DOKUZ EYLUL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINATION OF RESERVOIR PROTECTION ZONES IN WATERSHEDS BY A PHYSICALLY BASED APPROACH

by
Ali GÜL

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İZMİR

DETERMINATION OF RESERVOIR PROTECTION ZONES IN WATERSHEDS BY A PHYSICALLY BASED APPROACH

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Ali GÜL

DETERMINATION OF RESERVOIR PROTECTION ZONES IN WATERSHEDS BY A PHYSICALLY BASED APPROACH

ABSTRACT

Watershed management and catchment scale studies have become increasingly important in determining the impact of human development on water quality both within the watershed as well as that of receiving waters. One way of preventing water bodies from being polluted by many different kinds of pollutants is to design protection zones around those water bodies. The determination of reservoir protection zones is a significant issue in many parts of the world. The width of the protected area is one of the basic factors to be considered when setting up and managing the zones.

Today, most countries face difficulties in accomplishing sufficient reservoir protection strategy due to either the shortcomings in their central and local legislations or to the presence of too many regulations. The restrictions applied by authorities as ruled by legislations have direct impacts on the social and economical activities of the population residing in the basin. Besides, a protection strategy based on a fixed zoning system somehow fails to detect the variable protection needs when applied invariably for all basins, even of varying sizes and with distinct drainage characteristics. The approach employed in this study provides a comparably practical methodology for deciding upon an optimum protection distance in a watershed. Its most distinctive outcome is the feasibility of defining protection zones of variable distances for the applications in different catchments, but securing all assessments to be based on a single scientific reasoning. It basically considers a number of individual analytical components including the average times it takes water to travel within protection zones down to reservoir, the potential diffuse pollution risks originating from certain types of land uses, the potential role of sedimentation in a catchment to trigger pollution transfer and amplify pollution impacts on reservoir systems, and the utility of land as a resource.

Keywords : reservoir, protection zone, flow duration, sedimentation, geographic information systems

AKARSU HAVZALARINDA HAZNE KORUMA BÖLGELERİNİN FİZİKSEL TABANLI BİR YAKLAŞIMLA BELİRLENMESİ

ÖZ

Akarsu havzalarının yönetimi ve havza genelindeki araştırmalar, hem havzalar hem de alıcı ortamlardaki su kalitesi üzerine insan etkilerinin belirlenmesi noktasında giderek artan bir öneme sahip olmuştur. Su kaynaklarının çeşitli kirleticiler tarafından kirlenmesini önlemedeki yöntemlerden biri de, bu kaynaklar etrafında koruma bölgelerinin oluşturulmasıdır. Hazne koruma bölgelerinin belirlenmesi, dünya üzerindeki değişik kısımlarda önemli bir konu olarak ortaya çıkmaktadır. Koruma bölgesinin genişliği, bölgelerin oluşturulması ve yönetimi sırasında göz önünde bulundurulması gereken etmenlerden biridir.

Günümüzde ülkelerin birçoğu, merkezi ve bölgesel yasama eksiklikleri ya da yönetmelik fazlalığı nedeniyle yeterli bir hazne koruma stratejisi belirlemede güçlükler yaşamaktadır. Yetkili kurumlarca yönetmeliklerde belirtildiği şekliyle uygulanan kısıtlamalar, havzalarda ikamet eden nüfusun sosyal ve ekonomik faaliyetleri üzerine doğrudan etki yaratmaktadır. Bunun yanı sıra, sabit bölgeleme sistemine dayalı bir koruma stratejisi, özellikle farklı büyüklüklere ve akış özelliklerine sahip havzalar için uygulandığında değişken koruma ihtiyaçlarının belirlenmesine tam olarak cevap verememektedir. Bu çalışmada önerilen yaklaşım, herhangi bir havzada en uygun koruma mesafesine karar verebilmek için oldukça pratik bir yöntem ortaya koymaktadır. Yöntemin en belirgin getirisi, tüm değerlendirmeleri tek bir bilimsel mantığa dayalı olmak üzere, farklı havza uygulamaları için değişken mesafeli koruma bölgesi tanımında sağladığı esneklik olmaktadır. Yöntem, koruma bölgeleri içerisinde suyun hazneye ulaşıncaya kadarki akış süreleri, çeşitli arazi kullanımlarından kaynaklanan olası yayılı kirlilik riskleri, kirlilik taşınımını başlatma ve hazne sistemleri üzerinde kirlilik etkilerini artırmada sedimentasyonun etkisi ve arazinin bir kaynak olarak kullanımını da içeren bir dizi bağımsız analitik bileşeni dikkate almaktadır.

Anahtar sözcükler : hazne, koruma bölgesi, akış süresi, sedimentasyon, coğrafi bilgi sistemleri

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CHAPTER ONE

INTRODUCTION

1.1 Causes of Pollution in Water Supply Reservoirs and Possible Prevention Measures at Watershed Level

Pollution of water stored in a water supply reservoir results from either point or nonpoint sources. The pollutants that are imported from either type of sources in a watershed and released to surface or ground water affect water and environmental quality in reservoirs (FAO, 2001). Point source pollution may be caused by nutrients and toxic materials originating from the activities where wastewater is routed directly into receiving water bodies by, for example, discharge pipes, where they can be easily measured and controlled (FAO, 1996). The control of this specific kind of pollution has been the primary focus of efforts to protect and improve reservoir water quality until recent decades. This is mostly due to the relatively easier control of point source pollution through much simpler measures such as water-quality standards and permitting programs which establish limits on the kind or amount of pollutants each point source may discharge into a body of water (Gale et al., 1996).

Nonpoint source water pollution, also called diffuse pollution, arises from a broad group of human activities for which the pollutants have no obvious point of entry into receiving watercourses. Agriculture, forestry, residential, and urban development are examples of nonpoint sources of pollutants. Today, the major reasons of contaminant and nutrient loading into most streams and lakes are nonpoint pollution mechanisms that include agricultural runoff, erosion from urban or deforested areas, surface mining, or atmospheric depositions (Cooke, Welch, Peterson, & Nichols, 2005). Obviously, non-point source pollution is much more difficult to identify, measure and control than point sources (FAO, 1996; FAO, 2001). This is mostly due to the fact that any control effort requires interventions in land use that are more difficult to implement for economic and political reasons (Harper, Brierley, Ferguson, & Phillips, 1999).

Once pollutants from either point or nonpoint sources are exposed to runoff, they are transported in two ways (or phases): the dissolved or soluble phase and the sediment-bound or solid phase. Whatever the mechanisms of generation and transfer, contaminants, excessive nutrients, organic matter, and sediments constitute major risks on water quality in reservoirs. Contaminants may include metals, pesticides, oils, and other pollutants in industrial, agricultural, and urban waste outputs. Potential prevention or rehabilitation measures include elimination of or controlled discharge from point sources and managing the watershed in terms of land uses (FAO, 2001). Nutrient pollution, especially from nitrogen and phosphorus, has consistently ranked as one of the top causes of degradation in some waters for more than a decade. Excess nitrogen and phosphorus lead to significant water quality problems including harmful algal blooms, hypoxia and declines in wildlife and wildlife habitat (US EPA, 2009). Sediments that are normally the major nonpoint source of pollution originate from erosion processes within reservoir catchments, within the river channels feeding the reservoir, and from the shore of the reservoir itself. Sediment particles have two methods of transport such that smaller particles are suspended in water resulting in cloudy or muddy water, while larger sediment particles roll or hop along the land surfaces or stream bottoms from the force of the moving water. Thus, sediment-bound pollutants may be classified as either the suspended sediment composed of small particles or the bottom sediment with the larger particles (Arnold, Coffey, Line, Spooner, & Moody, 2009). Sedimentation increases turbidity, and decreases depth and thereby storage capacity of a reservoir. Beside such physical negativities, sedimentation amplifies water pollution due to the transfer of sediment-bound pollutants. A significant amount of pollutants in urban stormwater runoff is, for instance, transported as sediment-bound contaminants, making it important to have a clear understanding of the amount of pollutants attached to the different sediment sizes so that treatment facilities can be designed to effectively target the removal of the most polluted sediment sizes (Vaze, & Chiew, 2004).

In watershed approaches to pollution control, the drainage basin is considered as the fundamental freshwater management unit for addressing both water quantity and water quality issues, as the water quality of a reservoir is a direct function of the quantity and types of materials entering them from their surrounding drainage basins. This necessitates introducing a set of control measures that are directed to the sources of pollution in drainage basins, the mechanisms of their transport to reservoirs, and their changes within the water body via degradation, transformation, etc (Jørgensen, Löffler, Rast, & Straškraba, 2005).

1.2 Potential Benefits of Reservoir Protection Zones and Basic Design Principles in Water Quality Management

Watershed management and catchment scale studies have become increasingly important in determining the impact of human development on water quality both within the watershed as well as that of receiving waters. One way of preventing the water bodies from being polluted by many different kinds of pollutants is to design certain protection zones adjacent to those indicated water bodies. In the broader sense, such conservation areas work environmentally as they do not only improve water quality by removing sediment, fertilizers, pesticides, pathogens, and other potential contaminants from runoff, but also control soil erosion by both wind and water, improve soil quality, enhance fish and wildlife habitat, reduce flooding, conserve energy, protect buildings, roads, and livestock, and conserve biodiversity (NRCS, 2009). The effects of protection zones in removing non-point source pollution can be examined from their mechanical, chemical, or biological functions. From the mechanical perspective, the velocity of surface flow and consequently its sediment carrying capacity are reduced due to the increased hydraulic roughness of vegetation cover in protection zones. In addition, the filtering effect through infiltration is enhanced because of longer time span required for surface flows to move across protection zones as a result of reduced velocities. The chemical and biological functions of riparian buffer zones pertain to the processes that are activated in the riparian ecosystem for transforming pollutants into different compounds (Narumalani, Zhou, & Jensen, 1997).

The determination of protection zones for a drinking water reservoir is a significant issue in many parts of the world. In this regard, current approaches for integrated river basin management extend the activities for protection of drinking water sources beyond only controlling the individual sources of contamination by addressing problems and solutions on a regional or watershed scale. The establishment of one or more protection zones close to the surface water intake is commonly accepted worldwide as a common pollution control measure for the reservoirs, provided that the entire watershed boundaries are judicially identified for the reservoir system by managers of public water systems or other involved authorities (Gül, Fıstıkoğlu, & Harmancıoğlu, 2009). Two points should basically be considered when setting up and managing the zones. First, the width should be large enough to ensure that the draining water remains over the protected area long enough for the silt and nutrients to be retained. As time is a necessary factor for the performance of protection zones for rehabilitating pollution through a number of physical, chemical and/or biological processes, a sufficient width that will be traversed by water in a longer time must be provided for the zones to increase their capacities against pollution. The second important component in the design of protection zones is the vegetation type which can be anything from grassland to woodland on a larger scale or a grass margin as long as it is well established and not intensively managed. Indeed, the role of vegetation in trapping sediments and adhering phosphorus is another important task expected from protection zones. Vegetation plays an important role in removing and retaining particulates as dense vegetation on a protected area increases the hydraulic roughness, decreasing overland flow velocity and sediment transport capacity.

1.3 Common Practices of Protection Zones and the Associated Problems

In recent years, developing water protection strategies to prevent drinking water sources from contamination has become a high priority throughout the world. In most of these strategies, the segmentation of the delineated watershed areas into several zones is preferred. The segmentation is generally achieved by defining areas closest to the intake, where most types of contamination sources can directly impact the water supply, and more distant areas. Despite all these efforts, most countries still face difficulties in accomplishing sufficient protection through a proper strategy in this respect due to either the shortcomings in their central and local legislations or to the presence of too many regulations and different applications from foreign examples.

In the United States (US), the legal basis for delineating reservoir protection zones differs even between the States. Although the Safe Drinking Water Act (SDWA) (first issued in 1974, amended later in 1986 and finally in 1996), which authorizes the Environmental Protection Agency (US EPA) to set standards of drinking water quality and oversee all states for the implementation of these, took a major new step in drinking water protection, the source water assessment programs established by each state differ, depending on the nature and threats to the water resources and the drinking water program priorities in a particular state. However, each assessment program must include delineating (or mapping) the source water protection areas, and conducting an inventory of potential sources of contamination in those areas (US EPA, 2004). Some States apply a bipartite system by defining a closer zone (or segment) in a 500-foot buffer around reservoir/stream and a remote zone in the remainder of the watershed (or two remote zones depending on the watershed size). The delineation of surface water protection areas in Pennsylvania is applied by considering a zoning based on the time of travel (TOT) for flow in watersheds (5-hour TOT for Zone A and 25-hour TOT for Zone B), while in Nebraska the segmentation of a watershed is performed by distinguishing 3-hour, 6-hour and 12-hour TOT zones within a 24-hour TOT zone called the assessment area (DEP 2000; CDPH, 2001).

Water and Rivers Commission in Western Australia published a series of guidelines for protecting water quality against the risks arising from mining and mineral processing and specifically defined the limits and operational rules of reservoir protection zones to protect the water sources from contamination in close proximity of the reservoirs. In a protection zone, which is defined to consist of a 2-kilometer buffer identified over the land from the high-water level of the reservoir, no public access or the installation and operation of some facilities for above-ground storage of fuel or toxic/harmful chemicals are allowed (WRC, 2000a). A following policy document introduces some amendments to the definition of reservoir protection zone by allowing the determination of the extent of, or the necessity for, these zones on a case by case basis (WRC, 2003). In addition to the relatively stricter protective measures in close vicinity of a reservoir, a three-level priority classification is additionally defined for the management of land surrounding the reservoirs, based on the three different land management objectives: pollution risk avoidance in the primary zone for ensuring no degradation in water quality, risk minimization in the secondary zone for maintaining existing quality, and risk management in the remotest zone for maintaining the water quality within health guidelines (WRC, 2000b; DoW, 2008).

In Europe, the Water Framework Directive (WFD), which is the most substantial piece of water legislation by the European Commission and which established a new, integrated approach to the protection, improvement and sustainable use of surface waters, gives member states some requirements to take account of pressures on water quality from point and diffuse sources and ensures that necessary measures to meet quality objectives are selected (Chave, 2001; Holland, 2002). Yet, there are currently no common rules in the European Union for defining protection zones over land to secure reservoir water quality, and most countries are still experiencing a transition period at present from individual practices to a common implementation strategy (Gül et al., 2010).

The first legal basis of protection zones to be identified around water supply reservoirs in Turkey, called the Water Pollution Control Regulation (WPCR) of the Turkish Republic, was issued in 1988. This regulation that regulates the use of surface waters and surrounding territories as regards the pollution risks on water supply sources considered a four-level protection by successively defining absolute, short-range, medium-range and long-range protection zones around the reservoirs. The zonal widths were defined as 300 m for the absolute zone starting from the reservoir boundary, 700 m for the short-range zone starting from the boundary of the absolute zone, and 1 km for the medium-range zone measured from the boundary of short-range zone, finally allocating the rest of the watershed for the long-range zone. As the first application, the local authority in Istanbul, Istanbul Water Works and Sewerage Administration (ISKI), that is responsible for the reservoirs in the city, mainly used the protection approach introduced by WPCR, but with some modifications amended in 1996 for defining specific rules in a local legislation and regulating the lists of permitted and prohibited activities within the zones (Beler Baykal, Tanik, & Gonenc, 2000). WPCR was revised by the Ministry of Environment and Forestry (MoEF) and issued on 31.12.2004 with major changes for the definition of absolute and short-range protection zones. It defines four types of protection zones around the drinking water bodies unless any other specific clause or a local protection strategy is constituted by the local authorities: (1) the absolute protection zone in the band from the maximum water surface of the reservoir up to a distance of 100 m; (2) the short-range (or proximate) protection zone from the absolute zone boundary to 900 m; (3) the medium-range (or mediate) protection zone from the short-range zone boundary to 1 km; and (4) the long-range (or remote) protection zone in the basin area remaining between the medium-range zone and the boundaries of the drainage basin (MoEF, 2004). In the absolute protection zone, no constructions other than the necessary facilities that belong to either the sewerage systems of existing structures or the project of water supply are allowed. In the short-range zone, all settlements for tourism, housing or industries are prohibited as well as the deposition of any kind of solid waste. Agricultural activities and grazing are allowed under the control of the Ministry of Agriculture and Rural Affairs, providing that artificial fertilizers, pesticides or insecticides are not use for the allowed activities. Besides, the application of relevant practices to reduce erosion is principally advised. In the medium-range protection zone, the use of artificial fertilizers, pesticides, insecticides, etc., the deposition of solid wastes, and the construction of industrial or domestic facilities are not allowed. Although protective measures are not so intensive in the long-range zone, the industries which generate hazardous wastes or industrial waste water are not allowed within the band of 3 km measured from the boundaries of the medium-range zone.

The new version of WPCR has been greatly opposed as it changes the width of absolute zone from 300 m to 100 m by including the remaining 200 m to the short-range zone. With this modification, it is generally stated that the new version prioritizes the utility of land, but not actually the protection of watersheds. Besides, some regulations applied by local authorities still do not seem to have enough capacities for adaptation to the new definitions. For instance, the Catchment Control Regulation (CCR), issued on 01.04.2002 by Izmir Water and Sewerage Administration (IZSU) of the Izmir Metropolitan Municipality, supersedes the WPCR in local applications though it was issued earlier, and thus does not cover the changed definitions (IZSU, 2002).

Beside the efforts of forming legal infrastructure, a number of studies previously focused on the potential impacts of alternative land uses which would be allowed or restricted in the protection zones, and suggested alternative solutions to the problems that relate to different land uses risking the water quality (Tanik, Beler Baykal, & Gonenc, 2000; Akkoyunlu, Yuksel, Erturk, & Bayhan, 2002). Such studies have also great importance in water quality management due to the conflicts which frequently arise between the interest in development of land and the desire to preserve drinking water supplies from contamination (Whipple, 1993).

1.4 Basic Problems Addressed by the Study and the Points of Origin

Due to the requirements set out in national or local legislations, authorities responsible for securing the water quality in water supply reservoirs apply restrictions on collective settlements, industrial and agricultural developments particularly in the protection zones of the reservoir. Such restrictions have direct impacts on the social and economical activities of the population residing in the basin. For example, farmers are adversely affected by the limitations imposed on their agricultural activities as mostly no subsidies can be provided to make up for their loss. Besides, the regulatory management of reservoir catchments is essentially hindered by the presence of too many authorities from national, provincial and regional levels, too many policies and complex, often conflicting, laws and regulations. This situation leads to several legal problems and further complicates the management of water and land resources (Gül et al., 2010).

Furthermore, the descriptive differences between the legislations from different levels or the different practices performed by the authorities of different regions lead to disparities between the basins that are subject to quite different protective measures and zoning systems in spite of their analogous basin characteristics. Besides, when a protection strategy that is prescribed by the regulations and is based on a fixed zoning system is invariably applied to different basins of varying sizes and of distinct drainage characteristics, it somehow fails to detect the variable pollution loads and meet corresponding protection needs, which arise from the land uses in different-sized basin sections, thus are expected to basically differ with the basin size and characteristics.

In summary, the major challenges in reservoir protection and disputes in current applications mostly relate to the lack of scientific basis of the existing protection regulations that helps make them widely acceptable by and easily verifiable to the public. A sound reservoir protection strategy (1) which is practically applicable to all catchments of variable sizes and characteristics, (2) which takes account of topographic, hydraulic and other relevant characteristics in drainage basins as well as the potential sources of pollution, and (3) which is based on a single scientific reasoning even for different applications in different basins would substantially fill the voids encountered in managerial efforts for securing the water quality in reservoirs. A comprehensive modeling of catchment hydraulics and pollution mechanisms can be an alternative to tackle the problems mentioned. Yet, a model setup which is structured and validated individually for an area and corresponding model outcomes will remain particular to the modeled area, without providing a common practical operability for other examples from different regions. This normally increases the time that is required for generating the results from a study and delays the response time to decision-making, since a new model set-up and calibration will always be necessary for each of the desired applications (Gül et al., 2010).

The overall approach presented in this study addresses the above challenges arising from the current practices of reservoir protection and it provides guidance for an alternative strategy to achieve a practical solution. In doing this, the method employs a set of spatial criteria to aid decision-making on reservoir protection and to develop a practical methodology that deals with the derivation of such criteria in the general framework of a multi-criteria decision-making process, without detailing the major physical processes that govern flow conditions and the pollution transfer mechanisms in a watershed. In this regard, the approach is expected to contribute to protection zone design with its increased practicality and similar use in common applications, which may not always be achieved from case-specific modeling exercises.

CHAPTER TWO

APPLIED METHODOLOGY FOR ASSIGNING RESERVOIR PROTECTION ZONES

2.1 Deriving elementary parameters using physical catchment characteristics

The proposed approach in the study is based on the determination of a proper, functional and serviceable protection distance, measured from the reservoir boundaries, by considering the average time allocated within the protection zone for the rehabilitation of water quality, the available land that is not occupied by the protection zone and thus is not restricted to settlements or commercial activities, and the estimated serviceability degree of the protection zone against the potential pollution load sourcing from the unprotected areas. In this respect, the analyses mainly focus on computing the travel times of flow from the reservoir catchment down to the drinking water supply reservoir, the available unoccupied areas beyond the spatial extent of candidate fixed-distance protection zones around the reservoir, the shares of risk-prone areas, which potentially act as pollution sources outside the protection space for their downstream, to approximate the amount of pollution transferred by the surface water, and the sediment delivery capacity of the unprotected land to take account of the amount of sediment-bound pollution moving towards the protection zone.

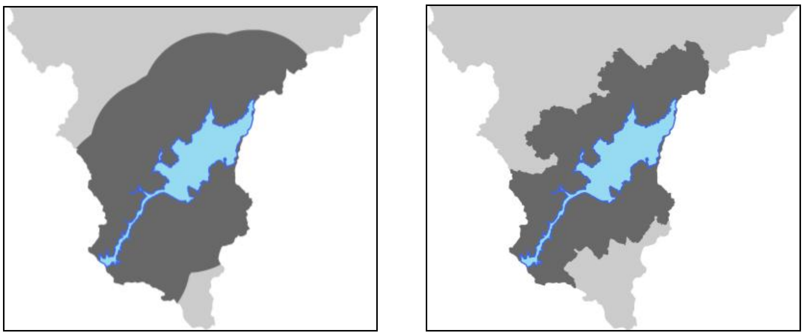
2.1.1 Alternative Methodologies for Determining the Spatial Extent of Protection Zones

While establishing zones around surface water bodies for protecting the quality of drinking water from potential pollution arising from their catchments, a variety of methods may be used. The use of maps available from previous research activities can be an option for defining protection zones within a watershed. The most commonly used maps are related to flood plains, hydrologic units and/or specific land-uses in the watershed.

Modeling is another option that may be more accurate and precise provided that a proper setup for the model is performed and accurate and precise data are used as model input. The models can be used to identify the areas within the watershed that would have the greatest impact on the quality of the drinking water source or to assess the impact of various point or nonpoint sources of contaminants. Yet, modeling has a number of challenging and demanding tasks that include collecting specific data required by the model, performing a proper setup to help accurately model the physical environment and simulate the modeled process, calibrating the model and validating the consistency of model outcome. These inevitably make any modeling exercise quite time- and data-demanding.

There is also Time of Travel (TOT) method where the protection zone is defined by a threshold travel time that is computed along drainage networks down to the reservoir and that is typically based on the response times for controlling point pollution or on times desired within the protection zone for rehabilitating the quality of polluted water originating from non-point sources. This method may be used alone to construct varying time zones from the reservoir or in conjunction with the so-called fixed-distance method as a criterion to help make a decision on a proper protection distance.

