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A WATER QUALITY MONITORING NETWORK DESIGN METHODOLOGY FOR THE SELECTION OF CRITICAL SAMPLING POINTS: PART I

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Abstract. The principal instrument to temporally and spatially manage water resources is a water quality monitoring network. However, to date in most cases, there is a clear absence of a concise strategy or methodology for designing monitoring networks, especially when deciding upon the placement of sampling stations. Since water quality monitoring networks can be quite costly, it is very important to properly design the monitoring network so that maximum information extraction can be accomplished, which in turn is vital when informing decision-makers. This paper presents the development of a methodology for identifying the critical sampling locations within a watershed. Hence, it embodies the spatial component in the design of a water quality monitoring network by designating the critical stream locations that should ideally be sampled. For illustration purposes, the methodology focuses on a single contaminant, namely total phosphorus, and is applicable to small, upland, predominantly agricultural-forested watersheds. It takes a number of hydrologic, topographic, soils, vegetative, and land use factors into account. In addition, it includes an economic as well as logistical component in order to approximate the number of sampling points required for a given budget and to only consider the logistically accessible stream reaches in the analysis, respectively. The methodology utilizes a geographic information system (GIS), hydrologic simulation model, and fuzzy logic.

Keywords: critical source areas, design methodology, monitoring network, phosphorus transport, sampling points, small watershed, water quality

1. Introduction

One of the principal tools to ultimately understand the process dynamics of any watershed is a well-configured water quality monitoring network that evaluates current and emerging water quality problems. Ideally, the design of a water quality monitoring network should adhere to a universally adaptable design methodology, which not only incorporates valid procedures, but also permits flexibility in the design to accommodate for periodic modifications. However, a review of the literature reveals that past approaches to water quality monitoring network design have often been arbitrary, without a logical or coherent design strategy. Furthermore, once a network was established, there had commonly not been a re-assessment of the actual effectiveness and appropriateness of the established monitoring network design (Harmancioglu *et al.*, 1999; Ward, 1996). Information from monitoring networks can be used to improve decisions and direct limited resources toward critical problem areas in the watershed. However, the result of an improperly designed monitoring network is generally the collection of water quality data with little analytical value or decision-making value.

Each land unit area (cell) within a watershed has a pollution potential associated with it, depending on its topographic, soil, land use, climatic, and vegetative attributes (Vieux and Farajalla, 1994). Furthermore, as these attributes can vary significantly over a watershed, the spatial location of a land parcel within a watershed also plays a major part in defining its pollution potential. The theoretical importance and implications of including topography in identifying and controlling the location of potential source areas have been emphasized by a number of researchers (Kirby and Chorley, 1967; O'Loughlin, 1981; Burt and Butcher, 1986). It is well known that the relative degree and magnitude of hydrological processes are sensitive to topographic position within a watershed (Moore *et al.*, 1988a; Vieux and Farajalla, 1994). For example, potentially critical land parcels located in remote areas of the watershed, far away from a stream, may not pose much threat to the water resource. Additionally, if the flow paths of such cells to the stream are intersected by other land uses that are known to retain pollutants, their potential threat is further reduced. Therefore, it is essential to take the spatial dependency and topographic position of every watershed cell with respect to its pollution potential into account when assessing contributing areas. Furthermore, since the movement of a contaminant from any given watershed cell has a predefined surface and subsurface flow path, its stream entry point is mainly dependent on the given topography. Thus, for each stream cell, the surface and subsurface contributing areas can be defined and utilized to assign which cells within the watershed have a direct impact on a particular stream reach. This detailed information is needed in identifying candidate sampling points along a stream.

The objective of this research was to develop with minimal data and by using analytical tools such as a GIS, fuzzy logic, and the simulation model GWLF v. 2.0 (Haith *et al.*, 1992), a practical and scientifically-based design methodology for designating critical water quality monitoring network sampling points within small agricultural-forested watersheds with respect to total phosphorus (TP). In order to develop a basis for future implementations of this methodology for other contaminants, TP was selected as the illustrative contaminant under study since it can be used as a proxy for other conservative variables. The developed design methodology is called the Critical Sampling Points (CSP) methodology.

2. Critical Sampling Points Methodology

The spatial analysis of TP transport in small, mostly agricultural-forested watersheds requires that the pollution potential of the surface and subsurface flow be treated separately, although recognizing that they are intrinsically connected. The pollution potential derived from the surface is in essence based upon topographic as well as land use attributes. On the other hand, the pollution potential from the subsurface is more difficult to evaluate since for most watersheds around the world not enough subsurface detail is available, much less in digital GIS format. For this reason, the CSP methodology builds solely upon the subsurface components offered by the simulation model GWLF, namely groundwater, septic tanks, and point sources. An additional component to estimate stream bank erosion was added to the GWLF code and is also included in the subsurface analysis.

The CSP methodology requires the watershed under study be discretized into square cells. The cell size will depend upon the detail of data as well as computational resources available. Obviously, the finer the resolution of the grid, the potentially more accurate the results.

2.1. Phosphorus sources and transport

Phosphorus, an essential element in the metabolic reactions of animals and plants, naturally occurs in aquatic and terrestrial environments. Since phosphorus is found under normal, natural circumstances at very low concentrations, it acts as a growth-limiting factor in most freshwaters. However, accelerated eutrophication can lead to nuisance algal blooms and fish kills due to diminished reoxygenation of the water body and thus depleted dissolved oxygen levels and increased turbidity (Horne and Goldman, 1994; Harper, 1992; Meybeck *et al.*, 1990).

