). Depth-integrated mean *E. coli* counts for Transect 14 were 1.02, 1.3, 1.41, and 1.68 at 0-m, 0.5-m, 1-m, and 1.5-m, respectively, and may indicate several dynamics interacting at one time, including sedimentation, UV / ozone-induced mortality, starvation, or density dependent

transport. Schillinger and Gannon (1982, 1985) demonstrated the affinity of *E. coli* for specific particle-size clay fractions suspended in laboratory water columns, and from these results mass-dependent sedimentation in Catfish Pond can be inferred. As noted by Gannon et al. (1983), the term “disappearance” has been used to describe bacteria sedimentation, predation (Enzinger and Cooper 1976; McCambridge and McMeekin 1980; Gurijala and Alexander 1990), dilution (Bergstein-Ben Dan and Koppel 1992), and death (Crane and Moore 1986) and conforms to Chick’s Law (Chick 1908), which holds:

$$\frac{N_t}{N_0} = e^{-Kt} \tag{15}$$

While results of the present study conform to the Time, Distance, Mass model for bacteria transport and attenuation (Figure 26), bacteria adhesion to clay particles probably was not the sole factor contributing to *E. coli* disappearance from the water column after storm events. Turbidity measures the optical qualities of water and relates best to tripton, or inanimate colloidal-sized particles, but may not appropriately reflect bacteria adhesion to other vectors, namely phytoplankton. In Catfish Pond a weak, though pervasive and statistically significant ($r^2 = .18$, $p < .001$), correlation between *E. coli* and chlorophyll-*a* was apparent, and supports the assertion of previous investigators that enteric bacteria may derive some benefit from adhesion to plankton or gilvin (dissolved humic matter) (Roszak and Colwell 1987). *Escherichia coli*

enumerated in the euphotic zone displayed an unexpected population dynamic in close time sequence with the magnitude and duration (20 days) of a phytoplankton bloom, and to a lesser degree with blooms occurring during later phases of the study (Figure 25a, b). Life cycles for enteric *E. coli* can span 20 minutes to 24-h (Liu 1999), and no plausible explanation exists to explain an apparent phytoplankton (lifecycle: 24 to 48-h) linkage spanning at least 20 bacteria generations. Findings from this work may suggest one of the following relationships between *E. coli* and phytoplankton, with nutrients as a common link: symbiosis (two organisms living together with mutual benefit), commensalism (interaction between two organisms where at least one benefits), or amensalism (relationship between two organisms where one is harmed) (e.g. Roszak and Colwell 1987).

Other significant and well-documented effects of phytoplankton can be interpreted from the chlorophyll-*a* data. Boyd (1990) described water chemistry dynamics in ponds influenced by phytoplankton, including changes driven by dissolved oxygen and pH. In Catfish Pond, dissolved oxygen ($r^2$ = .39, p << .001) and pH ($r^2$ = .36, p << .001) and their related derivatives, Eh ($r^2$ = .40, p << .001) and conductivity ($r^2$ = .56, p << .001), generally displayed very weak relationships to *E. coli* (Figure 15 – 18), with positive correlation in few pond transects. Extremely high or low pH (driven by photosynthesis) can disrupt normal bacteria cell function and cause the organism to lyse, which is a fatal condition (Booth 1985). Catfish Pond experienced neutral to mildly buffered

conditions (pH 7 to 10) for the duration of the 2000 field season and results from this study contradict the findings of Parhad and Rao (1974) and Pearson et al. (1987), whose observations of *E. coli* and fecal coliforms suggested pH > 9.0 as a causal agent in bacteria mortality. However, results from this study (Table 1) are consistent with the findings of Booth (1985), who reported that nutrient levels are important in organisms resisting high pH. As nutrients were depleted in the pond bacteria may have succumbed to high pH, but no qualitative or quantitative evidence exists to evaluate the hypothesis. A second mitigating factor could be that Catfish Pond was augmented with nutrients, which introduced a degree of artificiality into the system and was not representative of ambient environmental conditions in which bacteria normally persist.

Schultz and Gerhardt (1969) observed that the driving force for nutrient exchange in aquatic environments results from constant changes in water chemistry during given time periods. Augmenting Catfish Pond with ammonium polyphosphate fertilizer (11-37-0, N:P:K) provided sufficient nitrogen for *E. coli* and other nitrogen-fixing organisms to initiate a bacteria bloom (Figure 21). Nutrient addition also precipitated a phytoplankton bloom (Figure 25a, b) and revealed a weak statistical relationship between chlorophyll-*a* ($r^2$ = .18, $p < .001$) and *E. coli*. Weak interaction between phytoplankton and *E. coli* may indicate no biocidal activity or other negative causative effect of phytoplankton - *E. coli* cohabitation, as previously suggested by Cabridence and Lepailleur (1969, *as cited in* Verstraete and Voets 1976).

Nutrients (Figure 19 – 24) displayed a separate and distinct group dynamic in the fate of *E. coli*. In general, bacteria are 50% carbon and 10% nitrogen as measured by dry weight, with a carbon assimilation efficiency of 5%. Although surface waters at Whitehall Experimental Forest are poorly buffered, which might suggest carbon as the primary limiting nutrient in *E. coli* growth, ambient carbon concentrations (6 μg/L, Figure 19) were sufficient to support stated metabolic requirements. Following addition of ammonium polyphosphate (11-37-0) to Catfish Pond, major peaks and extinction curves in *E. coli* densities were observed in time phase with nitrite concentrations (Figure 21). Of note, plots of nitrate and ammonia observations (Figure 22 – 24) do not exhibit the same response with regard to bacteria densities, and normal nitrification (oxidation) processes probably best explain lags in data. In addition to bacteria losses or inactivation attributable to light ($r^2$ = .17, p << .001) (Verstraete and Voets 1976; Kapuscinski and Mitchell 1983; Barcina et al. 1989, 1990) and photooxidation (Curtis 1990), starvation and nutrient availability - especially of $NO_{2-}$ ($r^2$ = .55, p << .001) - is assessed as a possible determining factor in the fate of *Escherichia coli* in the Catfish Pond watershed. Further research is needed to better understand the nutritive requirements and chemical constraints for *E. coli* in temperate habitats.

### 5.3 Conceptual models

An examination of relevant literature yields a Time, Distance, Mass (TDM) model with temperature (Bissonnette et al. 1975; Gorden and Fliermans 1978), ultraviolet radiation (Grigsby and Calkins 1979; Barcina et al. 1989, 1990) and turbidity (Schillinger and Gannon 1982, 1985) as primary dependent variables (Figure 26). In addition to data results established in Tables (2.0 – 2.15), a subset of non-transformed *E. coli* data (*N*=600) subjected to Principle Component Analysis (PCA) supports the TDM model and the dynamic (storm) stage the model better represents (Figure 28). Within the model, 69% of sample variance is contained within factor (*x*, distance) and 11% of sample variance is contained within factor (*y*, mass). Greater numbers of *E. coli* enumerated at each depth interval support theories of UV injury and mortality by photooxidation in the top 1-m of water; however, mass-dependent sedimentation and transport could also exist, especially under static, non-storm conditions. Model variables clearly emphasize temperature, light, and turbidity (Figure 27) driven by the physical variables of time, distance, and mass – ergo the bacteria transport discussion in section 5.1 - and support the findings of Crane et al. (1973), Kay and McDonald (1980), Gannon (1983) and Schillinger and Gannon (1982, 1985), among others.

However, the TDM model reflects only one condition for the Catfish Pond watershed. Principle Component Analysis of the full, transformed *E. coli* – water quality data matrix (*N*=4293, censured) builds upon results obtained in the TDM

model. Three specific areas of emphasis can be identified: (1) turbidity – *E. coli* interactions (Figure 8); (2) a weak, chaotic *E. coli* – nutrient dynamic (Figure 9); and (3) non-seasonal system, or physical, modulations (Figure 10). These observations suggest a second ecosystem dynamic at work, perhaps best represented by development of a Temperature, Density, Dispersion (TDD) model (Figure 29). The TDD model functions opposite the TDM model as the steady state in a system displaying "flip-flop" behavior, where hydrologic events act as agents of change, driving ecosystem conditions from the TDD steady state to the TDM dynamic state via major perturbations in flow.

Temperature induced transport (Figure 30) and discrete dispersion of indicator bacteria from the headwater stream through the pond was observed. At constant temperature, objects of mass display near-constant density, including *E. coli*, a motile species normally possessed of single flagellum and assessed as weak swimmers. Stephenson and Rychert (1982) and Buckley et al. (1998) found high densities of *E. coli* in stream sediments, and concentrations of stream bacteria were elevated throughout the period of this study (Figure 5). In addition, samples collected at all pond surface transects never reflected spatial attenuation of *E. coli* densities (Table 2.1 – 2.15). As depicted in Figure 30, the stream and pond experienced temperature stratification during static inter-storm periods. Because *E. coli* are weak swimmers, live at low Reynold's numbers, and are prone to be transported by mass dynamics, they were likely introduced from the stream into the pond in the cooler, denser waters of the stream-fed

euphotic zone. Once there, bacteria could live in a world free of damaging ultraviolet radiation and predacious zooplankton that populate the photic zone. Thus, their population density would be preserved, not attrited, and is best represented by the Temperature, Density, Dispersion model. During this experiment elapsed time between storm events was protracted – on the order of weeks - and surface water *E. coli* concentrations decreased to low levels. Bacteria densities also decreased within this time interval, but not in proportion to the photic zone (*see* Figure 27).

Conversely, as observed in Catfish Pond, storm events disrupt relative steady state systems displaying the temperature-density dynamic. Temperature stratification between the photic and euphotic zones is altered by storm inputs of warm, sediment-laden water into the system. Such storm pulses act as ecosystem resets, and flip the system in bi-modal fashion from a static to a dynamic state, represented here by the TDM and TDD models. These findings support the development of a composite TDM-TDD model to accurately describe systems in the bi-modal condition. As demonstrated in the current study, a “Bi-modal Transport and Fate” (BTF) model should incorporate physical, chemical, and biologic interactions to accurately predict ecosystem dynamics relative to pathogen transport and fate.

# CHAPTER 6

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Conclusions

The results of this investigation demonstrate the reliability and repeatability of Defined Substrate Technology (DST) method for detecting and quantifying *Escherichia coli* at the watershed scale. Previous investigations describing the hydrologic transport of indicator bacteria were consistent with our results, showing that stream discharge and precipitation are the primary variables affecting bacteria distribution. The DST method was also successfully paired with genetic ribotyping to determine that 42.9% of *E. coli* in the Catfish Pond watershed emanated from whitetail deer. Within that number 35 ribotypes were determined to originate from wild deer and 11 ribotypes were determined to originate from penned deer, implying diet affects *E. coli* ribotype diversity (Hartel et al. 2003).

Nutrition, specifically nitrogen availability, was determined to be the major factor affecting the fate of waterborne *E. coli* within the pond. A second factor group comprised of dissolved oxygen, pH, Eh, and conductivity was highly correlated to bacteria densities, but not confirmed as a causal factor in *E. coli* mortality. Bacteria displayed a possible dynamic with phytoplankton, which could

not be further described. Temperature and density-dependent transport of bacteria was observed and a unified conceptual model proposed.

Effectiveness of impoundments in mediating bacteria densities is closely linked to total watershed drainage area, percent impervious surfaces, type and volume of stormwater inflows, and landscape wasting. With the exception of two storm events, during this study all bacteria were entrained within Catfish Pond and attenuated within days or weeks. Mediation benefits of small impoundments in decreasing *E. coli* densities can be short-circuited when large (non-design) storms exceed permanent pool storage capacity and decrease hydraulic residence time.

### 6.2 Recommendations

1. Defined Substrate Technology appears suitable for large scale spatial observation, but remains labor intensive, which precludes collection of large data sets. Automation technology, such as that employed within the Environmental Process Control Laboratory (EPCL), exists to streamline bacteria collection and enumeration, and should be researched further.

2. Turbidity measures the optical qualities of colloids in water and has been widely reported as a prime measure of bacteria transport and disappearance. However, turbidity may not provide a representative measurement of chlorophyll-*a*, which this investigation found to be correlated with *E. coli*. Further work is required to elucidate the components of turbidity-bacteria interactions in the natural environment.

3. Studies examining predation and other dynamics affecting aquatic bacteria have been conducted; however, few results have been incorporated into a holistic ecosystem model to explain bacteria transport and fate at the watershed scale. Data from this work and earlier investigations suggest zooplankton display a strong seasonal component and can exert sufficient predatory influence on lotic environments to affect the fate of *E. coli* and other enterobacteria, and should be investigated.

4. Chlorophyll-*a* data suggest that on certain spatial and temporal scales *E. coli* may be linked to phytoplankton or other pheophytin-containing organism(s). Whether this relationship is coincidental, opportunistic, or symbiotic remains unknown, but could indicate commensalism, amensalism, or predation. Such relationships could be important to accurately model pathogens in the environment, and should be researched further.

5. Ribotyping offers great promise as a tool for evaluating Best Management Practices, compliance with TMDL requirements and mitigating excessive regulation. However, additional protocols should be developed to investigate wider scientific applications such as forensic hydrology, monitoring genetically modified organisms, and movement of endangered species.

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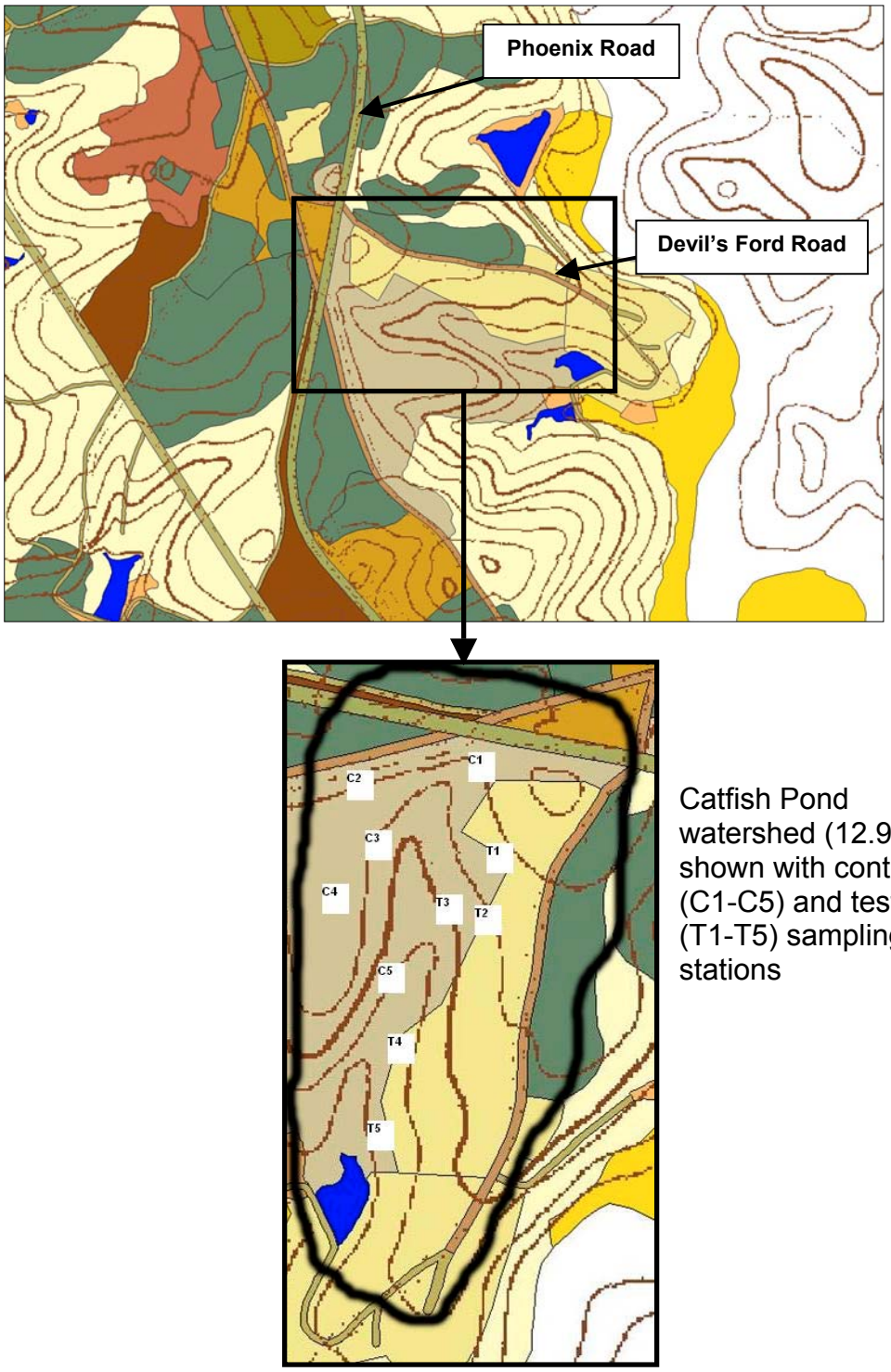
# APPENDIX A

# FIGURES




Catfish Pond watershed (12.9 ha) shown with control (C1-C5) and test (T1-T5) sampling stations

Figure 1. Geospatial rendering of Catfish Pond watershed, Whitehall Experimental Forest, Athens-Clarke County, Georgia