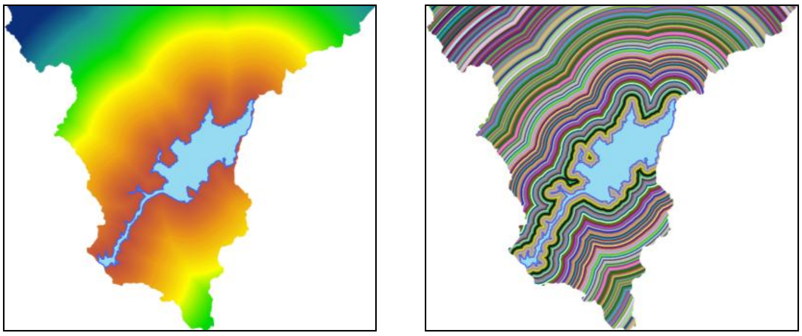
In fixed-distance method, setbacks from reservoir boundaries, tributaries, or the intake are established by assigning certain fixed distances. While not technically sophisticated, the method is relatively simple to implement and provides a starting point for assessment and protection efforts (Harter, & Rollins, 2008). A distance considered in this method from a location in the watershed down to the reservoir can be computed in a number of different ways: Euclidean distance (also called planimetric distance, straight-line or Euclidean metric), surface distance (also called path distance or surface-weighted distance), or downstream flow distance (also called downstream flow length) (Fig. 2.1). Euclidean distance is the 2-norm distance between two points in the Euclidean space and it takes neither the curvature of Earth’s surface nor the routes of water flow into consideration. Surface distance is the actual distance over the surface traveled from any location in the watershed to the reservoir along a Euclidean path projected on it. Downstream flow distance, on the other hand, can be the length of actual or projected flow path along which water travels from any watershed location down to the reservoir. Among all these alternatives, fixed-distance zoning based on Euclidean distances are generally preferred in managerial applications worldwide to facilitate mapping and provide an operational practicality (Gül et al., 2010).



(a) (b)

Figure 2.1Different spatial extents for a 5-km zone generated through the computations of (a) straight-line distances and (b) downstream flow distances from the reservoir.

For identifying the boundaries of an effective and sufficiently functional protection zone, an investigation set is first to be generated in order to assess the added value of expanding protection zone limits and to decide on an efficient distance from the reservoir by comparing between different feasible alternatives. In the current study, protection zones that vary incrementally with a selected unit width of 100 m are considered as the main investigation set and all computations are repeated for each potential zone that has certain distance from the reservoir boundaries. For doing this, the Euclidean distance to the closest source needs to be computed for each location in the entire watershed (Fig. 2.2(a)). The incremental segments and thus the boundaries of a protection zone that has a certain distance away from the reservoir can be displayed by reclassifying the Euclidean distance layer into zones of 100-m. width in the Euclidean space (Fig. 2.2(b)).



(a) (b)

Figure 2.2 (a) Euclidean distances measured from the reservoir and (b) the boundaries of protections zones structured around the reservoir.

2.1.2 *Computing Travel Times of Water Flow to the Reservoir*

Normally, a number of physical, chemical and/or biological processes can work together or separately within a stream to reduce a contaminant's concentration or convert/degrade the contaminant to a less threatening form (Correll, 1996). However, time must indeed be provided for these processes to occur. Generally, there is less potential for the concentration of a contaminant to be reduced when there is a shorter time-of-travel between the point where the contaminant enters the stream and the reservoir intake point (TNRCC, 1999). In this regard, the pollution prevention measure for a drinking water supply reservoir, based on the determination of stream flow time of travel, facilitates better management of those stream reaches which are the most critical to protecting water intakes from upstream sources of contamination.

For analyzing and assessing preferable widths of reservoir protection zones, an approach mainly based on the distinction between runoff patterns and thus the varying travel times of flow to the outlet in a watershed is employed in the study. The required time for a water droplet to travel over the surface of a corresponding drainage area down to the reservoir inlet point is the basic factor considered throughout the hypothetical development of flow in a basin. The characteristics that relate to travel time computations for distinct runoff patterns were initially defined and then revised by the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) after decades of research (LMNO, 1999). Essential analyses involve a number of catchment characteristics that include surface roughness, channel properties, flow patterns and slope. SCS (Soil Conservation Service, forerunner of NRCS) (1986a) indicates that there are typically three different runoff patterns in a watershed: sheet flow, shallow concentrated flow, and channel flow. Sheet flow is the type of flow that occurs in the upper reaches of a watershed and persists for a maximum of 300 ft. Yet, more recent research at the NRCS and relevant discussions among the scientific interest groups indicated that it is very unusual to observe sheet flow after a distance of 100 ft instead of 300 ft, so the definitions were revised, based on this new maximum length for sheet flow (Merkel, 2001). Further downstream along the flow paths, water typically becomes more concentrated by constituting the specific flow form of shallow concentrated flow. After shallow concentrated flow, water collects in natural or man-made channels finally resulting in channel flow. In cases where water moves through a watershed in some combination of sheet flow, shallow concentrated flow, stream flow and also flow within storm drainage structures (pipes, canals, etc.), pipe flow hydraulics additionally needs to be considered for the piped sections.

The most fundamental element of hydrologic computations and the starting point of all performed analyses is the elevation model of the basin considered. It is necessary for subsequent operations to delineate hydrological boundaries of the basin and the river network, partial drainage zones above any watershed point, drainage pathways to a corresponding outlet (e.g. inlets of the reservoir), and potential directions of flow as well as the flow lengths downstream and upstream. Differentiation between the flow patterns and segmentation of a watershed into flow zones are possible through a number of spatial operations performed over the elevation model and its derivatives. In doing this, the visible stream channels are initially designated as channel flow zones. The stream network can be easily extracted from the derivatives (i.e. flow direction and flow accumulation maps) of an elevation model by defining certain threshold of flow accumulation to differentiate between channel flow and overland flow at points where channelization starts, or may be adapted from an available map of streams which might have been previously generated by considering more realistic characteristics of basin geomorphology. Yet, if the latter option is preferred, it should be secured that the adapted stream network is spatially compatible with the digital elevation model as the succeeding analyses would use this model as the base map. Sheet flow zones are later delineated by using upstream (or upslope) flow lengths, which are defined for every watershed location as the maximum length of all available upstream flow paths originating from different flow start points and finally reaching the same watershed location for which the length is computed. It is obvious that there would be more than one upstream length for every point in a flow network, but there will be a unique maximum upstream length. Sheet flow zones constitute the watershed segments with the upslope lengths less than 100-feet. The segmentation is completed by assigning the rest of watershed area to shallow concentrated flow zones between the two others.

Travel times of flow for unit land portions in every flow segment can be computed through corresponding equations by using the distinct flow patterns and the above catchment characteristics. As the governing equation changes for each type of flow, the calculated times may remarkably differ along the pathways of flow. Travel time (hr) for sheet flow can be calculated by using the following formula, which was further simplified from the kinematic wave equation to avoid computational complexities:

$$T_{t,sheet\ flow} = [0.007(nL)^{0.8}]/[P_2^{0.5} * S^{0.4}] \tag{2.1}$$

where n is the Manning roughness coefficient; L is the flow length in feet up to 100 feet; P_2 is the rainfall depth in inches for a rainfall with a 24 hours duration and 2-years time of recurrence; and S is the slope of the land surface computed as rise/run (in ft/ft). Assumptions that attend this simplified form of Manning’s kinematic solution are shallow steady uniform flow, constant intensity of rainfall excess (that part of a rain available for runoff), rainfall duration of 24 hours, and minor effect of infiltration on travel time. Rainfall depth can be obtained from IDF curves representative of the project location.

Travel time of shallow concentrated flow that occurs after a maximum of 100 feet depends on its average velocity, V_{ave}, which is a function of the watercourse slope, S (ft/ft), and the type of surface cover. Average velocities (ft/s) can be computed by the following formulas, defined for both paved and unpaved surfaces:

$$V_{ave} = 20.3282 S^{0.5} \text{ (for paved surfaces)} \tag{2.2}$$

$$V_{ave} = 16.1345 S^{0.5} \text{ (for unpaved surfaces)} \tag{2.3}$$

By using these average velocities, the time of travel (hr) for surface waters in shallow concentrated flow areas can be computed by:

$$T_{t,shallow\,cocnc.\ flow} = L/(3600 * V_{ave}) \tag{2.4}$$

where L is again the flow length in feet and V_{ave} is the average velocity in feet/seconds.

Channel flow occurs in open channels that are generally assumed to begin where surveyed cross section information is obtained or where channels are visible on aerial photographs. Average velocity for this type of flow is usually determined by Manning's equation for bank full elevation:

$$V_{ave} = [1.49 R^{2/3} * S^{0.5}]/n \tag{2.5}$$

where V_{ave} is the average velocity (ft/s); R is the hydraulic radius (ft); S is the slope of the hydraulic grade line (channel slope, ft/ft); and n is the Manning's roughness coefficient for open channel flow. The calculated average flow velocity is then used in the following equation to obtain travel times for channel flow:

$$T_{t,channel\ flow} = L/(3600 * V_{ave}) \tag{2.6}$$

As time of concentration for the watershed is the total time for water to move through each flow regime until it reaches the collection point, NRCS offers a simplified mathematical expression for calculating total travel times (T_t) of flow in watersheds as a combination of travel times (in hours) for individual flow patterns (LMNO, 1999):

$$T_{t,total} = T_{t,sheet\ flow} + T_{t,shallow\,cocnc.\ flow} + T_{t,channel\ flow} \tag{2.7}$$

However, the bulk application of the above summation is not an ordinary task in GIS environment as there are several routes in a watershed the water follows before arriving at reservoir boundaries. This requires a spatial combination of all zonal times, which are first computed only to the zone outlet, into total times for each point over the entire watershed that represent the time it takes water to reach the inlet points where the flow joins the reservoir water. As the travel times for stream channels, $T_{t,\text{ channel flow}}$, are computed down to the reservoir (if there is no piped outlet at the end), they are equivalent to the total travel times for the points on the stream network. However, some adjustments are still needed for the points inside the shallow concentrated and sheet flow zones. The combination of channel flow and shallow concentrated flow time values is simply done by increasing all shallow concentrated flow time values along any route, $T_{t,\text{ shallow conc. flow}}$, by the time value of the point further downstream on the same route, $T_{t,\text{ channel flow}}$, where the channel flow starts. A similar adjustment is performed for the times computed within the sheet flow zones by increasing the zonal time values, $T_{t,\text{ sheet flow}}$, now by the combined time values (i.e. combined for channel and shallow concentrated flow) of the downstream points where sheet flow changes into shallow concentrated flow along different flow routes (Fig. 2.3).

$$T_{t,total}\ (\ for\ \ cf\ ) = T_{t,channel\ flow}$$

$$T_{t,total}\ (\ for\ \ scf\ ) = T_C + T_{t,shallowcocnc.\ \ flow}$$

$$T_{t,total}\ (\ for\ \ sf\ ) = T_B + T_{t,sheet\ flow}$$

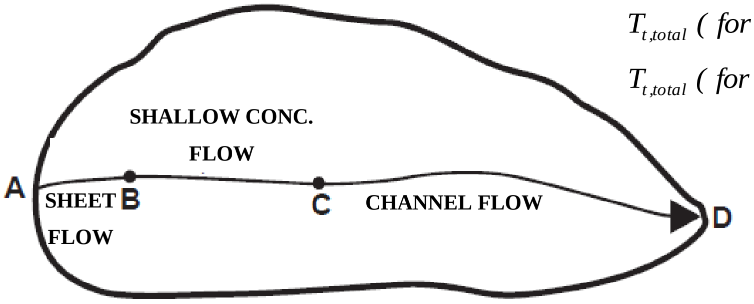


Figure 2.3 Different flow segments on a flow path in a watershed, and the combination of partial times within the segments into total time values for flow down to the outlet.

2.1.3 Computing Sediment Yield within the Reservoir Catchment

As an additional criterion for assessing the serviceability of reservoir protection zones against sediment-bound pollution loads, an accurate estimation of sediment yield for the reservoir catchment reserves an important place in the proposed methodology for designating the necessary protection. The Universal Soil Loss Equation (USLE) (Wischmeier, & Smith, 1978) is an empirical model used for this purpose and it serves to estimate annual soil loss due to sheet or rill erosion from individual patches of land or from a wider area composed of several patches. In this respect, USLE has the advantage of providing long-term estimates of average annual soil loss from small areas and is considered a ‘good model’ if the purpose of modeling is to arrive at global estimates of soil erosion (Fistikoglu, & Harmancioglu, 2002). Although the model was created for use in selected cropping and management systems, it is also applicable to non-agricultural conditions such as construction sites. It enables planners and decision-makers to project limited erosion data to many locations and conditions not directly represented by research.

Five major factors, each of which is the numerical estimate of a specific condition that affects the severity of soil erosion at a particular location, are used to calculate the soil loss for an area. As the erosion values reflected by these factors can vary considerably due to varying weather conditions, the values obtained from the USLE more accurately represent long-term averages (Stone, & Hilborn, 2000). The USLE method is expressed by the following equation:

$$A = R * K * L * S * C * P \tag{2.8}$$

where A is the computed average annual soil loss per unit area (tons/ha/yr), R is rainfall factor, K is soil erodibility factor, L is slope length factor, S is slope (steepness) factor, C is crop/vegetation and management factor and P is support practice (also called erosion control or conservation) factor.

As the erosion potential is greater for greater intensity and duration of the rain storm, the R-factor in USLE characterizes the climatic influence on the average rate of soil loss. Thus, a proper estimate needs to be made for the study area based on the climatic conditions. Its value can be received from available tables previously published for the region, computed by using specifically-developed software and annual precipitation data, or an acceptable estimate can be appointed with some effort. In case that rainfall parameters needed for a direct estimation of the R-factor or necessary tools are not available, correlations between the R-factor and readily available meteorological parameters can be used to estimate R in a simplified approach (Van der Knijff, Jones, & Montanarella, 2000a).

K-factor is a measure of the susceptibility of soil particles to detachment and transport by rainfall and runoff. It is the average soil loss in tons/ha per unit area for a particular soil in cultivated, continuous fallow with an arbitrarily selected slope length of 72.6 ft. and slope steepness of 9%. Soil texture is the principal factor affecting K, but structure, organic matter and permeability also contribute (Stone, & Hilborn, 2000). A proper value can be estimated from soil maps, if available, for the study region. If soil texture that is determined from the percentages of clay, silt and sand particles in soils is spatially known at a sufficient resolution for the study area, the following equation obtained from a regression analysis on a world-wide dataset of all measured K-values can be used to approximate the K-factor values:

$$K = 0.0034 + 0.0405\, exp\left[-0.5\left(\frac{log\, D_g + 1.659}{0.7101} \right)^2 \right] \qquad (2.9)$$

where K is soil erodibility factor, D_g is geometric mean weight diameter of the primary soil particles (mm). D_g is a function of surface texture, and its value can be calculated using:

$$D_g = exp\left(\sum f_i\, ln\left(\frac{d_i + d_{i-1}}{2} \right) \right) \qquad (2.10)$$

For each particle size class (clay, silt, sand), d_i is the maximum diameter (mm), d_{i-1} is the minimum diameter and f_i is the corresponding mass fraction (Van der Knijff et al., 2000a; Van der Knijff, Jones, & Montanarella, 2000b).

C-factor is originally a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. It is used in the USLE equation to include the relative effectiveness of soil and crop management systems in terms of preventing soil loss. While a good estimate can be obtained through the multiplication of two separate factors; crop type factor and tillage method factor (Tables 2.1 & 2.2), any direct value (potentially ranging between 0.04 for thick meadow and 1.00 for continuous fallow land or bare soil) can also be assigned by considering the vegetation density over the land in relation to the standard condition of bare soil. Although the characteristics of vegetation and management types can slightly differ between regions, it would not negatively affect the overall quality of results if proper values are assigned for the two factors by considering the default values provided in relevant literature. Land-cover maps help much at this point for spatially assigning C-factors to the study area. As the value of C mainly depends on the vegetation's cover percentage and growth stage, a map of Normalised-Difference Vegetation Index (NDVI) generated from satellite imagery or other kinds of remotely-sensed data can be used from the hypothetical relationship between NDVI and corresponding C values to approximate C using the following provisional formula:

$$C = exp\left[-\alpha \frac{NDVI}{(\beta - NDVI)} \right] \tag{2.11}$$

where α, β are the parameters that are based on the NDVI - C relationship. Although the parameter values may change depending on the shape of the "NDVI vs. C" curve, an α-value of 2 and a β-value of 1 seem to give reasonable results (Van der Knijff et al., 2000a; Van der Knijff et al., 2000b).

Support practice factor P reflects the effects of practices that will reduce the amount and rate of the water runoff and thus reduce the amount of erosion. It is again the ratio of soil loss by a support practice to that of straight-row farming up and down the slope; hence, the value normally range from 0.25 (for strip cropping and contour application) to 1.0 (for straight-row farming up and down the slope as was used in USLE experiment).

The USLE L and S factors are mostly combined into a single factor referred to as the slope factor, LS. The computation of LS values has been the largest problem in using USLE, especially when applying it to real landscapes within a GIS. Here, field measurements generally provide the best estimates, yet they are not available or practically collectable in many cases (Hickey, Smith, & Jankowski, 1994; Van Remortel, Maichle, & Hickey, 2004). Fortunately, GIS packages are now able to support the algorithms necessary for slope length calculations.

Table 2.1 Default crop type (CT) factors

Crop Type	**CT Factor**
Grain Corn	0.40
Silage Corn, Beans & Canola	0.50
Cereals (Spring & Winter)	0.35
Seasonal Horticultural Crops	0.50
Fruit Trees	0.10
Hay and Pasture	0.02

Table 2.2 Default tillage method (TM) factors

Tillage Method	**TM Factor**
Fall Plow	1.0
Spring Plow	0.90
Mulch Tillage	0.60
Ridge Tillage	0.35
Zone Tillage	0.25
No-Till	0.25

Among various approaches and algorithms for quantifying slope length, the USLE-based algorithm, which was developed and previously presented by Hickey et al. (1994) and Hickey (2000), was utilized in this study in its most recent form that was amended by Van Remortel et al. (2004) via the modification of a few assumptions in the code concerning the treatment of high points, flat areas, slope breaks, and other specific slope criteria. One of the assumptions that the algorithm considers is that the highest cumulative slope length takes precedence in areas of converging flows. The second assumption relates to the areas where deposition, not erosion, is the dominant process, and for defining the areas of deposition accordingly, the algorithm includes a mechanism called the cutoff slope angle which is defined as the change in slope angle from one location to the next along the direction of flow. Although the code suggests default cutoff factors of 0.7 for slopes less than 5% and 0.5 for slopes greater than or equal to 5%, it does allow the user to specify any cutoff value. It is important to note that the algorithm only consider the nearest upslope location in the cutoff calculations, i.e. not an average upslope or maximum uphill slope angle (Hickey, 2000). For computational reasons, the code also assigns a 0.1 degree value for slopes equal to zero with the assumption that all cells, even essentially flat areas such as dry lakes, have slopes greater than 0.00 in degrees.

As USLE uses the concept of the unit experimental plot which is defined as being a flat (unridged) bare fallow plot 72 ft long (22.13 m) on a 9% slope cultivated up and down the slope (Wischmeier, & Smith, 1965; Wischmeier, & Smith, 1978), the USLE L-factor is often expressed as;

$$L = (\lambda / 22.13)^m \tag{2.12}$$

where L is the slope length normalized to the 22.13-m-long slope, λ is the slope length (m) and m is an empirical exponential coefficient that is derived based on Table 2.3 as suggested by Renard, Foster, Weesies, McCool, & Yoder (1997). The slope length λ is only the upstream length computed either to a flow start point or to a point where the length measure is reinitiated due to slope cutoff (i.e. potentially a deposition point upstream). The S component of USLE LS-factor is computed from the following equation:

$$S = 0.065 + 0.0456(slope) + 0.006541(slope)^2 \tag{2.13}$$

where slope is actually the percent slope steepness.

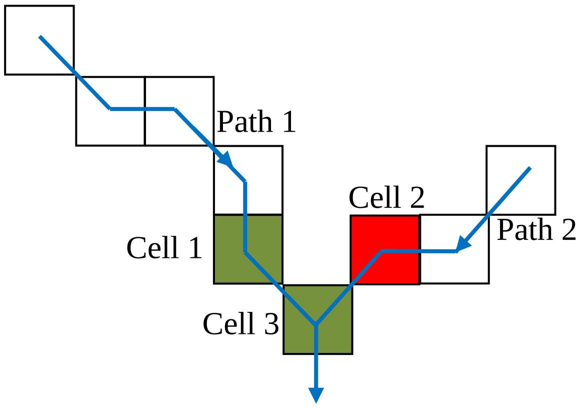
As USLE gives an estimate of soil loss from a drainage area and not essentially from the computation location, it is important in spatial operations to consider the percent slope steepness and the slope angle values, which are respectively used in computing the S-factor and the m exponent of the L-factor, as values averaged along the path for which the slope length λ is computed (i.e. neither the actual values for the computation location nor the average value for the area draining to this location). The same logic also applies to the other factors; R, K, C, and P, finally to be used in the USLE equation. This provides computational compatibility later when calculating erosion from or deposition into any single location within the watershed, and prevents the occurrence of irrational values that may result especially at converging-flow locations, where the slope length of the convergence location can be assigned from a longer flow path (with a different origin) than the path considered for its upstream neighbor on another flow path.

Table 2.3 Slope-length exponent derivation based on the down slope angle

Slope Angle (degrees)	**M Value**	**Slope Angle (degrees)**	**M Value**
$S \leq 0.1$	0.01	$6.3 \leq S < 7.4$	0.37
$0.1 < S < 0.2$	0.02	$7.4 \leq S < 8.6$	0.40
$0.2 \leq S < 0.4$	0.04	$8.6 \leq S < 10.3$	0.41
$0.4 \leq S < 0.85$	0.08	$10.3 \leq S < 12.9$	0.44
$0.85 \leq S < 1.4$	0.14	$12.9 \leq S < 15.7$	0.47
$1.4 \leq S < 2.0$	0.18	$15.7 \leq S < 20.0$	0.49
$2.0 \leq S < 2.6$	0.22	$20.0 \leq S < 25.8$	0.52
$2.6 \leq S < 3.1$	0.25	$25.8 \leq S < 31.5$	0.54
$3.1 \leq S < 3.7$	0.28	$31.5 \leq S < 37.2$	0.55
$3.7 \leq S < 5.2$	0.32	$37.2 < S$	0.56
$5.2 \leq S < 6.3$	0.35		

After spatially computing all necessary factors for the USLE equation, the long term average annual rate of erosion (ton/ha/yr), which results from sheet or rill erosion on a field slope based on rainfall pattern, soil type, topography, crop system and management practices, can be computed by the multiplication of all the overlaid components. As USLE produces an estimate of gross erosion, but does not indicate how much eroded soil is actually transported by streams, a sediment delivery ratio (SDR) may be input to determine the sediment leaving any catchment. Although several models and procedures have been previously developed to estimate SDR, there is still no precise procedure for computing it. SDR can be affected by a number of factors including sediment source, texture, nearness to the main stream, channel density, basin area, slope, length, land use/land cover, and rainfall-runoff factors (Ouyang, & Bartholic, 1997). Generally, a relationship known as the SDR curve is established between SDR and the drainage area (USDA SCS, 1979), yet there are other types of formulation that count for some other parameters such as slope, gradient, relief-length ratio and the long-term average SCS curve number.

For computing the net soil movement (erosion or deposition) within patches, fields, or catchments, patch-level output from USLE can be used. The net soil loss or deposition at any location (i.e. any single grid cell) can be computed as the difference between the amounts of soil loss from the higher location to the lower location along the direction of flow. In the current study, a new code was developed by using the Visual Basic programming language for performing this computation as a spatial operation. The code simply processes all cell locations of the USLE product. It checks the USLE slope length grid for detecting the cell location, among the eight surrounding cells, which uses the same flow path for computing the slope length λ as is used for the computing that of the central cell. As was previously discussed for other operations, such an analytical logic prevents the occurrence of any irrational value, especially at the flow convergence locations, which may result from computing the difference between the two sequential cells (along the flow direction) which do not share the same maximum flow path length (Fig. 2.4). The resulting USLE rate differences (still in tons/ha/yr) should then be multiplied by the cell area for obtaining the final amounts of erosion or deposition in tons/yr.