In the landscape, there are numerous sources of phosphorus, including agricultural runoff, urban runoff, industrial effluents, municipal wastewater treatment plants, septic tank systems, stream bank erosion, decaying plant material, animal wastes, and wildlife, among others. In many cases, agriculture can be the main source of phosphorus (Mattikalli and Richards, 1996). On the other hand, in many forested watersheds, reduced phosphorus inputs can be expected due to the geochemical and biological processes in the upper soil layers that retain phosphorus effectively (Mulholland, 1992). In the last 30 years, more attention has been directed toward the role of nonpoint sources of phosphorus pollution. Nonetheless, it is universally recognized that by proper management practices, the transport of phosphorus loads from the various source areas to streams and lakes can effectively be controlled (Bottcher *et al.*, 1995).

In terms of phosphorus transport from the surrounding landscape to surface water bodies, the two principal mechanisms are erosion and runoff. The two principal transport forms of phosphorus are particulate and dissolved phosphorus, which make up what is known as total phosphorus (TP). Although the entire TP mass is not immediately bioavailable, using TP measurements to predict trophic response of water bodies has been shown to be valid. To a lesser degree, phosphorus can be exported via subsurface runoff. The movement and transport of phosphorus through the soil profile generally takes place by leaching and preferential flow via macropores (Sims *et al.*, 1998). Nonetheless, when establishing a phosphorus budget for a watershed where erosion processes play a dominant role in the movement of phosphorus through the landscape, it is of prime importance to consider the phosphorus attached to the sediment (Kronvang, 1992). Eroding soil and plant material along with stream bank and channel bed erosion are the major phosphorus sources reaching the stream in this case. Certain land uses with permanent vegetative cover, such as grassland or forest, experience less surface erosion. However, such land uses may still be affected by stream bank erosion. Research has demonstrated that the particulate phosphorus fraction increases as erosion increases, reflecting the importance of sediment particles transported by surface runoff (Randall *et al.*, 1998).

2.2. Surface Loading Considerations

2.2.1. *Derivatives of the Elevation Surface*

Several geomorphological studies have shown that every land surface exhibits definite patterns and structures that lend themselves to further detailed analysis (Evans and Cox, 1999). There are numerous topographic variables that have a pronounced effect on the delivery of TP via surface runoff to a stream. A mathematical model of the terrain surface, as represented by a digital elevation model (DEM), can be used to derive a number of important TP-load delivery determinants that embody the geometric properties of the surface.

Slope. Slope is defined as the rate of change in elevation and affects the overall rate of movement of substances downslope (Guth, 1995). It represents the first derivative of elevation with respect to distance in any direction. The slope is of great importance with respect to the potential for land resource degradation (Moore *et al.*, 1988b). By controlling the rate of energy expenditure available to propel the surface flow, the slope has an effect on the flow rates of sediment and water. In general, steeper slopes increase the potential for erosion and surface runoff.

Profile Curvature. The profile curvature for a point on a topographic surface is the second derivative of elevation with respect to distance along the line of maximum slope. It shows the curvature perpendicular to the slope direction and pictorially describes the shape of the slope in a downward direction. This topographic attribute, therefore, has a strong influence on surface runoff, soil erosion, and deposition processes (Evans and Cox, 1999). Profile curvature is related to the acceleration and deceleration of surface water flow, and consequently, is a decisive factor in the determination of the pathway of water and depositional materials.

Plan Curvature. The plan curvature is defined as the second derivative of elevation with respect to distance measured perpendicular to the line of maximum slope, and describes the shape of relief in this direction. It is the curvature along the contour and describes how the aspect changes. Furthermore, it is a measure of topographic divergence and convergence and, therefore, has a great influence on the concentration of water across a terrain surface (Thorne *et al.*, 1987).

Parallel to profile curvature, plan curvature has not received much attention in soil erosion and hydrologic models. Many past theoretical and field investigations have excluded this factor for convenience reasons and usually restricted their research to slopes with essentially zero curvature. However, several investigators, such as Jahn (1964), have demonstrated qualitatively that soil erosion rates are impacted by the type of plan curvature present.

Aspect and Solar Radiation. The aspect of a terrain indicates the direction of slope and represents the downslope direction of the maximum rate of elevation change from a point to its immediate surrounding points (ESRI, 1999). Moreover, aspect is used as an indication of flow direction and, therefore, is indirectly used in the derivation of many watershed attributes that require knowledge of the flow path.

The aspect of a land surface plays an important role in the amount of solar radiation received at each point across the terrain, especially in hilly and mountainous areas. For example, in the northern hemisphere, grape growers know that north-facing slopes receive considerably less solar radiation than south-facing slopes (Keightley *et al.*, 2001). Potential solar radiation may be defined as the theoretical value representing the shortwave radiation received at a sloping location if the atmosphere were absent (Swift, 1976). Although there are several important components of radiant energy, shortwave radiation is usually the single most important parameter affecting differences in local areas. Equation (1) gives the daily potential solar radiation received at an inclined location without considering atmospheric effects (Lee, 1978):

$$S_p = \frac{60 S_0}{r^2} \frac{24}{\pi} (\cos\phi \cos\delta)(\sin\eta - \eta\cos\eta) \tag{1}$$

where S_p is the daily potential solar radiation (cal/cm^2/day), S_0 is the solar constant (cal/cm^2/min), r is the ratio of the earth-sun distance to its mean, δ is the solar declination (degrees), ϕ is the terrestrial latitude (degrees), and η is the hour angle of sunrise or sunset (hr-degree).