Figure 2.  Catfish Pond, Whitehall Experimental Forest

Figure 3.  Storm flows, Catfish Pond watershed, Whitehall Forest

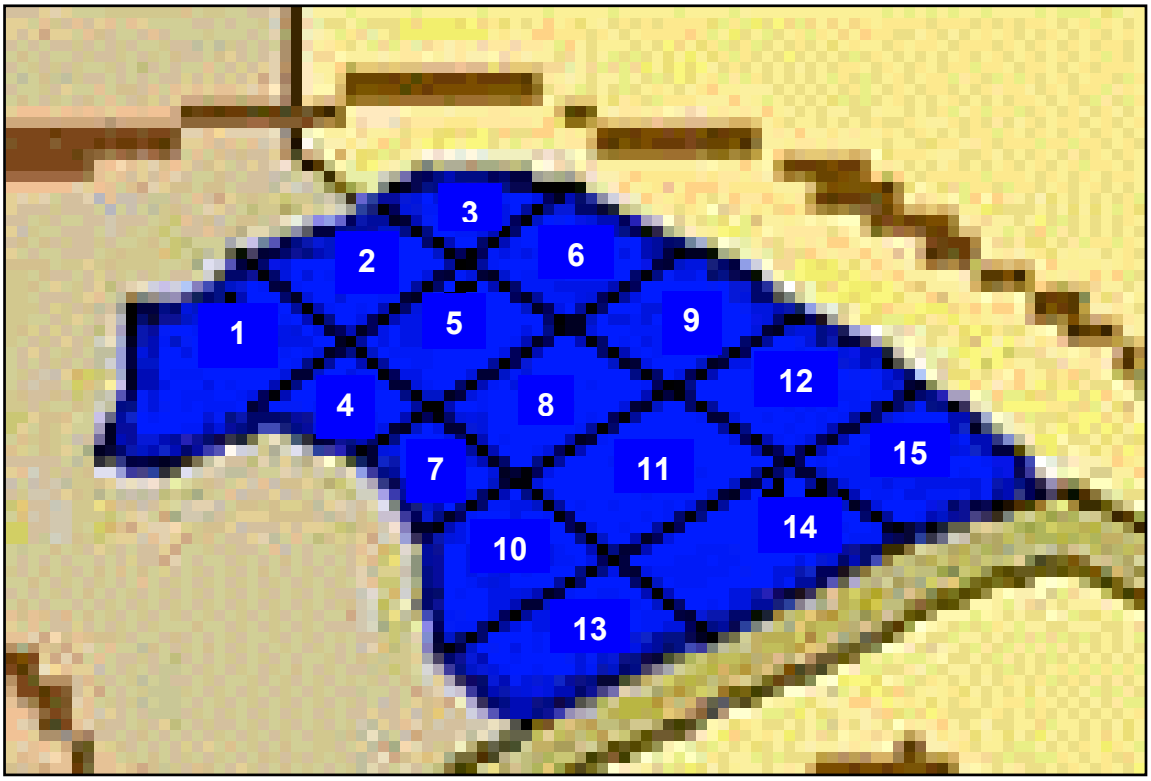



Figure 4. Sampling transects, Catfish Pond

**Figure 5. *E. coli* (CFU/100mL) vs time (days)**
**Catfish Pond Watershed, Whitehall Forest, 6/11/00 - 10/13/00**

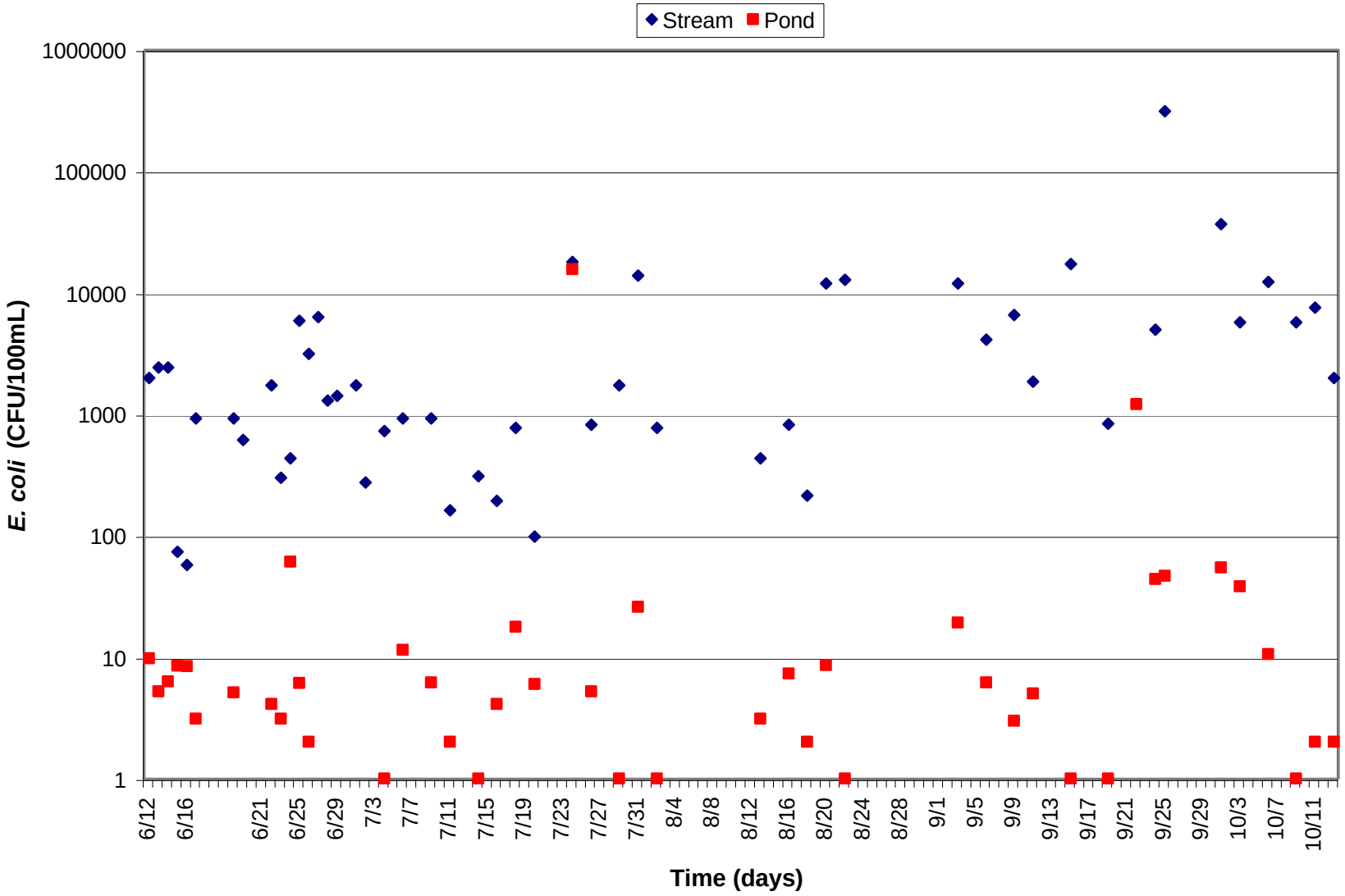


**Figure 6. Hydrograph: 23 July 2000**
**Stream Stage (ft) and *E. coli* (CFU / 100mL)**

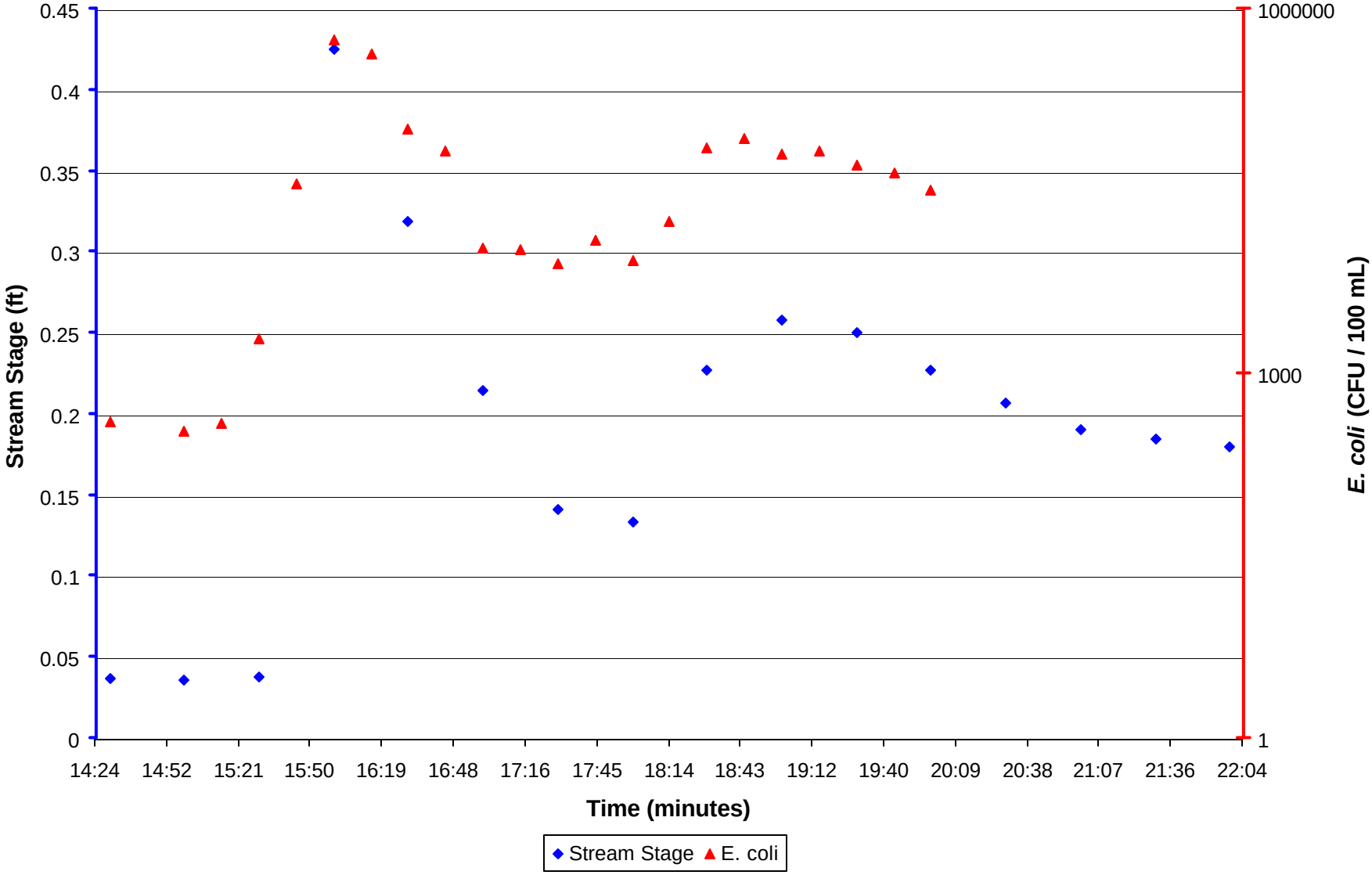
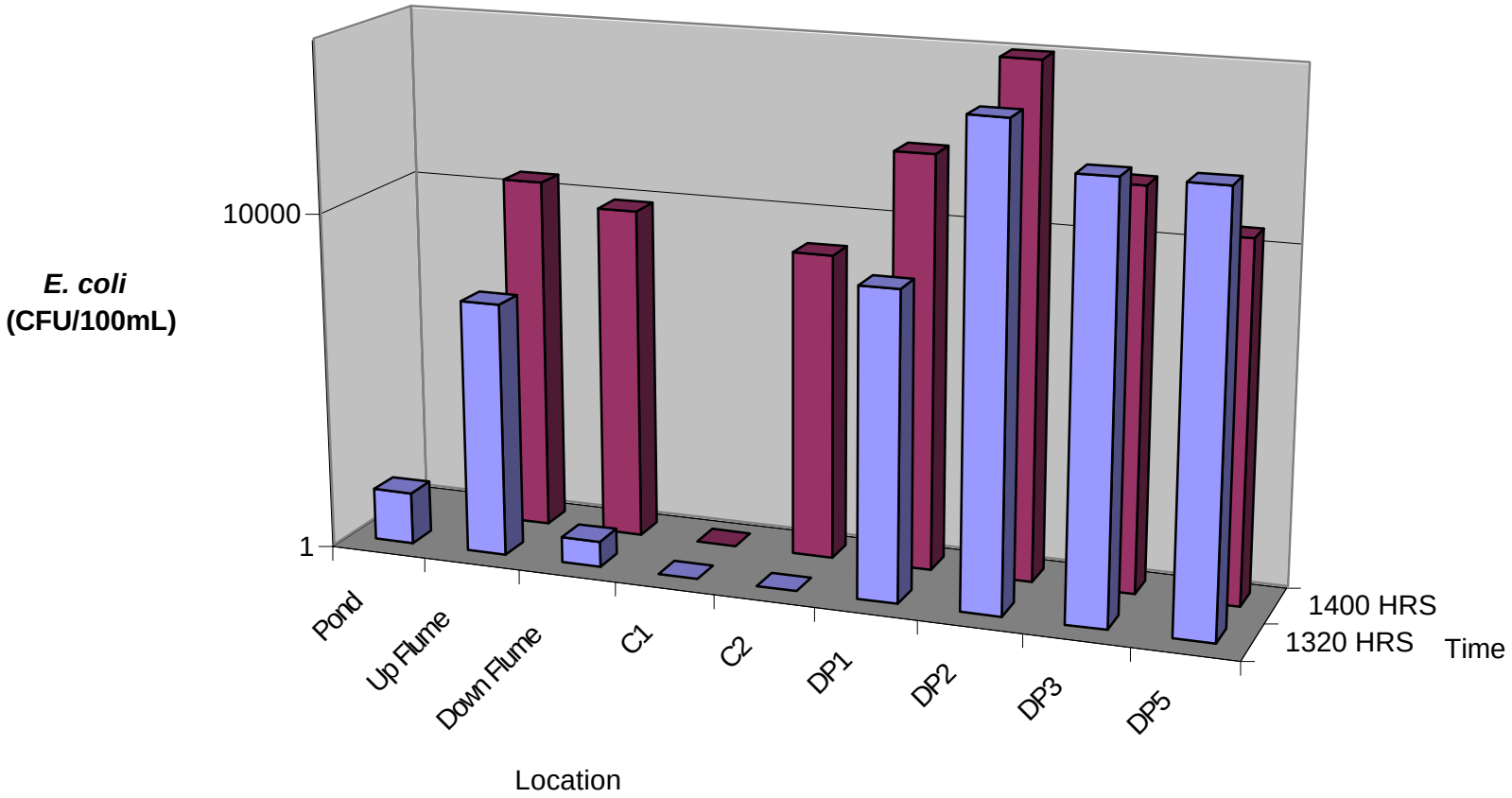


**Figure 7. *Escherichia coli* (CFU/100mL)**
**Catfish Pond Watershed - 19 January 2001**




| | Pond | Up Flume | Down Flume | C1 | C2 | DP1 | DP2 | DP3 | DP5 |
|---|---|---|---|---|---|---|---|---|---|
| 1320 HRS | 4.1 | 1000 | 2 | 0 | 0 | 4100 | 387300 | 110000 | 109500 |
| 1400 HRS | | 14800 | 8400 | 0 | 4000 | 73300 | 1203310 | 49600 | 16100 |

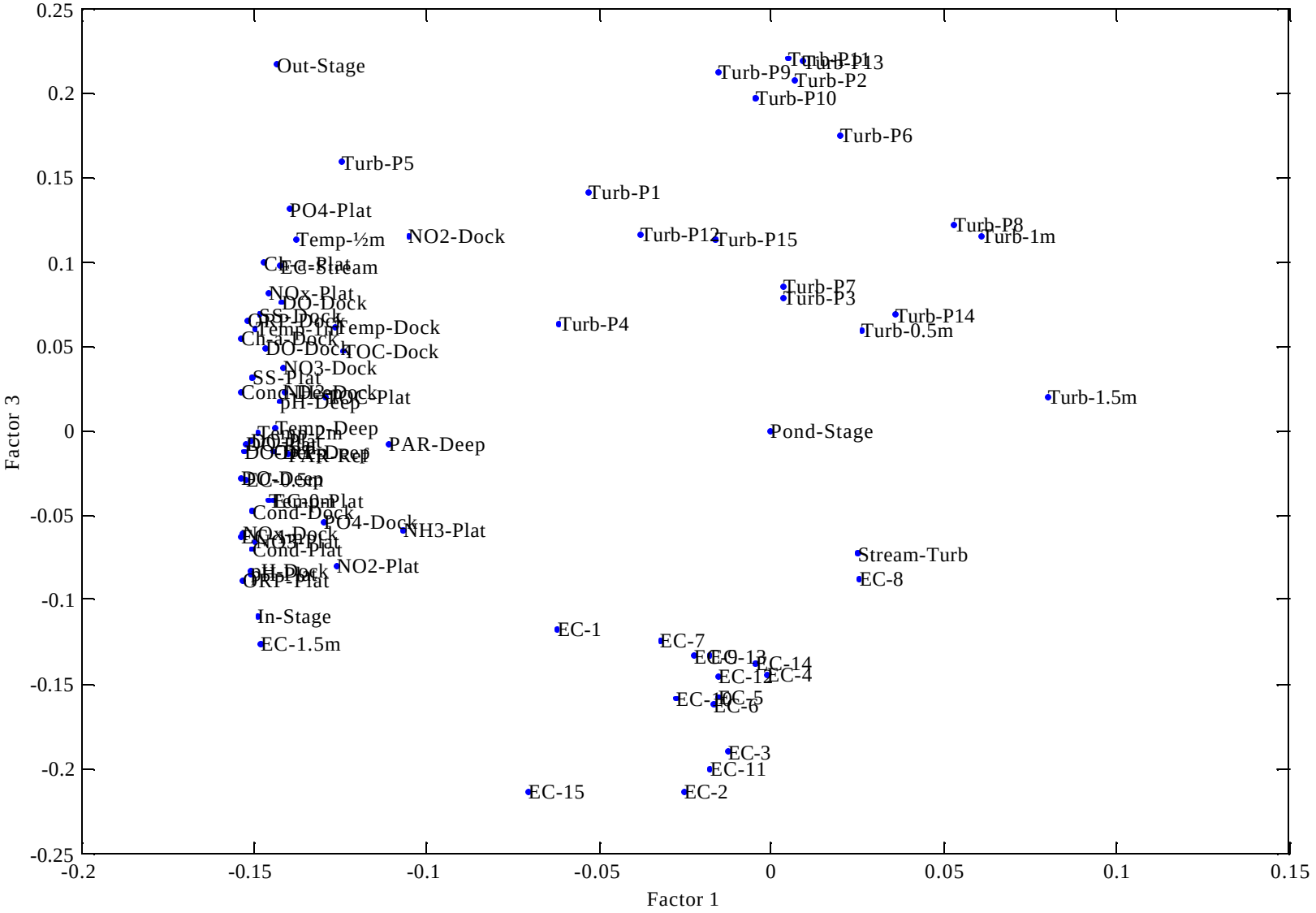
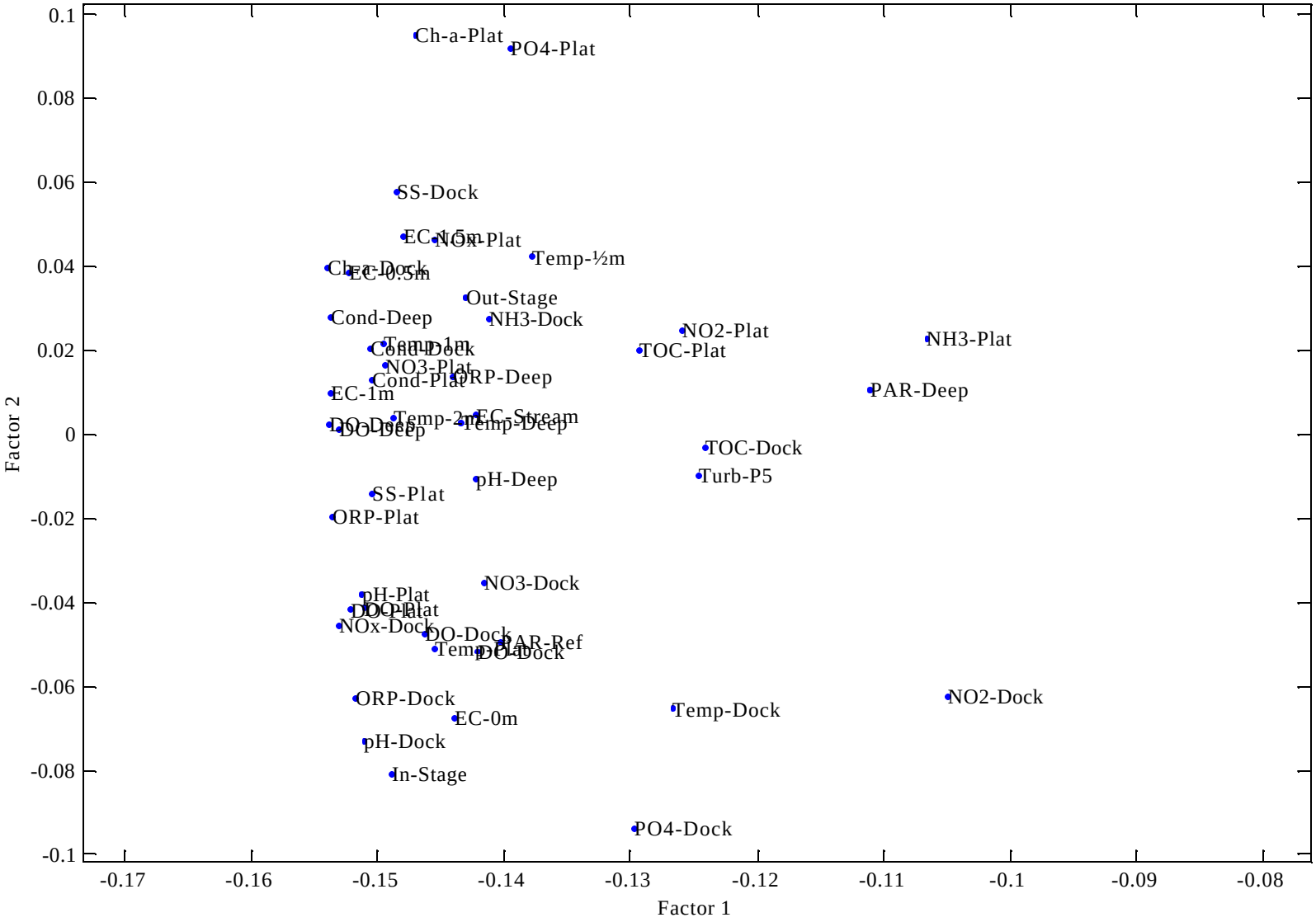



**Figure 8. Principle Component Analysis of *E. coli* censured data: Turbidity.**




EC-15

**Figure 9. Principle Component Analysis of *E. coli* censured data: Nutrient dynamic.**

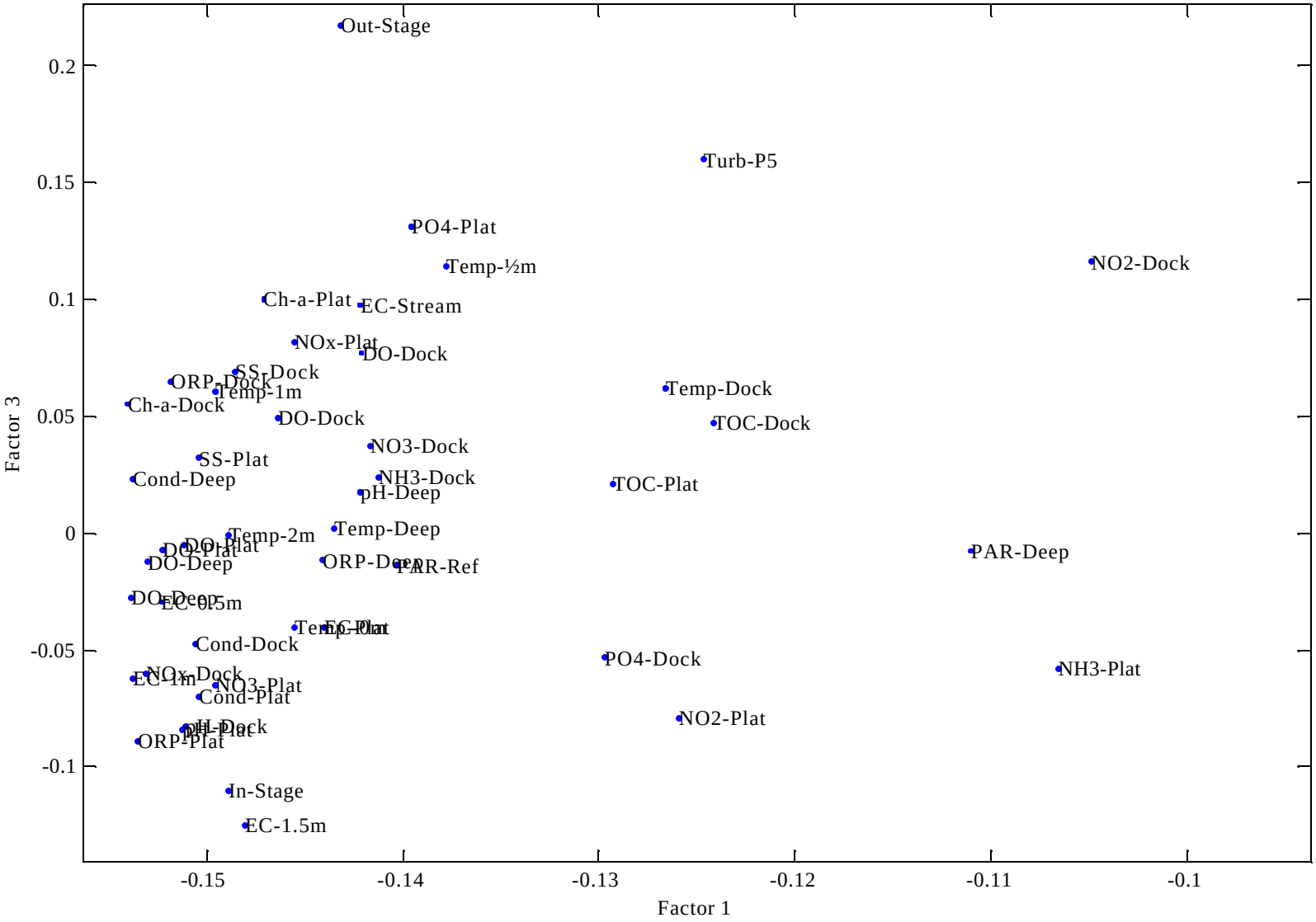



**Figure 10. Principle Component Analysis of *E. coli* censured data: Physical modulations.**

**Figure 11. Cumulative Precipitation (0.01") vs. Time (days)**
**Catfish Pond Watershed, Whitehall Experimental Forest, 6/11/00 - 10/13/00**