Net soil movement for the “Cell 3” is to be computed by using the difference between the USLE rates of “Cell 3” and “Cell 1” (i.e., the green cells), and not between the values of “Cell 3” and “Cell 2” as the maximum slope lengths considered for these cells are from different flow paths.

Figure 2.4 A sketch for indicating the use of sequential grid cells in computing the net soil movement.

2.2 Generating the Functionality Indices Used for Assigning an Optimum Protection Distance

The approach developed in the study is originally an index-based approach that basically count on the time that is available within the zone for reducing the pollution through a number of bio-chemical processes, the size of the area that is not occupied by the protection zone and thus is open to commercial activities and settling, the ratio of sedimentation outside the protection zone to the total sedimentation within the reservoir catchment (as proxy to the transfer of associated phosphorus and nitrogen), and the ratio of specially-weighted agricultural and urban land uses outside the protection space to those of the total catchment (as proxy to surface water-driven pollution potentially arising from land sources).

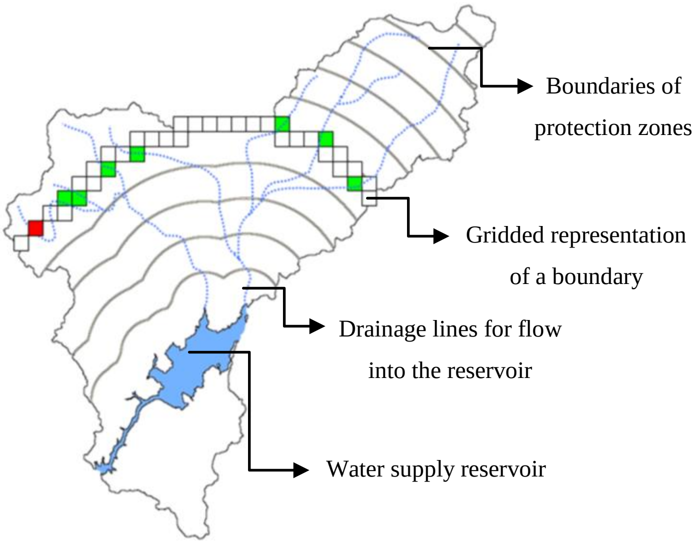
2.2.1 Computing the Time Allocation Index for Protection Zones

Considering the entire process of computing total travel times for reservoir catchments as explained in Section 2.1.2, a time value that is calculated on a specific boundary point of a protection zone actually indicates the total downstream travel time of flow which accumulates from its corresponding catchment and enters the protection zone at that specific location. In this respect, averaging these time values along the boundaries (or boundary grid points) of any protection zone would roughly give the time that is available within the zone for reducing the pollution through a number of bio-chemical processes. However, in performing such an averaging one should be careful not to include any boundary point which does not flow directly into the protection zone, or in other words, which either flows along the boundaries or outwards from the protection zone. This is indeed necessary to prevent double-counting of the flow times assigned to the boundary grid points that lie along the same drainage line or to exclude the points where the flow is directed outwards. By securing this, an average flow time computed from the boundaries of a protection zone down to the reservoir will represent the time that is purely allocated on average to the rehabilitation of the pollution coming to the protection zone. This obviously needs the selection of proper computational points (i.e. the inward flow points) where the flow is always directed to the interior of a protection zone (Fig. 2.5).

After computing average travel times for the protection zones, a time allocation index ranging between 0 and 1 can be calculated for each zone by comparing individual average zonal times to the maximum available in the whole protection zones set as in the following equation:

$$I_{TA,i} = Tt_{AVE,i} / Tt_{AVE,max} \tag{2.14}$$

where $I_{TA,i}$ denotes the time allocation index, $Tt_{AVE,\ i}$ is the average travel time computed for the ith zone, and $Tt_{AVE,\ max}$ is the maximum of all average zonal times in the basin. Here, the protection zone that provides the maximum average travel time for the flow to reach the reservoir is regarded as the maximum capacity that can be supplied by considering all potential protection zones in a watershed.



Average travel time allocated within a protection zone should be computed by only using the inward flow cells (in green in the figure) of the gridded zone boundary.

Any boundary cell from which the flow is not directed into the protection zone (in white), or after which the flow leaves the protection space at any instant (in red) should be omitted while calculating the average.

Figure 2.5 Selection of inward flow points from the boundaries of protection zones.

2.2.2 Computing the Land Utility Index for Protection Zones

A negative aspect of applying protection zones around a water supply reservoir is the restrictions or the total prohibition of certain social and economic activities of the population residing in the catchment area, in order to ensure the necessary levels of quality conditions in the water body as a whole (Samoylenko, & Tavrov, 1997). With this consideration, it is very obvious that any land that is not occupied by a protection zone, and thus is open to settling as well as commercial activities such as industries or agriculture, could be regarded as a gain. The proposed land utility index computes the ratio of unoccupied spaces in a catchment to the total catchment area to simply quantify this. The mathematical expression is as follows:

$$I_{LU,i} = A_{Ext,i} / A_{Total} \tag{2.15}$$

where $I_{LU,i}$ is the land utility index computed from the share of the unoccupied area for the i^{th} zone, $A_{Ext,i}$, in the total catchment area, A_{Total} (Fig. 2.6).

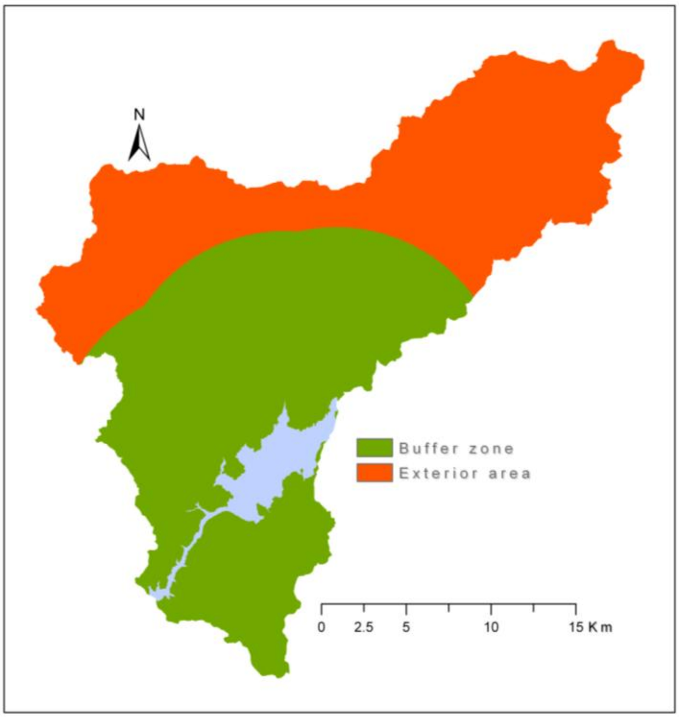


Figure 2.6 The spatial extent of a protection zone and the corresponding unoccupied area.

With a different perception, the land that is left open outside a protection zone can also be regarded as the area for which the protection zone would potentially serve. However, this does not affect the process of index computation, as the index value, which would indicate a positive aspect in any case, will be used as a multiplier while computing the final aggregated indices to be utilized for making decisions.

2.2.3 Computing the Sedimentation Index for Protection Zones

Runoff and soil erosion are the two processes in reservoir catchments known to collectively cause degradation in soil and water quality. The most obvious effect of high sediment content on water quality is turbidity. High turbidity can have detrimental effects on phytoplankton productivity because of attenuation of incoming light. If the suspended load has high organic carbon content, the biochemical oxygen demand will be raised, and conversely, the dissolved oxygen levels will decrease. Sediments are also capable of transporting loads of adsorbed (or sediment-bound) nutrients, pesticides, heavy metals, and other toxins. Sediment particles can contain heavy metals as a part of the structure, as exchangeable cations, or as adsorbed and precipitated matter. Soluble nutrients are transported by surface flow while insoluble forms of nutrients and nutrients adsorbed to sediment particles are transported by erosion, finally causing the eutrophication of a water body.

A specific index is suggested in the study for taking into consideration the extra load and impact of sediment-bound pollution on reservoirs and the zones that provide certain protection against the pollution. The computation of sedimentation index is based on the ratio of total net erosion outside a protection space to that of the entire reservoir catchment. For doing this, it is necessary to compute the total eroded and deposited amounts over the net soil movement data generated at the last step of the procedure explained in Section 2.1.3, first for the unoccupied spaces of each potential protection zone and then for the whole catchment. The general equation can be given as follows:

$$I_{S,i} = (E_{Ext,i} - D_{Ext,i})/(E_{Total} - D_{Total}) \tag{2.16}$$

where $I_{S,i}$ stands for the sedimentation index computed for the i^{th} zone, $E_{Ext,i}$ and $D_{Ext,i}$ are respectively the erosion and deposition amounts (tons/yr) summed over the unoccupied space (i.e. the exterior area) of the i^{th} zone, and E_{Total} and D_{Total} are again the total erosion and deposition amounts (tons/yr), respectively, computed this time over the entire catchment (in other words, the yearly rate of net eroded material arriving at the reservoir).

2.2.4 Computing the Urban and Agricultural Land-based Diffuse Pollution Index for Protection Zones

Although there is general agreement on considering agriculture as the main nonpoint source of nutrients to water (Ripa, Leone, Garnier, & Lo Porto, 2006), the emissions of nonpoint source pollutants as a result of agricultural activities and urban runoff collectively contribute to a great deal of surface water pollution. However, agriculture still has an important share in nonpoint source pollution due to the high percentage of land covered by crops in most watersheds and the heavy use of fertilizers in modern intensive agriculture, while most of the urban runoff pollution comes from limited areas, such as the industrialized and highly urbanized sections of a city.

The derivation of land-based diffuse pollution index is based on the ratio of the size of agricultural and urban areas outside a protection zone to the total size of these land uses within the catchment. Relevant spatial information can be extracted from a land cover map if available for the basin and can be used as proxy to different land use types. In the study, however, an additional spatial smoothing operation through the use of Corilis methodology (Ifen, 2000; Páramo, 2008) is suggested for converting from a static land cover map, which only provides information at approximately the date of data acquisition, into a probability map displaying the “intensities” or “potentials” of a given land cover type in each point of a territory, and for each point of the land, the potential information present in its neighborhood.

The spatial smoothing process generates weighted averages based on the cell value of every location (i.e. 1 to indicate an urban cell or an agricultural cell and 0 for the remaining) by considering a 9x9 neighborhood with the cell size or resolution of 100 m. In the Corilis methodology, the weighting factors are calculated according to the Biweight function:

$$w = (1 - (d / R)^2)^2 \tag{2.17}$$

where w is the weight, d is the distance of a neighbor location to the center and R is the chosen radius (1 km in the study). The weights decrease to 0 as the distance between the considered point and the centre of the 9x9 window increases as given in the following matrix form:

$$W_{9x9} = \begin{pmatrix} 0.0000 & 0.0000 & 0.0400 & 0.1024 & 0.1296 & 0.1024 & 0.0400 & 0.0000 & 0.0000 \\ 0.0000 & 0.0784 & 0.2304 & 0.3600 & 0.4096 & 0.3600 & 0.2304 & 0.0784 & 0.0000 \\ 0.0400 & 0.2304 & 0.4624 & 0.6400 & 0.7056 & 0.6400 & 0.4624 & 0.2304 & 0.0400 \\ 0.1024 & 0.3600 & 0.6400 & 0.8464 & 0.9216 & 0.8464 & 0.6400 & 0.3600 & 0.1024 \\ 0.1296 & 0.4096 & 0.7056 & 0.9216 & \mathbf{1.0000} & 0.9216 & 0.7056 & 0.4096 & 0.1296 \\ 0.1024 & 0.3600 & 0.6400 & 0.8464 & 0.9216 & 0.8464 & 0.6400 & 0.3600 & 0.1024 \\ 0.0400 & 0.2304 & 0.4624 & 0.6400 & 0.7056 & 0.6400 & 0.4624 & 0.2304 & 0.0400 \\ 0.0000 & 0.0784 & 0.2304 & 0.3600 & 0.4096 & 0.3600 & 0.2304 & 0.0784 & 0.0000 \\ 0.0000 & 0.0000 & 0.0400 & 0.1024 & 0.1296 & 0.1024 & 0.0400 & 0.0000 & 0.0000 \end{pmatrix}$$

As the smoothing technique is applied separately to the urban and agricultural land cover maps, they should be merged into a single map for computing the total sizes of urban and agricultural areas. In combining the two maps, the cell values of the already-known urban and agricultural areas are preserved as 1, while the greater of the weighted potentials individually computed from the maps is assigned for the open neighborhood spaces that are not covered by any of the two types (Fig. 2.7).

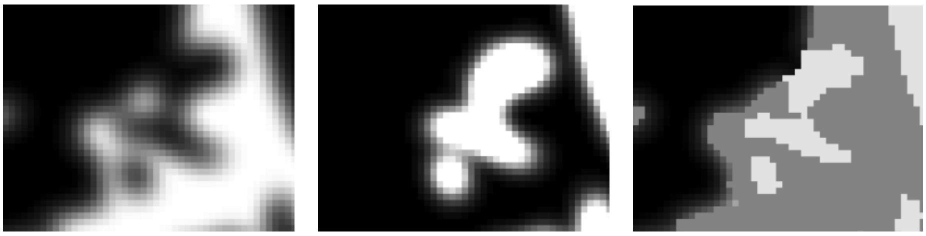


Figure 2.7 Land use intensities/potentials resulting from the smoothing process on (a) agricultural and (b) urban areas, and (c) the combined image.

The diffuse pollution indices can then be computed by comparing the total weighted area (i.e., potential or intensity) of the combined urban-agricultural land outside a protection zone to the catchment total:

$$I_{DP,i} = WA_{Ext,i} / WA_{Total} \tag{2.18}$$

where $WA_{Ext,i}$ is the weighted sum of the urban-agricultural land outside the i^th^ protection zone, and WA_{Total} is the same weighted area accumulated within the entire catchment. Since the runoff generated from a particular land use and the material applied to the land governs the concentrations of pollutants, some additional weights can also be defined, while computing the area sums of the index, to differentiate between the pollution rates that may arise from urban and agricultural areas.

2.2.5 Computing the Zonal Functionality (or Serviceability) Indices for Making Decisions

For making a decision on a proper protection and assigning corresponding distance, all sub-indices need to be aggregated into a final index called the zonal functionality index (or zonal serviceability index). The final index that would allow ranking between varying alternatives for reservoir protection should combine:

i. the positive aspects of the time sufficiently allocated within a protection zone,

ii. the gains from potential uses of unoccupied spaces for settling and commercial activities,

iii. the potential degree and size of the rehabilitation service to be expected from a protection zones against sedimentation and the associated pollution, and

iv. the exposure of a protection zone to the potential pollution load arising from different land uses.

In this regard, the zonal functionality index is defined in the study with the following simple equation:

$$FI_i = [(I_{TA,i}^{wta} * I_{LU,i}^{wlu})*(I_{S,i}^{ws} * I_{DP,i}^{wdp})]^{(1/(wta+wlu+ws+wdp))} \qquad (2.19)$$

where the first part in parenthesis in the base of equation indicates the temporal gains and land savings for any protection case while the latter part indicates the size of the potential loads for which the protection zone will be expected to serve. The exponents; wta, wlu, ws, and wdp are the weights that may potentially be included, if desired, to reflect the heightened significance of any design component (represented by one of the sub-indices) in making the final decision and thus to increase the impact of this dominant component in the mathematical computation. It is very obvious from the equation that it originally yields a weighted geometric mean for all the factors considered. The preference with using the geometric mean instead of any other type like the arithmetic mean can be validated by considering, for example, the case of zero protection distance from the reservoir leaving the entire catchment open for use by human activities. In this specific case, the three indices for representing the land utility, sedimentation and nonpoint pollution issues would obtain the highest value of 1 while the time allocation index is zero. An arithmetic mean of all four indices has a value of 0.75. This is very misleading as there will be no time allocated for protecting the reservoir from the pollution load coming from the catchment entirely. A geometric mean, instead, computes zero value from the multiplication of all the sub-indices and takes this conflict into account by resulting in zero functionality particularly for the no-protection case. In making the final decision, the zone which gives the highest geometric average, that is, the highest overall functionality (or serviceability) can be selected with its optimum protection distance marked from the reservoir, and it can be accompanied with a protection case that include certain type of restrictions to be applied within the zone.

The overall approach, which yields a functionally-adequate protection for reservoirs against pollution from different origins, and which targets a compromise solution between the consideration of securing water quality and the concern regarding the utility of land as a primary resource for different livelihood needs, can be summarized in a dataflow diagram as shown in Fig. 2.8. In the figure, the input data sources, which are required to start necessary operations in different methodological components, and the intermediate data layers, which result from the intermediate operations during the entire process, are indicated in the shaded solid boxes, while the tasks or spatial operations which are performed to generate any intermediate layer or make the final decision are given in the dashed boxes.

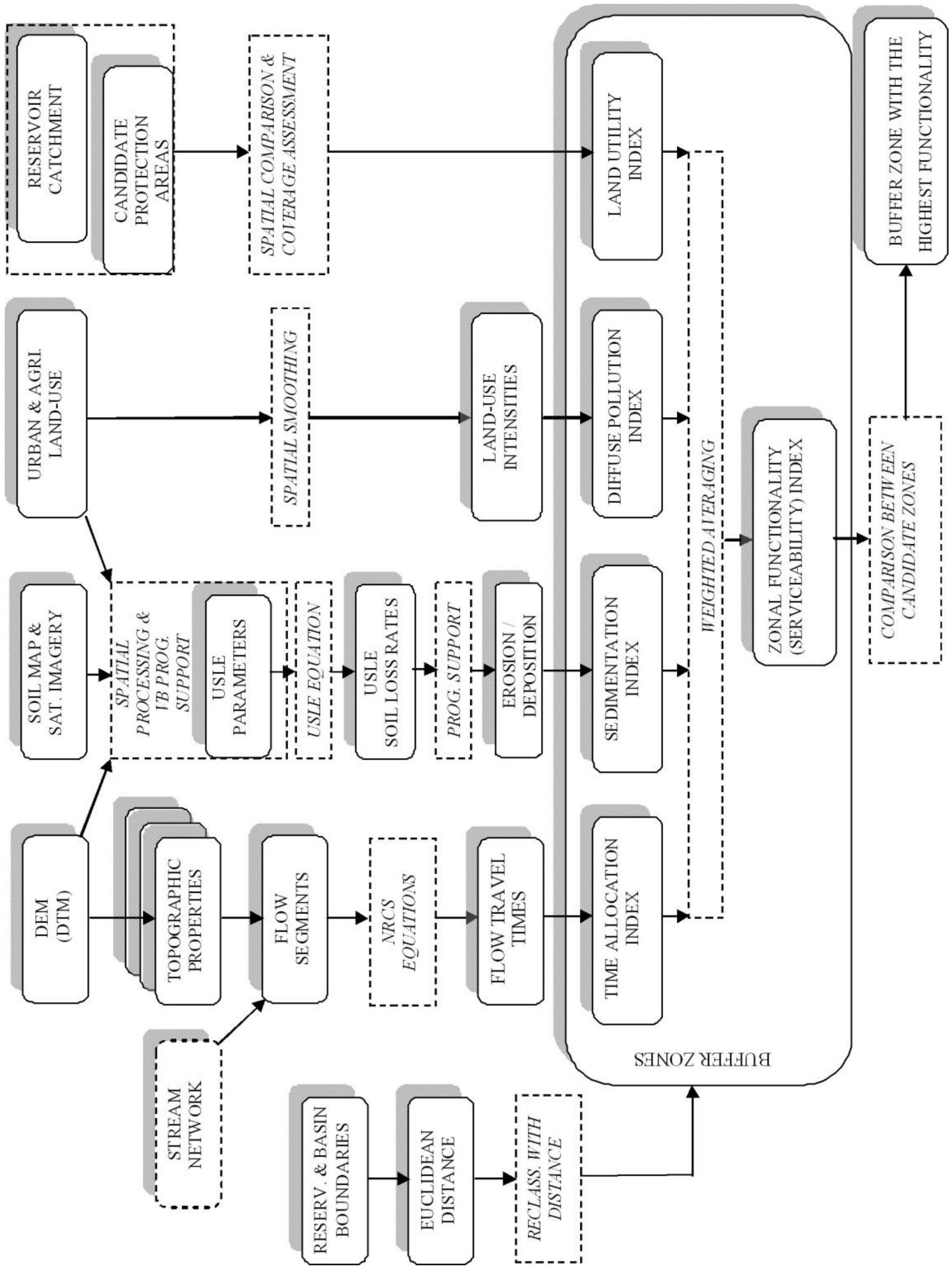


Figure 2.8 Dataflow diagram of the methodology for assigning reservoir protection zones.

CHAPTER THREE
DATA USE & SOFTWARE REQUIREMENTS

3.1 Primary Data Needs

The spatial approach presented in details in Chapter 2 actually does not consist of a data-intensive methodology. The basic sources of data required to perform the spatial operations in the study only include relevant land cover and soil information as well as few statistics to be extracted from the records of a selected number of meteorological stations located nearby the study area of interest.

3.1.1 SRTM (Shuttle Radar Topography Mission) Digital Terrain Elevation Data

The SRTM project is an international research effort of NASA, the US National Aeronautics and Space Administration, and the German and Italian Space Agencies, that obtained digital elevation models on a near-global scale to generate a high-resolution digital topographic database of Earth (Farr et al., 2007). Digital Terrain Elevation Data (DTED) was obtained at 1 arc-second resolution through procession of the interferometric radar data acquired during the entire project period. SRTM digital elevation model (DEM) provides a major advance in the accessibility of high quality elevation data for large portions of the tropics and other areas of the developing world (Fig. 3.1). The data covering all of the countries of the world is accessible from the CGIAR-CSI (Consultive Group for International Agriculture Research, Consortium for Spatial Information) GeoPortal with a resolution of 90m at the equator (CGIAR, 2004). All DEMs are arranged into tiles, each covering one degree of latitude and one degree of longitude, named according to their south western corners. The data is provided as a seamless dataset to allow easy mosaicing and is available in both ArcInfo ASCII and GeoTiff formats to facilitate their ease of use in a variety of image processing and GIS applications.

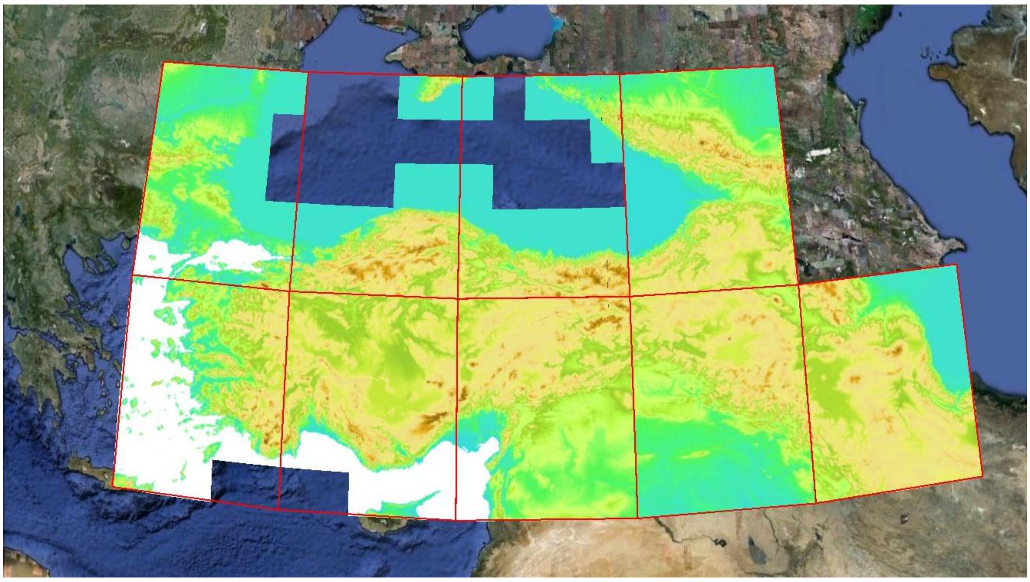


Figure 3.1 SRTM Digital Elevation Model (DEM) tiles covering Turkey.