For a given day, the variation of potential solar radiation over a given watershed is thus highly dependent on topography and is a function of only aspect and slope, if it is assumed that the watershed is small enough (less than 100 km^2) so that all points within the watershed can be assumed to have the same latitude. Differential exposure of slopes to solar radiation alone can produce local climatic extremes

(Frank and Lee, 1966). The daily potential solar radiation is also dependent on the time of year.

The solar radiation received by a watershed is quite important to a watershed's water balance since it influences the evaporation and transpiration processes occurring in the watershed. It has a profound effect on the hydrologic cycle, photosynthetic processes, as well as other natural phenomena. It represents the energy source that heats the plant, soil, and air mass, and, therefore, controls not only the biological activity and growth, but also acts as a driving force for many hydrological processes (Moore *et al.*, 1991). Also, incident solar radiation plays an important role in soil formation because by increasing the soil temperature, the soil microclimate is changed, including physical, chemical and biotic soil characteristics. Furthermore, solar radiation influences snowmelt processes which have been found to be sensitive to aspect and slope (Moore *et al.*, 1988a). Therefore, indirectly with respect to solar radiation, aspect needs to be included as a prime variable into any methodology of watershed processes.

Topographically Derived Indices. Various parameters have been mathematically derived from topographic attributes since landscape processes are normally dependent on and sensitive to landscape configuration. These indices are easy to compute and often act as a reasonable substitute for the direct, and often difficult or impractical, measurement or estimation of the spatial variability of soil properties (Moore *et al.*, 1993).

(i) Topographic Wetness Index. Probably the most frequently derived topographic index is the topographic wetness index, which is a function of slope and flow intensity. It is based on the variable source area theory of streamflow generation. In other words, it can be related to the size and spatial distribution of saturation zones for surface runoff generation. Since this index presents a relative measure of soil saturation for each sediment source, it signals the predisposition of each grid cell to be subjected to surface runoff (Moore *et al.*, 1988a). It can be defined as (Burrough and McDonald, 1998):

$$TWI = \ln\left(\frac{A_S}{\tan\beta}\right) \tag{2}$$

where *TWI* is the topographic wetness index (dimensionless), A_S is the contributing catchment area (m^2), and β is the slope (degrees).

(ii) Stream Power Index. The stream power index is calculated from the slope and flow intensity through each land cell, as seen by the following equation (Burrough and McDonald, 1998):

$$\omega = A_S * \tan\beta \tag{3}$$

where ω is the stream power index (unit less) and the other parameters are defined in Equation (2). Essentially, this index is a measure of the erosive power of overland flow and is directly proportional to the stream power (Burrough and McDonald, 1998).

(iii) Sediment Transport Index. Another index which can be derived from topographic attributes is the sediment transport index. It reflects especially the effects of topography on soil loss (Burrough and McDonald, 1998). Since it portrays the processes of erosion and sediment deposition, this index is quite reflective of the usual transport mechanism of TP over the land surface. It can be written as (Burrough and McDonald, 1998):

$$\tau = \left[\frac{A_S}{22.13}\right]^{0.6} * \left[\frac{\sin\beta}{0.0896}\right]^{1.3} \tag{4}$$

where τ is the sediment transport index (dimensionless) and the other parameters are defined in Equation (2).

2.2.2. *Other Relevant Variables*

Land Use and Buffering Potential. Watershed land uses play a crucial part in the final spatial distribution of a contaminant load delivered to a stream. In a rural watershed, the potential impact originating from each source area will be diminished according to not only its spatial location within the watershed, but also due to its relative position with regard to potentially P-retaining land uses that lie along the contaminant's flow path to the stream entry point. In other words, there will be a definite difference between an agricultural land use which lies directly next to a stream and one that is located further away and intersected, or "buffered", by other less potentially P-threatening land uses, such as uncultivated grassland. Generally, the buffering concept has not been incorporated into stand-alone hydrologic simulation models.

One of the major effects of the presence of vegetation remains the attenuation of sediment-bounded contaminants from nonpoint pollution sources. This is a particularly important detail when considering phosphorus, as phosphorus most often reaches streams adsorbed to soil and organic materials transported by surface runoff after rainfall events (Pionke *et al.*, 1995). Surface vegetation can filter out soil particles as well as drastically reduce the momentum and impact of overland flow. The type of existing land use generally indicates the kind of vegetation that is present, and, therefore, reveals if any buffering action can be expected. Various studies have qualitatively shown that both forest and grasslands can act as buffers by reducing the levels of sediments and nutrients from surface runoff (Bottcher *et al.*, 1995; Cooper *et al.*, 1987).

Flow Path Length. A longer flow path will provide more opportunity for retention and deposition of particulates, and evaporation as well as plant and soil uptake for surface water (Fraser *et al.*, 1996). Upland sources deliver less sediment, and thus contaminants, than do source areas adjacent to streams. Therefore, the source areas closer to the stream, due to land use characteristics as well as proximity, are often responsible for contributing most of the nonpoint source pollution in a watershed, even though perhaps area-wise only constituting a small percentage of the total area. Accurately tracing the flow from a point in the watershed to its stream entry point along its flow path is a very important aspect of hydrologic and erosion modeling that is often not incorporated in most models due to their lack of rigorous spatial representation.