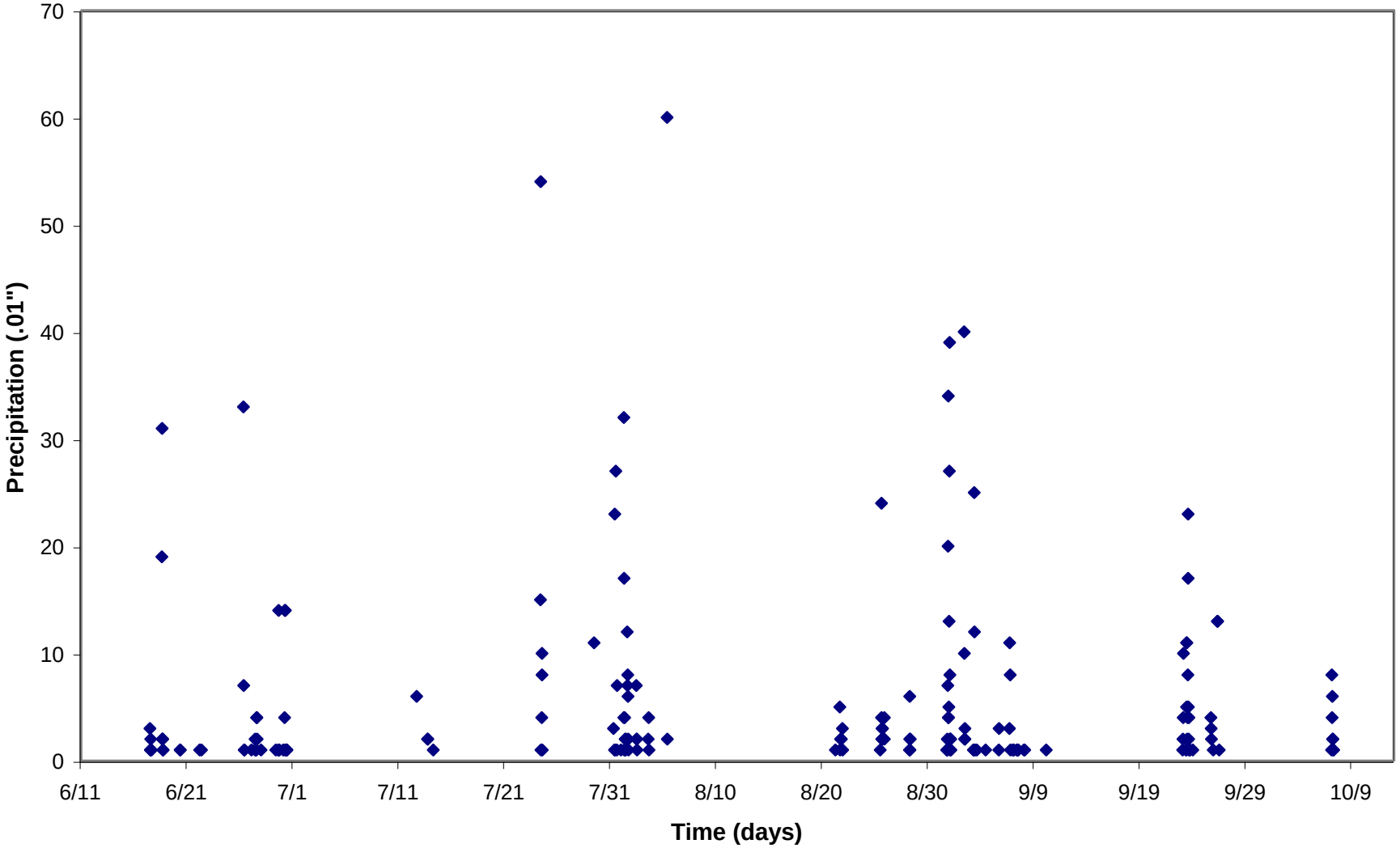


**Figure 12. Precipitation and Hydrograph Response of Headwater Stream, Catfish Pond Watershed, Whitehall Forest: 22 - 23 September 2000**

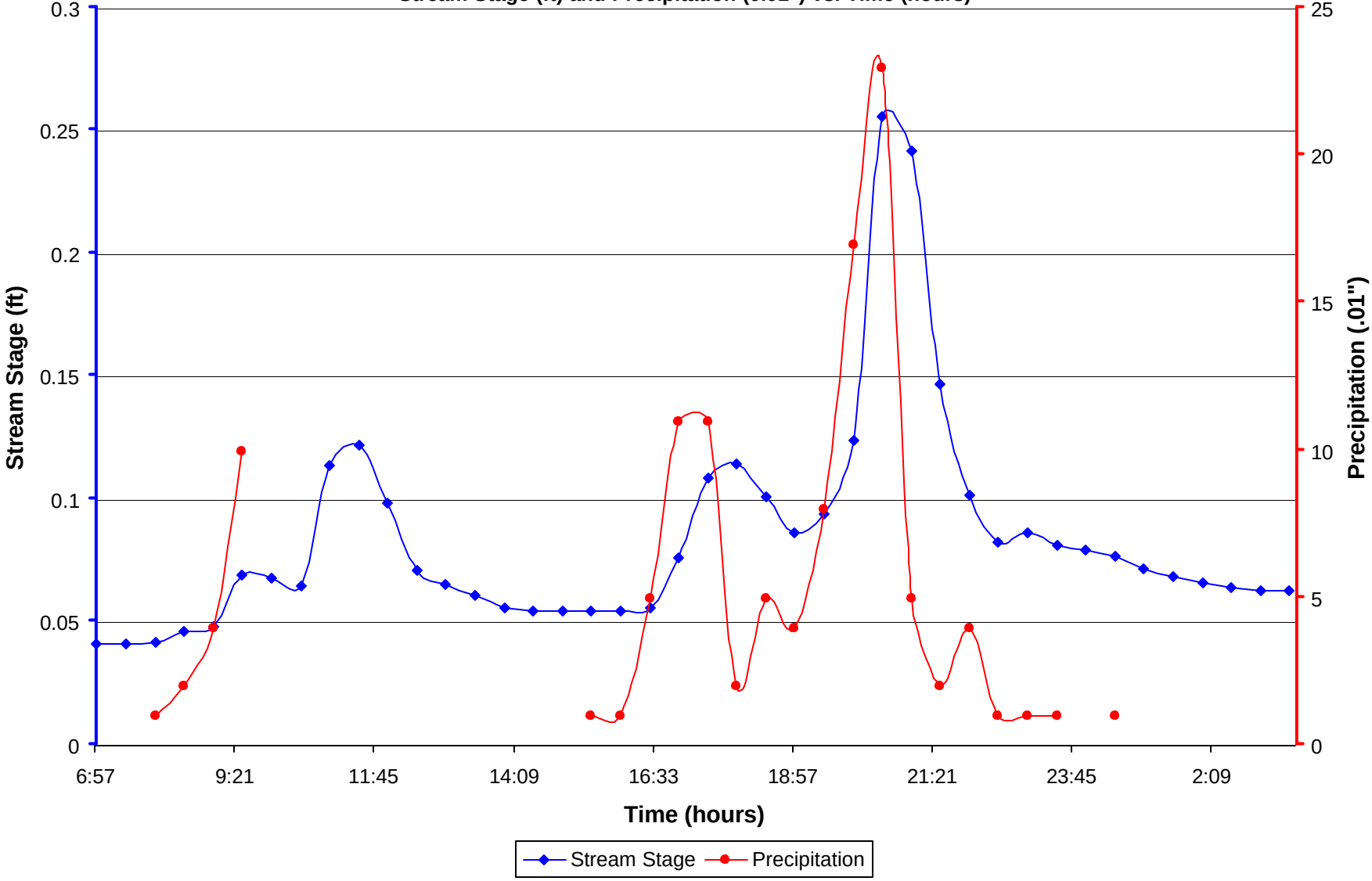


**Figure 13(a). Suspended Solids (FTU) and Turbidity (NTU) vs. Time (days)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

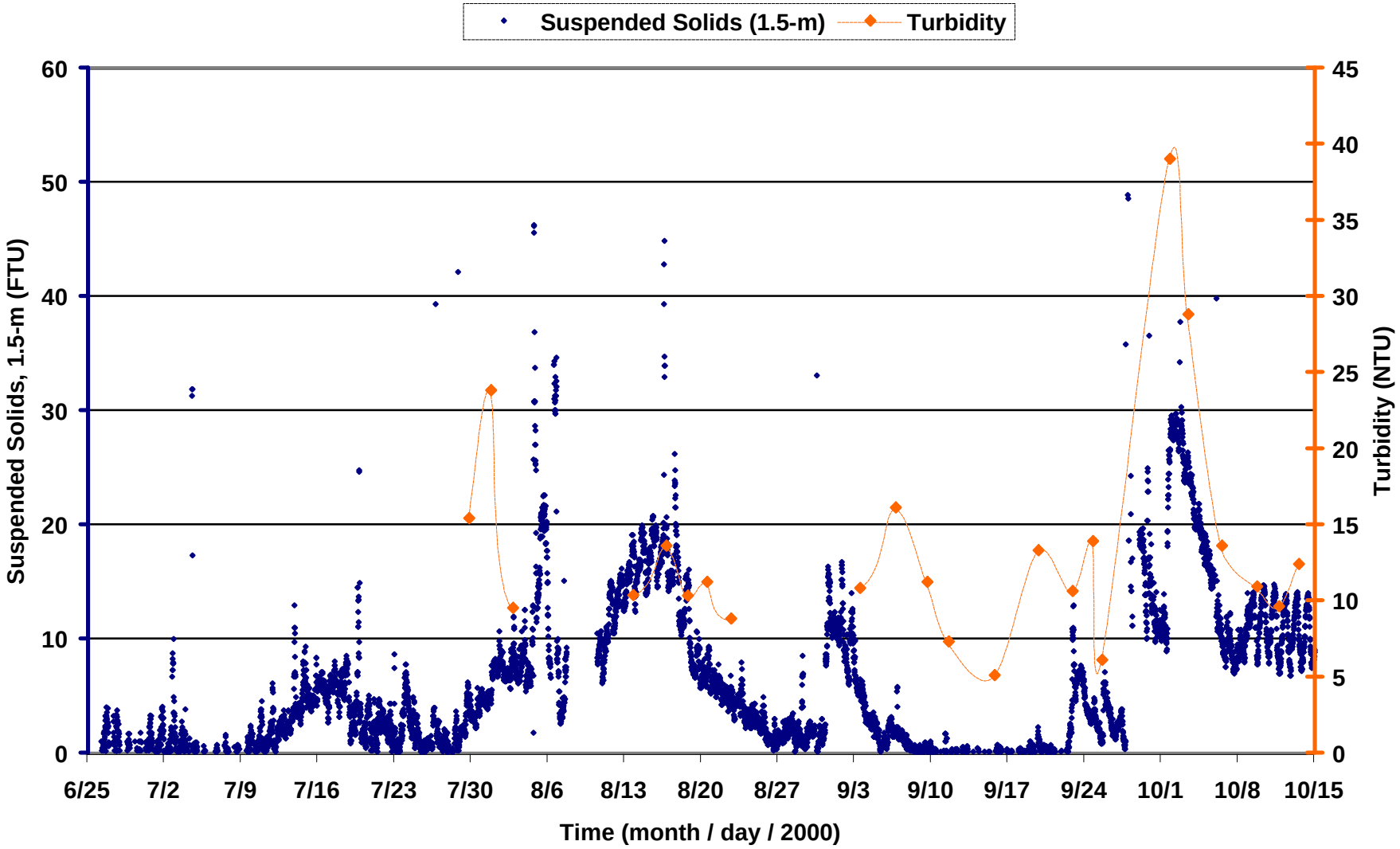


**Figure 13(b). Suspended Solids (FTU) and *E. coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/25/00 - 10/15/00**