3.1.2 Corine Land Cover (CLC) Data

CORINE (Co-ordination of Information on the Environment) Land Cover database is one of the main outputs generated from the I&CLC2000 project jointly coordinated by the European Environment Agency (EEA) in Denmark and the DG Joint Research Center (JRC) of the European Commission (EC). CLC2000 data set, for which the CLC90 inventory and its updates are key reference data sets, provides an inventory of the Earth surface features for managing the environment. As only the features that are relatively stable in time were basically mapped while generating the CLC data, it does not indicate diurnal, seasonal, or short-term changes (e.g., vegetation cycle or flooding). The CLC2000 data updated from CLC90 data is for the year 2000, with ± 1 year. The minimum unit for inventory is 25 ha and the minimum width of linear features (e.g., water courses) is only 100 m, meaning that the features and the land cover units smaller than this size were aggregated into a relevant neighbor type (JRC, 2005). As indicated in Appendix 1, the CLC nomenclature is hierarchical and mainly distinguishes 5 classes at the first level, 15 classes at the second level, and 44 classes at the third level. For use in the study, the CLC2000 data for the study region was received from the databases of the Ministry of Environment & Forestry in Turkey (Fig. 3.2).

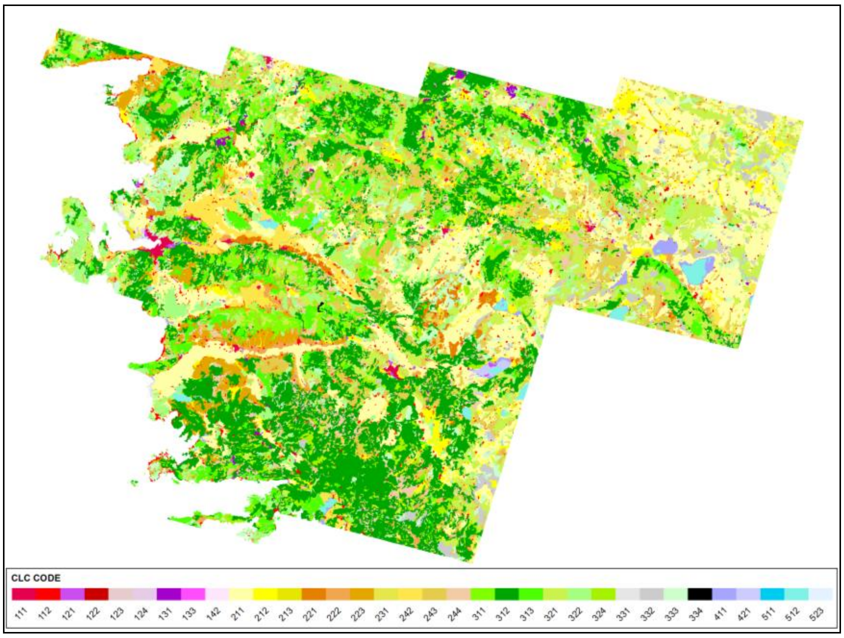


Figure 3.2 CLC2000 land cover data for the study region.

The final land-related data set to be used in performing necessary spatial operations in the study lacks a proper display for small-sized settlements and agricultural units due to the basic limitations with data resolution of the CLC data. For this reason, the CLC2000 data was merged with relevant spatial information that was extracted from the master plan of the metropolitan city Izmir, obtained from the Izmir Metropolitan Municipality (Fig. 3.3).

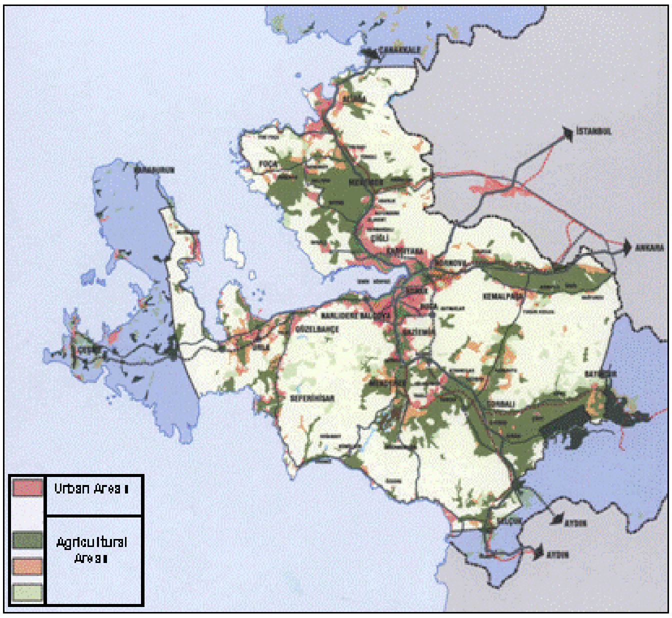


Figure 3.3 Master plan for the metropolitan area (IBB, 2006).

3.1.3 Soil Data

The information on soil types required for the spatial operations to estimate sedimentation in the study region was received from the soil database of Turkey provided by the Ministry of Agriculture & Rural Affairs. The basic data included in the database were generated by using relevant information on major (also called large) soil groups; a number of soil characteristics including depth, slope, drainage, structure, salinity, and alkalinity; some other soil characteristics such as salty areas, alkaline areas, stony areas, and rocky areas; specific land cover types; erosion degrees for water and wind erosion; land use potential of the land classified into a number of classes and sub-classes; and other kinds of geographic data that include rivers, dams, lakes, ponds, seas, settlements, and industrial areas (Fig. 3.4).

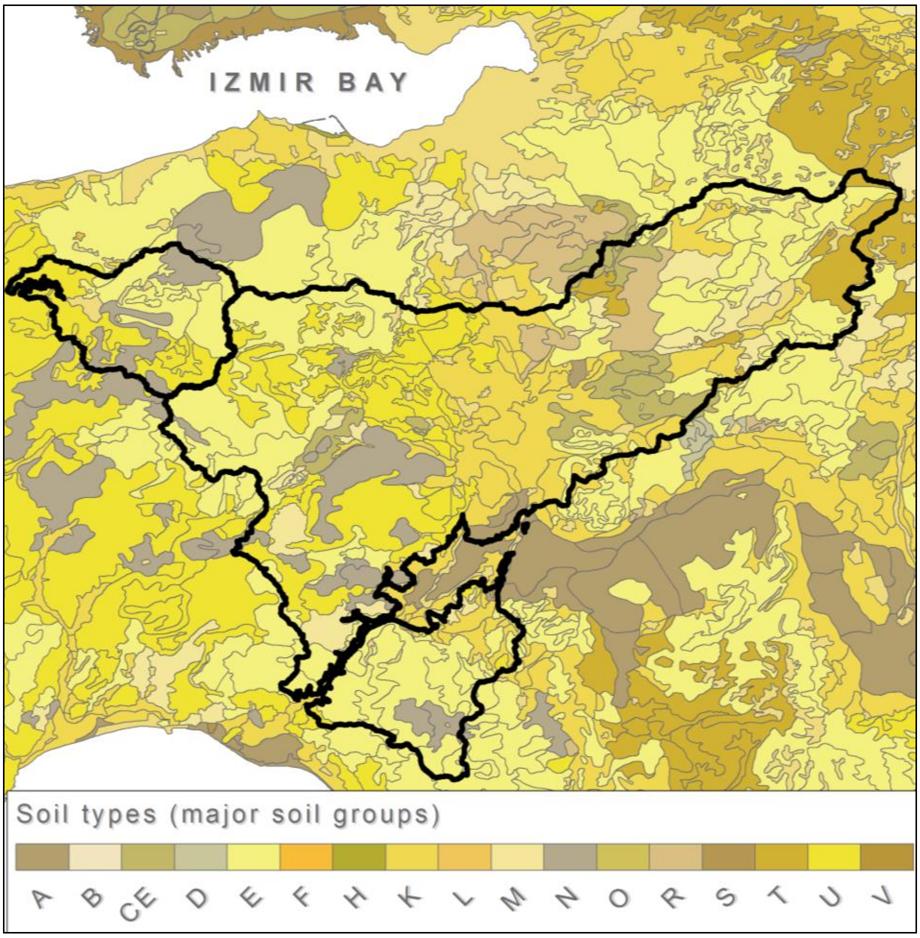


Figure 3.4 Spatial distribution of major soil groups in and around the study region.

As there was no attribute information about surface textural class of soils in the project region linked to the soil polygons of the soil database, some additional data was received from the Joint Research Centre (JRC) of the European Commission. The additional data include the percentages of clay, silt and sand proportions of soils, which were also transformed into desired texture codes of Soil Geographical Database Version 4.0 by using the texture class’s triangle, as well as the dominant surface tectural class of the soil typological units (STUs) (Aksoy, Panagos, Montanarella, & Jones, 2010).

3.1.4 Meteorological Data

The meteorological data was primarily used to obtain the average depths of rainfall with 24-hour duration and 2-year time of recurrence for the selected case-study catchments in the study. These relevant statistics for the meteorology stations in proximity of the study region were obtained from the Frequency Atlas of Maximum Precipitation in Turkey, as given in Table 3.1 and shown in Fig. 3.5. The atlas that was prepared as a comprehensive study evaluating the analysis results of maximum rainfall data all over Turkey includes point precipitation-duration-frequency values as well as some other statistical parameters of precipitation series. These point rainfall statistics were basically computed for identifying the relationship between various rainfall values and were determined by the best fit distribution function of the series (DSI, 1990).

Table 3.1 Long-term average depths (P) of rainfall with 24-hour duration and 2-year recurrence interval, estimated for the meteorological stations in the region

Station Name	**P (mm)**	**Station Name**	**P (mm)**
Dagkizilca	82.32	Seferihisar	59.30
Degirmendere	88.93	Torbali	56.41
Gumuldur	63.69	Urla	69.46
Izmir	57.86		

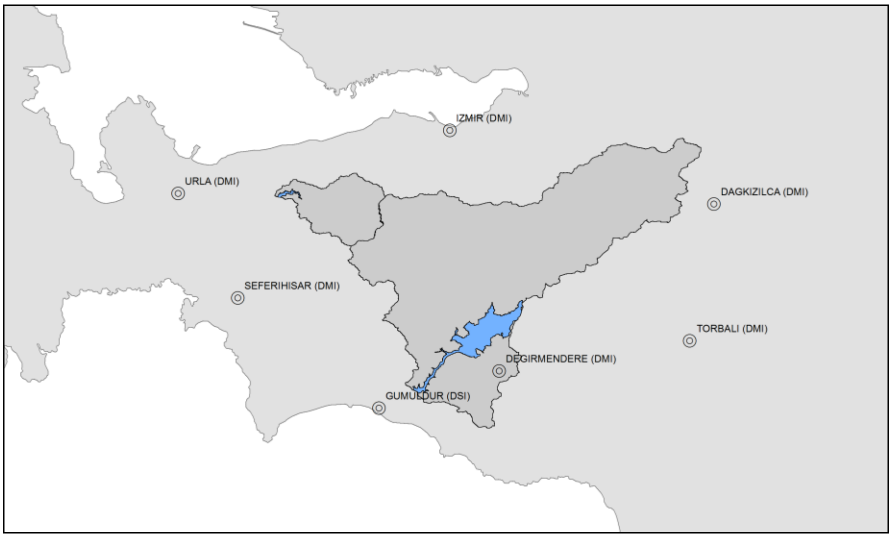


Figure 3.5 Locations of the selected meteorology stations within the study region.

3.1.5 Landsat 5 TM Images

The Landsat program, which is a joint initiative of the U.S. Geological Survey (USGS) and NASA, is the longest running enterprise for acquisition of imagery of Earth from space. Landsat's Global Survey Mission is to establish and execute a data acquisition strategy that ensures repetitive acquisition of observations over the Earth's land mass, coastal boundaries, and coral reefs. On board Landsat 5, there is a multispectral scanning radiometer called Landsat Thematic Mapper (TM) and this sensor provides nearly continuous coverage from July 1982 to present.

The TM sensor has seven bands that simultaneously record reflected or emitted radiation from the Earth's surface in the blue-green (band 1), green (band 2), red (band 3), near-infrared (band 4), mid-infrared (bands 5 and 7), and the far-infrared (band 6) portions of the electromagnetic spectrum. TM band 2 can detect green reflectance from healthy vegetation, and band 3 is designed for detecting chlorophyll absorption in vegetation (Fig. 3.6(a)). TM band 4 is ideal for near-infrared reflectance peaks in healthy green vegetation, and for detecting water-land interfaces (Fig. 3.6(b)). TM band 1 can penetrate water for bathymetric (water depth) mapping along coastal areas, and is useful for soil-vegetation differentiation, as well as distinguishing forest types. The two mid-infrared bands on TM are useful for vegetation and soil moisture studies, and discriminating between rock and mineral types. The far-infrared band on TM is designed to assist in thermal mapping, and for soil moisture and vegetation studies. Landsat 5 TM imagery can be accessed for different acquisition dates through the EROS data center (Earth Resources Observation and Science) of USGS (USGS, 2010a; USGS, 2010b).

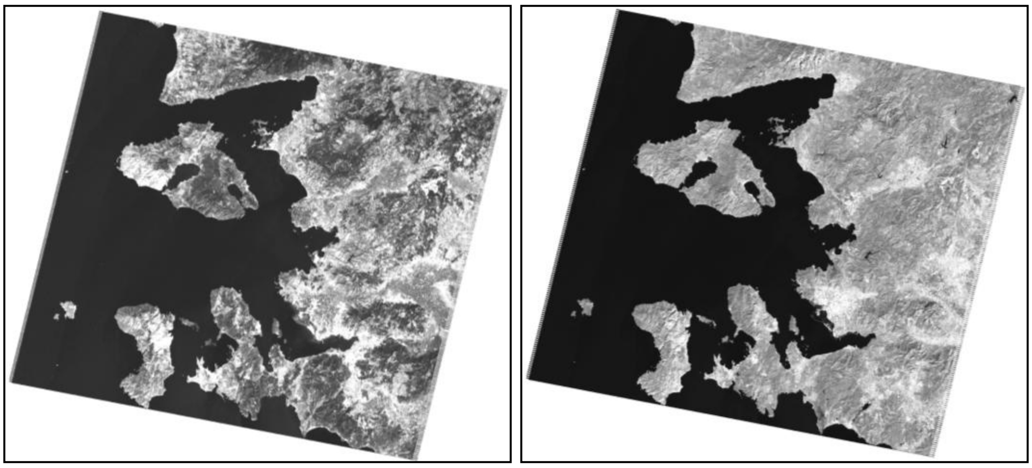


Figure 3.6 Landsat 5 TM (a) band 3 and (b) band 4 images of September, 28, 2009 selected from the image tile covering the study region.

3.2 Software Requirement(s)

Despite its rather little data needs, the proposed approach in the study requires the use of advanced GIS software to perform all necessary operations spatially on catchment scale. ArcGIS version9.3 software developed by the ESRI Company in the US as an integrated collection of GIS software products was used in the study to this end. The software provided a standards-based platform for spatial analysis, data management, and mapping. The study also required a compiler to perform additional computations in the Visual Basic (VB) programming language, and the Microsoft Office Excel software to generate the indexical values previously mentioned in Chapter 2 and finally to prepare a set of related graphics on results.

CHAPTER FOUR
CASE-STUDY APPLICATIONS FOR VALIDATING THE USE OF METHODOLOGY

4.1 Description of the Case-Studies

For validating the overall functionality of the proposed approach, describing the main operational steps, and relating them to the use of basic catchment characteristics, two case-studies were mainly selected. The first of the case-studies, Tahtali Catchment, gained primary importance especially after the Tahtali Dam was commissioned and began to supply water in 1997. The catchment for the reservoir, which potentially supplies 128 million m^3 of water, has an area of about 546 km^2 (IZSU, 2009a). It is roughly located between the coordinates of 38° 02' 45" N-26° 57' 40"E and 38° 23' 10"N-27° 22' 30E" (Fig. 4.1). The area holds a total population of about 100 000 residing in 32 settlements of variable sizes. The major activity in the basin is agriculture. Despite its significance for the metropolitan Izmir, the reservoir is prone to significant levels of environmental pollution originating from domestic, industrial and agricultural discharges originating from its catchment area. Recently, there have been a number of studies that treat water quality issues within the catchment and the reservoir and some efforts for mitigating the reservoir pollution, the quality of surface waters and hence that of reservoir contents has degraded in the last decade as an inevitable result of the hectic commercial activities in the region. Currently, authorities apply restrictions on collective settlements, industrial and agricultural developments particularly in the protection zones of the reservoir. Such restrictions have direct impacts on the social and economical activities of the population residing in the basin (Gül et al, 2010).

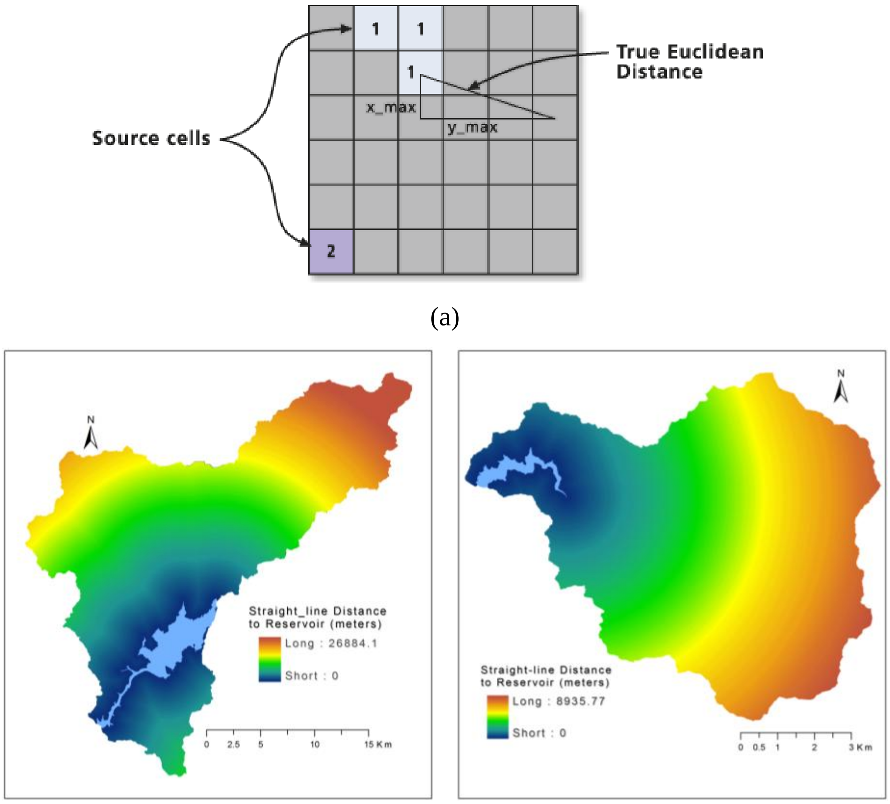
The second case-study, Camli Catchment, is also important from the perspective of pollution control as there is a construction project in the pipeline that targets bringing the metropolitan Izmir another reservoir that would supply water to its vicinity and the downtown (Fig. 4.1). A yearly average of 21,5 million m^3 (0,68 m^3/s) of water is expected to be supplied from the reservoir primarily for drinking purposes. The reservoir has a drainage area of approximately 62 km^2, and receives an annual average of 22.54 million m^3 of water from this area (IZSU, 2009b). Vineyards constitute the major share of products received from the agricultural activities in the region. In the near past, the area received prior attention due to the activities of a gold mine near the Menderes County's Efemçukuru Village, which has been sealed and shut down by the Metropolitan Municipality of Izmir. The Metropolitan Municipality claims that the gold mine cannot be licensed as the area is determined as being part of an area of conservation of the planned Camli Dam.

Figure 4.1 Locations of the Tahtali and Camli reservoir catchments.

4.2 Generating the Analysis Set of Potential Protection Zones

In the study, the analysis sets were generated for both case-studies in order to apply all the analytical steps, and validate the final use and effectiveness of the proposed methodology. To this end, potential protection zones that incrementally varied with a selected unit width of 100 m were composed. The selection of the incremental width for diversifying the zones depends very much on the desired precision with the protection distance to be organized from the reservoir. If the distances of 550 m or 760 m can be regarded, for example, as feasible options for the final decision, then the increments to be used in the analyses should respectively be 50 m or 10 m, rather than 100 m. The only restriction here is with the selected resolution of the digital data layers used in the overall procedure. In other words, any selected cell size of 100 m while processing grid-based data, for example, does not allow for generating zonal boundaries with 10 m intervals, restricting the selection of the smallest interval only to 100 m.

Considering this, the boundaries of candidate protection zones were spatially determined by calculating first the shortest distances to the reservoir. These are true Euclidean distances, which may be different from the sum of cell distances, and are actually represented by the hypotenuse calculated with the other two legs of the triangle (i.e., x_max and y_max) (Fig. 4.2(a)). In this way, two raster maps showing the shortest straight-line distances of each location to the reservoir were obtained as in Figs. 4.2(b) and 4.2(c).

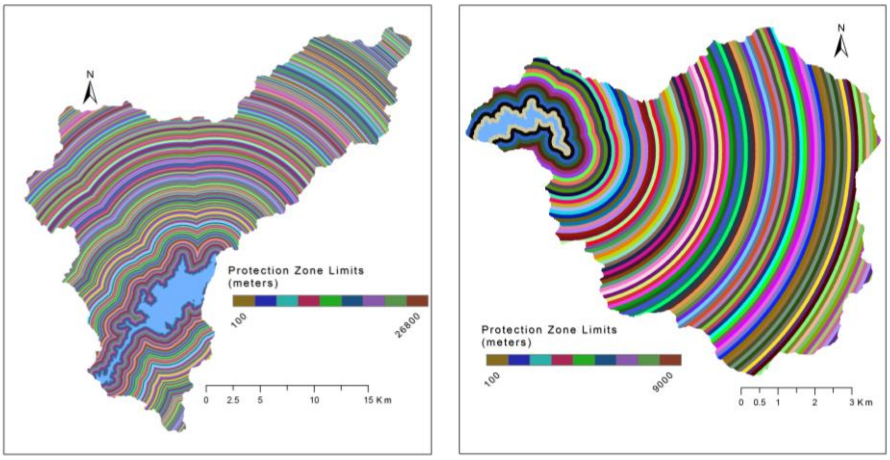


(a)

(b) (c)

Figure 4.2 (a) Computation of true Euclidean distance on a grid; and straight-line distances measured from (b) the Tahtali reservoir and (c) the Camli reservoir.

The boundaries and spatial extents of potential protection areas were then obtained by reclassifying the resulting distance maps with the distance step of 100 m. The process resulted in a total of 269 zones for the Tahtali case and 90 zones for the Camli case, the closest zone having no distance from the reservoir (i.e., referring to no protection) while the remotest zone slightly exceeding the catchment. As can be viewed in Figs. 4.3(a) and 4.3(b)), the geometric extents of the zones that are much closer to the reservoir resemble the shapes of the reservoirs while for the remoter zones the irregularity in shape gets gradually lost making the zones more rounded at their boundaries.