Soil Permeability. In many parts of the world, there is a general lack of detailed soils information. For many areas, especially less inhabited ones, there will be slightly more extensive soils data available only if, for instance, a specific project has been undertaken. Typically, only topographic maps and general land cover information are available. To develop a methodology that is meaningful, the properties of the soil need to be incorporated as an input variable since they determine the movement of contaminants. However, it should be noted that in the case of phosphorus, usually the export via surface water is more important than through the subsurface as groundwater or interflow (Smith *et al.*, 2000). Also, to date there is not a single, universally accepted soil characteristic that can be used in the prediction of contaminant transport in a natural setting (Barnes, 1997). Nevertheless, the CSP methodology includes the soil permeability to represent the subsurface movement of a contaminant. Although this variable may not be available in every case, other often available secondary variables can be used to estimate soil permeability.

2.2.3. *Fuzzy Classification Task*

Fuzzy logic provides an improvement and extension to conventional logic and has great potential in natural phenomena modeling, where class overlap is frequent. Fuzzy logic can cope with problems of uncertainty and may actually provide more precise information than conventional Boolean logic, which divides data into discrete classes, and hence is prone to information loss (Burrough *et al.*, 1992). Although fuzziness implies vagueness, it actually refers to the fact that most real-world sets do not have sharp transitions between classes. Moreover, few thresholds in nature are solely abrupt. Because both abrupt and gradual transitions in space can be represented, fuzzy set theory has not only be beneficial in data structuring, but also in the incorporation into geographic information systems (Burrough, 1989; De Gruijter *et al.*, 1997). Davidson *et al.* (1994) demonstrated in a comparison between the capabilities of fuzzy logic and conventional Boolean techniques that the fuzzy logic techniques had definite advantages in terrain evaluation studies.

To meet the goal of developing a practical, universal methodology for designing water quality monitoring networks, the CSP methodology incorporates eleven input variables (slope, profile curvature, plan curvature, potential solar radiation, topographic wetness index, sediment transport index, stream power index, flow path length, buffering potential, permeability, and land use) that can be considered to justifiably indicate the potential pollution originating from the land surface. With the exception of the variable "land use," which inherently is a discrete variable, all variables are continuous, or at least their output ranges can be continuously represented. In other words, a land use according to the CSP methodology, as represented by a grid cell, is either considered to be in one land use category or the other, but not part of two or more.

In order to develop realistic fuzzy classifications of the fuzzy input variables, the literature was reviewed to unearth, wherever possible, reasonable discrete classifications of the variable in question. The next step was then to use these retrieved discrete classifications in order to build the fuzzy classifications, in which each discrete class was translated (fuzzified) to give a smooth, and thus more realistic, fuzzy transition between classes. Table I provides the literature that was used to derive

TABLE I
Literature sources used in the fuzzy system development

Variable	Source for fuzzy system development	Low pollution potential	High pollution potential
Slope (degrees)	International Geographical Union's Commission on Geomorphological Survey and Mapping (IGU-CGSM) (Clark and Small, 1982)	Low	High
Profile Curvature (1/100 m)	ESRI (1999)	High Negative Value (concave)	High Positive Value (convex)
Plan Curvature (1/100 m)	ESRI (1999)	High Positive Value (convex)	High Negative Value (concave)
Potential Solar Radiation (normalized)	No literature source found (Equal interval classes assumed)	Low or High	High or Low
Topographic Wetness Index (normalized)	No literature source found (Equal interval classes assumed)	Low	High
Sediment Transport Index (normalized)	No literature source found (Equal interval classes assumed)	Low	High
Stream Power Index (normalized)	No literature source found (Equal interval classes assumed)	Low	High
Buffering Potential (normalized)	No literature source found (Equal interval classes assumed)	High (many buffering cells)	Low (few buffering cells)
Flow Path Length (m)	No literature source found; estimated	Long	Short
Permeability (cm/hr)	FAO (1985) classification system	High	Low

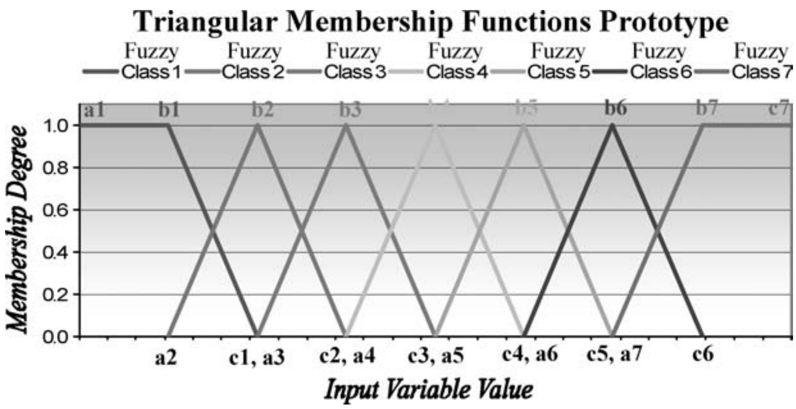

Figure 1. Triangular membership functions prototype.

the fuzzy representations of each input variable. However, before constructing the membership functions, it is important to decide which values of the input variables are likely to cause a higher potential of pollution from the land surface. Detailed descriptions of what constituted a low and high pollution potential for each fuzzy input variable are given in Table I.

Each grid cell in the watershed will have values for each input variable. To provide a more realistic and smooth transition, seven input and output ranges were chosen to represent the fuzzy system and were solved by the Combs Method (Andrews, 1997). Triangular membership functions were chosen for their simplicity and unambiguousness in classifying the fuzzy input variables. In addition, the final output from the fuzzy logic system can be structured to give output values between 0.0 and 1.0, and therefore, permit a relative comparison between all grid cells in the watershed. The output ranges of the fuzzy system were chosen as singletons. Figure 1 gives the prototype of triangular membership functions having seven classes that are used in the CSP methodology's fuzzy system. The curve of the triangular membership functions is a function of a vector, x, and depends on three scalar parameters a, b, and c, as given by Bojadziev and Bojadziev, 1995:

$$f(x; a, b, c) = \begin{cases} \dfrac{x-a}{b-a}, & a \le x \le b \\ \dfrac{x-c}{b-c}, & b \le x \le c \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where the parameters a and c define the "feet" of the triangle, while the parameter b identifies the peak.