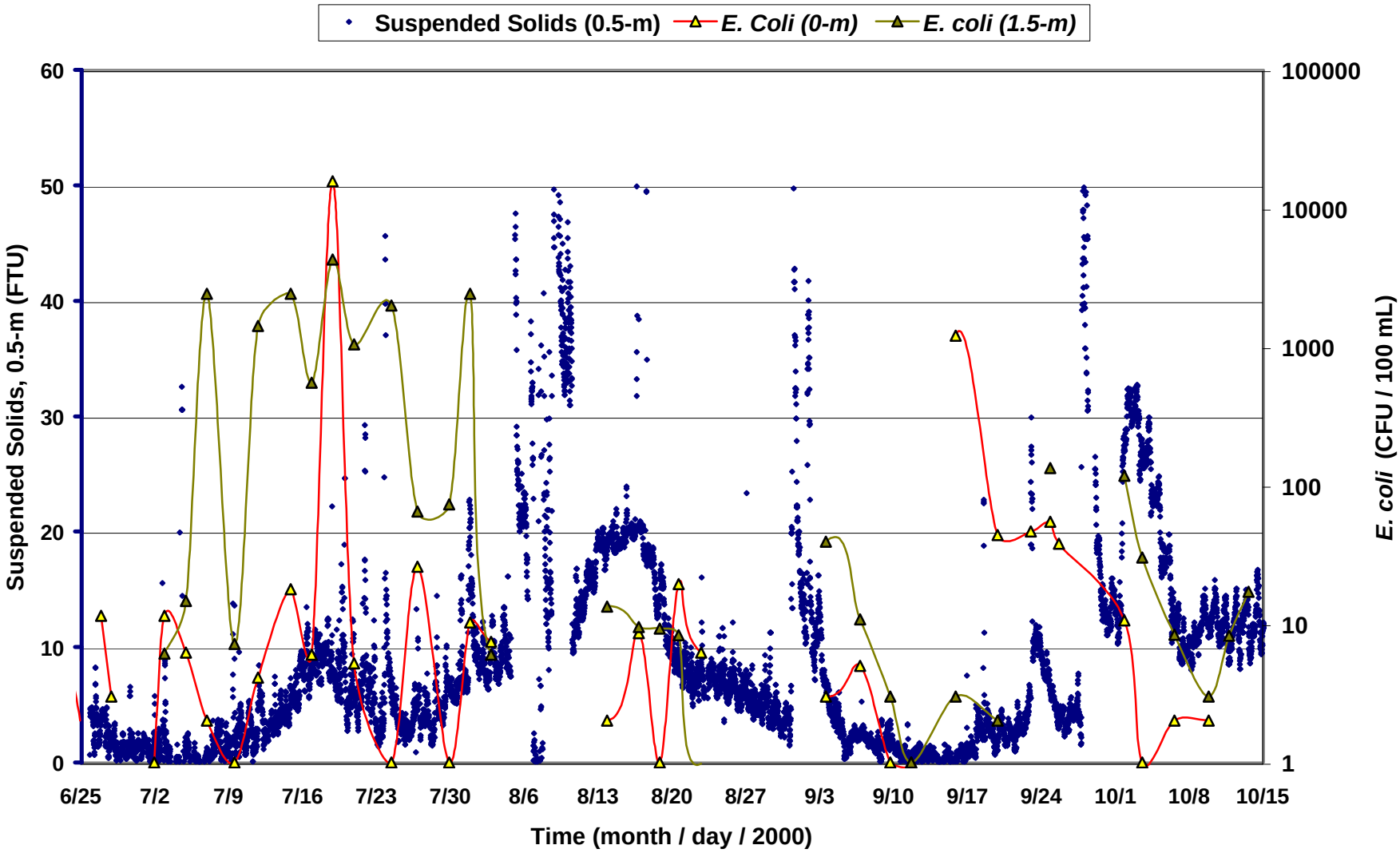


**Figure 14(a). Temperature (°C) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

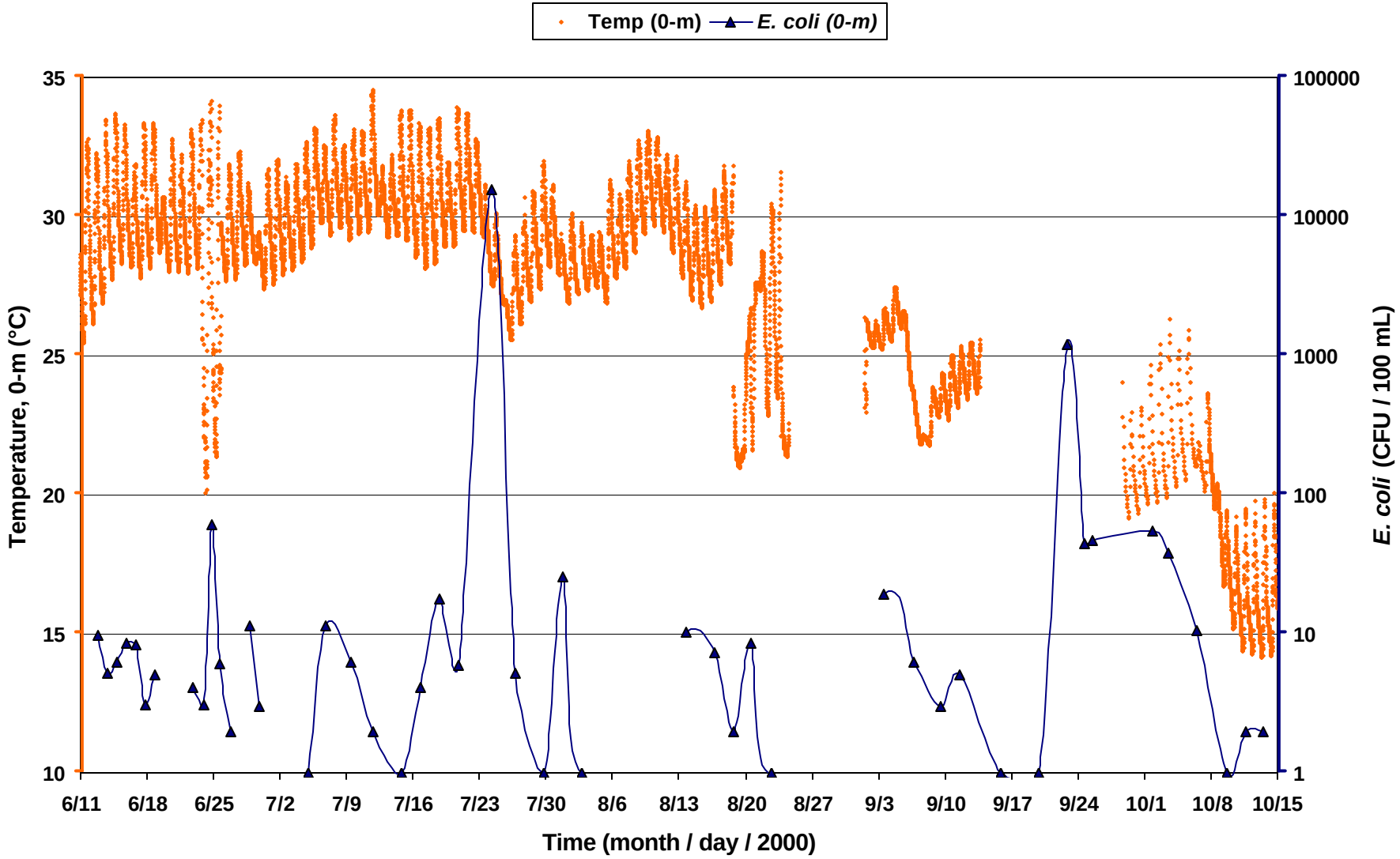


**Figure 14(b). Temperature (°C) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

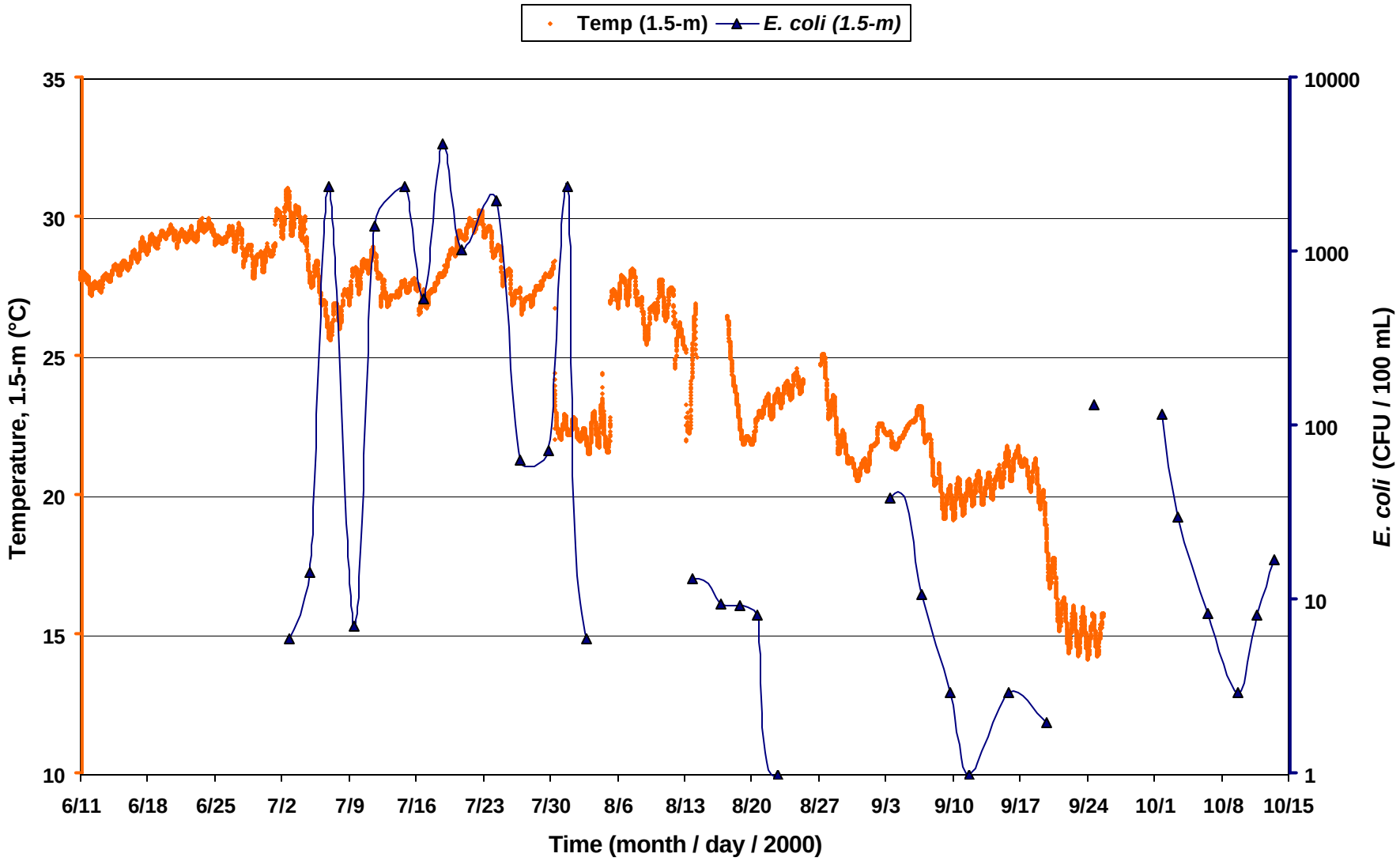


**Figure 15(a). Dissolved Oxygen (mg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

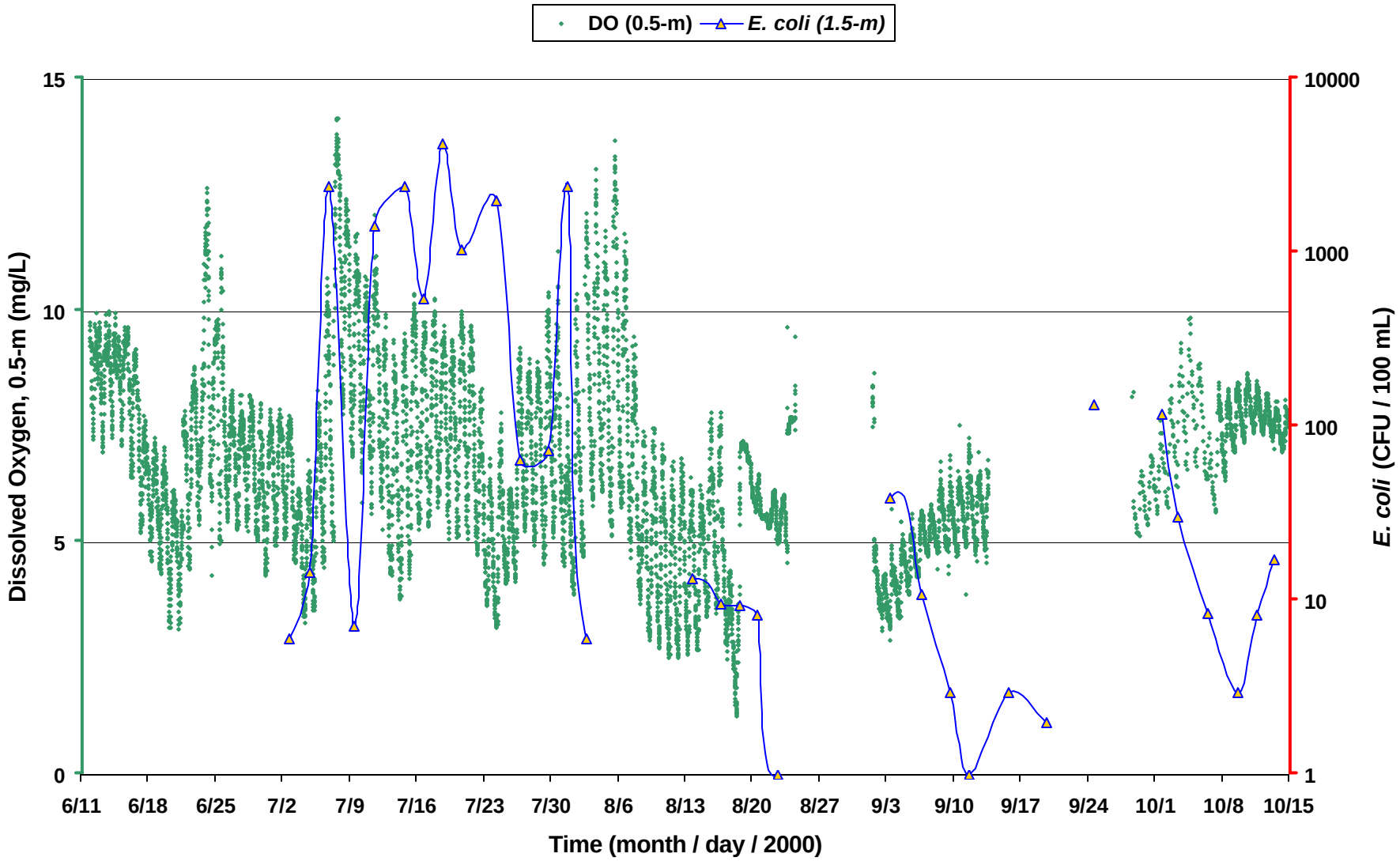


**Figure 15(b). Dissolved Oxygen (mg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/25/00 - 10/15/00**

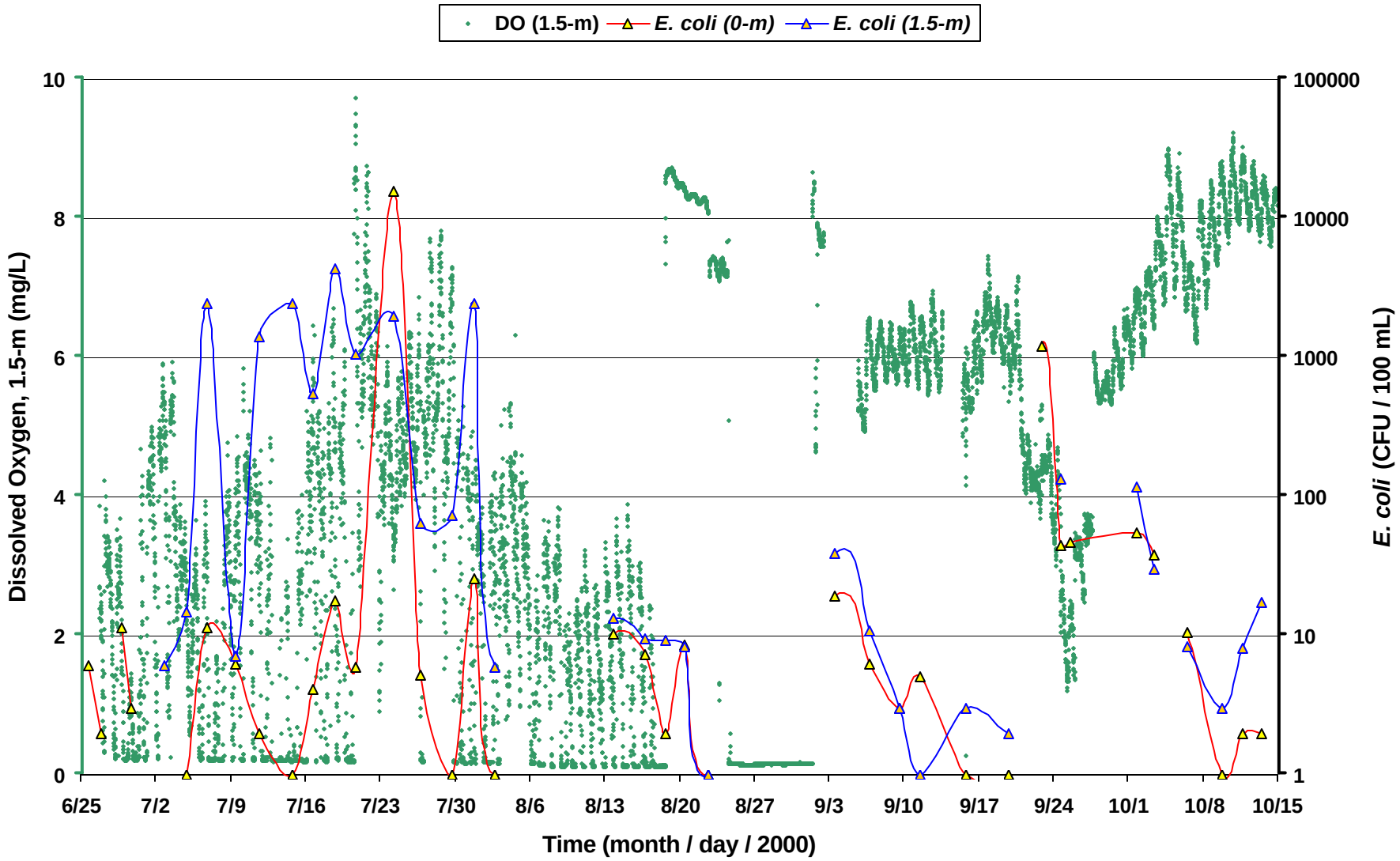


**Figure 15(c). Dissolved Oxygen (mg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

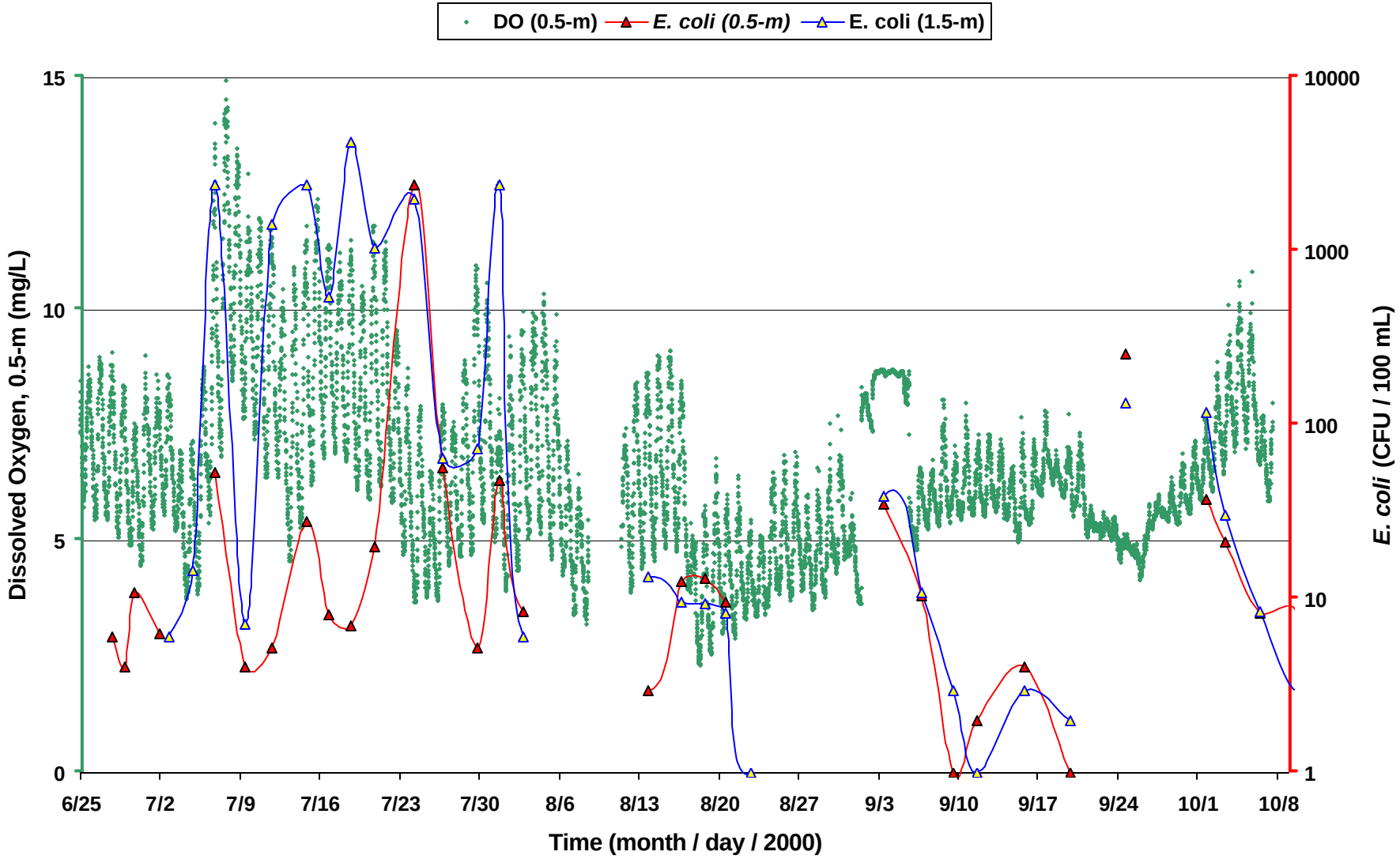