(a) (b)

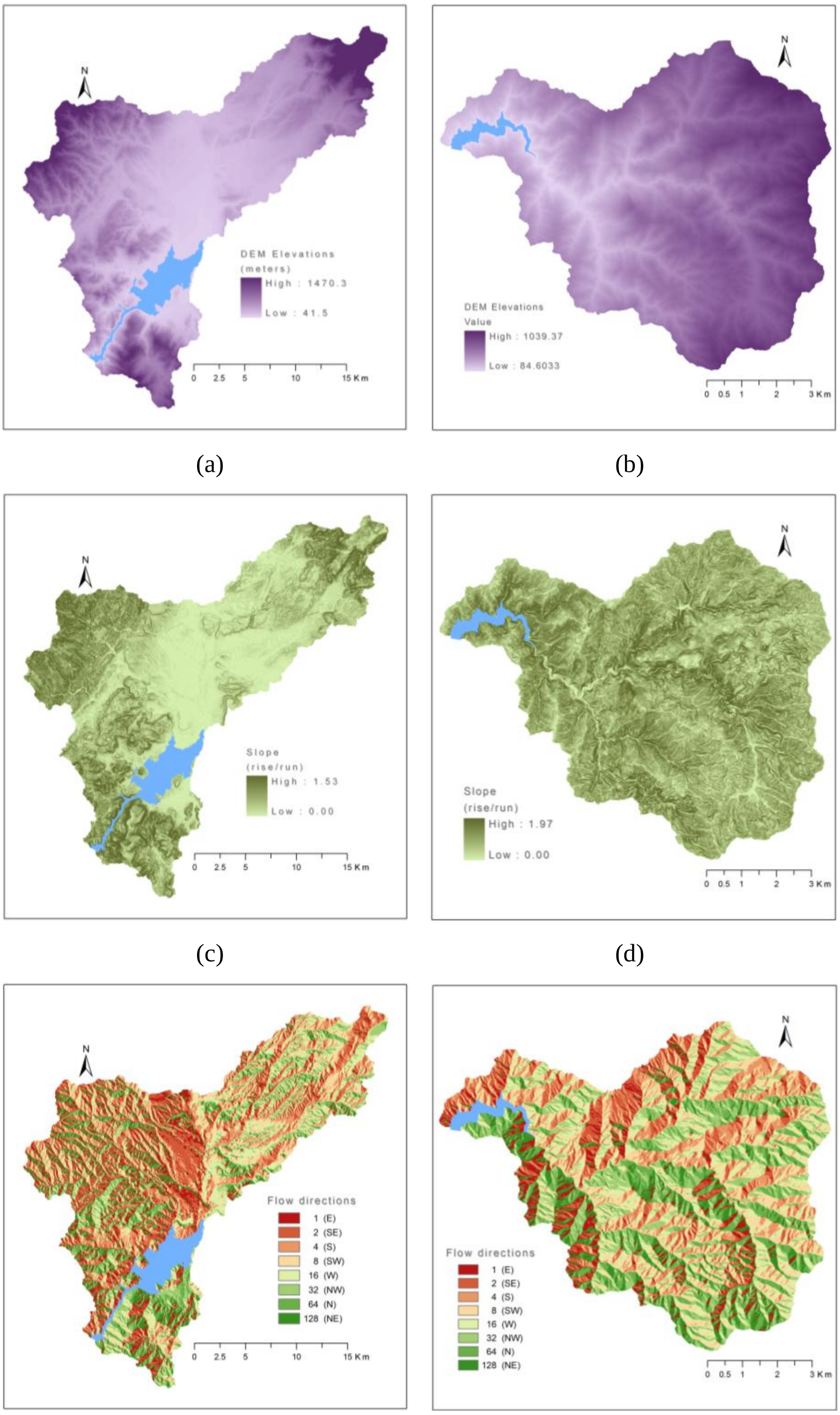
Figure 4.3 Boundaries of fixed-distance protection zones generated around (a) Tahtali and (b) Camli water supply reservoirs.

4.3 Catchment Segmentation Based on the Flow Types

The estimation of travel time for flow in a watershed depend upon watershed characteristics (e.g., drainage area and topography) as well as climatic conditions, required accuracy, limitations with the data, and available time for generating results. In this regard, all the spatial operations performed to this end intensively use a number of watershed characteristics. Here, the most fundamental element is the elevation model (DEM) that is expected to accurately represent the basin topography. A DEM is an ordered array of ground elevations relative to a datum, normally expressed as meters above mean sea level (Fig 4.4(a) & 4.4(b)).

The other two types of spatial data derived from DEM are surface slope and the directions of surface flow. Surface slope identifies the steepest downhill slope for a location on a surface and can be calculated as percent slope or degree of slope. In the study, the slope maps were generated with the values converted from the percentages to indicate rise/run values, i.e. the rate of change in elevation per unit horizontal length (Figs. 4.4(c) & 4.4(d)). The computation of flow directions on a surface is one of the keys to deriving hydrologic characteristics about a catchment. In this computation, the DEM that corresponds to a surface topography is taken as input; the direction of flow is determined by finding the direction of steepest descent, or maximum drop, from each location. To provide simplicity in grid-based computations, eight valid output directions relating to the eight adjacent cells into which flow could travel are primarily considered. In this way, the directional values of 1, 2, 4, 8, 16, 32, 64, and 128 denote the main directions of East (E), South-East (SE), South (S), South-West (SW), West (W), North-West (NW), North (N), and North-East (NE), respectively. The raster layers for indicating the flow directions on both case-studies were produced in the study by using the nomenclature given above (Figs. 4.4(e) & 4.4(f)).

By using the above-mentioned data input, the computational process of obtaining travel times of flow that will be later used in the computation of a relevant index requires the segmentation of watershed into zones of different flow types. In order to accurately determine the travel times in a watershed, the hydraulics of each part of the flow path must be considered separately, by dividing the flow path, for example, into overland flow, channel flow, and even pipe flow segments (SCS, 1986a; SCS, 1986b). Overland flow may be considered to include sheet flow, which is basically expected by NRCS to occur for less than 100 ft but not in a longer distance regardless of the evenness of the surface, and the shallow concentrated flow, which may be alternatively defined as small channel flow as concentrated flow starts to move along the drainage lines that vary from visible stream channels. Channel flow basically includes channelized flow where surveyed cross sections usually are available or can be estimated through spatial calculations.



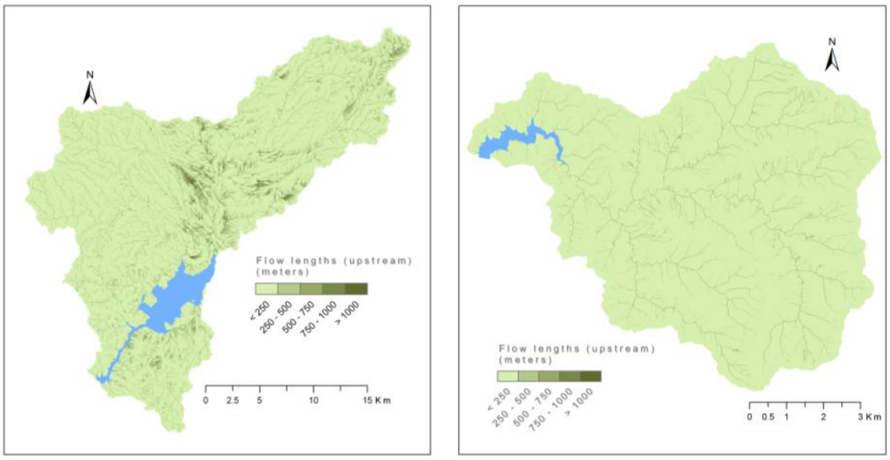
(a) (b)

(c) (d)

(e) (f)

Figure 4.4 Digital elevation models (DEMs) of (a) Tahtali and (b) Camli catchments; terrain slopes of (c) Tahtali and (d) Camli catchments; and the directions of water flow in (e) Tahtali and (f) Camli catchments.

In order to differentiate between the varying flows for the reservoir catchments in the study, the stream networks were first cut out of the entire watershed coverage to be assigned as channel flow segments. Further segmentation of the rest of the watershed into sheet and shallow concentrated flow areas require another data layer that basically show the length of the longest flow path drawn from a watershed point to its corresponding flow-start point located upstream, selected among all available paths over which the water flows into the considered location (Figs 4.5(a) & 4.5(b)). For identifying sheet flow areas, the longest upstream flow lengths assigned to every cell on the grid layer were used and the cells which have shorter upstream lengths than 100 ft were included into sheet flow areas. Such logic can indeed be used as there is no possibility of observing sheet flow at longer distances from the starting points of flow (Merkel, 2001). Here, it should be noted that the upstream flow length grid only holds the distance information from the topographically remotest start point. This would not bring any major problem as the distances measured along alternative routes to a given point, other than the longest one, are shorter and they will anyway stay inside the sheet flow areas.



(a) (b)

Figure 4.5 Upstream flow lengths in (a) Tahtali and (b) Camli catchments.

The segmentation process ends by assigning the rest of the watershed segments remaining between the sheet flow and channel flow zones as shallow concentrated flow areas (Fig. 4.6).

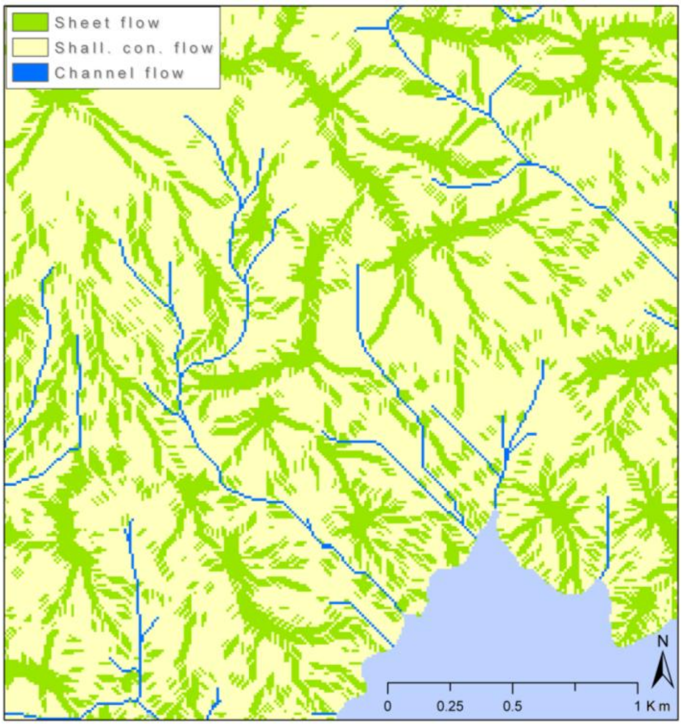
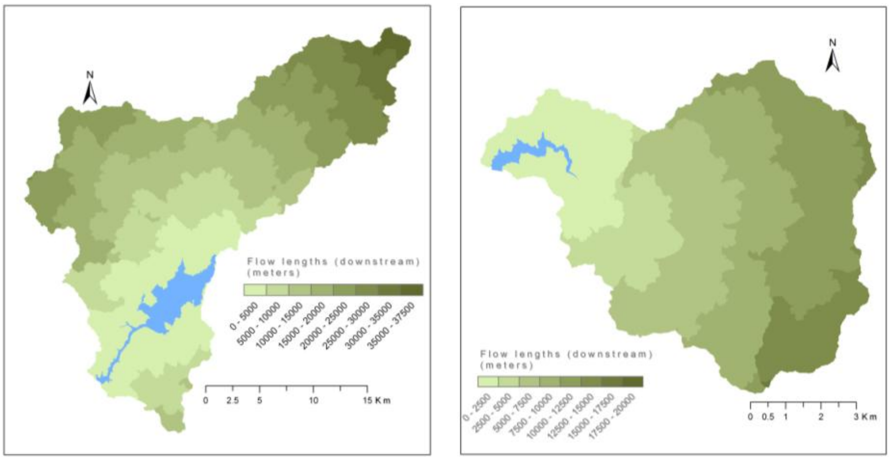


Figure 4.6 Flow development zones in a watershed.

4.4 Computing Total Travel Times of Flow to the Reservoir and Generating the Time Allocation Indices for Alternative Zones

Following the watershed segmentation, the zonal travel times were computed again for the catchments in both case-studies by using the sheet flow equation in Section 2.1.2. For performing the computation, the downstream lengths of flow measured from any location to the last point downstream within the zone was required as the flow length input, L. Figs. 4.7(a) and 4.7(b) show the downstream lengths computed for the entire watershed down to the reservoir. Yet, for the sheet flow computations, the lengths were to be measured only down to the zone outlet (i.e. the points where shallow concentrated flow starts), but actually not until the reservoir. For providing this, the flow directions data layer was clipped by the sheet flow zones and the downstream lengths were computed in the same way as was performed for the entire watersheds as in the figure. This computation yielded zero distance values at the boundaries of the sheet flow zones while getting higher values as going further upstream within the zones. Furthermore, the other two necessary inputs of the sheet flow equation, the surface roughness coefficient and the surface slope, were averaged, by using the VB code specifically developed for this purpose (given in Appendix 3.3), along each flow path starting form an individual location and ending at any outlet point on the sheet flow zone boundary. This is a necessary operation to use the input values as averages along the flow paths for which travel times are computed.



(a) (b)

Figure 4.7 Downstream flow lengths in (a) Tahtali and (b) Camli catchments.

The values of rainfall depth in inches for a rainfall with a 24-hour duration and 2-year time of recurrence were computed by using the rainfall values from the seven meteorological stations neighboring the region (Fig. 4.8). The areal averages of the rainfall depths were calculated as 3.016 in (7.661 cm) and 2.336 in (5.934 cm) for the Tahtali and Camli catchments, respectively. By using these average depths, averaged roughness coefficients, averaged slopes, and the specific downstream flow lengths computed within the zone, sheet flow travel times were finally computed for every cell location.

For computing travel times of flow within the areas of shallow concentrated flow, average velocities were first computed by using the following formula defined for unpaved surfaces. Here, the values averaged along the flow routes and until the zone outlet by using the code in Appendix 3.2 were similarly used as the slope input in the equation. As the computation of zonal times of flow travel similarly requires the determination of downstream flow lengths from any point in the zone down to the zone outlet, the flow directions were first cut out of the full data layer to solely represent the directions within the shallow concentrated flow areas, and then the downstream flow lengths were computed. By using the resulting average velocities and the downstream lengths computed for every location in the zone, the zonal time values were computed accordingly.

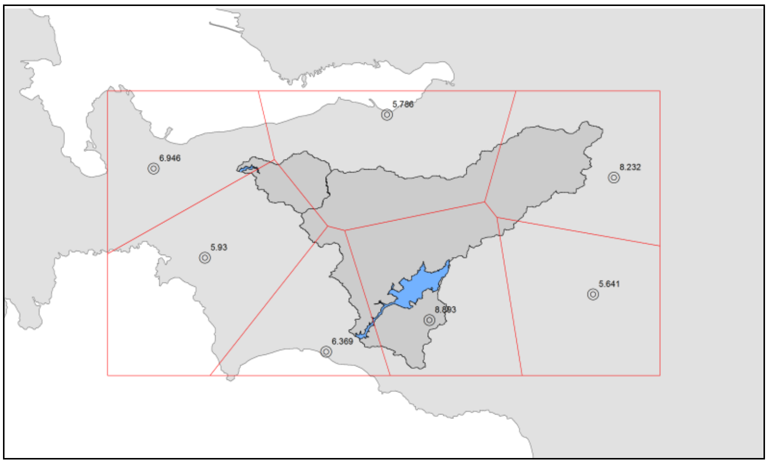
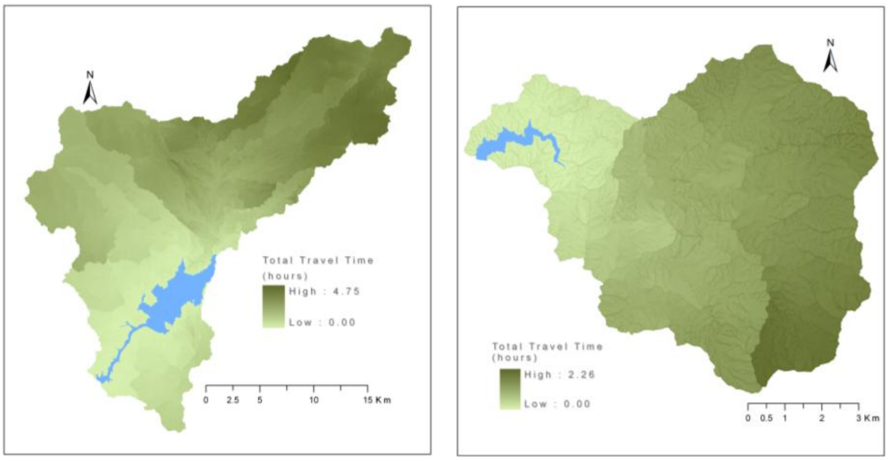


Figure 4.8 Constructing Thiessen polygons from the rainfall values at the meteorological stations around the reservoir catchments.

The average velocities required from computing the travel times of channel flow were determined by using the slopes averaged along the stream channels (using the code in Appendix 3.1) as well as the hydraulic radius and channel roughness values determined from the information collected in the field surveys. Here, there was no need to recalculate downstream flow lengths as the length values from the data layer computed for the entire watershed would simply indicate the actual lengths required for the channel flow zones until the reservoir. The zonal travel time values for channel flow segments were finally computed in the same way with the shallow concentrated flow segments by using the zonal average flow velocities and the distances to the reservoir.

After compiling the zonal travel times separately for each of the three flow segments, the only remaining operation was to combine all into a seamless data layer showing the total travel times for all places in the catchments down to the reservoir, rather than the zonal times only to the zone outlets where the type of flow changes.

This was performed in a three-phased process by using the code given in Appendix 3.4. First, all grid cells in the shallow concentrated flow zones were traced downstream to locate the channel flow cells which they finally flow into and then to add these values of the most upstream channel flow cells to the previously computed time values of shallow concentrated flow. After this operation of merging the travel time values of shallow concentrated flow with those of the channel flow, a value in the shallow flow zone represents the total time down to the reservoir, rather than only to the zone outlet. A similar operation was performed as the second step, but this time to combine the zonal sheet flow time values with the resulting values of the previous step, i.e. with the corrected (or increased) time values of the shallow concentrated flow cells. Again by doing this, the time values computed for individual sheet flow locations turns out to be the total time values from these locations to the reservoir. The third step is actually required for merging the corrected time values from three different flow segments into a single data layer that represents the total travel times of flow within the catchment (Figs. 4.9(a) & 4.9(b)).



(a) (b)

Figure 4.9 Total travel times computed at the watershed scale down to (a) Tahtali and (b) Camli reservoirs.

The final work that relate to the flow travel time is the generation of time allocation indices for candidate protection zones that will be considered as one of the criteria in making the final decision. As any computed total travel value within the watershed is actually the necessary time for the flow to arrive at the reservoir, an average time computed from the boundary of a protection zone would help roughly indicate the time it takes water to flow from the boundary to the reservoir. However, it should be secured in this averaging to exclude the boundary points which do not flow directly into the protection zone for the basic reasons mentioned previously in Section 2.2.1. In the study, all the points that form the boundaries of protection zones were traced downstream, the ones from which the flow does not leave the considered protection zone at any instant of time were detected, and the zonal time averages were finally computed with the help of the code given in Appendix 3.5 and by using the total time values only at such points separately identified for the protection zones (Fig. 4.10).

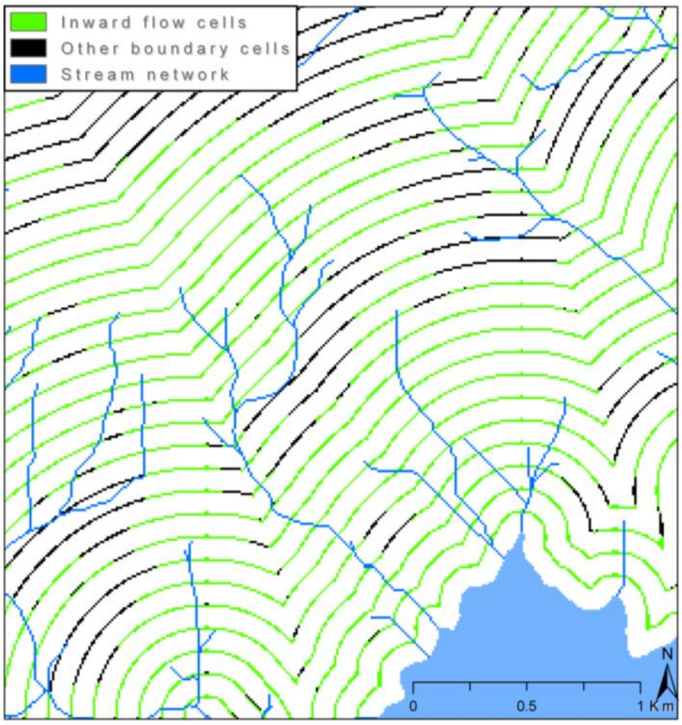
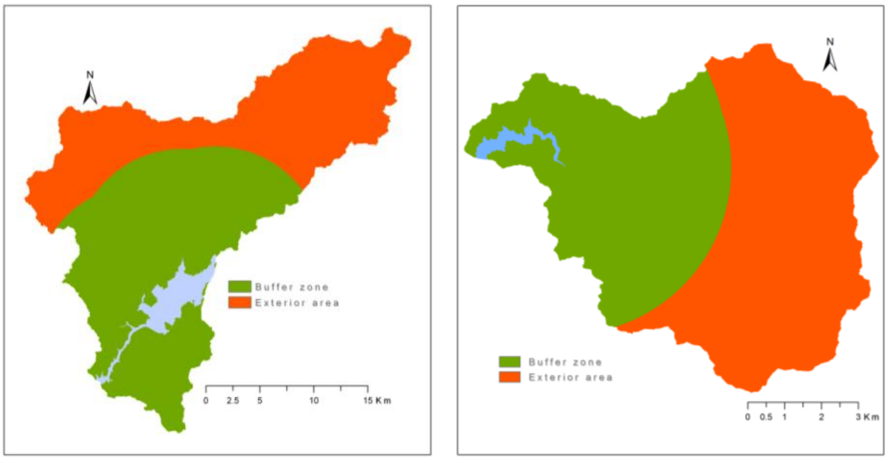


Figure 4.10 Determination of inward flow locations along the boundaries.

4.5 Computing the Land Utility Index for Protection Zones

Land utility index was originally included in the study in order for making a compromise decision that will secure sufficient protection against pollution as well as addressing the subject of land economy to alleviate potential disputes led by the allocation of land for protection purposes. The computation of indices, which indicate the portion of the land that is still utilizable after implementing certain protection, were performed for the entire set of potential protection zones by simply proportioning the area of the land outside the protection space (i.e. the exterior area) to the total area of the reservoir catchment (Fig. 4.11(a) & 4.11(b)).



(a) (b)

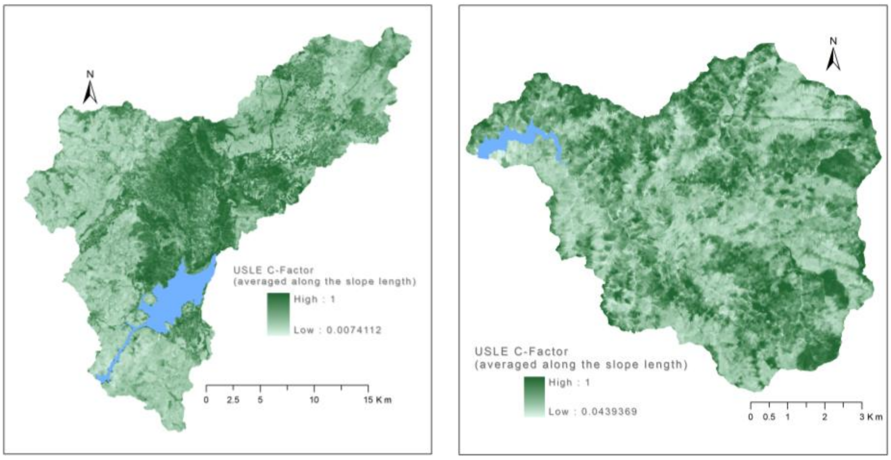
Figure 4.11 Relative distributions of a fixed-distance protection zone and its exterior area at the scales of (a) Tahtali and (b) Camli catchments.