Tables II and III provide a detailed account of the chosen scalar parameters a, b, and c that define the triangular membership functions for each fuzzy input variable

TABLE II

Triangular membership function definitions for slope, profile curvature, plan curvature, annual potential solar radiation, and topographic wetness index

	Fuzzy input variable									
	Slope, °		Profile curvature, 1/100 m		Plan curvature, 1/100 m		Annual potential solar) radiation (normalized)		Topographic wetness) index (normalized)	
Vertex	Position	Description	Position	Description	Position	Description	Position	Description	Position	Description
a1	0.0		$-\infty$	Very	$+\infty$	Very	0.0/1.0		0.0	
b1	0.25	Plain	−4.0	Concave	4.0	Convex	0.125/0.875	Class 1	0.125	Class 1
c1	1.25		−1.2		1.2		0.25/ 0.75		0.25	
a2	0.25	Slightly	−4.0		4.0		0.125/0.875		0.125	
b2	1.25	sloping	−1.2	Concave	1.2	Convex	0.25/0.75	Class 2	0.25	Class 2
c2	3.5		−0.2		0.2		0.375/0.625		0.375	
a3	1.25	Gently	−1.2	Slightly	1.2	Slightly	0.25/0.75		0.25	
b3	3.5	inclined	−0.2	concave	0.2	convex	0.375/0.625	Class 3	0.375	Class 3
c3	10.0		0.0		0.0		0.5		0.5	
a4	3.5	Strongly	−0.2	Essentially	0.2	Essentially	0.375/0.625		0.375	
b4	10.0	inclined	0.0	uniform	0.0	uniform	0.5	Class 4	0.5	Class 4
c4	25.0		0.2		−0.2		0.625/0.375		0.625	
a5	10.0	Steep/	0.0	Slightly	0.0	Slightly	0.5		0.5	
b5	25.0	Very steep	0.2	convex	−0.2	concave	0.625/0.375	Class 5	0.625	Class 5
c5	45.0		1.2		−1.2		0.75/0.25		0.75	
a6	25.0		0.2		−0.2		0.625/0.375		0.625	
b6	45.0	Precipitous	1.2	Convex	−1.2	Concave	0.75/0.25	Class 6	0.75	
c6	72.5		4.0		−4.0		0.875/0.125		0.875	
a7	45.0		1.2	Very	−1.2	Very	0.75/0.25		0.75	
b7	72.5	Vertical	4.0	convex	−4.0	concave	0.875/0.125	Class 7	0.875	Class 7
c7	90.0		$+\infty$		$-\infty$		1.0/0.0		1.0	

TABLE III

Triangular membership function definitions for stream power index, sediment transport index, flow path length, buffering potential, and soil permeability

	Fuzzy input variable									
	Stream power index (normalized)		Sediment transport index (normalized)		Flow path length, m		Buffering potential (normalized)		Soil permeability, cm/hr	
Vertex	Position	Description	Position	Description	Position	Description	Position	Description	Position	Description
a1	0.0		0.0		$+\infty$	Extremely	1.0		$+\infty$	Very
b1	0.125	Class 1	0.125	Class 1	400.0	far	0.875	Class 1	35.0	rapid
c1	0.25		0.25		200.0		0.75		18.85	
a2	0.125		0.125		400.0		0.875		35.0	
b2	0.25	Class 2	0.25	Class 2	200.0	Very far	0.75	Class 2	18.85	Rapid
c2	0.375		0.375		75.0		0.625		9.5	
a3	0.25		0.25		200.0		0.75		18.85	Moderately
b3	0.375	Class 3	0.375	Class 3	75.0	Far	0.625	Class 3	9.5	rapid
c3	0.5		0.5		30.0		0.5		4.15	
a4	0.375		0.375		75.0	Slightly	0.625		9.5	
b4	0.5	Class 4	0.5	Class 4	30.0	far	0.5	Class 4	4.15	Moderate
c4	0.625		0.625		10.0		0.375		1.25	
a5	0.5		0.5		30.0		0.5		4.15	Moderately
b5	0.625	Class 5	0.625	Class 5	10.0	Close	0.375	Class 5	1.25	slow
c5	0.75		0.75		5.0		0.25		0.315	
a6	0.625		0.625		10.0	Very	0.375		1.25	
b6	0.75	Class 6	0.75	Class 6	5.0	close	0.25	Class 6	0.315	Slow
c6	0.875		0.875		3.0		0.125		0.065	
a7	0.75		0.75		5.0		0.25		0.315	Very
b7	0.875	Class 7	0.875	Class 7	3.0	Adjacent	0.125	Class 7	0.065	slow
c7	1.0		1.0		0.0		0.0		0.0	

TABLE IV
Relative TP export potential with respect to land use

Land use category	Relative TP export potential
Row Crops (RC)	1.00
Urban (U)	0.96
Grassland (G)	0.31
Non-Row Crops (NRC)	0.29
Forest (F)	0.08
Water Bodies (WB)	0.00

incorporated in the CSP methodology, along with a qualitative description of each class.