**Figure 16(a). Eh (mV) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

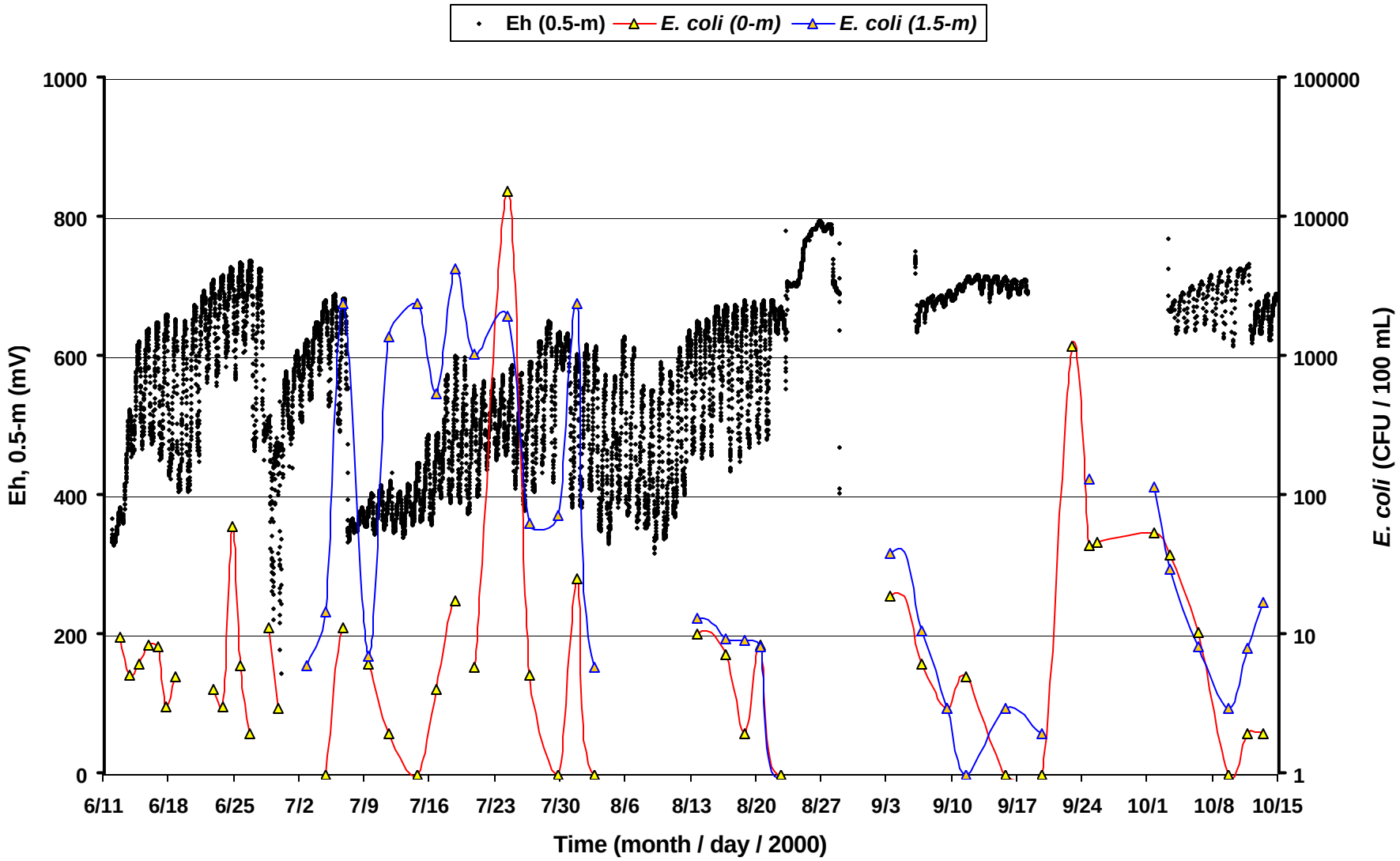


**Figure 16(b). Eh (mV) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

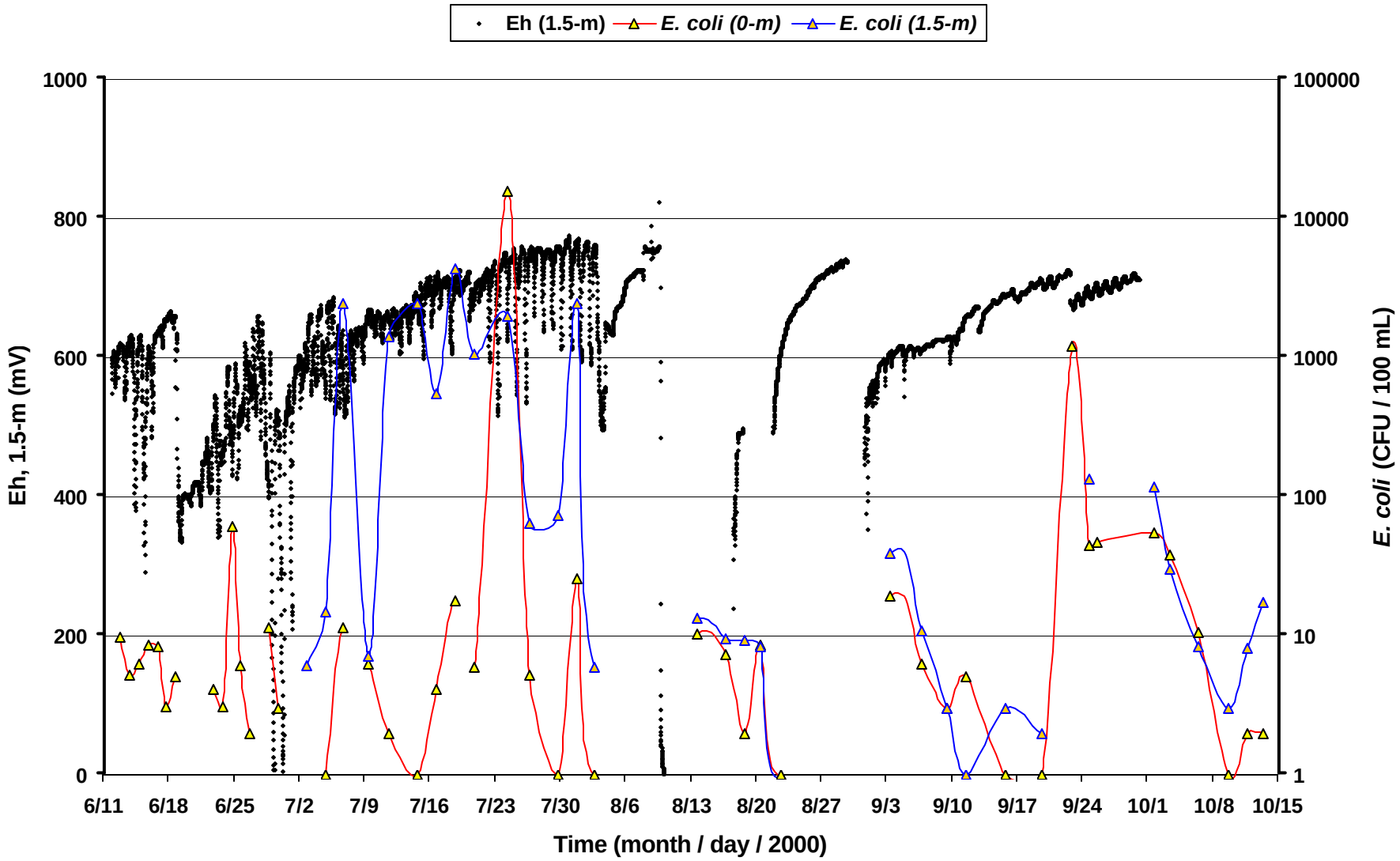


**Figure 16(c). Eh (mV) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

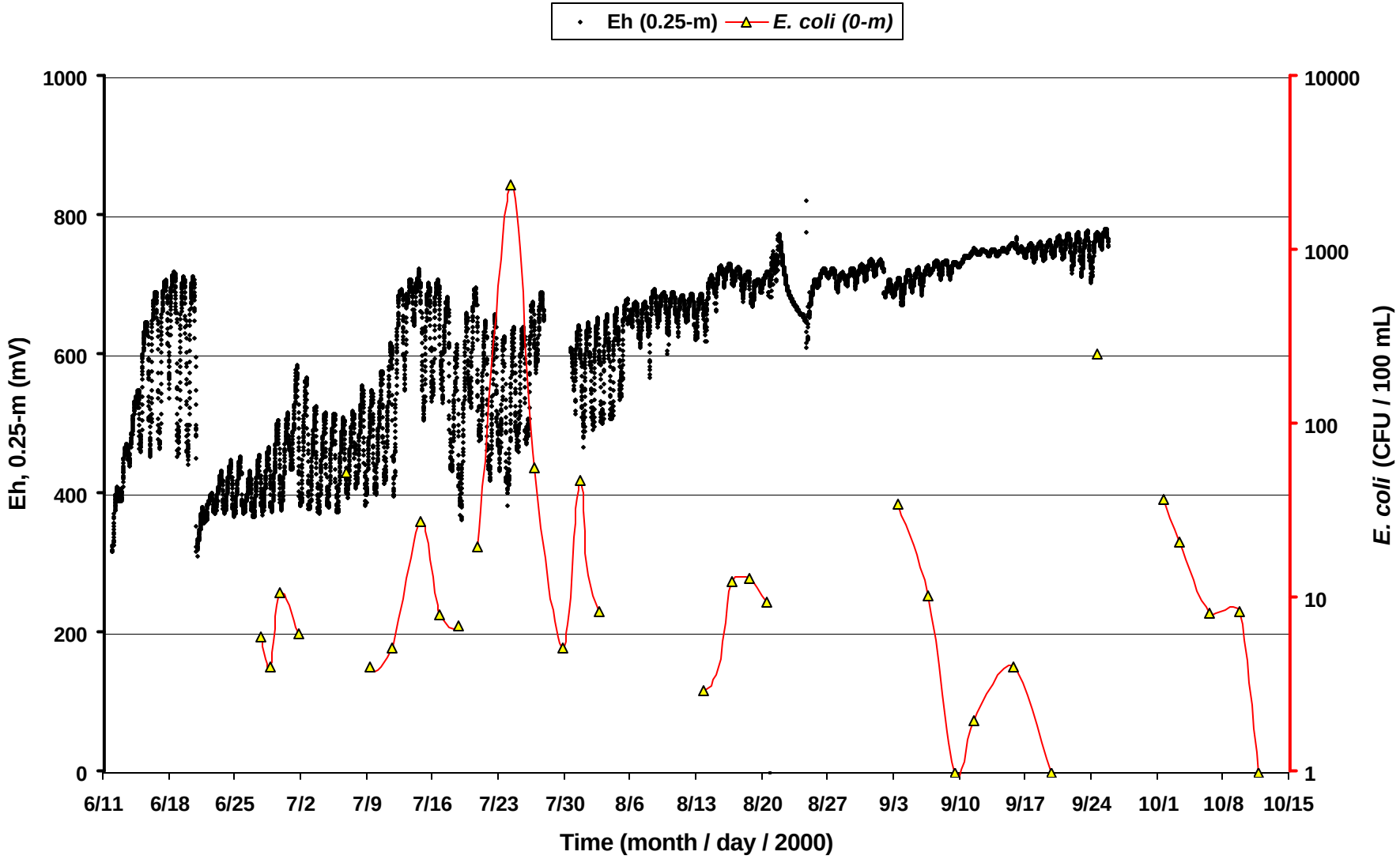


**Figure 17(a). pH and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

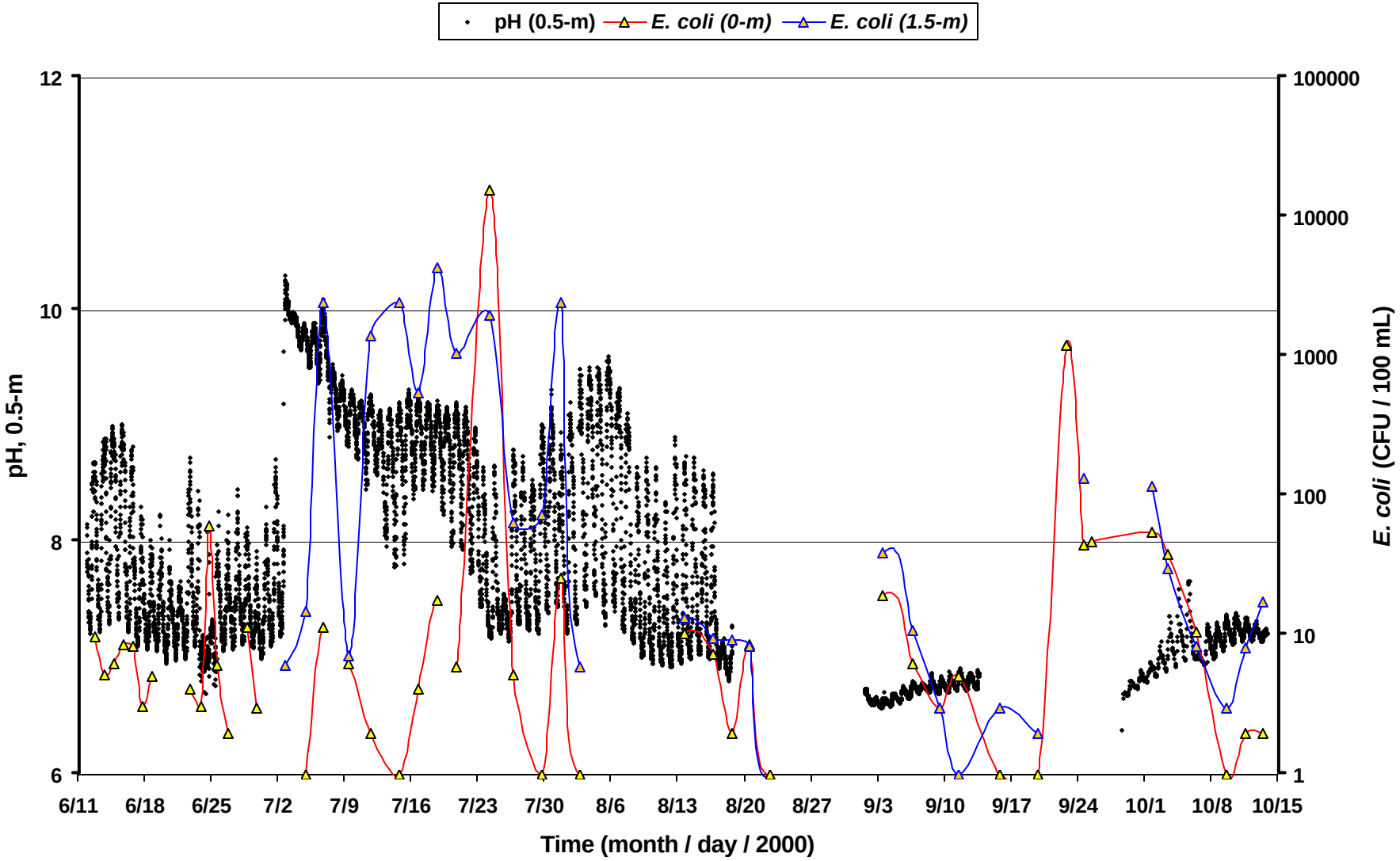


**Figure 17(b). pH and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

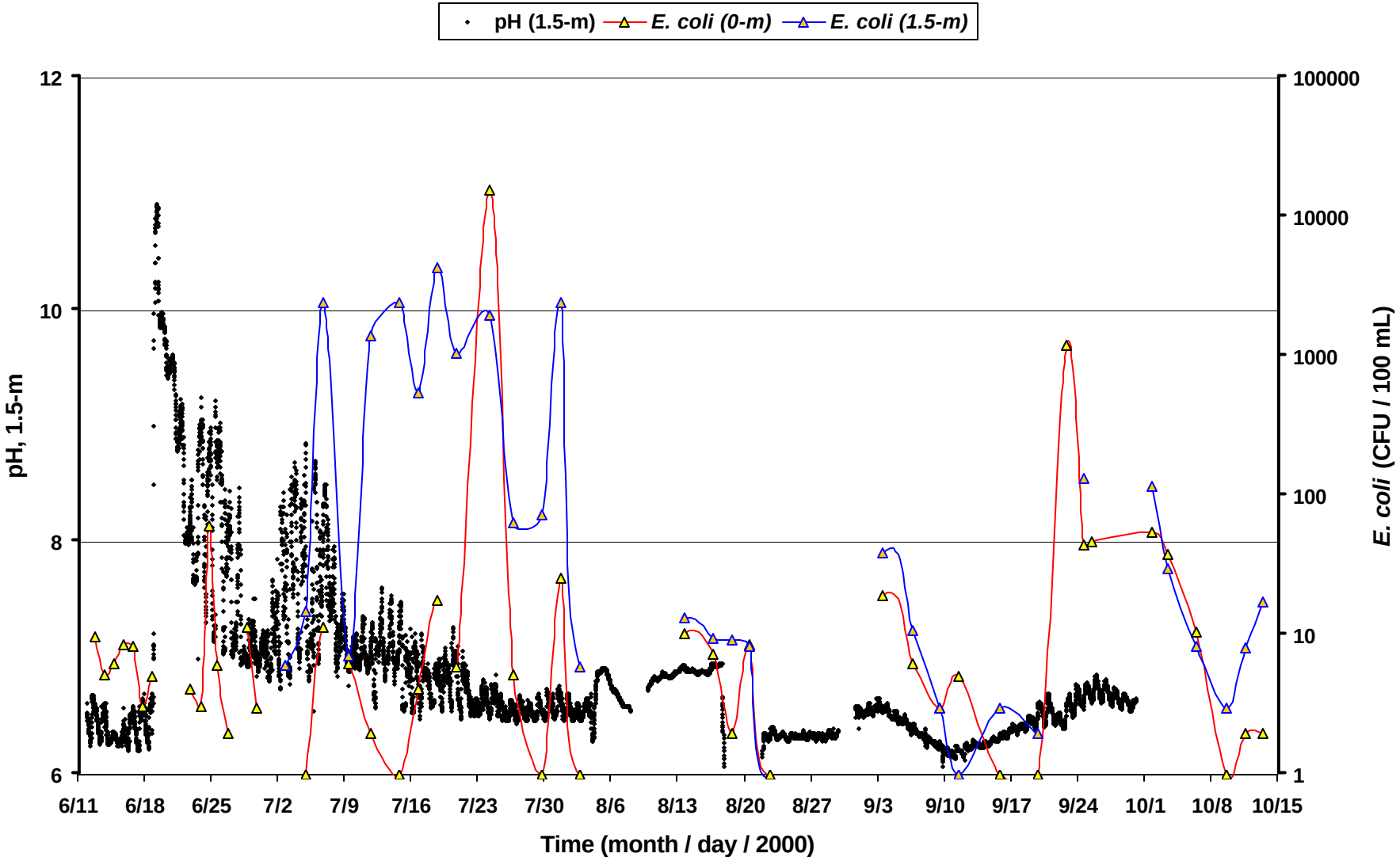


**Figure 17(c). pH and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

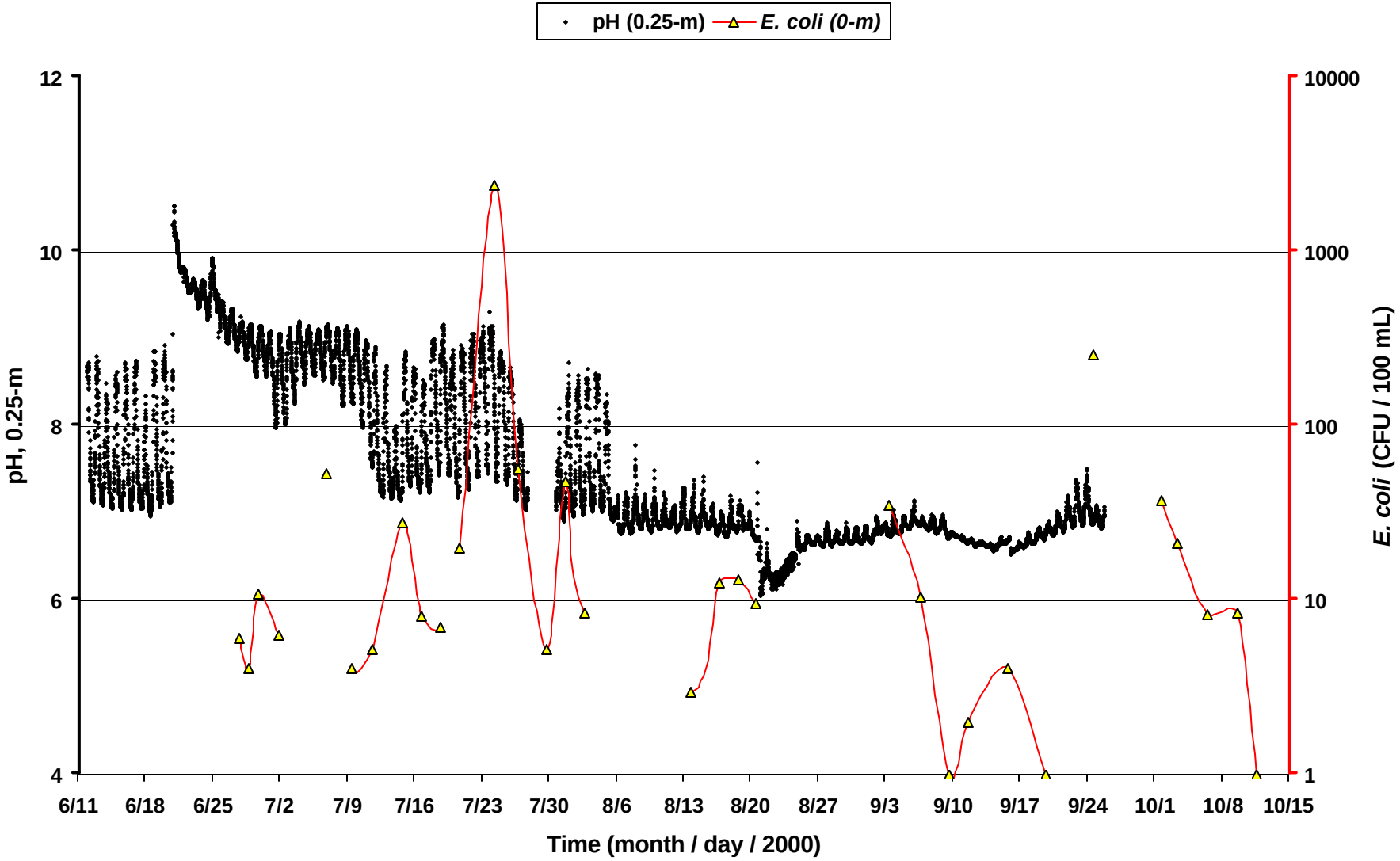


**Figure 18(a). Conductivity (µS/cm) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

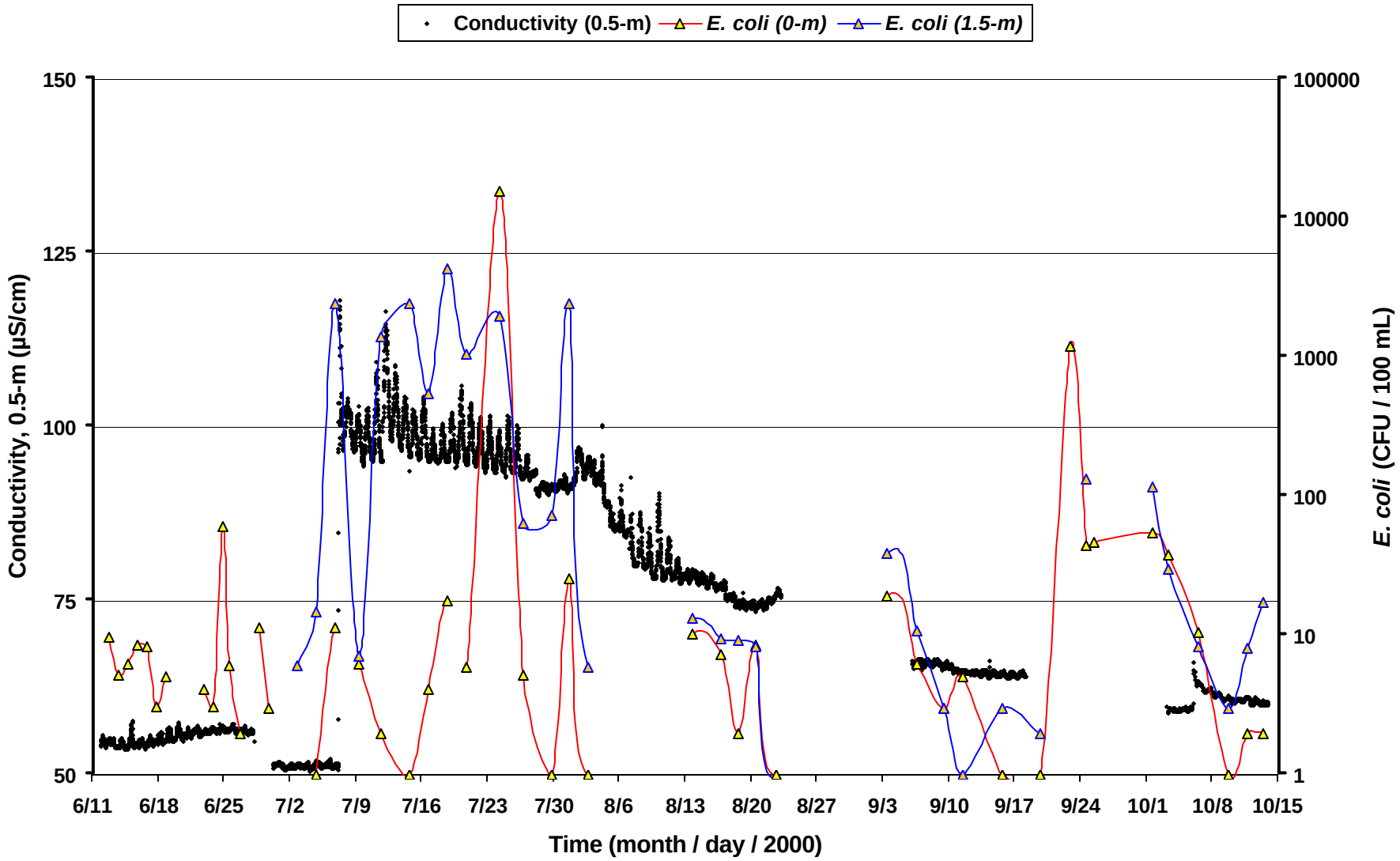