4.6 Assessing Sedimentation in Reservoir Catchments and Generating the Sedimentation Indices to Help Decision-Making

For including the estimated impacts of sedimentation in reservoir protection and thus the final decision on necessary protection, the rates of sediment transport are first to be determined in catchments. In the study, USLE empirical equation was used to this end. In USLE, the process of estimating potential long-term average soil losses from different parts of reservoir catchments depends mainly on the determination of five major factors known as rainfall factor, soil erodibility factor, slope length factor, slope steepness factor, crop/vegetation factor, and support practice factor.

For the region of case-studies in the study, a proper estimate for the R-factor, which approximately reflects the climatic influence on the average rate of soil loss in the region, was identified as 150 by using the distribution of mean annual rainfall index prepared by Doğan (1987).

The spatial distributions of the C-factor in both study catchments were determined by using Eq. 2.11 in Chapter Two (Figs. 4.12(a) & 4.12(b)). For doing this, NDVI indices were first generated by using the band 3 and 4 images of the Landsat 5 TM data dated 28.09.2009 on which the cloud cover was the lowest for the study region. The values of α, β parameters were assigned as 2 and 1, respectively, as advised by Van der Knijff et al. (2000a). The results for the Camli catchment were also compared to the results of a previously-completed project where the C values are simply based on the vegetation densities derived from satellite imagery (Harmancıoğlu, Fıstıkoğlu, & Gül, 2003).



(a) (b)

Figure 4.12 Spatial distributions of USLE C-factor averaged along the computed slope lengths over the drainage area of (a) Tahtali and (b) Camli reservoirs.

K-factors inside the catchment were determined from the available soil maps by using the information on soil depth, texture and erodibility defined for different soil classes. In doing this, soils were first classified into four groups (1 for low erodibility while 4 to indicate high erodibility) based on the soil erodibility definitions already provided in the soil database based on the USDA (United States Department of Agriculture) system (USDA, 1993). Soil polygons were also classified into another layer with respect to the soil depth information which was extracted from the slope-depth combination defined for the soil types in the database, and the indices ranging between 1 for shallow soils and 4 for deeper soils were assigned for different soil types. For performing a third type classification based on the soil texture information, texture types for all soil polygons were first determined by using the sand, silt and clay proportions of the surface soil layers and the soil texture triangle given in Fig. 4.13. After assigning all soil polygons into major textural classes defined by the USDA (e.g., clay, sandy clay, loam, silt loam, loamy sand, etc.), a further classification was performed by converting these major types into gradation types that indicate fine, medium and coarse soils, in the way suggested by the General Directorate of Agrarian Reform of the Turkish Ministry of Agriculture & Rural Affairs (MARA, 2005), with corresponding indices ranging between 1 and 3. USLE K-factors shown in Table 4.1 were finally determined by using the soil characteristics in terms of depth, texture and erodibility, and the values, ranging from 0.19 for the low-erodible, deeper and fine soils to 0.30 for the intensively-erodible, very shallow and coarser soils, were finally determined for the soil polygons within the study sites (Figs. 4.14(a) & 4.14(b)).

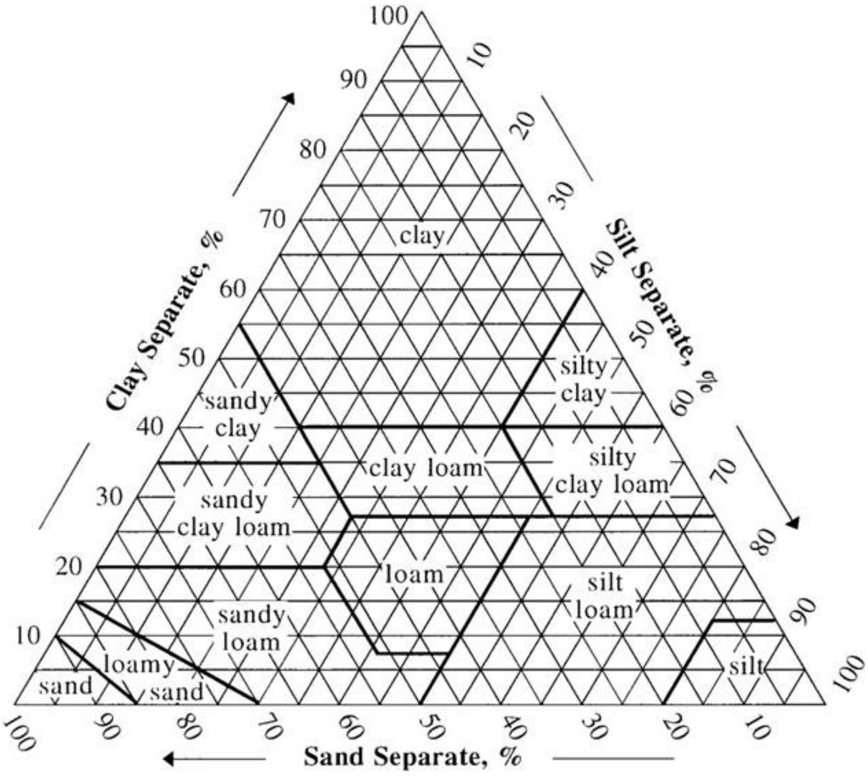


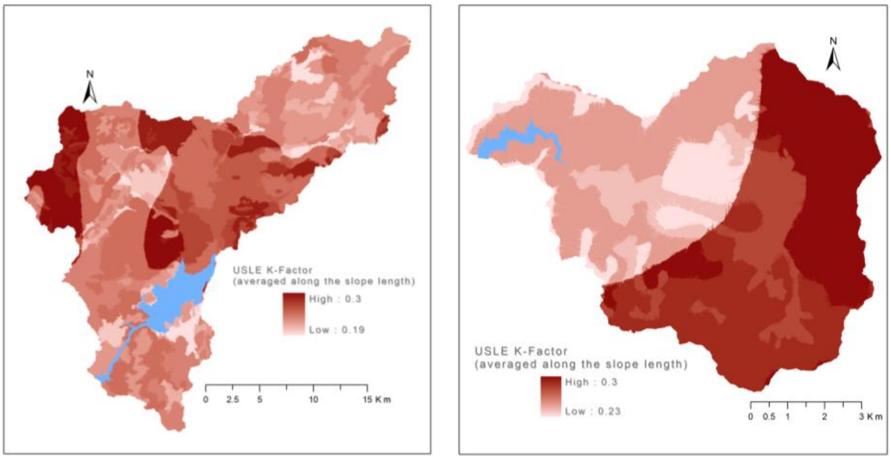
Figure 4.13 Soil texture triangle (USDA, 1993).

Table 4.1 USLE K-factors estimated for soil polygons with different soil characteristics

Texture Index *	**Depth Index**	**Erodibility Index**	**Estimated K-factor**
1	**1**	**1**	0.22
1	1	**2**	0.23
1	1	**3**	0.24
1	1	**4**	0.25
1	**2**	**1**	0.21
1	2	**2**	0.22
1	2	**3**	0.23
1	2	**4**	0.24
1	**3**	**1**	0.20
1	3	**2**	0.21
1	3	**3**	0.22
1	3	**4**	0.23
1	**4**	**1**	0.19
1	4	**2**	0.20
1	4	**3**	0.21
1	4	**4**	0.22
2	**1**	**1**	0.27
2	1	**2**	0.28
2	1	**3**	0.29
2	1	**4**	0.30
2	**2**	**1**	0.26
2	2	**2**	0.27
2	2	**3**	0.28
2	2	**4**	0.29
2	**3**	**1**	0.25
2	3	**2**	0.26
2	3	**3**	0.27
2	3	**4**	0.28
2	**4**	**1**	0.24
2	4	**2**	0.25
2	4	**3**	0.26
2	4	**4**	0.27

* K-factor values are given in the table only for the fine and medium texture types with corresponding index values of 1 and 2, respectively.

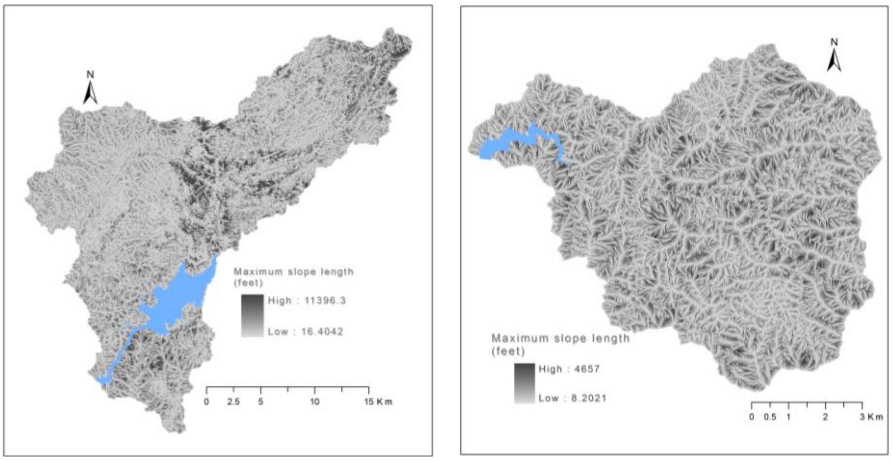
The support practice factor of 1.0 was included in the final computations by assuming that there is no significant practice of any protection measure against the erosion in the catchments. By doing this, it was also aimed to represent the worst conditions in the catchment with regard to the potential erosion problem, and thus to be on the safe side when making the final decision on reservoir protection.



(a) (b)

Figure 4.14 Spatial distributions of USLE K-factor averaged along the computed slope lengths over the drainage area of (a) Tahtali and (b) Camli reservoirs.

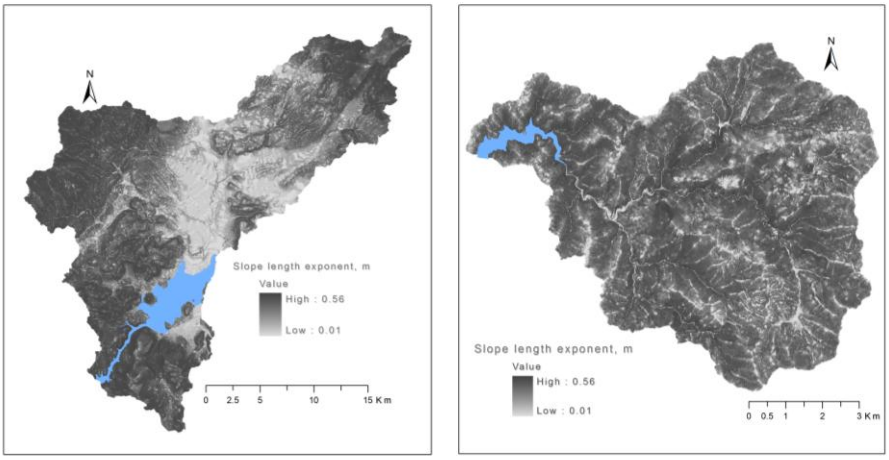
The other significant factor in the USLE equation is the LS slope factor generated from the slope-length factor, L, and the slope steepness factor, S. While computing the values of the L component, the code prepared by Van Remortel in the Arc Macro Language (AML) of the ArcInfo Workstation GIS software, with primary contributions by Hickey, Hamilton and Maichle (Van Remortel et al., 2004), was utilized for obtaining the field slope lengths (i.e. the original λ values) measured from the most upstream points or the points where there is cut off in the slope gradient (Figs. 4.15(a) & 4.15(b)). The code simply takes the maximum length if there are more than one flow paths arriving at the same location (i.e. at the points of merging flows). Although the code is able to give some other kinds of further processed data that include the USLE L-, S-, and the final LS-factors as well as the slope-length exponent, m; these outputs were not used in the computations in the study due to some basic reasons. The code computes the S constituent in a different way from the one used in the study by using the algorithms defined in Renard et al. (1997) and defined separately for the slopes higher or lower than 9%. Besides, the S-factor computation is performed by the code only by using the actual cell values for slopes rather than the slopes averaged along the upstream slope length as is preferred in the study.



(a) (b)

Figure 4.15 The maximum slope lengths for (a) the Tahtali and (b) Camli reservoir catchments.

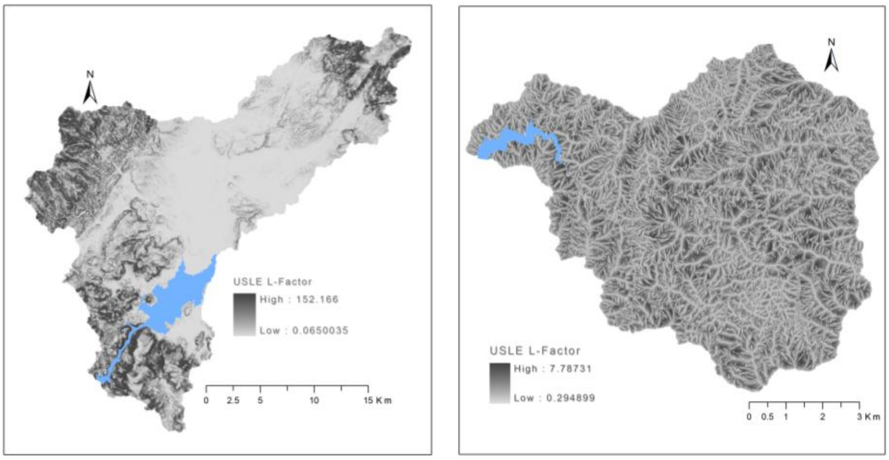
Another conflicting issue relates to the computation of the L-factor by the code. When computing L-factor values, the code assigns the values of the slope-length exponent (m) immediately considering the slopes of the individual grid cells even though it is preferred in the study to compute the m values based again on the average slopes along the slope lengths (Figs. 4.16(a) & 4.16(b)).



(a) (b)

Figure 4.16 The values of slope-length exponent, m, for (a) the Tahtali and (b) Camli catchments estimated from the average slopes along the paths of the maximum slope lengths.

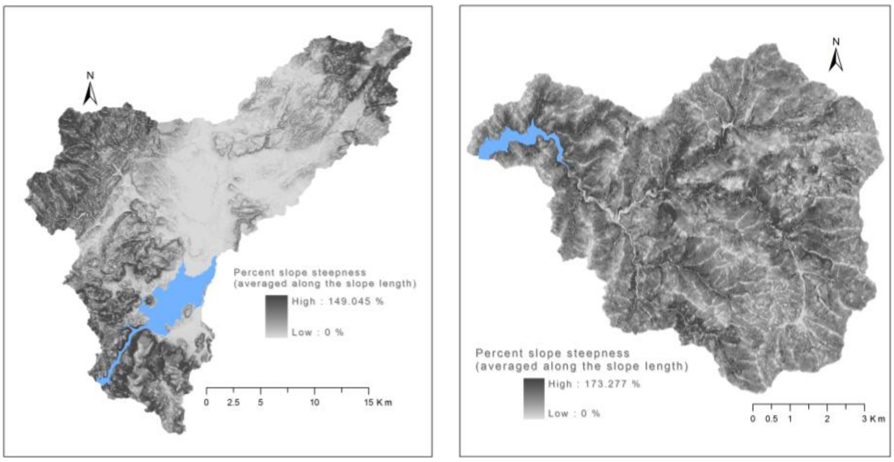
All these different uses only make the λ field slope lengths applicable in the study, but not the rest of the outcomes generated by the code. The λ slope lengths estimated by the AML code was used in Eq. 2.9 in Section 2.1.3 to obtain the normalized slope length, L, for the entire catchments (Figs. 4.17(a) & 4.17(b)).



(a) (b)

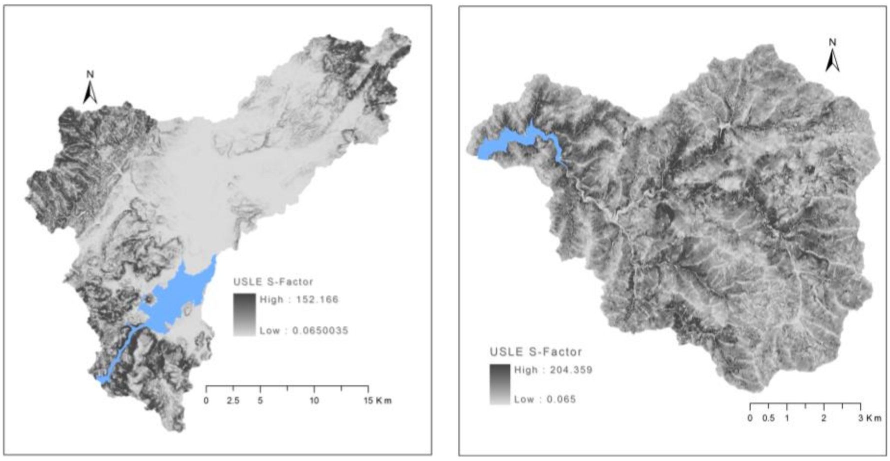
Figure 4.17 The distribution of the resulting USLE L-factors within (a) the Tahtali and (b) Camli catchments.

The desired values of average slopes were obtained for both catchments by using the code in Appendix 3.6, which was developed additionally for the study (Figs. 4.18(a) & 4.18(b)). In these calculations, the averaging of the upstream slopes for a grid cell was performed only considering the slope values on the route for which the slope length were computed for that specific cell location. This has primary importance especially at the junctions where flows from different routes merge. Instead of considering all the routes coming to a cell location, only the one which gives the maximum slope length was basically considered and its slope values were included in the computation. A much general averaging would, otherwise, lead to ambiguities when calculating the difference of sedimentation rates between two consecutive cells, one receiving the slope length input from a path while a different, but longer path is considered for the downstream cell located at a point where the flows combine. In the final step relating to the use of basin slope, the USLE S-factors were computed by using the percent slope averages in Eq. 3.10 (Figs. 4.19(a) & 4.19(b)).



(a) (b)

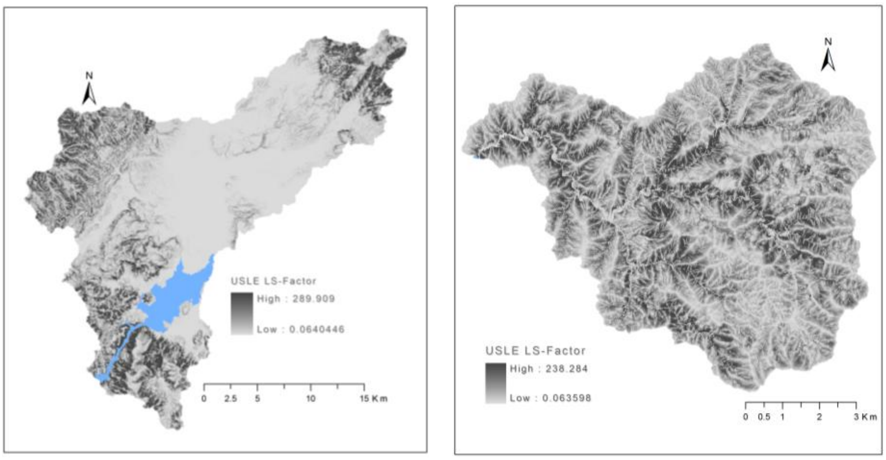
Figure 4.18 Percent slope steepness values averaged along the paths of the maximum flow lengths for (a) the Tahtali and (b) Camli catchments.



(a) (b)

Figure 4.19 USLE S-factors computed for (a) the Tahtali and (b) Camli catchments.

The L- and S-factor values that resulted from the previous steps were then multiplied to obtain the last component, LS, of the USLE soil loss equation (Figs. 4.20(a) & 4.20(b)).

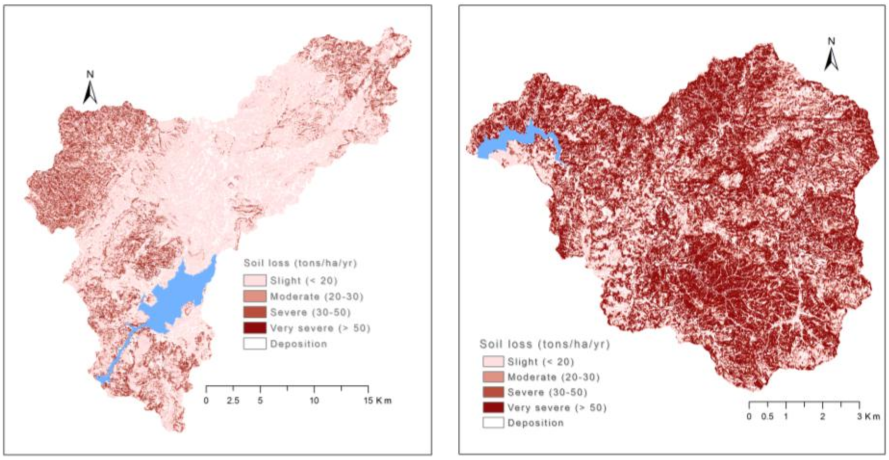


(a) (b)

Figure 4.20 Spatial distribution of the USLE slope factors, LS within (a) the Tahtali and (b) Camli reservoir catchments.

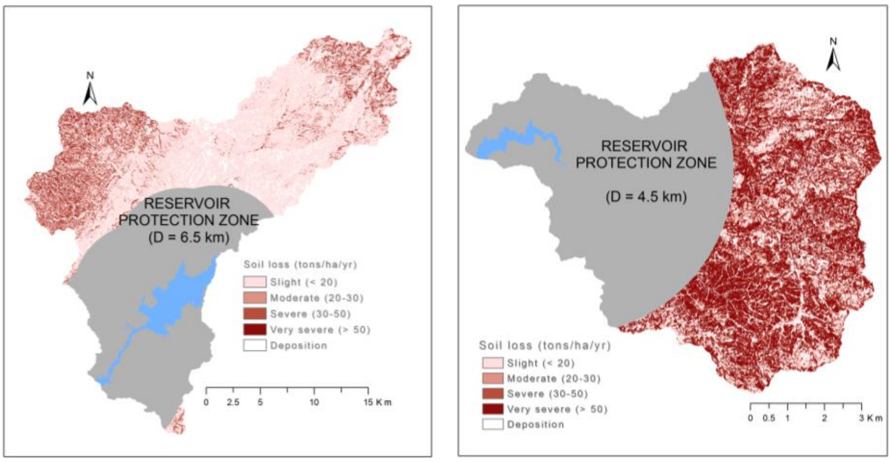
After generating all necessary factors, the annual average soil losses from the catchments were computed by multiplying the R-, K-, LS-, C-, and P- factors as indicated by the empirical USLE equation, and the entire reservoir catchments were characterized based on the intensities of potential erosion due to water runoff. As USLE estimates only the gross erosion, it does not compute deposition, thus does not tell about the amounts that actually reaches any location. For this reason, additional spatial analysis was performed by using the code in Appendix 3.7 to determine the net soil loss from or deposition at any location as the difference between the soil losses estimated for that location and that of a higher location along the reverse direction of flow. This operation also allowed a differentiation between the patches of soil erosion and deposition (Figs. 4.21(a) & 4.21(b)).

The final step in the assessments of soil erosion is to find out potential impacts of sedimentation processes within the catchment on the setup of certain protection around the reservoir. The sedimentation index, which was suggested in the study to this end, was computed by considering the total net loads of the soil transported from the unoccupied land of a protection case, and then relating this to the total net load observed within the entire catchment (Figs. 4.22(a) & 4.22(b)).