In the CSP methodology, each input variable is examined and categorized independently of the other variables, according to its pollution potential from the land surface. Only during the fuzzy logic computations are the individual pollution potentials from each input variable used conjunctively to arrive at an overall surface pollution potential with respect to these ten fuzzy input variables, which is then normalized so that the highest overall surface pollution potential is given a value of one.

2.2.4. *Non-Fuzzy Classification Task*

The land use variable is not incorporated into the fuzzy logic scheme. The land use categories employed in the CSP methodology are given in Table IV. An extensive literature review was undertaken to principally compile reported values of TP export coefficients from different land uses. Export coefficients suggest the proportion of the total nutrient lost to surface water. This literature survey included papers by Armstrong *et al.* (1974), Beaulac and Reckhow (1982), Clesceri *et al.* (1986a, b), Dillon and Kirchner (1975), Donigian *et al.* (1990), Frink (1991), Hartigan *et al.* (1983), Johnes (1990, 1996), Omernik (1976), Prairie and Kalff (1986), Rast and Lee (1983), Reckhow *et al.* (1980), Sonzogni *et al.* (1980), USEPA (1976), Uttormark *et al.* (1974), and Vaithiyanathan and Correll (1992). From these studies, relative TP export potential with respect to each of the given land uses was derived between 0.0 and 1.0. The land use category apparently having the greatest potential of TP pollution is Row Crops, which are known to have high soil losses (Burns, 1980). On the other hand, Forest is at the lower end of the pollution potential, which is supported by numerous past research efforts. The category Water Bodies is given a value of 0.00 and indicates the fact that water bodies, such as ponds and lakes, can generally be considered to be sinks of TP by trapping sediments and organic matter that otherwise would be transported downstream (Janus *et al.*, 1990).

2.2.5. *Linkage of Fuzzy and Non-Fuzzy Components*

In the CSP methodology, weights between 0.0 and 1.0 are designated to each input variable. By assigning a weight to each input variable, a decision on the relative

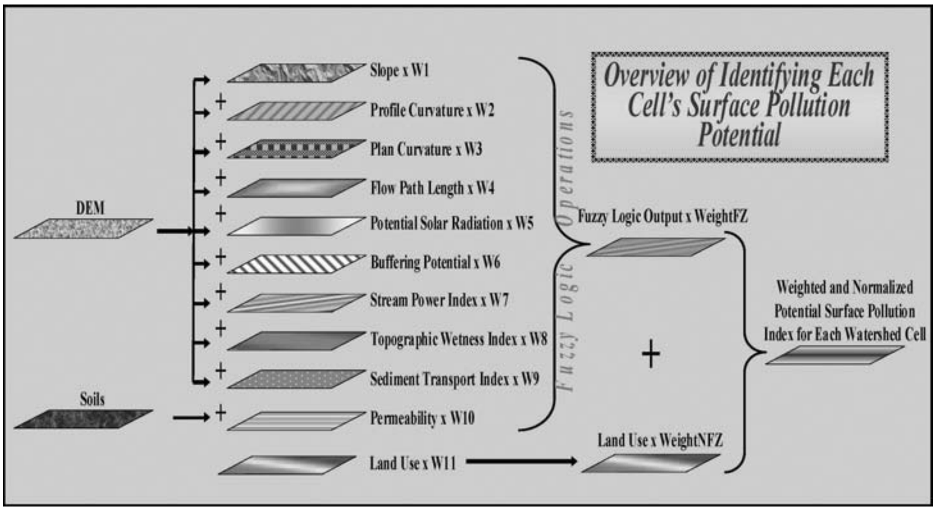

Figure 2. Overview of estimation of surface pollution potential for each watershed cell.

importance of each individual input variable can be made with respect to how much each variable will influence the surface TP load. Some watershed managers may also have intimate knowledge of the watershed in question, and thus can decide from their own expertise or professional judgment which input variables are more important than others. Additionally, the weighting scheme provides the means of excluding an input variable from the analysis. From the chosen weight distribution, the fuzzy and non-fuzzy components of this methodology are linked by a second weighting scheme, in which two linkage weights are computed that correspond to the relationships of the input variables expressed by the initial weighting scheme:

$$Weight\ FZ = \frac{\sum_{i=1}^{10} W_i}{\sum_{i=1}^{11} W_i} \tag{6}$$

$$Weight\ NFZ = \frac{W_{11}}{\sum_{i=1}^{11} W_i} \tag{7}$$

where *Weight FZ* is the fuzzy-non-fuzzy linkage weight for the fuzzy component (i.e., for the 10 fuzzy input variables), *Weight NFZ* is the fuzzy-non-fuzzy linkage weight for the non-fuzzy component (i.e., for the "land use" input variable), and W_i are the individual weights for all input variables ($\sum_{i=1}^{10} W_i$ are the fuzzy input variables and W_{11} is the "land use" variable).

Figure 2 gives a pictorial overview of how the surface pollution potential for each cell in the watershed is estimated.

2.3. Subsurface Loading Considerations

The subsurface module of the CSP methodology consists of four components, namely TP loads from groundwater, septic systems, point sources, and stream bank erosion. Since the output of the hydrologic simulation model GWLF is used as input to the CSP methodology, the selection of the four subsurface components is based exclusively upon the available output from the GWLF model.

Groundwater. Inherently, a baseline nutrient concentration is associated with the groundwater of watersheds that needs to be considered in the calculation of total loads within a watershed. In the GWLF model, the dissolved phosphorus load at the watershed outlet from groundwater is described as part of a lumped parameter model (Haith *et al.*, 1992). In the CSP methodology, the groundwater load from the GWLF model is evenly distributed across the entire watershed.