**Figure 18(b). Conductivity (µS/cm) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

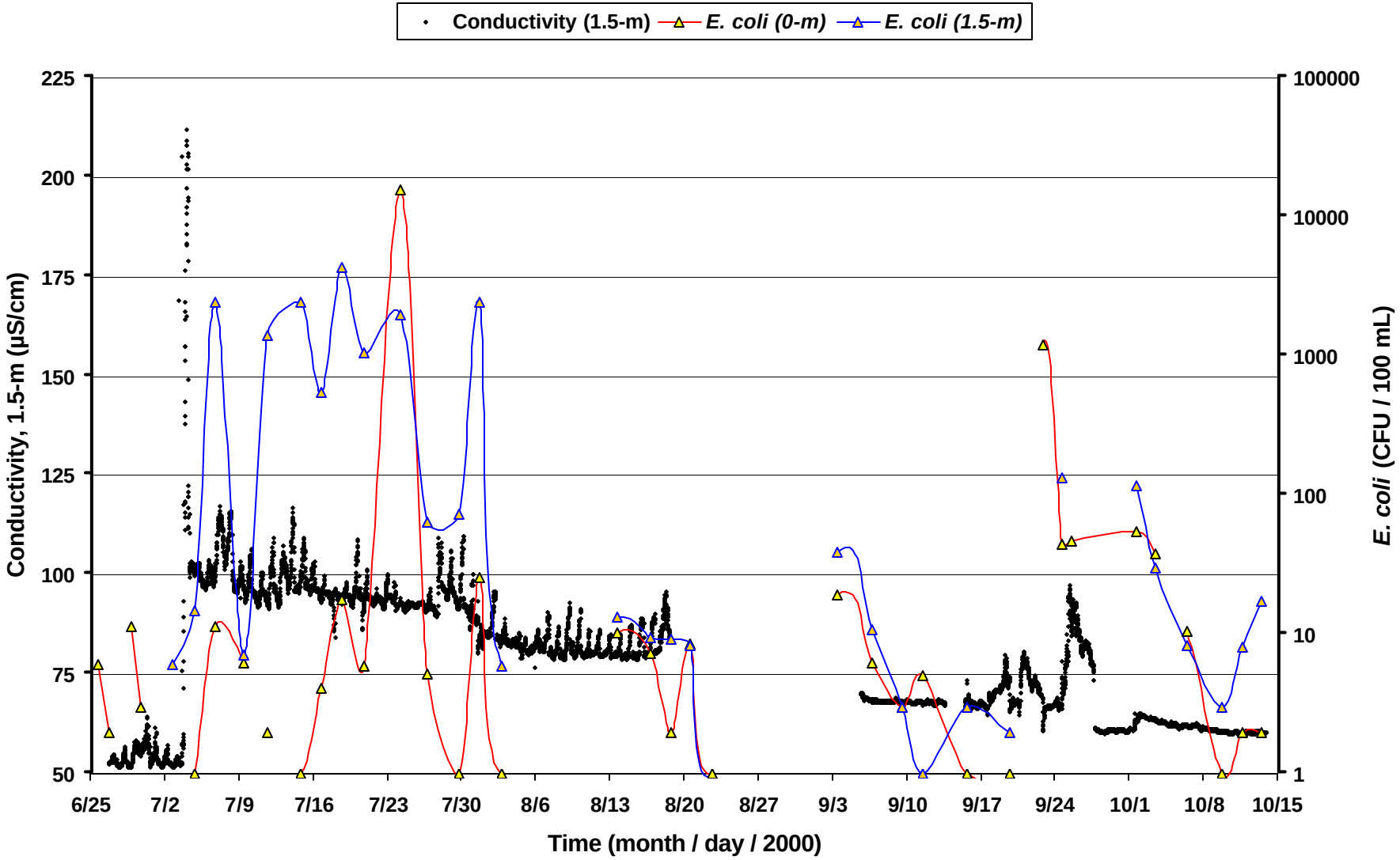


**Figure 18(c). Conductivity (µS/cm) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

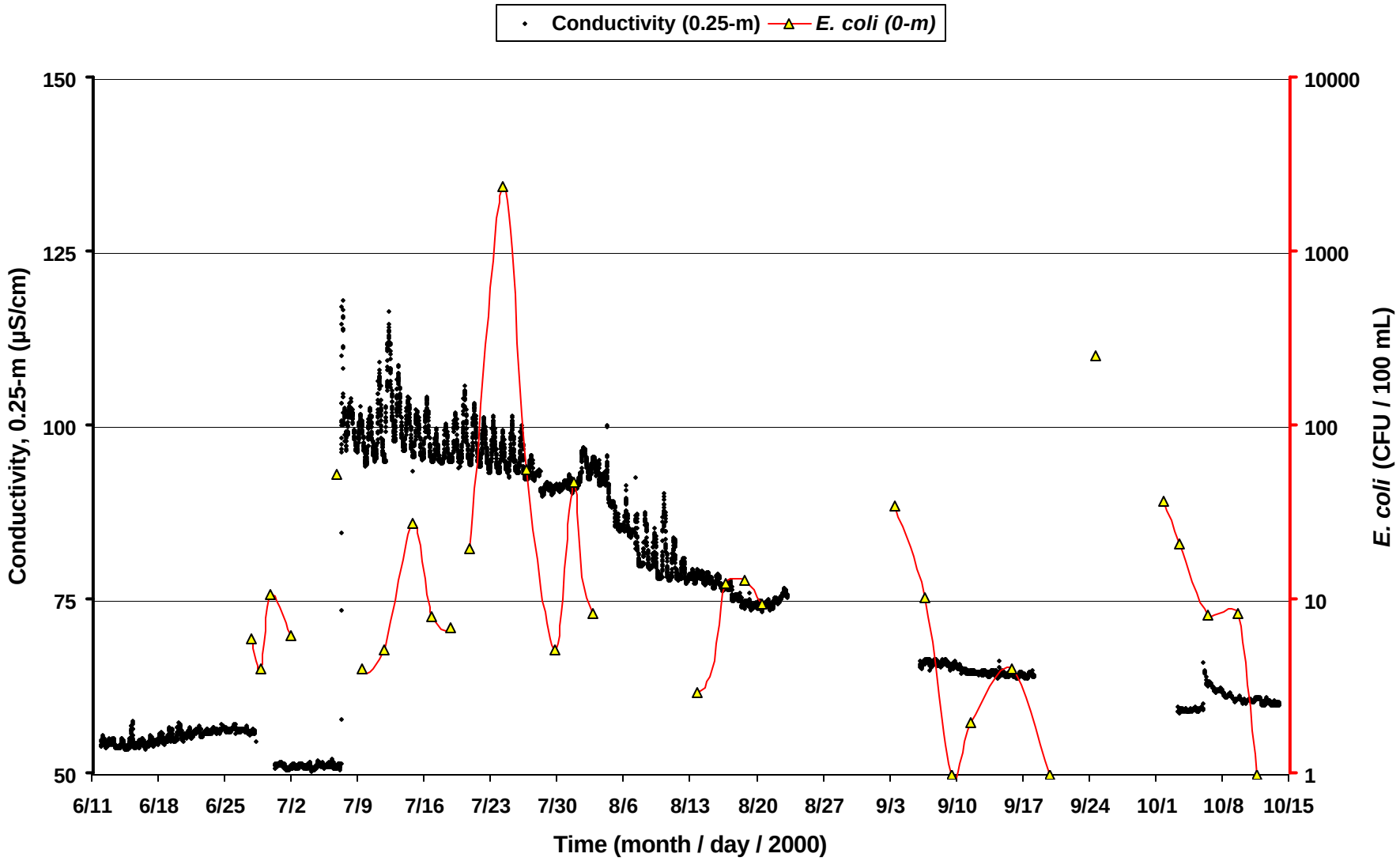


**Figure 19(a). TOC (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

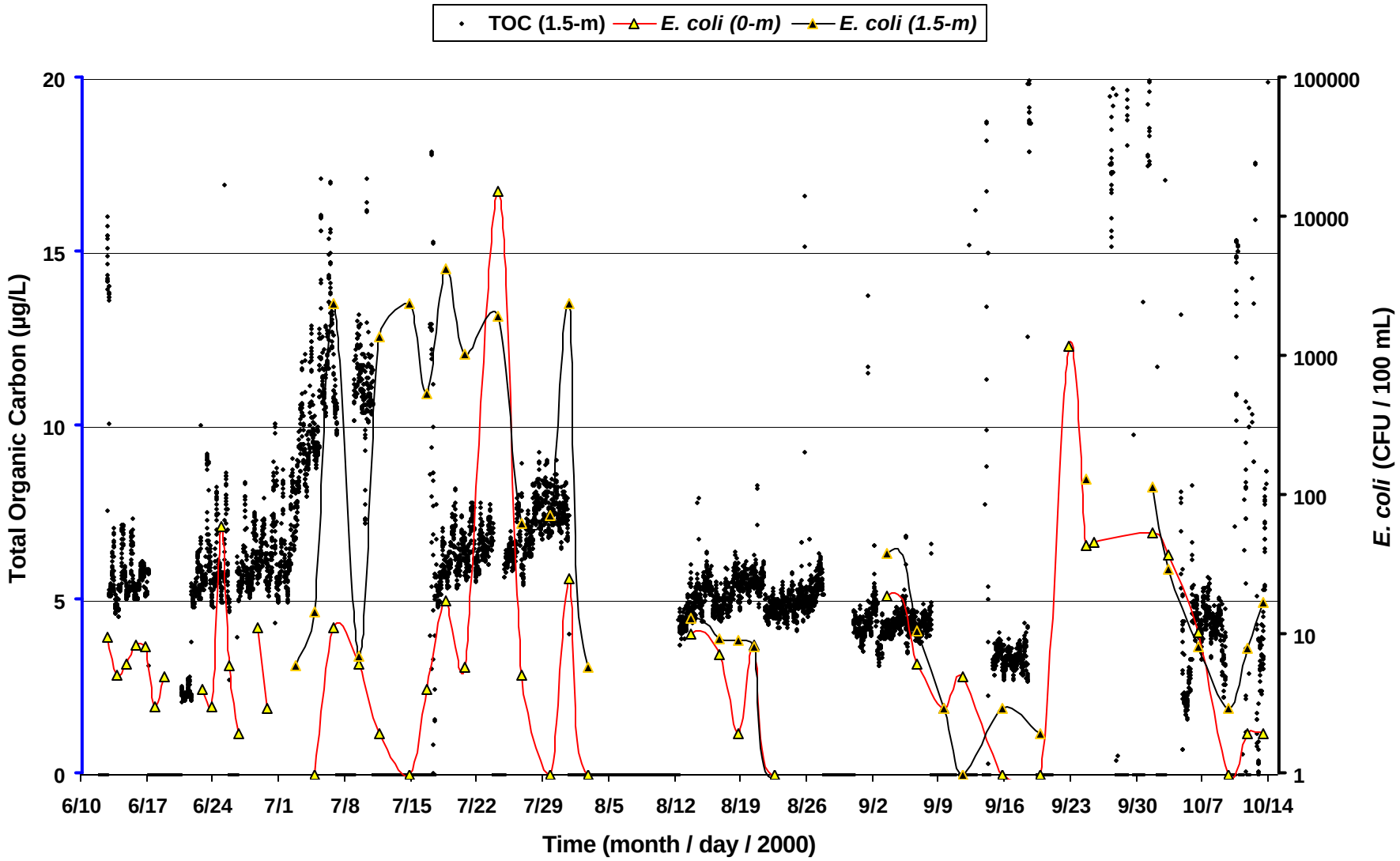


**Figure 19(b). TOC (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

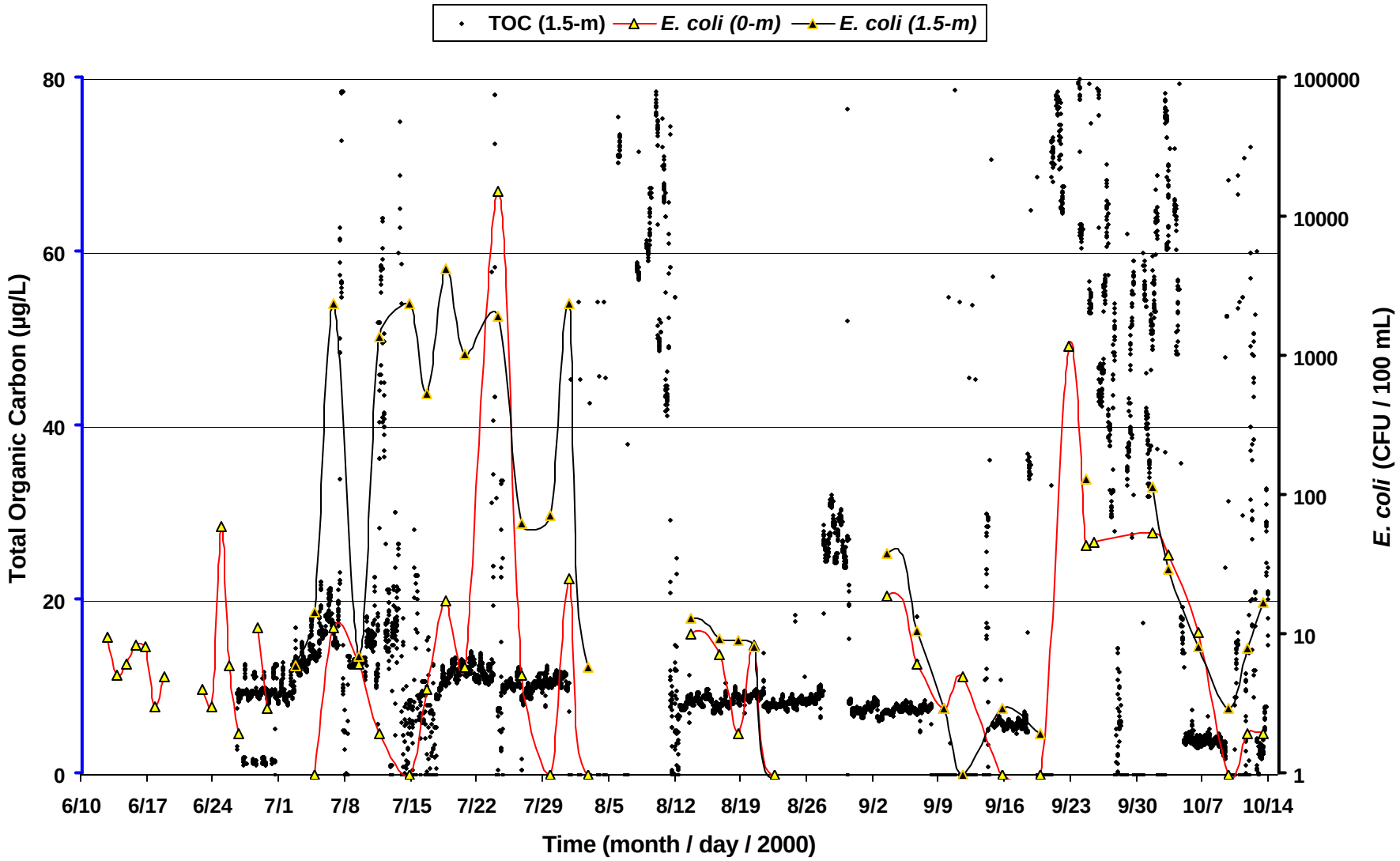


**Figure 20(a). $PO_4$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

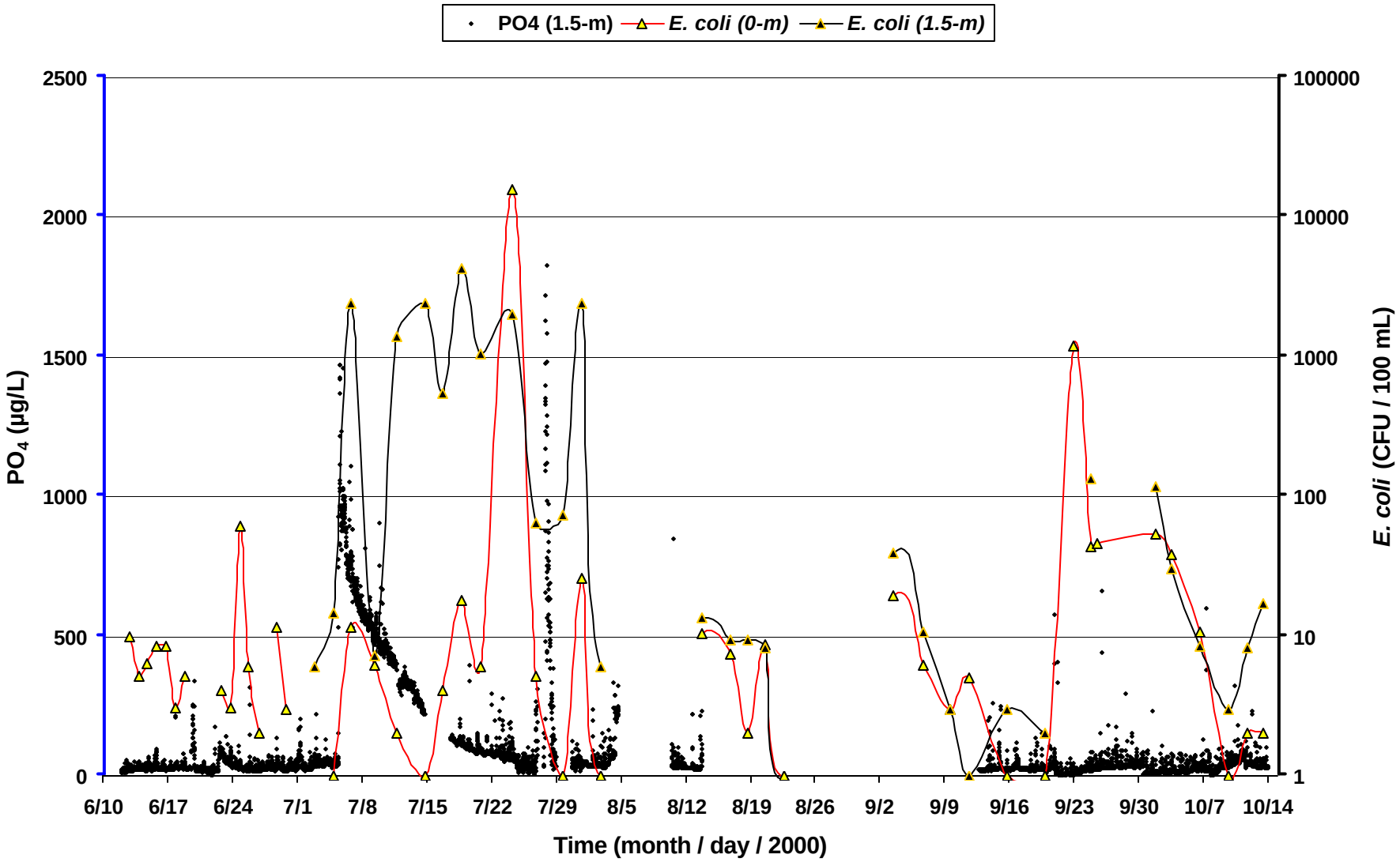


**Figure 20(b). $PO_4$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

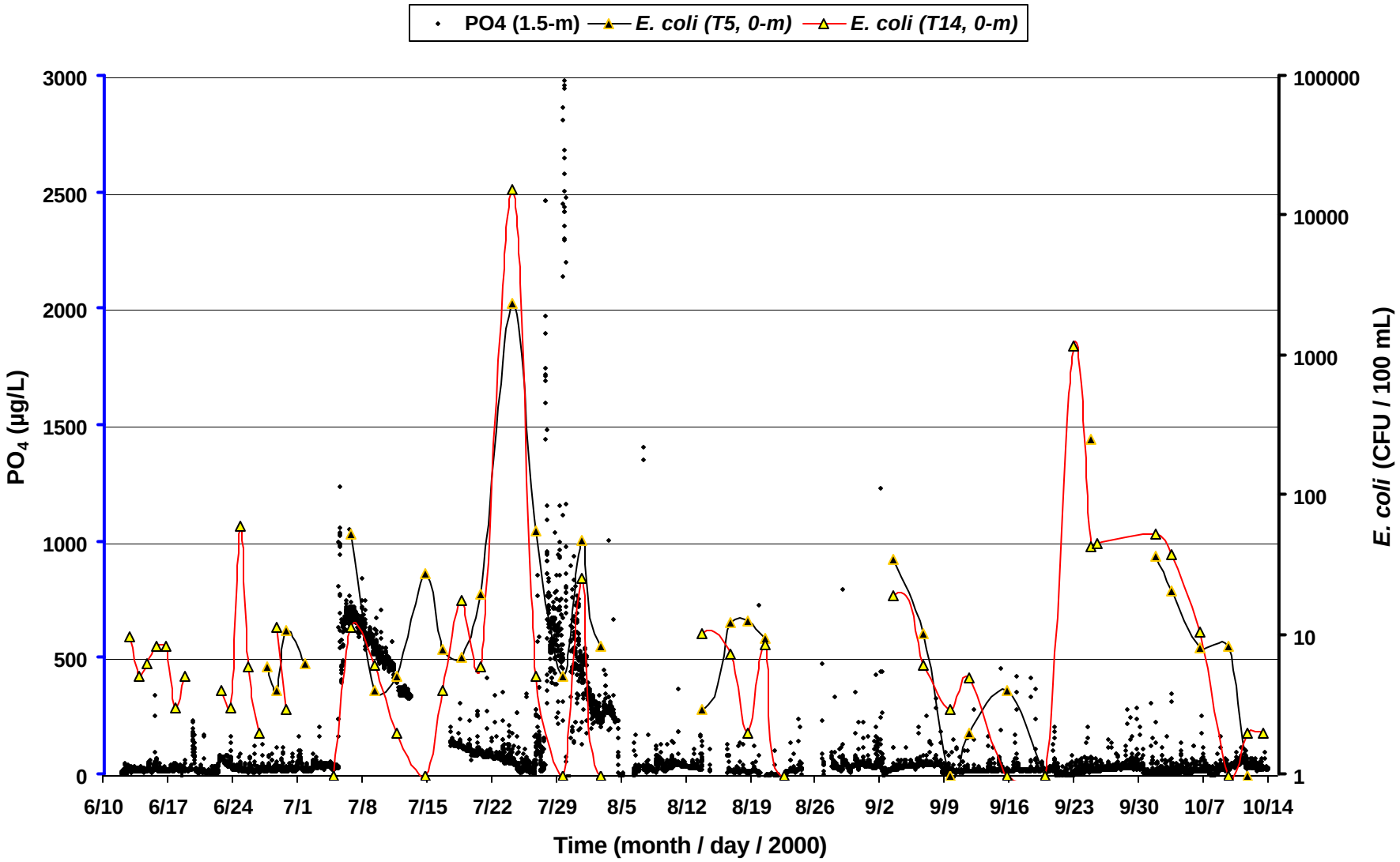