(a) (b)

Figure 4.21 Estimated annual rates of soil erosion and deposition arising from upstream sections within (a) the Tahtali and (b) Camli reservoir catchments.

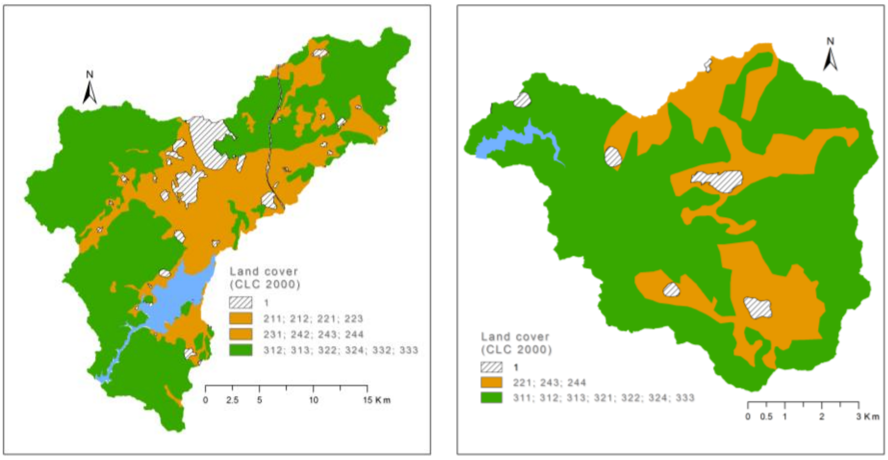


(a) (b)

Figure 4.22 Distribution of yearly average sedimentation outside the sample protection zone (a) with the distance of 6.5 km measured from the Tahtali reservoir, and (b) with the distance of 4.5 km from the Camli reservoir.

4.7 Computing the Pollution Index for Diffuse Pollution from Urban and Agricultural Land Use

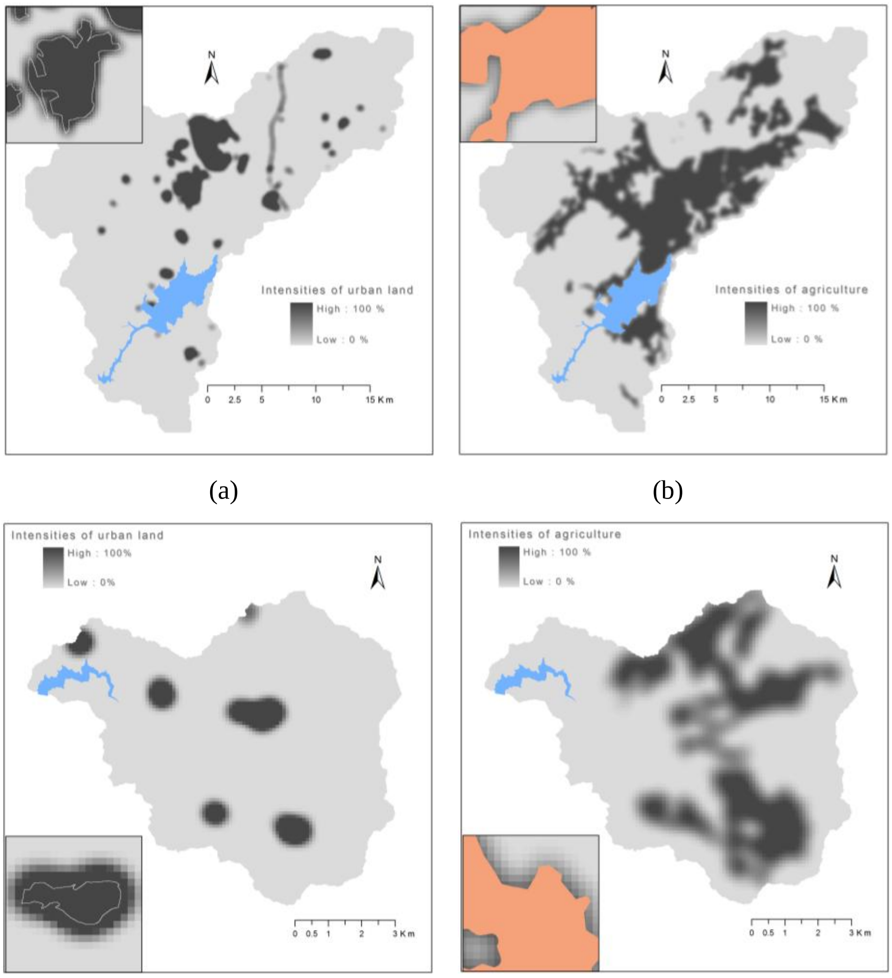
The generation of a relevant measure for indicating the rates of diffuse pollution originating from urban and agricultural nonpoint sources depends very much on a land use map that accurately specify the spatial extent of the activities on urban and agricultural land. In the study, CLC 2000 land cover map, which was modified with more precise information from the master plan of the metropolitan city Izmir, was used as a proxy to represent the land uses in the case-study catchments (Figs. 4.23(a) & 4.23(b)).



(a) (b)

Figure 4.23 Land cover types in (a) Tahtali and (b) Camli catchments, based on the Corine land cover classification.

Due to the basic reasons explained in the relevant methodological section of Chapter Two, some particular spatial smoothing was practiced on both the urban and agricultural land to generate the intensities of these land use types in their neighborhood. For doing this, a Gaussian type statistical function called Biweight was applied as a spatial filter, given in Section 2.2.4, over the gridded surfaces of both urban and agricultural lands to estimate some kinds of extended intensities (or simply the likelihoods) in their vicinity according to the distance from the known land use. This process resulted into probability surfaces varying from 0 to 1 (or from 0% to 100%) for the presence of urban and agricultural CLC class within the considered smoothing radius of 1 km (Fig. 4.24).

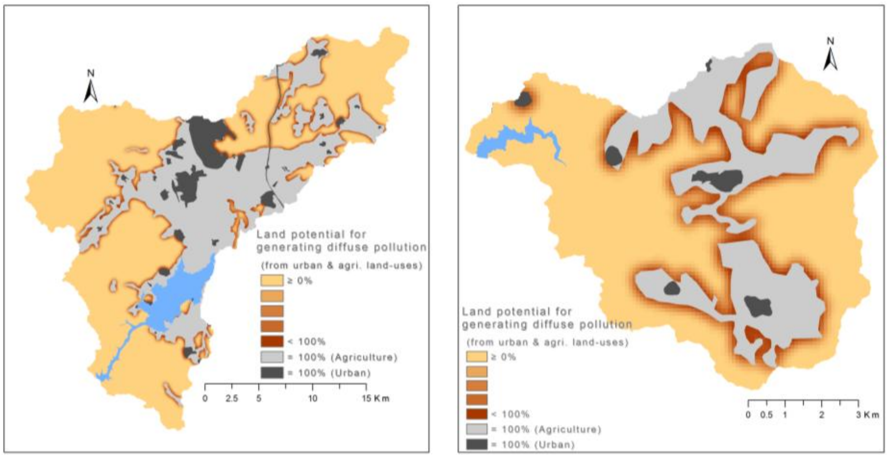


(a) (b)

(c) (d)

Figure 4.24 Intensities (also called potentials or likelihoods) of (a) urban and (b) agricultural areas in Tahtali catchment, and of (c) urban and (d) agricultural areas in Camli catchment.

For approximating potential loads of diffuse pollution from urban and agricultural land uses and then generating a relevant index to rank different alternatives of protection zones based on the spatial extent of these major land uses, the intensities of urban and agricultural areas in different raster layers were combined into a single layer that indicates the spatial distribution of the potentials of land to generate diffuse pollution, mainly due to these specific land uses (Figs. 4.25(a) & 4.25(b)). In performing this combination, the original locations of urban and agricultural areas from the land cover map were retained with full potentials in the final map, and the areas with lesser intensities were appended to these known uses, but with decreased pollution potentials. The final diffuse pollution indices for the protection zones were generated by first computing the totals of urban and agricultural areas, weighted by the land potentials, outside the protection zones; and then relating them to the total weighted area within the entire catchments.



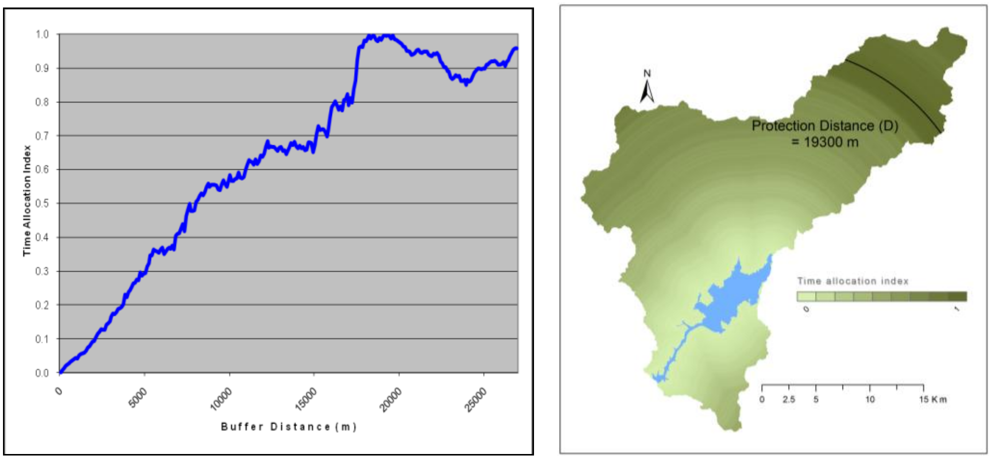
(a) (b)

Figure 4.25 Land potentials for urban and agricultural areas in (a) Tahtali and (b) Camli catchments, based on the combined intensities.

CHAPTER FIVE
RESULTS AND DISCUSSION

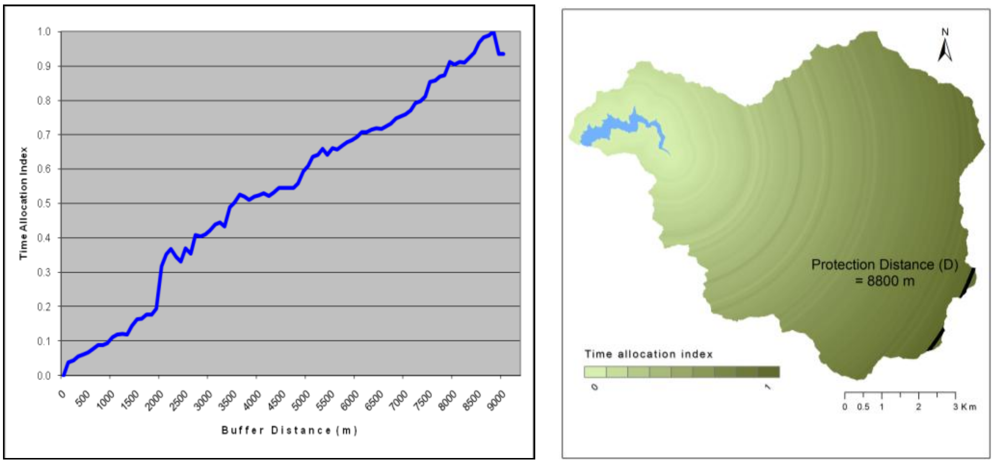
The whole procedure of assessing varying capacities of different protection zones in prior to making the final decision is originally a process that depend on a number of sub-indices that respectively indicate the time component for mitigating water pollution, the economical perspective of land allocated for protection purposes, and the degree of service expected from a protection zone when intercepting loads of pollution and sediment. All these indices end up with a final aggregate index that facilitates decision-making on necessary measures for protection water supply reservoirs via the establishment of protection zones.

The most significant element of the approach presented in this study is the time allocation index and the way it is constructed. When the time averages computed from the boundaries of protection zones for all alternatives are compared to the maximum available time in the watershed and a relevant index in generated in this way, an upward trend is observed in the values as the protection zone gets widened to the most remote parts of the watershed (Figs. 5.1 & 5.2). It is very normal to have higher times as the boundary of a potential protection zone move away from the reservoir, bringing in longer distances for the pollutants to travel within the zone. However, the relationship between the time and the protection distance is not necessarily of a linear type due to the basic conceptual differences between the processes of structuring the protection zones and computing the times of travel. The segmentation of watershed and the computation of travel times of flow from every point on the catchment until the reservoir are realized by strongly considering the hydraulic and hydrologic characteristics as well as the topography, yet the boundaries of potential protection zones one of which will be assigned as the final protection rule are formed simply by using a straight-line distance measure in the Euclidean space. The differing geometries of the protection areas with respect to their distances from the reservoir and/or the different compositions of the flow types between the protection zones may also be expected to result in such a non-linear increase of the time values by the protection distance, as these are the constitutive factors that strongly affect the flow travel times computed and then averaged for the protection zones.



(a) (b)

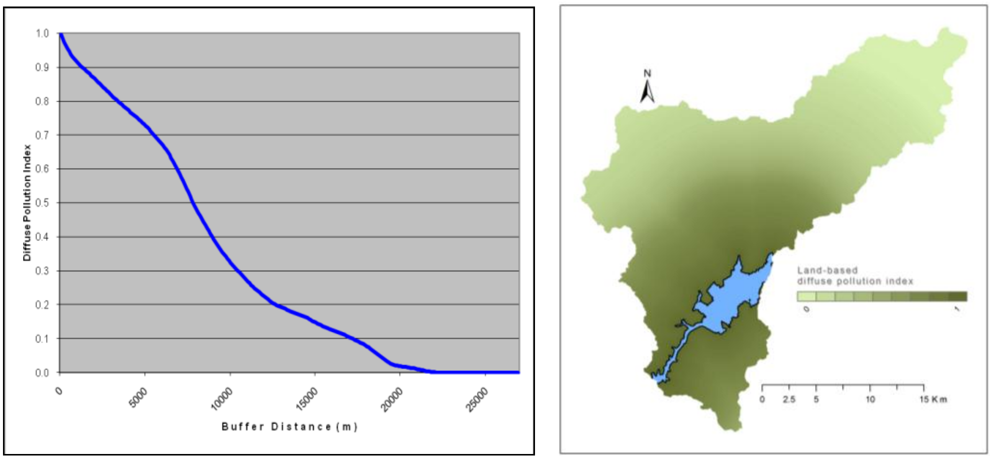
Figure 5.1 (a) Graphical distribution of the average times of flow travel, computed from the boundaries of the protection zones with varying Euclidean distances; and (b) spatial illustration of the zonal average times changing with the distance (D) from the Tahtali reservoir. The distance of 19300 m. in the figure corresponds to the maximum available time index for the catchment.



(a) (b)

Figure 5.2 (a) Graphical distribution of the average times of flow travel, computed from the boundaries of the protection zones with varying Euclidean distances; and (b) spatial illustration of the zonal average times changing with the distance (D) from the Camli reservoir. The distance of 8800 m. in the figure corresponds to the maximum available time index for the catchment.

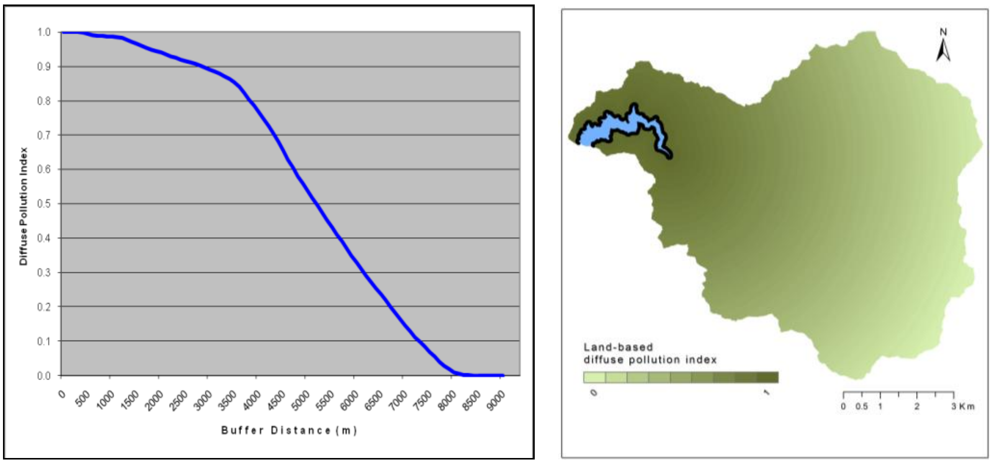
The figures of diffuse pollution index, which were computed for the urban and agricultural land uses within the catchments especially due to the need of representing potential diffuse pollution from these nonpoint sources by their total areas as a spatial measure, show primary differences between the two case-studies. In the case of Tahtali catchment, there is almost a stabilized rate of change in the index value as the protection distance increases up to 20 km (Fig. 5.3). For the Camli catchment, the change in the index value is sharper after a distance of approximately 4 km (Fig. 5.4). Such a different view can best be explained by the varying densities of the urban and agricultural land uses within the two catchments. In the Camli case, the land occupied (currently or potentially) for these uses is not in close proximity of the Camli reservoir, while in the Tahtali case, the use of land especially by agricultural activities starts immediately at the reservoir boundary, particularly in the north.



(a) (b)

Figure 5.3 (a) Graphical distribution and (b) spatial distribution of the land-based diffuse pollution index displayed against the varying Euclidean distances from the Tahtali reservoir. The maximum index value of 1.0 is obtained necessarily for the case of zero protection distance, i.e. no protection case.

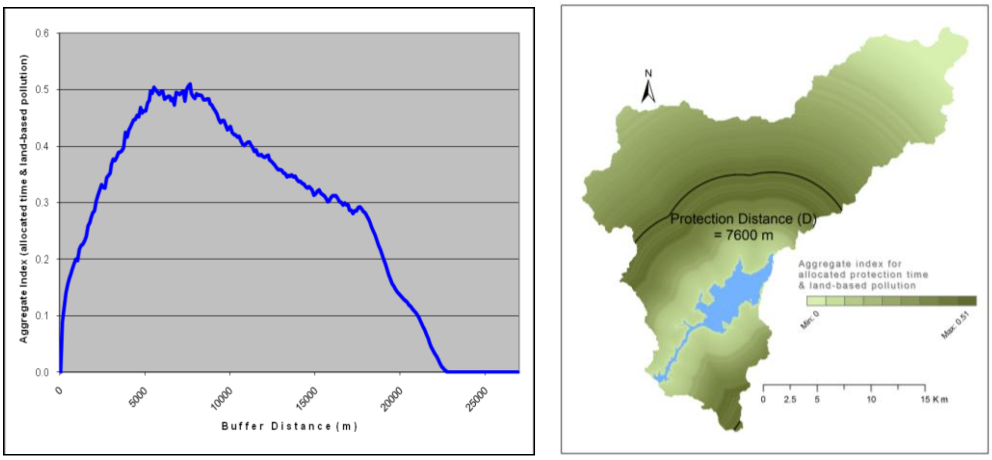
An aggregate index can immediately be structured for both case-studies by combining the time index, which was generated based on the average time allocated within a protection zone for rehabilitating polluted water, and the diffuse pollution index, which in principle indicate the potential degree of pollution originating from urban and agricultural activities over the land.



(a) (b)

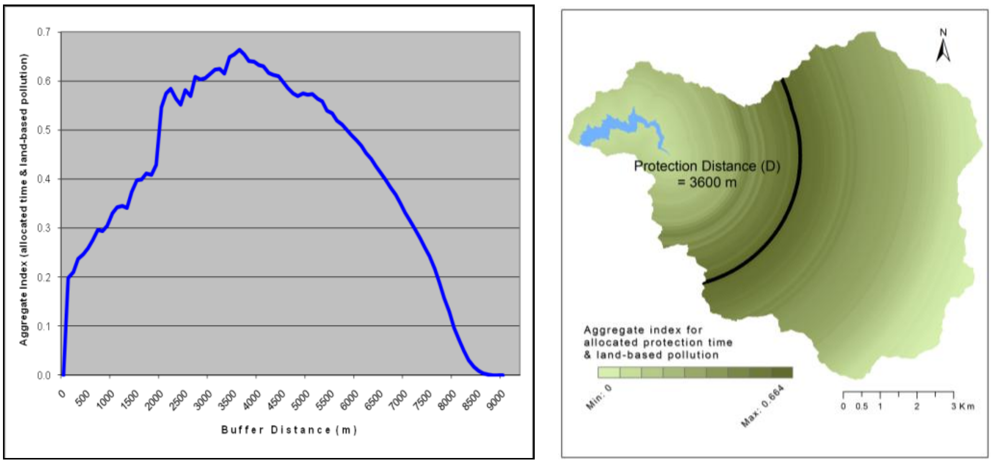
Figure 5.4 (a) Graphical distribution and (b) spatial distribution of the land-based diffuse pollution index displayed against the varying Euclidean distances from the Camli reservoir. The maximum index value of 1.0 is obtained necessarily for the case of zero protection distance, i.e. no protection case.

Such an immediate assessment, without taking into account the impacts due to sedimentation in the catchments and the economic uses of the land, provides an early estimate to the width of the desired protection zones that are to be settled around the reservoirs in the two catchments. The results indicate protection distances of 7.6 km and 3.6 km, foreseen from the assessments up to this stage, for the Tahtali and Camli reservoir catchments, respectively (Figs. 5.5 & 5.6).



(a) (b)

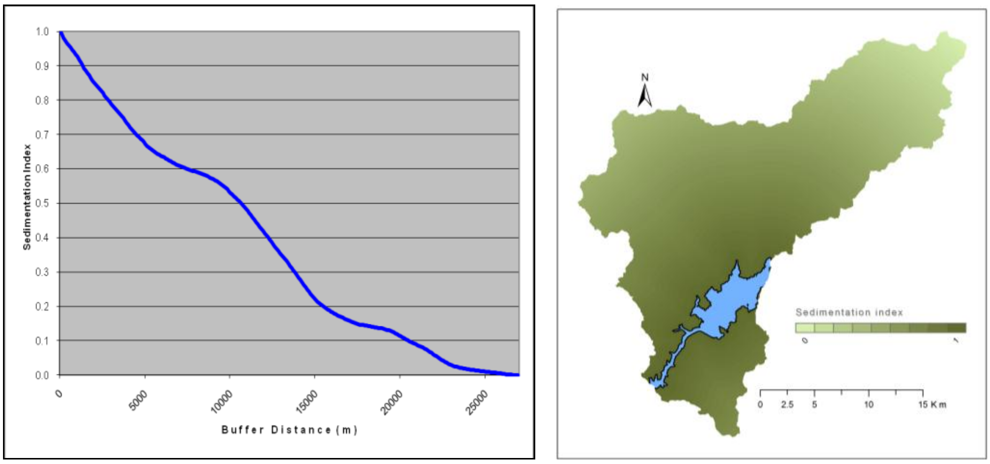
Figure 5.5 (a) Graphical distribution and (b) spatial distribution of the aggregate index for the Tahtali reservoir catchment, generated based on the available protection times within the zones and the potential land-based pollution. The distance (D) of 7600 m. corresponds to the maximum index value determined for the catchment.