Septic Systems. Septic systems are individual sewage treatment systems that present a potential for impacting groundwater with a number of contaminants, including TP. Generally, the soil functions as a part of the sewage treatment in a septic system. Mandel's (1993) model for evaluating the impact of septic systems on water quality forms the basis for the septic system component of GWLF. In the CSP methodology, the septic system load obtained from the GWLF model is assumed to be proportional to the urban area in the watershed.

Point Sources. Point sources can represent a major dissolved nutrient load in a watershed. Although it is recognized that much has been accomplished in recent decades to reduce the point source impact to water bodies, it is still important to include this pollution source to accurately account for all phosphorus loads in a watershed (USGS, 1999). In the CSP methodology, detailed knowledge of the point source locations is assumed. Consequently, the point sources are assigned to the corresponding stream reaches.

Stream Bank Erosion. At times, stream bank erosion can be a significant source of sediment and consequently phosphorus load, especially in watersheds where livestock have regular access to open streams. Evans (2002) reports that the mechanisms of stream bank erosion are extremely difficult to model with accuracy without relying upon secondary variables in the prediction of stream bank erosion. In an algorithm employed in the GIS-interface GWLF model (AVGWLF (ArcViewGWLF), Evans, 2002), stream bank erosion estimation is based on a geomorphological approach that first computes a lateral erosion rate as a function of monthly streamflow, animal density, percent developed land, average curve number, and average erodibility factor of the watershed. In the CSP methodology, the stream bank erosion TP load is uniformly distributed to all stream cells.

3. Determination of the Critical Sampling Points

3.1. Potential surface pollution analysis

After each input variable is assigned a relative weight between 0.0 and 1.0, indicating its importance with respect to the other input variables, the fuzzy logic operations can be performed. Subsequently, the non-fuzzy land use variable is included in the analysis to obtain for each watershed cell an index, indicating the potential of pollution from the land surface. The index values of all member cells in each surface contributing area (SCA) are summed to give a total for each SCA. Thus, for each stream cell, which fundamentally represents the outlet of its corresponding SCA, a summed index value is obtained. In order to arrive at a potential surface pollution index with values ranging between 0.0 and 1.0, the index values for the stream cells are normalized so that the highest value is assigned a value of 1.0. To estimate the TP load distribution along the stream coming from the land surface, the TP load from all source areas, as predicted by the GWLF model, is utilized. This predicted value from the GWLF model is appropriately distributed proportional to the index value of each stream cell:

$$SC\,Load_i = \frac{PSurfPI_i}{\sum_{i=1}^{n} PSurfPI_i} \times GWLF\ Load_{sa} \tag{8}$$

where $SCLoad_i$ is the estimated TP surface load at stream cell I (kg), $PSurfPI_i$ is the potential surface pollution index at stream cell i (dimensionless), $\sum_{i=1}^{n} PSurfPI_i$ is the sum of potential surface pollution indices from all stream cells (dimensionless), and $GWLFLoad_{sa}$ is the TP load from all source areas, as estimated by the GWLF model (kg).

Additionally, the TP load distribution across the watershed can be estimated through use of the potential surface pollution index value assigned to each watershed cell along with the estimated TP load from GWLF. Such an inspection can provide insight into the critical areas of the watershed with respect to potential surface pollution. Theoretically, the sum of these estimated loads from each watershed cell relative to each SCA reflect the total surface TP load coming from each SCA to its stream entry point.

3.2. Potential subsurface pollution analysis

Not only is an estimation of the potential pollution stemming from the surface necessary, but also the load associated with subsurface flow. In the CSP methodology, four subsurface source components, as previously discussed, are incorporated. For the septic system component, the loads are allocated proportional to the actual area sizes of the urban zones in the rural watershed. This implies that the larger the farm building area, the more people are expected to contribute to the septic system load on that farm. Additionally, it is assumed that all residential urban areas in the watershed are residences that have a septic system. However, if more detailed knowledge of the exact locations of the residences which have septic systems is available, this information may be used instead. The CSP methodology counts the total number of grid cells that represent residential buildings in the watershed and uses this value along with the GWLF septic systems load value to assign each building grid cell a septic system load. Since each SCA corresponds to a particular stream cell, an estimated septic systems load at each stream reach can be estimated by linking the number of building cells to each SCA. For the point sources component, point source loads from the GWLF model are assigned to particular stream reaches to accurately reflect their spatial location within the watershed. For the groundwater component, the groundwater load obtained from the GWLF simulation is uniformly distributed across the watershed to each watershed cell. Again utilizing the SCAs linked with each stream reach, the groundwater load can be assigned to each stream cell. Hence, the larger the SCA, the greater will be the load for the corresponding stream reach. It is assumed that the SCA is conceptually equal to the subsurface contributing area. In the GWLF model, the groundwater load is assumed to come from the groundwater discharge from the shallow saturated zone. Therefore, it is assumed that the shallow saturated drainage zone follows the surface drainage area. Especially for watersheds that have high water tables that follow the surface topography, this will be a reasonable assumption. For the stream bank erosion component, on the other hand, the GWLF-derived stream bank erosion load for the watershed is distributed uniformly to the stream cells. Consequently, local variability of stream stretches that might experience greater or lesser stream bank erosion is not taken into account. As a final step, all four subsurface stream loads are summed to estimate the total subsurface load expected at each stream cell in the watershed:

$$TotSubsurfLd_i = SepticSLd_i + PtSLd_i + GWLd_i + SBELd_i \tag{9}$$

where $TotSubsurfLd_i$ is the estimated total subsurface load at stream cell i (kg), SepticSLd_i is the estimated septic systems load at stream cell i (kg), $PtSLd_i$ is the estimated point sources load at stream cell i (kg), $GWLd_i$ is the estimated groundwater load at stream cell i (kg), and $SBELd_i$ is the stream bank erosion load at stream cell i (kg). Subsequently, the greatest total subsurface TP load is normalized to one to obtain a potential subsurface pollution index for each stream cell.