**Figure 21. $NO_2$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

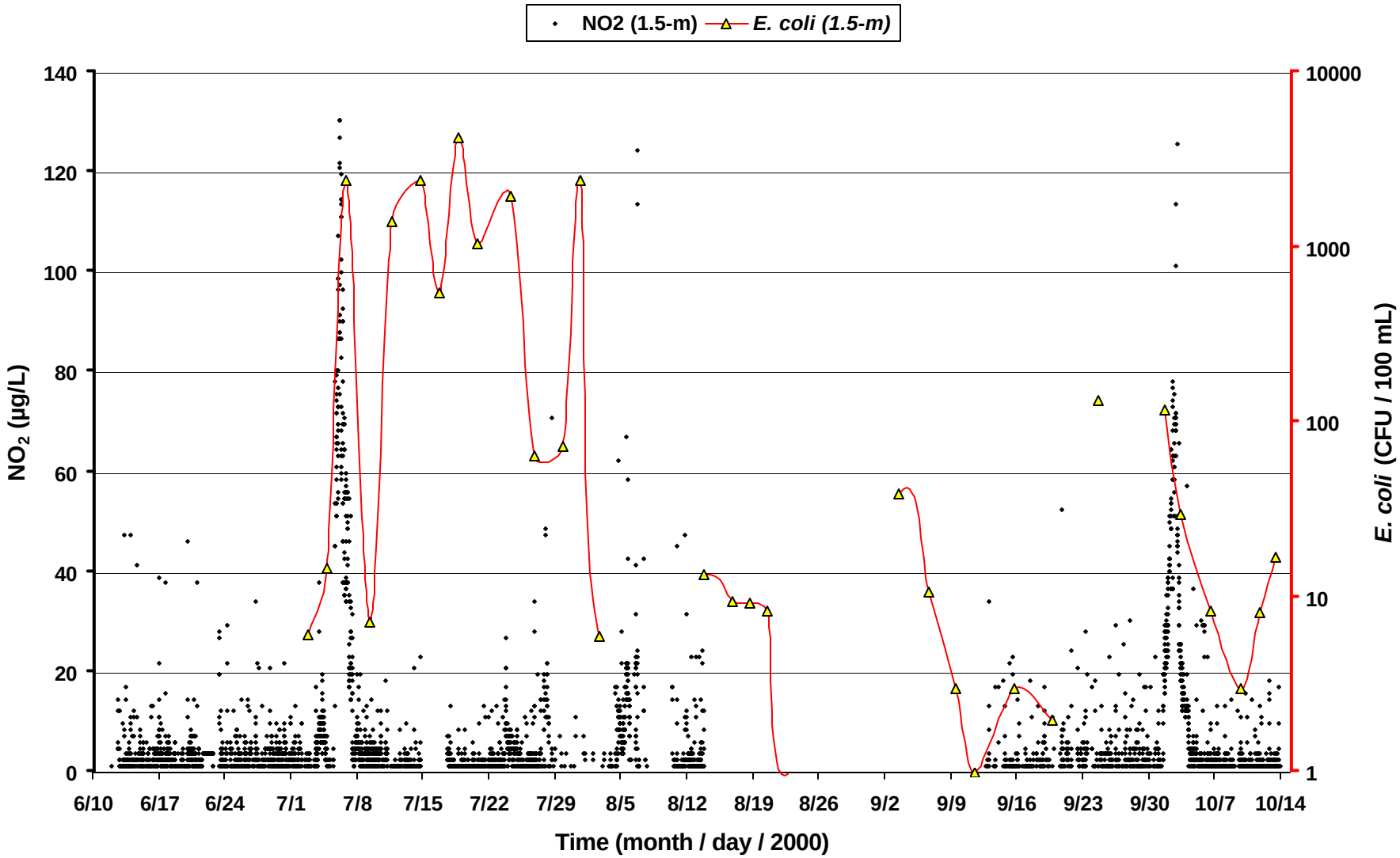


**Figure 22. $NO_3$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

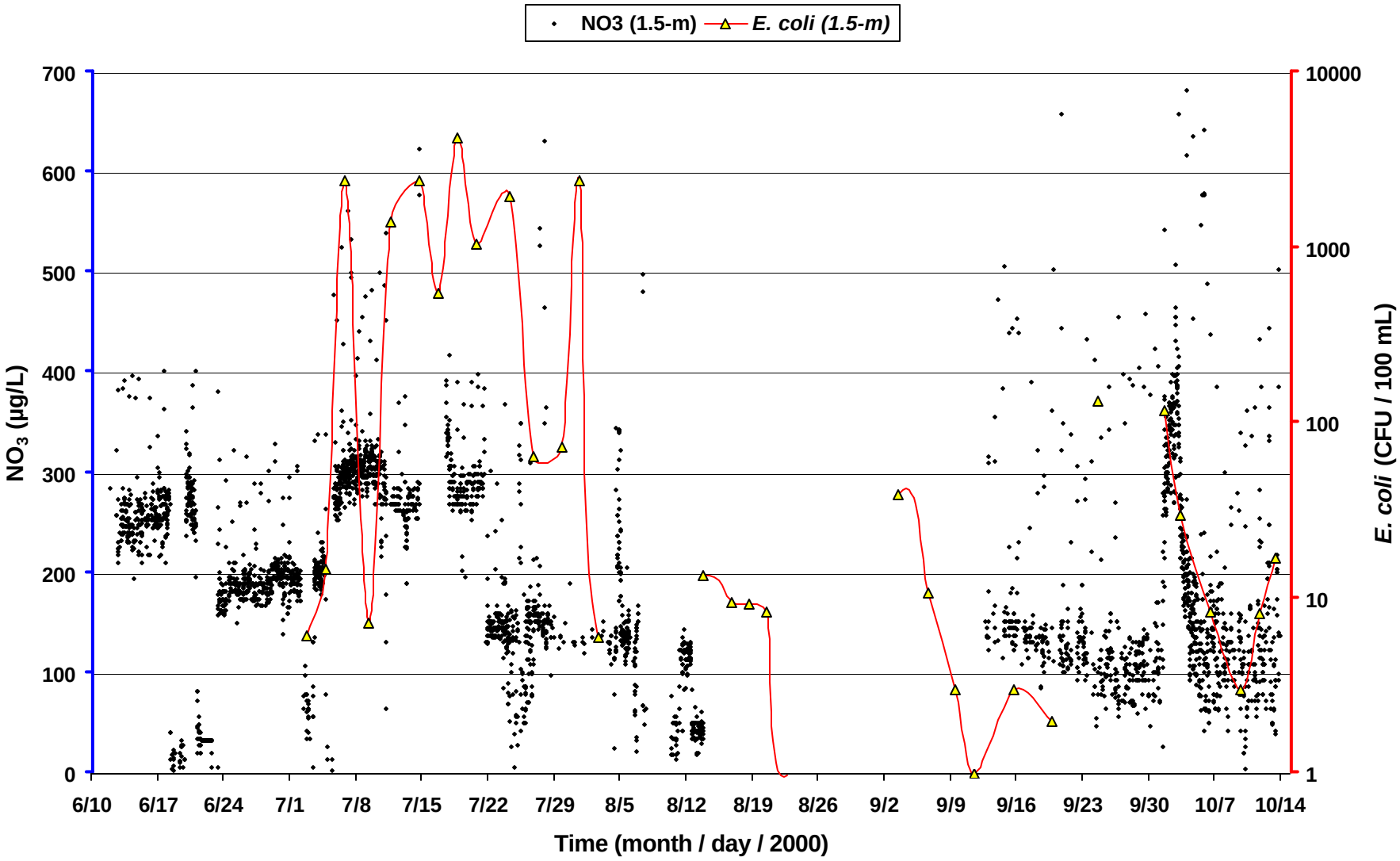


**Figure 23(a). N-$NH_3$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

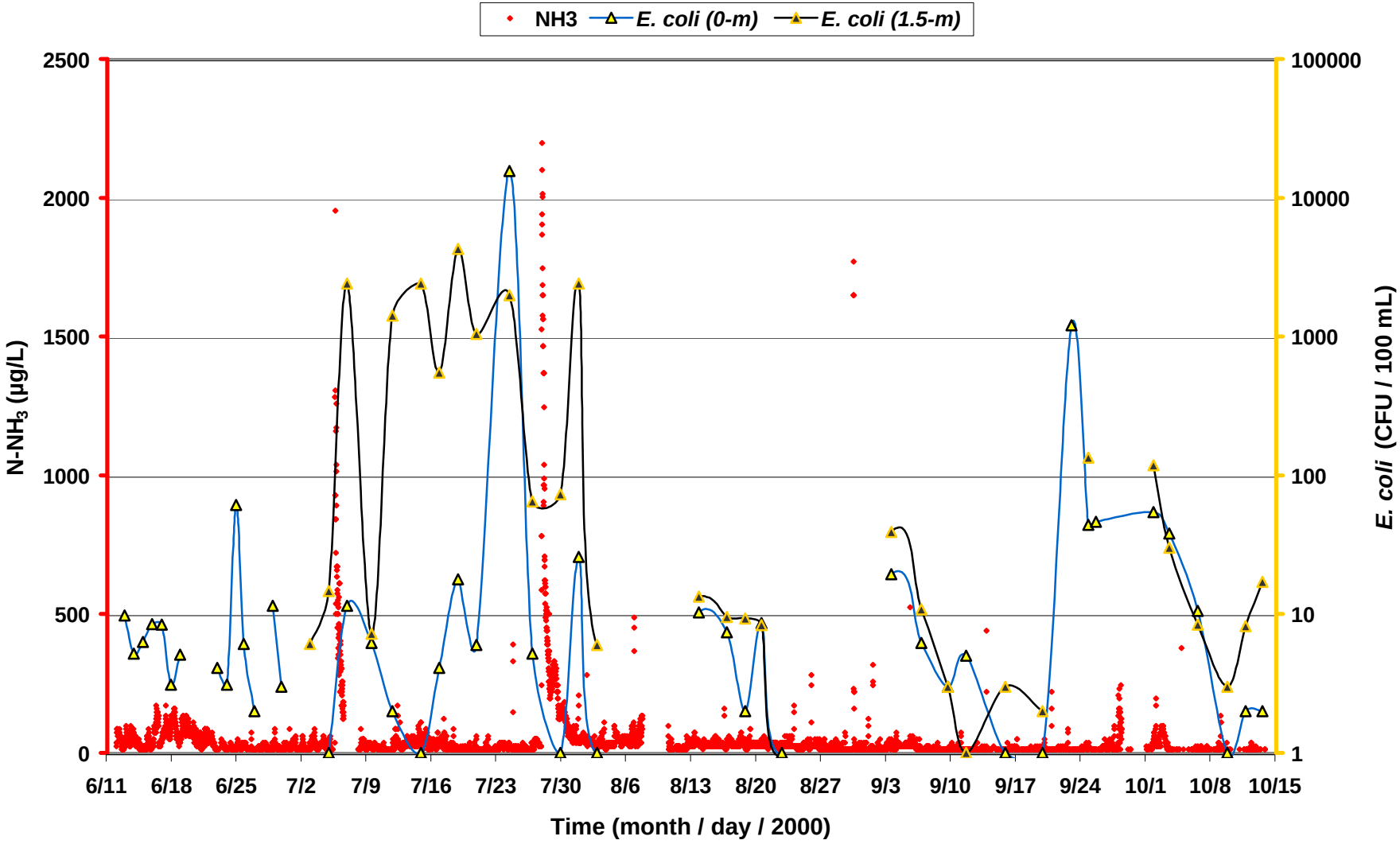


**Figure 23(b). N-$NH_3$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

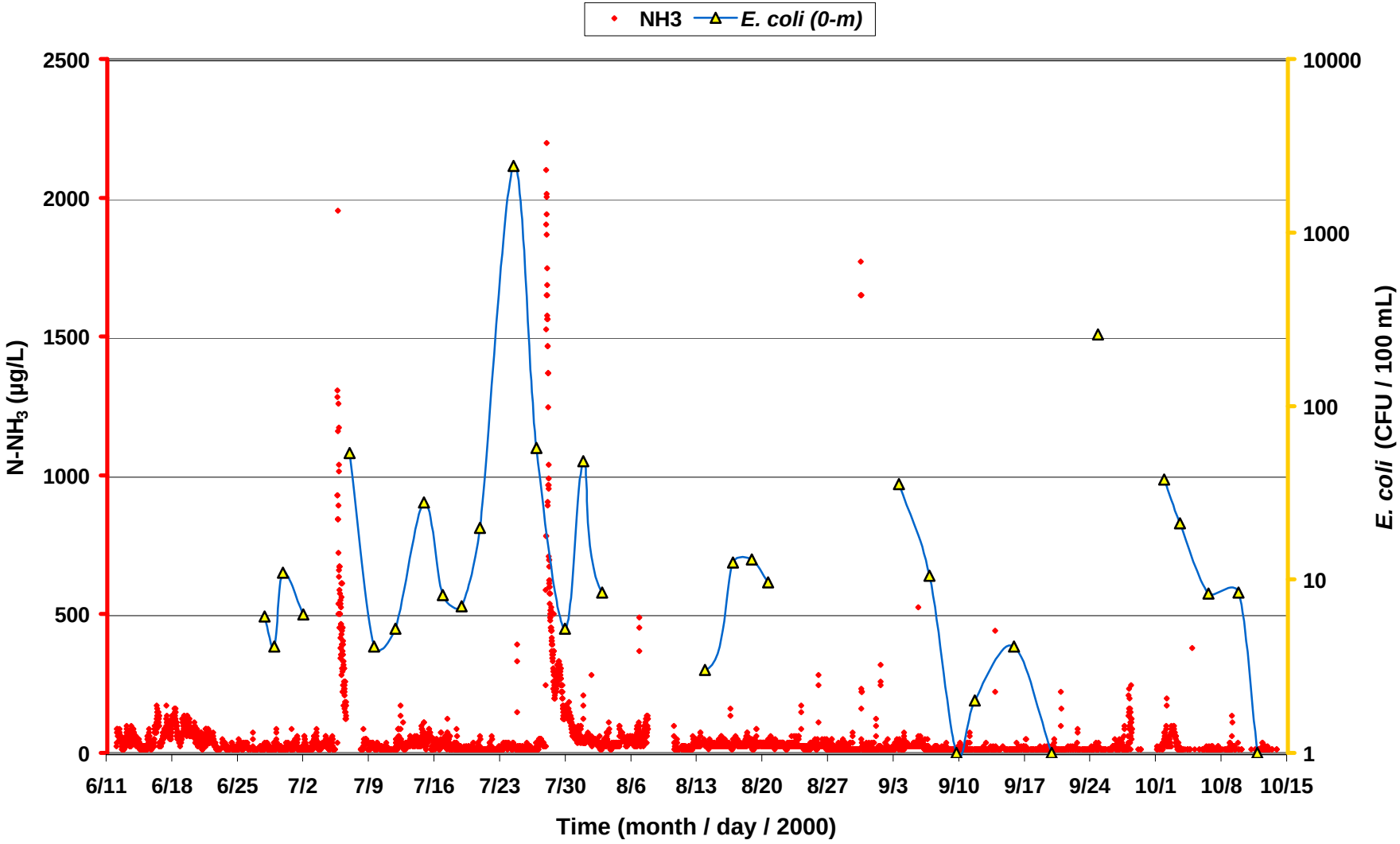


**Figure 24. $N_{OX}$ (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 5 (Platform), Catfish Pond, Whitehall Forest, 6/27/00 - 10/13/00**

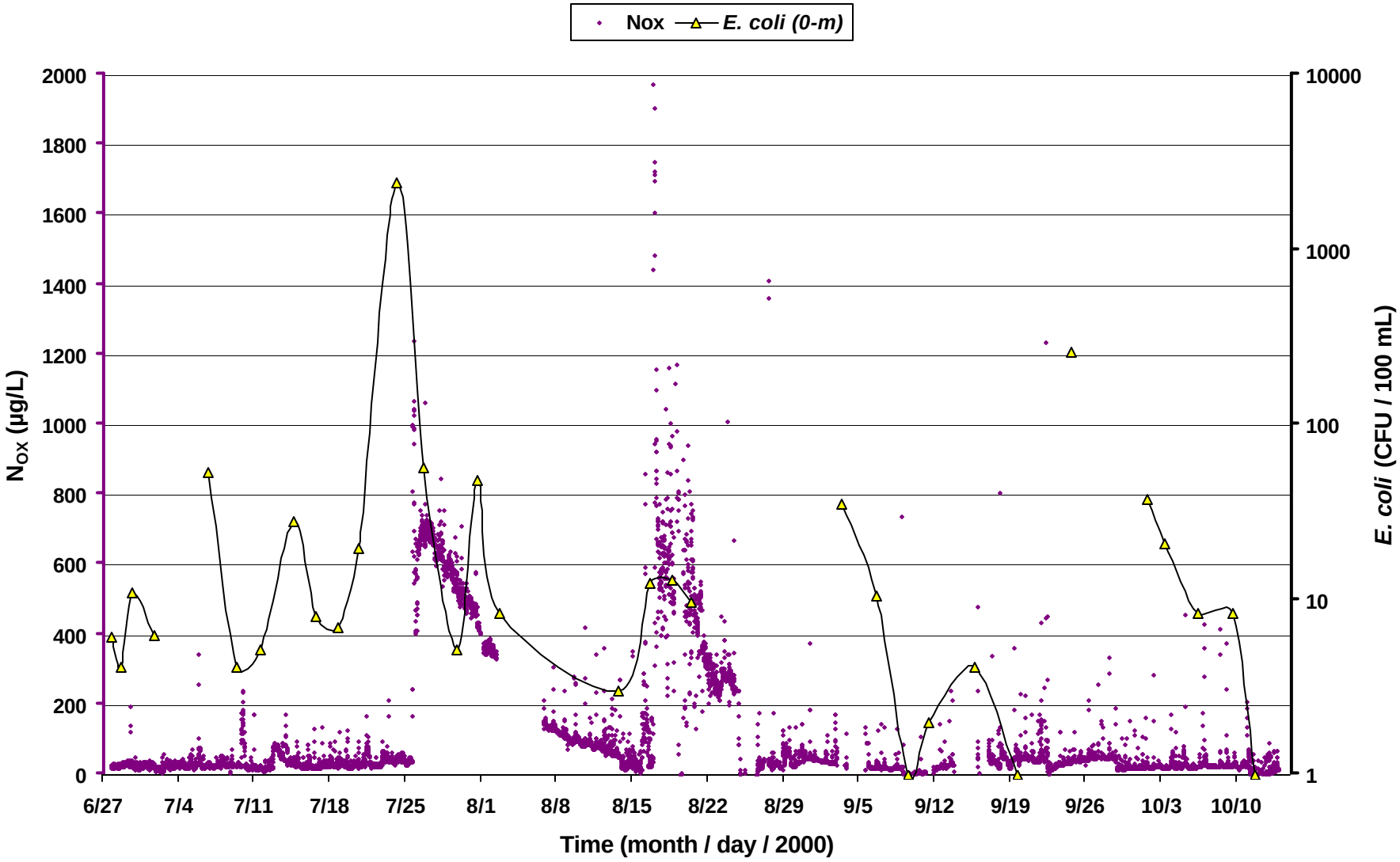


**Figure 25(a). Chlorophyll-*a* (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 14, Catfish Pond, Whitehall Forest, 6/23/00 - 10/13/00**