3.3. Potential stream pollution index and stream ranking

The total TP load at each stream cell is obtained by accumulating surface and subsurface TP loads, as estimated by the surface and subsurface components, respectively, in the CSP methodology. A Potential Stream Pollution Index (PSPI) for each stream reach in the watershed is calculated proportionally to the estimated stream TP load for each stream cell. All stream cells are subsequently ranked according to the PSPI and thus receive an integer between 1 and the total number of stream cells. A rank of 1 indicates that the stream cell has the highest potential TP load from surface and subsurface source areas. Such a critical stream cell would be a prime candidate as a sampling site in the watershed with respect to targeting TP loads. Additionally, the total watershed mass balance could be most easily manipulated by concentrating on the stream cells ranking highest.

Logistical Component. Many real-world watersheds include stream sections that are logistically-speaking impossible, or very problematic at best, to sample. For instance, restricted access to a stream section can be due to dense vegetation or private property access restrictions. In other cases, a stream segment may be impossible to gauge flow. The WQMSA model allows the user to identify and exclude those stream sections from the analysis.

Economic Component. The WQMSA model assumes that the analysis is for an annual time period with a given financial budget. For this purpose, the user may input the desired total number of sampling points or use the following equation to predict the number of economically possible sampling points:

$$nSt = \left(\frac{(C_{\text{tot}} - C_{ov} - (C_{tr} \times nTr) - (C_{rt} \times nRt) - C_{\text{other}f} - (12 \times C_{\text{other}v}))}{((C_{la} \times nTr) + (C_{rp} \times nTr \times nRp) + (C_{di} \times nTr))} \right) - 1 \tag{10}$$

where *nSt* is the number of sampling stations/points, excluding the watershed outlet station, C_{tot} is the total annual cost ($), C_{ov} is the annual administrative overhead cost ($), C_{tr} is the sampling trip cost ($/sampling trip), C_{la} is the laboratory analysis cost ($/sampling point/sampling trip), C_{rp} is the replicate analysis cost ($/replicate/sampling point/sampling trip), C_{di} is the data interpretation cost ($/sampling point/trip), C_{rt} is the data reporting cost ($/reporting interval), $C_{\text{other}f}$ are the other fixed (aggregated) costs ($), $C_{\text{other}v}$ are the other variable costs (aggregated) per month ($/month), *nTr* is the number of annual sampling trips, *nRp* is the average number of replicates at each sampling station/point, and *nRt* is the number of reporting intervals per year. As can be seen from Equation (10), the "−1" term, denoting the watershed outlet, is automatically excluded from the calculation of how many sampling points are possible since the watershed outlet is assumed to always be a sampling point. Furthermore, it should be noted that the cost for travel between sampling locations is not taken into account because the CSP methodology has been designed for rather small watersheds. Therefore, all field sampling activities are assumed to take place in a single day. Furthermore, the economic component includes the possibility of assigning permanent sampling stations in the watershed. However, for TP sampling the construction of permanent stations with electrical wire installation and generator purchase may possibly be only realistic at the watershed outlet. Nonetheless, the option of installing permanent sampling stations was included to make the CSP methodology as general and flexible as possible, and to permit network monitoring modifications and incorporation of other pollutants in future revisions.

Sampling Point Designation. After computing the PSPI with respect to TP loads for each stream cell, excluding the logistically inaccessible stream reaches from the analysis, and selecting the number of economically feasible sampling points for the watershed, the final analysis step that remains is to geographically identify these stream sampling points. According to the ranking of the stream cells via the PSPI and the number of economically possible sampling points, a recommendation with respect to the critical sampling locations can be made.

4. Conclusions

This paper has described the development of the CSP methodology, to be used in the sampling station allocation component of water quality monitoring network design. The methodology is intended to achieve improvements in current water quality monitoring network design strategies. It should be noted that it is not intended to provide final results that do not require any further periodic reappraisal and modifications. Instead, the methodology provides a means of periodically reassessing the critical sampling locations identified in previous analysis runs.

The proposed methodology emphasizes topographic, hydrologic, transport, vegetative, and soil factors as well as existing land use conditions as indicators of potential for TP load pollution. A surface and subsurface component are included in the model. However, due to the nature of the export and loss of TP, the surface component has been developed in greater detail. A normalized index, called the Potential Stream Pollution Index (PSPI), which is based upon all the surface and subsurface factors, is computed to represent an approximation of contamination risk. It provides a means of ranking surface and subsurface potential stream pollution. Watershed managers and planners may use the PSPI to evaluate and prioritize sites to target areas for detailed field investigations. In addition, once the model is used to identify high priority sites, controls may be identified in contributing areas of highest risk in order to minimize or reduce the total TP load in the watershed.

To test the applicability and practicality of the CSP methodology, it has been translated into a model and applied to a small experimental watershed, as illustrated by Strobl and Robillard (2002). Furthermore, the CSP methodology may not only be utilized in the scientific allocation of sampling stations, but also can potentially be applied in other research areas, such as best management practices assignment or in the determination of which watershed attributes are most critical for a particular watershed.

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