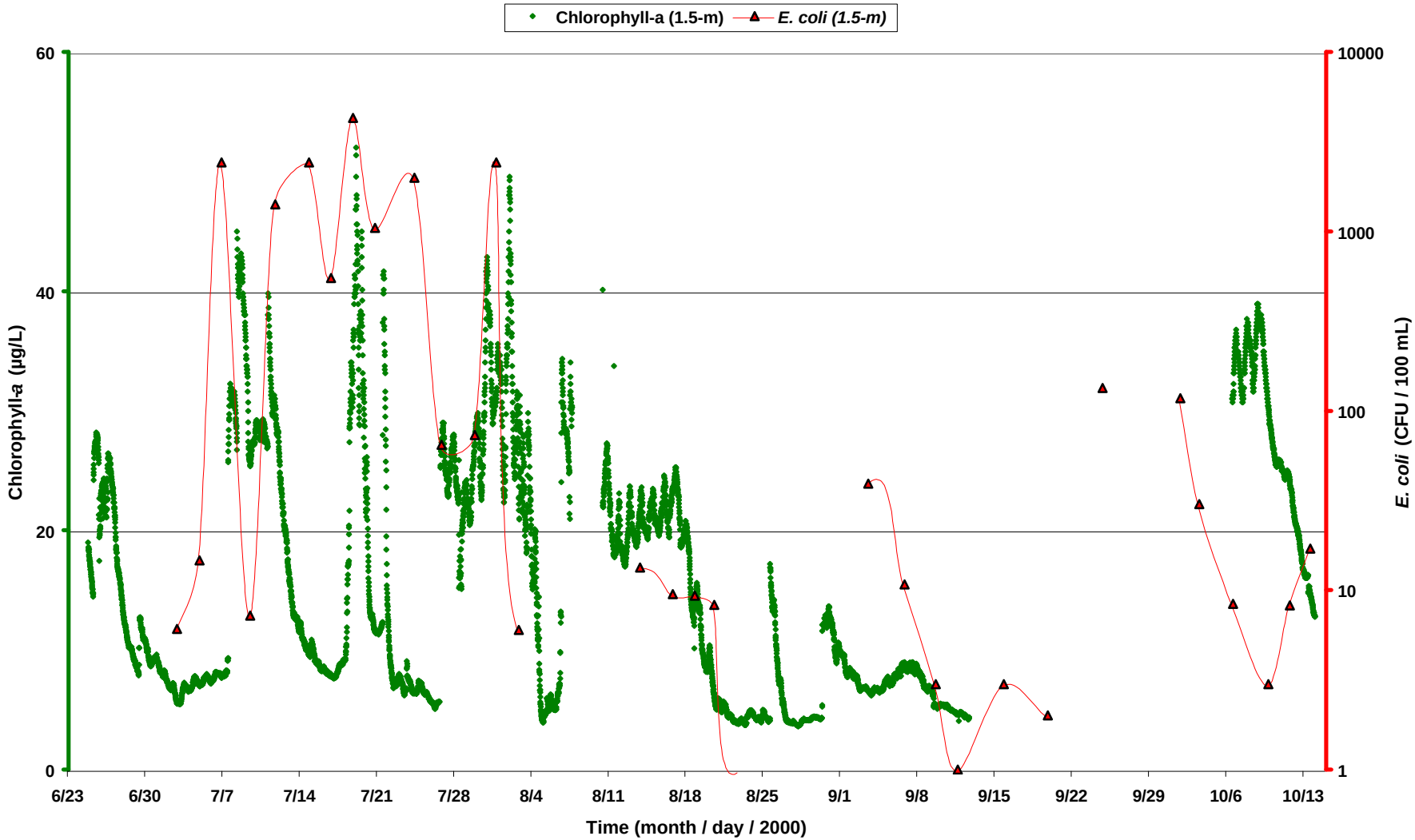


**Figure 25(b). Chlorophyll-*a* (µg/L) and *Escherichia coli* (CFU / 100 mL)**
**Station 5, Catfish Pond, Whitehall Forest, 6/11/00 - 10/13/00**

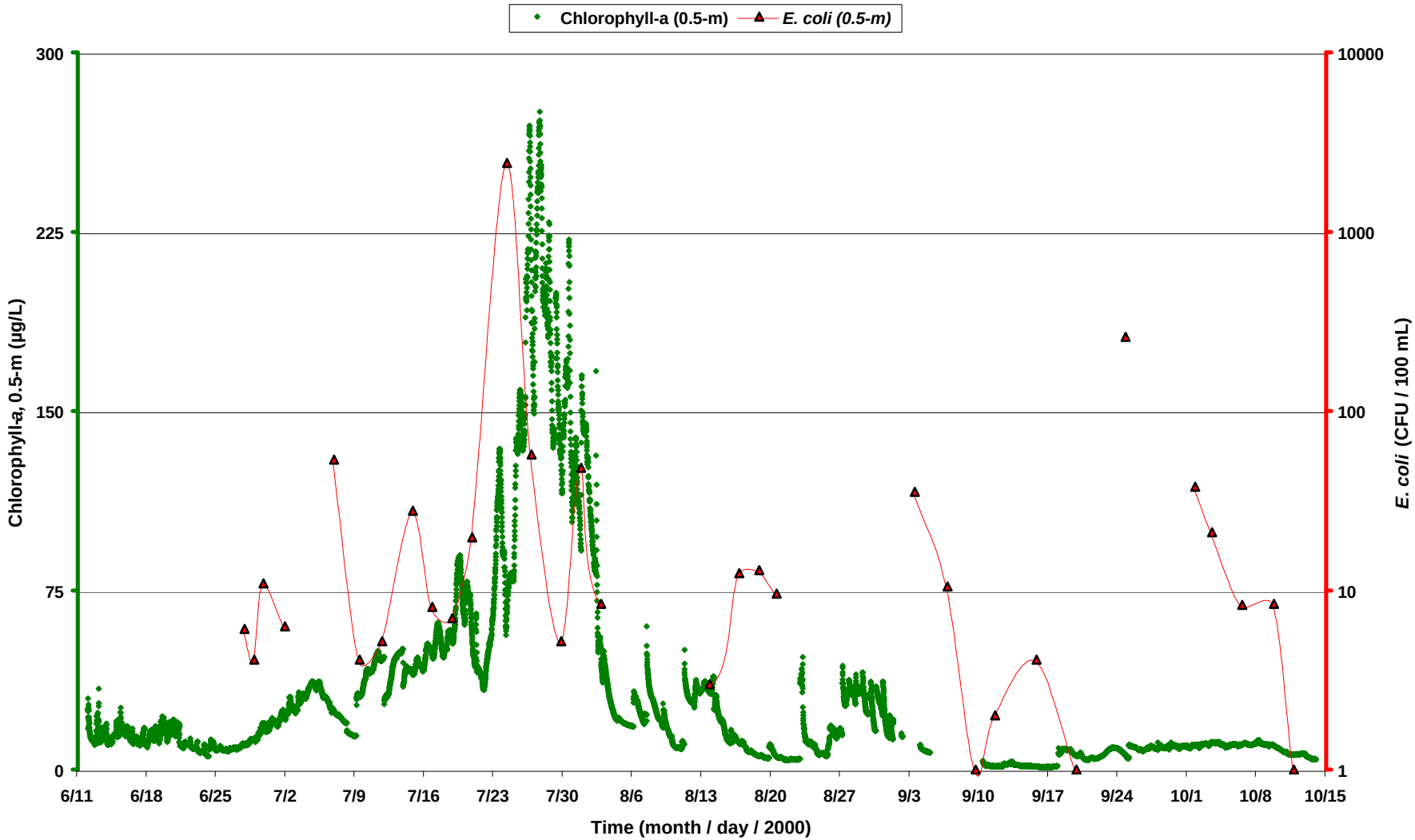
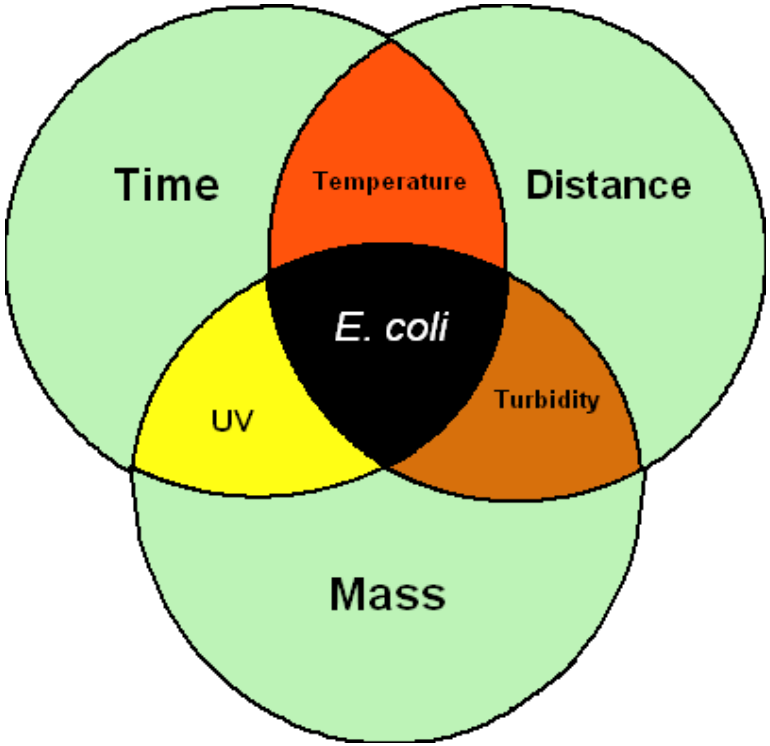


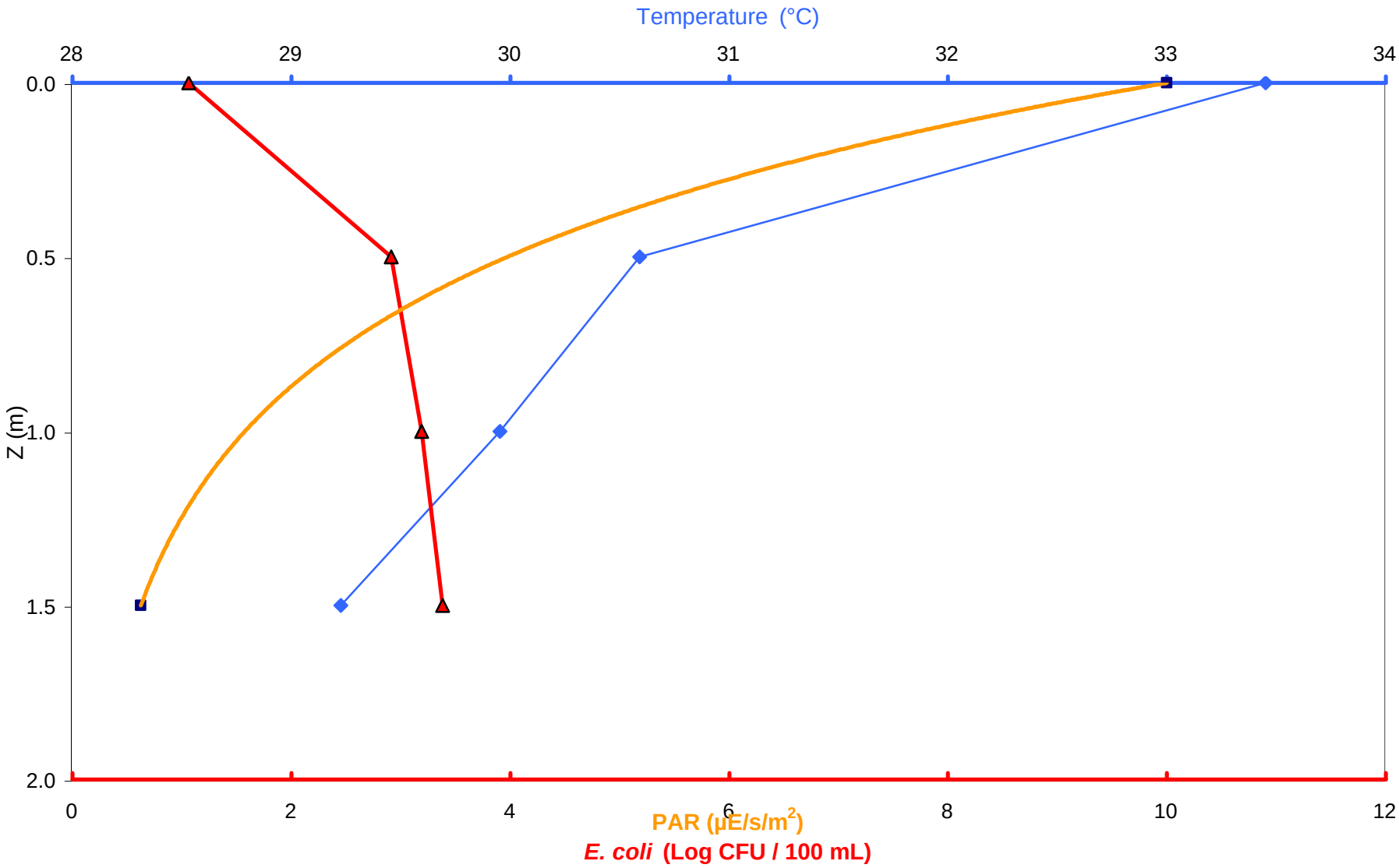
Figure 26. Time, Distance, Mass (TDM) conceptual model: Historical view on *E. coli* transport and fate.




- **Time, distance and mass are physical constants (Kay and McDonald (1980), McDonald and Kay (1981), Gannon et al. (1983).**
- **Temperature (Bissonnette et al. 1975; Gorden and Fliermans 1978), ultraviolet radiation (Grigsby and Calkins 1979; Barcina et al. 1989, 1990) and turbidity (Schillinger and Gannon 1982, 1985) are variable parameters displaying a high degree of annual seasonality.**

Modeled after Kay and McDonald (1980), McDonald and Kay (1981), Gannon et al. (1983) and Schillenger and Gannon (1982, 1985).

**Figure 27. Integrated Depth (Z) Profile: Temperature (°C), PAR (µE/s/m$^2$), and *E. coli* (Log CFU / 100 mL) Catfish Pond, Whitehall Forest, July 2000 (representative)**



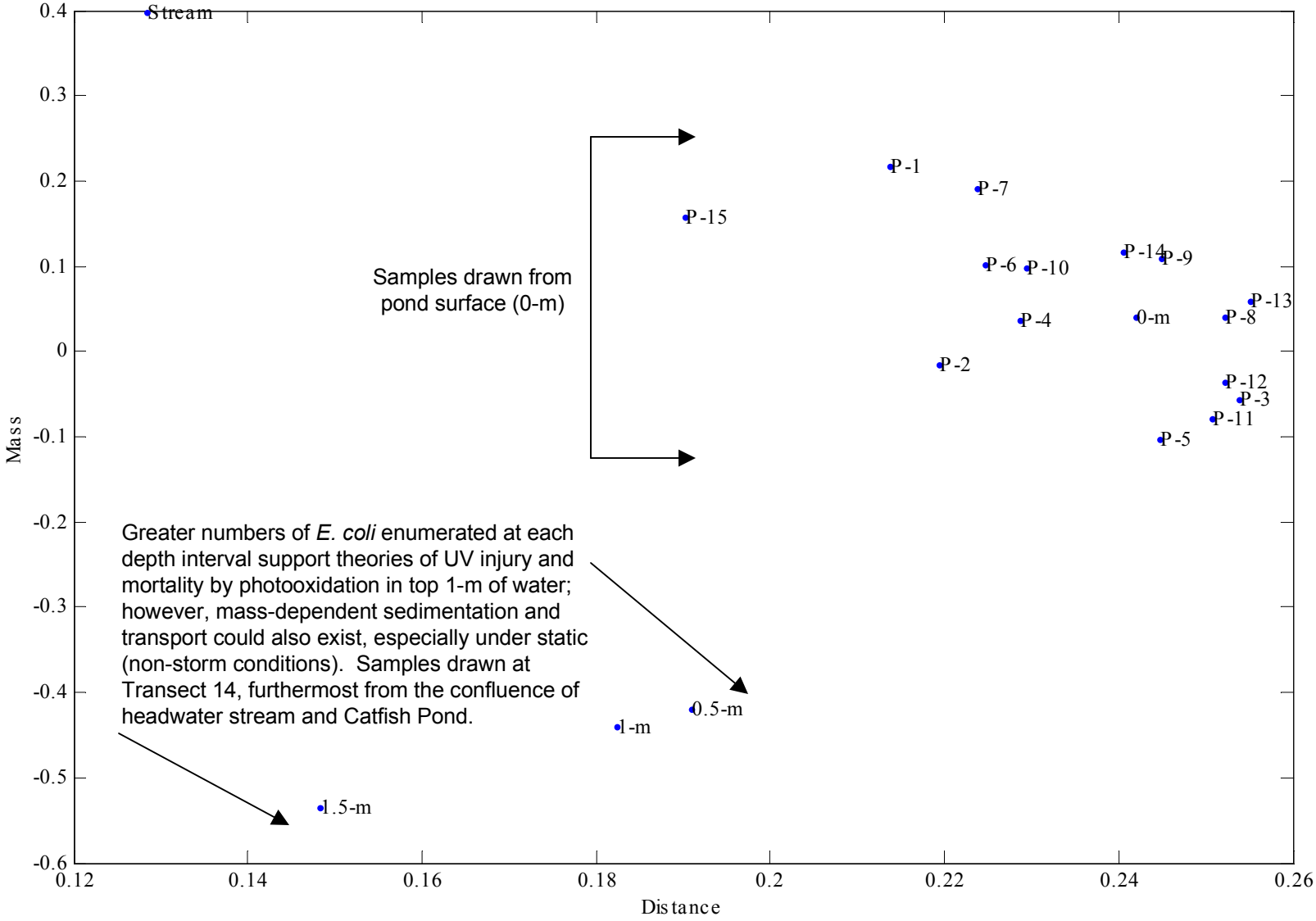



**Figure 28. Principle Component Analysis of *E. coli* censured data.**

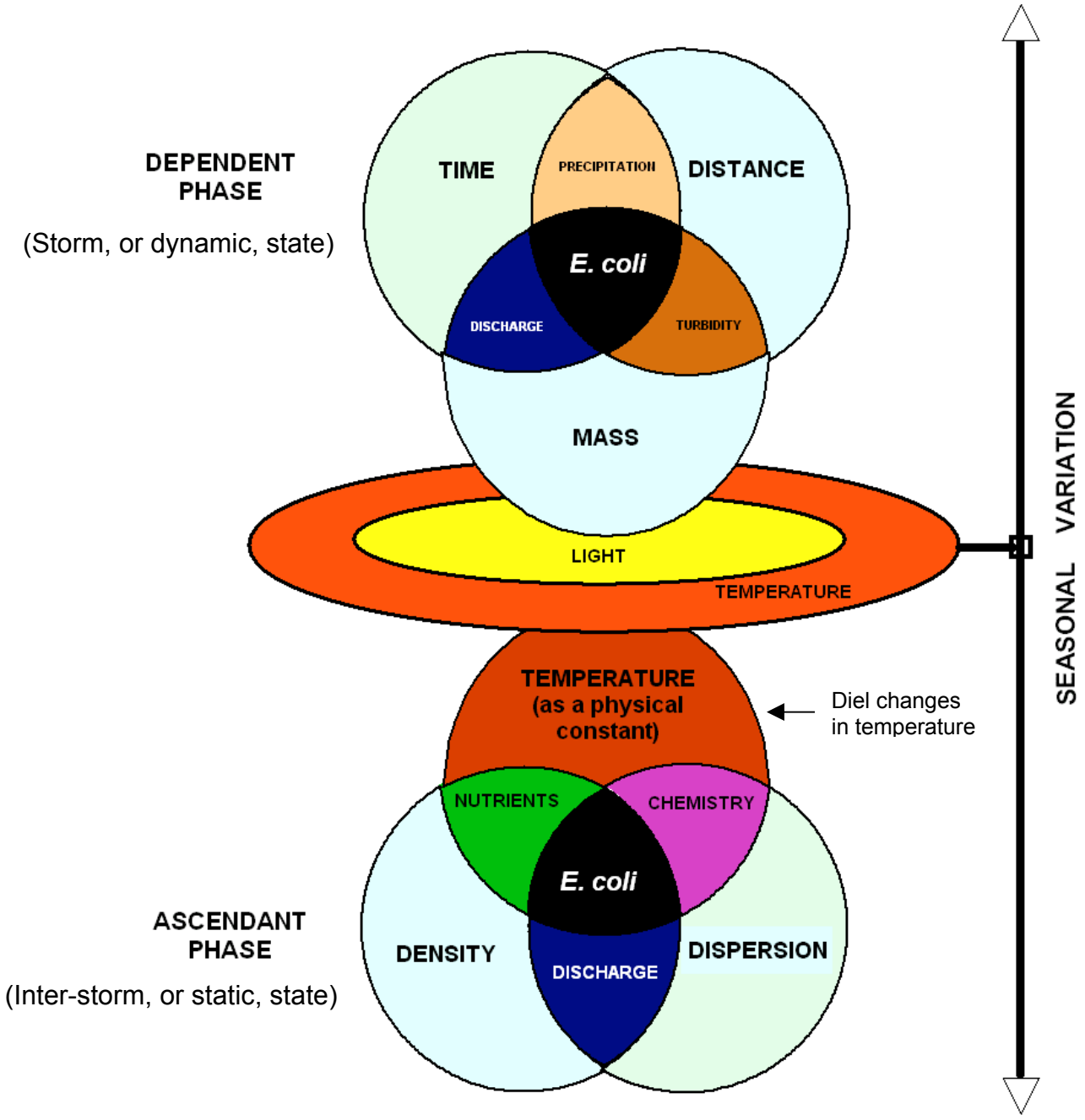



Figure 29. Bi-modal Transport and Fate (BTF) model for *Escherichia coli*

**Figure 30. Temperature (°C) and Headwater Stage (ft) Profile**
**Catfish Pond, Whitehall Forest, 6/23/00 – 8/4/00**