(a) (b)

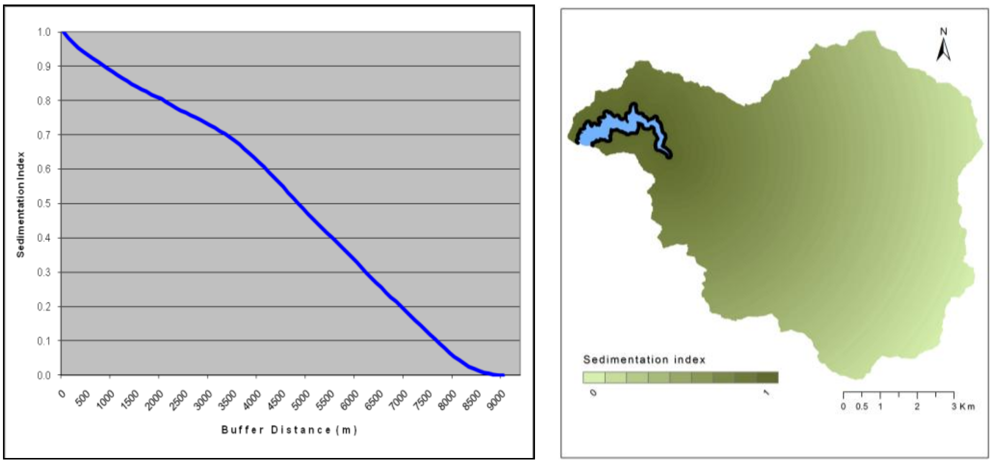
Figure 5.6 (a) Graphical distribution and (b) spatial distribution of the aggregate index for the Camli reservoir catchment, generated based on the available protection times within the zones and the potential land-based pollution. The distance (D) of 3600 m. corresponds to the maximum index value determined for the catchment.

The sedimentation indices that were generated for both the Camli and Tahtali case-studies provide a ranked assessment for the alternative protection zones based on the loading estimates of sediment and sediment-driven pollutants into the reservoir and indicate almost linear changes, for both cases, by the corresponding protection distances foreseen from the reservoirs (Figs. 5.7 & 5.8).



(a) (b)

Figure 5.7 (a) Graphical distribution and (b) spatial distribution of the sedimentation index displayed against the varying Euclidean distances from the Tahtali reservoir. The maximum index value of 1.0 is obtained necessarily for the case of zero protection distance, i.e. no protection case.



(a) (b)

Figure 5.8 (a) Graphical distribution and (b) spatial distribution of the sedimentation index displayed against the varying Euclidean distances from the Camli reservoir. The maximum index value of 1.0 is obtained necessarily for the case of zero protection distance, i.e. no protection case.

This seems to be mostly due to the homogeneous behavior of the catchment in producing and transferring sediment, which can further be explained by homogeneous resistance to erosion and homogeneous physiographical conditions over the entire catchment area. In the case of Camli catchment where the linearity of index change with distance is more visible, the almost rounded shape of the catchment can be regarded as another factor supporting the catchment response that lead to a linear change, as basin shape is generally believed to explain the unfolding of certain hydrological processes which inevitably affect the rates of erosion (Zăvoianu, 1985).

In the study, this specific index which was basically used to figure out the estimated degree and thus the potential impact of sedimentation in case of different protection zone alternatives was again combined with the aggregate index generated in the previous step. It is apparent from Fig. 5.9 that the sedimentation index incorporated into the overall analysis yield substantial decrease in the proposed protection distance in the Tahtali case. Although the contribution of this additional criterion does not bring a significant change in the distance value that is assessed to provide sufficient protection for the Camli reservoir, it leads to increased indexical values for the alternative protection zones that can be practiced around the reservoir in distances slightly shorter than 3600 m (Fig. 5.10).

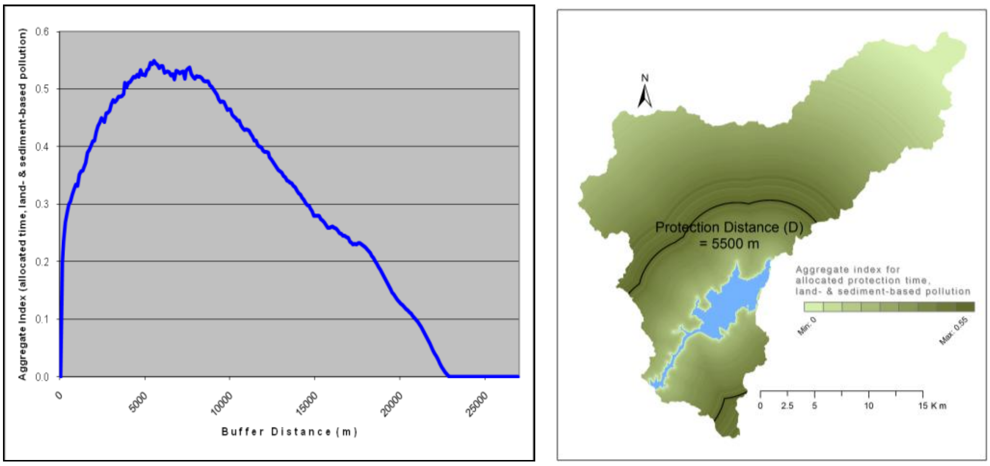
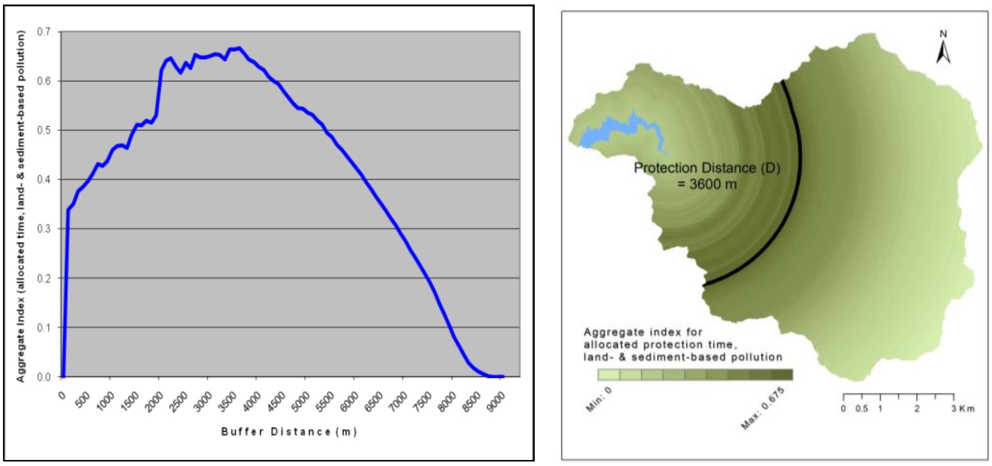


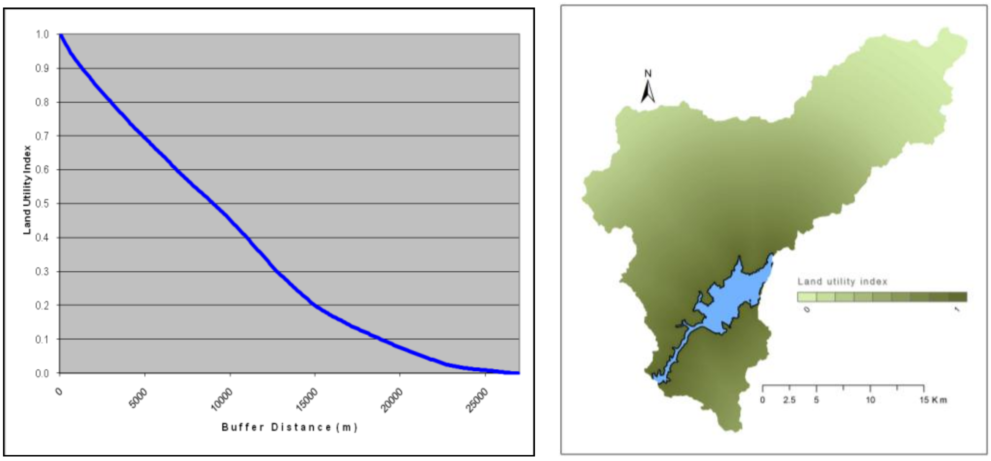
Figure 5.9 (a) Graphical distribution and (b) spatial distribution of the aggregate index for the Tahtali reservoir catchment, generated based on the available protection times within the zones, the potential land-and sediment-based pollution. The distance (D) of 5500 m. corresponds to the maximum index value determined for the catchment.



(a) (b)

Figure 5.10 (a) Graphical distribution and (b) spatial distribution of the aggregate index for the Camli reservoir catchment, generated based on the available protection times within the zones, the potential land-and sediment-based pollution. The distance (D) of 3600 m. corresponds to the maximum index value determined for the catchment.

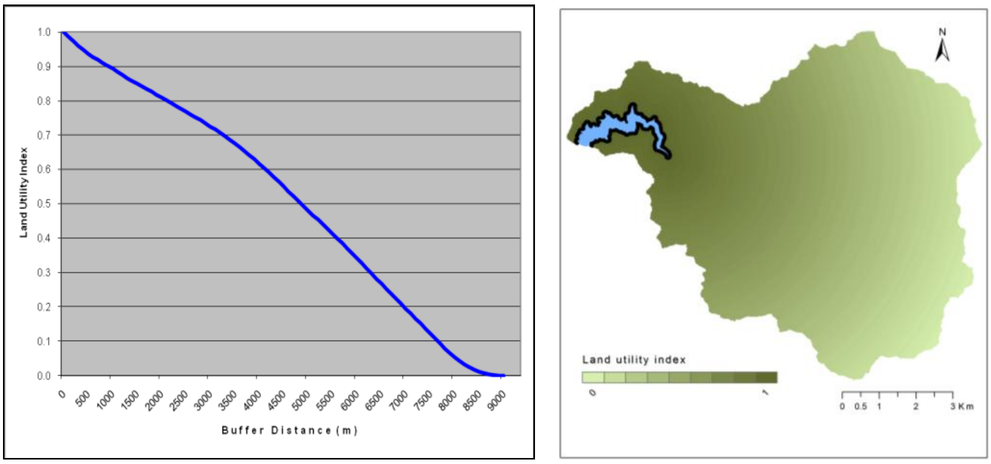
A protection zone is actually the contact zone between the reservoir and its catchment where a special regime of land use and economic activity is established to ensure the necessary levels of sanitary (i.e. environmental) conditions in the water body as a whole. The protection regime within the zones can be so severe as to range from the restriction right up to the total prohibition of some kind of polluting materials or of an economic activity. This will definitely have some negative consequences due to losses from economical use of the land. The land utility index, which actually takes account of the land occupied by protection zones within the catchments and thus was suggested for compromising the conflicting interests on both the water quality protection and the economic use of the land, gives basic indication on the rate of change in land availability as the protection zone expands to catchment boundaries (Figs. 5.11 & 5.12).



(a) (b)

Figure 5.11 (a) Graphical distribution and (b) spatial distribution of the land utility index displayed against the varying Euclidean distances from the Tahtali reservoir. The maximum index value of 1.0 indicating a complete utility of the land is obtained necessarily for the case of zero protection distance, i.e. no protection case.

When the land utility index is included in the assessments for determining the final protection distance, it is observed that the necessary width of protection decreases for the Camli catchment from its early estimate, as changing from 3.6 km to 2.2 km (Fig. 5.13), while for the Tahtali case the contribution of a new index does not affect the proposed protection distance (Fig. 5.14). The latter simply indicate that the protection design only from the potential pollution perspective in the case of Tahtali corresponds to the optimal design case by also securing the utility of land outside the protection space, even without considering it as additional criterion.

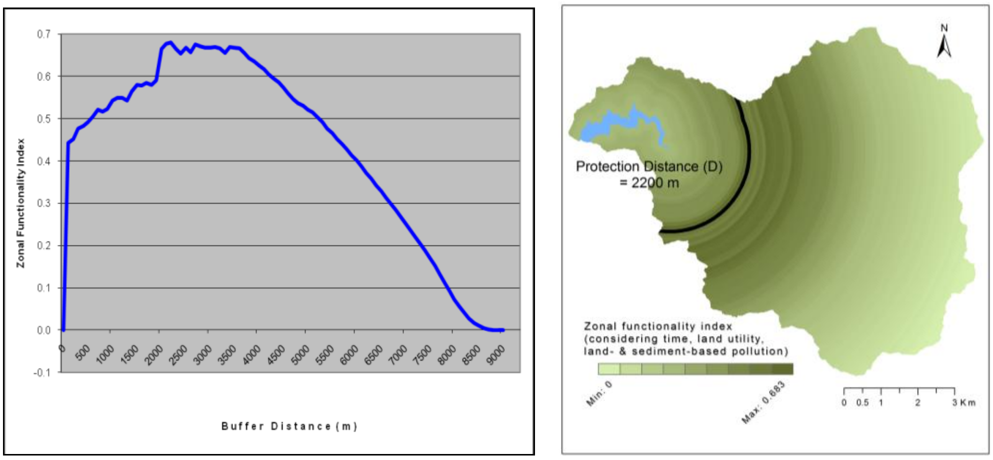


(a) (b)

Figure 5.12 (a) Graphical distribution and (b) spatial distribution of the land utility index displayed against the varying Euclidean distances from the Camli reservoir. The maximum index value of 1.0 indicating a complete utility of the land is obtained necessarily for the case of zero protection distance, i.e. no protection case.

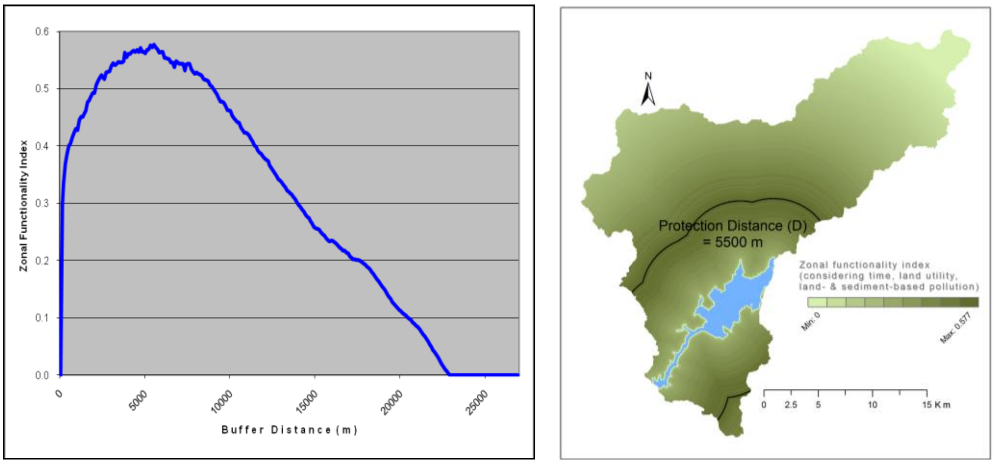
With these levels of reservoir protection that are provided after the application of the resulting protection distances in both catchments, the recommended zones seem to function by 57.7 % and 68.3 % within the Tahtali and Camli catchments, respectively. These ratios are to be considered as the average functionalities acquired from a number of different perspectives, which include the available time for mitigating pollution within protection zones, the expected capacity of zones against potential pollution from the catchment, and the potential utility of land as a resource.

When the overall reasoning and the indexical structure of the approach presented in the study are considered in relation to the constant zoning system that is advised and even ruled by the regulation for all catchment applications in Turkey (Fig. 5.15), the final outcomes seem to approximate to the medium-range protection. In order to allow further classification of the protection zones, i.e. to clearly differentiate between absolute, proximate, mediate and remote protection areas, it is also possible to improve the spatial approach through re-analysis of the final outcome by gradually decreasing the expected functionalities from the zones, while increasing the protective measures (e.g. adapting proper vegetation types and densities for different ranges; sorting out of the restricted/prohibited activities, etc.) as the zone gets closer to the water body.



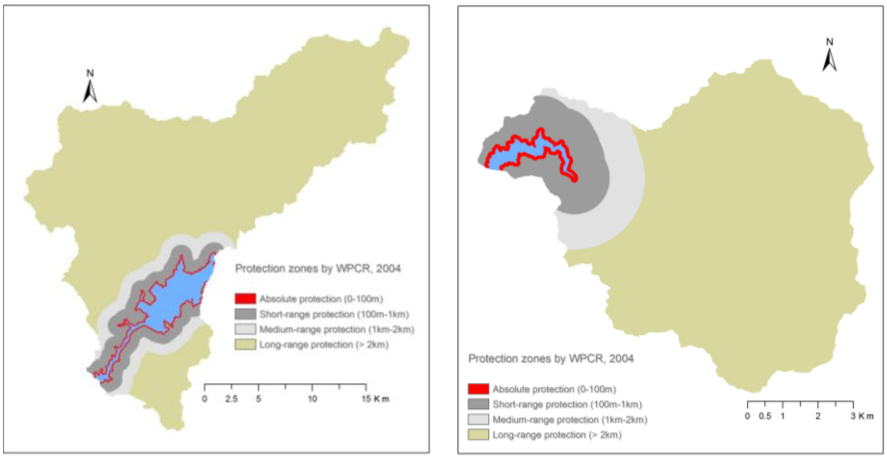
(a) (b)

Figure 5.13 (a) Graphical distribution and (b) spatial distribution of the final index generated to indicate the overall functionalities of the potential protection zones assessed for the Camli case-study. The distance (D) of 2200 m. corresponds to the maximum overall functionality that can be achieved within the catchment.



(a) (b)

Figure 5.14 (a) Graphical distribution and (b) spatial distribution of the final index generated to indicate the overall functionalities of the potential protection zones assessed for the Tahtali case-study. The distance (D) of 5500 m. corresponds to the maximum overall functionality that can be achieved within the catchment.



(a) (b)

Figure 5.15 (a) The application of reservoir protection zones at different levels in (a) Tahtali and (b) Camli catchments, as ruled by the Water Pollution Control Regulation (WPCR) revised in 2004.

CHAPTER SIX
CONCLUSIONS

Detailed assessments of the needs to water quality protection in a basin would originally necessitate a comprehensive modeling exercise that takes account of all necessary components in pollution modeling. Yet, a model structure which is set, calibrated and then validated for a study area will remain particular to the modeled area only with its calibrated parameters, without providing a common practical operability for the following potential applications in other areas. A new model set-up and calibration will always be necessary to repeat a similar exercise on different applications. This normally increases the time required for generating the results from such a study and delays the response time of the national or local institutions authorized for making proper decisions on pollution control.

Beside some other measures for preventing water bodies from being polluted by sediment and many different kinds of pollutants, the allocation of protection zones in varying distances around reservoirs, from which water is supplied for drinking or other purposes, has proved to be a proper action finding global acceptation for years. The major challenges in reservoir protection aimed through the use of protection zones mostly relate to the scientific and legal basis of the existing protection regulations and, thus, are mainly based on the needs for a sound reservoir protection strategy (1) which is practically applicable to all catchments of quite variable sizes and characteristics, (2) which takes account of topographic, hydraulic, hydrologic and other relevant characteristics in drainage basins as well as the potential pollution impacts from probable point and nonpoint sources, and (3) which is based on a single scientific reasoning that can be easily justified and advocated even for different applications in different basins. The individual assessments of specific protection needs for the reservoir catchments based on such a strategy greatly helps the authorities minimize the number of legal problems and disputes that currently arise from the identical application of protection zones in all reservoir catchments, despite their quite different sizes and characteristics, in the way as it is ruled by the regulations.

The approach employed in this study provides a comparably practical methodology for deciding upon an optimum protection distance in a watershed. Its most distinctive outcome is the feasibility of defining protection zones of variable distances for the applications in different catchments, but securing all assessments to be based on a single scientific reasoning. It addresses the main challenges arising from the current practices of reservoir protection and provides guidance for an alternative strategy to achieve a practical solution. It basically considers a number of individual analytical components including the average times it takes water to travel within protection zones down to reservoir, the potential diffuse pollution risks originating from certain types of land uses in catchments, and the potential role of sedimentation in a catchment to trigger pollution transfer and amplify pollution impacts on reservoir systems. The time component represented by the so-called time allocation index basically focuses on the assessment of an average time for a protection zone, which may be considered as temporal gain for decreasing the hazardous impacts of pollutants, and during which the polluted water will be retained within the zone and will be naturally treated through mechanical, chemical and biological processes to provide water having a desired quality for sanitary use. Potential pollution stresses on the quality of reservoir water are addressed by the use of a sedimentation index in which the transfer of both sediment and sediment-bound pollution is represented by the sediment yields from catchments, and a diffuse pollution index where the spatial extents of mainly urban and agricultural areas are considered as proxy to land-based diffuse pollution, rather than the exact estimates of pollution loads.

One of the management issues that take prior attention in applying a protection distance is the need for providing utility of the land. Indeed, the land is the natural resource that provides the means and opportunity for the production of goods and the supply of services as the common base for agricultural, industrial, commercial, recreational, residential and governmental activities. For this reason, the issue of land utility is also expected to be covered by a proper decision made for applying a certain protection measure for water quality. A different application would potentially raise the number of disputes between landowners and authorities, finally bringing additional pressures on authorities to limit the coverage of protection measures into a desired state which may not always be fitted to a sufficient level of water quality protection. Through the use of the land utility index, which takes account of the land unoccupied by any protection zone, the presented approach turns out to be a compromise way of tackling the protection issue together with the total utility of the land.

The methodological framework of the presented approach may be further extended for a final agreement on the required degree of reservoir protection within catchments by including a set of additional components, such as to represent ground water or vadose zone flow. Nevertheless, the results obtained from a study, as presented herein, sufficiently integrating a number of relevant spatial criteria may not be easily generated from only the lump-sum estimates of catchment characteristics. All the components included in the study can be collectively assessed and corresponding results can be generated through the use of a computer-based delineation tool potentially to be embedded later in GIS software. It is also noteworthy to mention here that the results obtained from an exercise as such and the final decisions made on these would normally need updating if the catchment characteristics considered in a previous application undergo considerable changes (e.g. major land-use/cover changes) in the future.

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APPENDICES

APPENDIX 1

APPENDIX 1.1: Corine land cover (CLC) classes

1. Artificial surfaces

- 1.1 Urban fabric
  - *1.1.1 Continuous urban fabric*
  - *1.1.2 Discontinuous urban fabric*
- 1.2 Industrial, comercial and transport units
  - *1.2.1 Industrial or commercial units*
  - *1.2.2 Road and rail networks and associated land*
  - *1.2.3 Port areas*
  - *1.2.4 Airports*
- 1.3 Mine, dump and construction sites
  - *1.3.1 Mineral extraction sites*
  - *1.3.2 Dump sites*
  - *1.3.3 Construction sites*
- 1.4 Artificial, non-agricultural vegetated areas
  - *1.4.1 Green urban areas*
  - *1.4.2 Sport and leisure facilities*

2. Agricultural areas

- 2.1 Arable land
  - *2.1.1 Non-irrigated arable land*
  - *2.1.2 Permanently irrigated land*
  - *2.1.3 Rice fields*
- 2.2 Permanent crops
  - *2.2.1 Vineyards*
  - *2.2.2 Fruit trees and berry plantations*
  - *2.2.3 Olive groves*
- 2.3 Pastures
  - *2.3.1 Pastures*
- 2.4 Heterogeneous agricultural areas
  - *2.4.1 Annual crops associated with permanent crops*

    - *2.4.2 Complex cultivation patterns*
    - *2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation*
    - *2.4.4 Agro-forestry areas*

- **3. Forest and seminatural areas**
  - 3.1 Forests
    - *3.1.1 Broad-leaved forest*
    - *3.1.2 Coniferous forest*
    - *3.1.3 Mixed forest*
  - 3.2 Scrub and/or herbaceous vegetation associations
    - *3.2.1 Natural grasslands*
    - *3.2.2 Moors and heathland*
    - *3.2.3 Sclerophyllous vegetation*
    - *3.2.4 Transitional woodland-shrub*
  - 3.3 Open spaces with little or no vegetation
    - *3.3.1 Beaches, dunes, sands*
    - *3.3.2 Bare rocks*
    - *3.3.3 Sparsely vegetated areas*
    - *3.3.4 Burnt areas*
    - *3.3.5 Glaciers and perpetual snow*
- **4. Wetlands**
  - 4.1 Inland wetlands
    - *4.1.1 Inland marshes*
    - *4.1.2 Peat bogs*
  - 4.2 Maritime wetlands
    - *4.2.1 Salt marshes*
    - *4.2.2 Salines*
    - *4.2.3 Intertidal flats*
- **5. Water bodies**
  - 5.1 Inland waters
    - *5.1.1 Water courses*
    - *5.1.2 Water bodies*

5.2 Marine waters

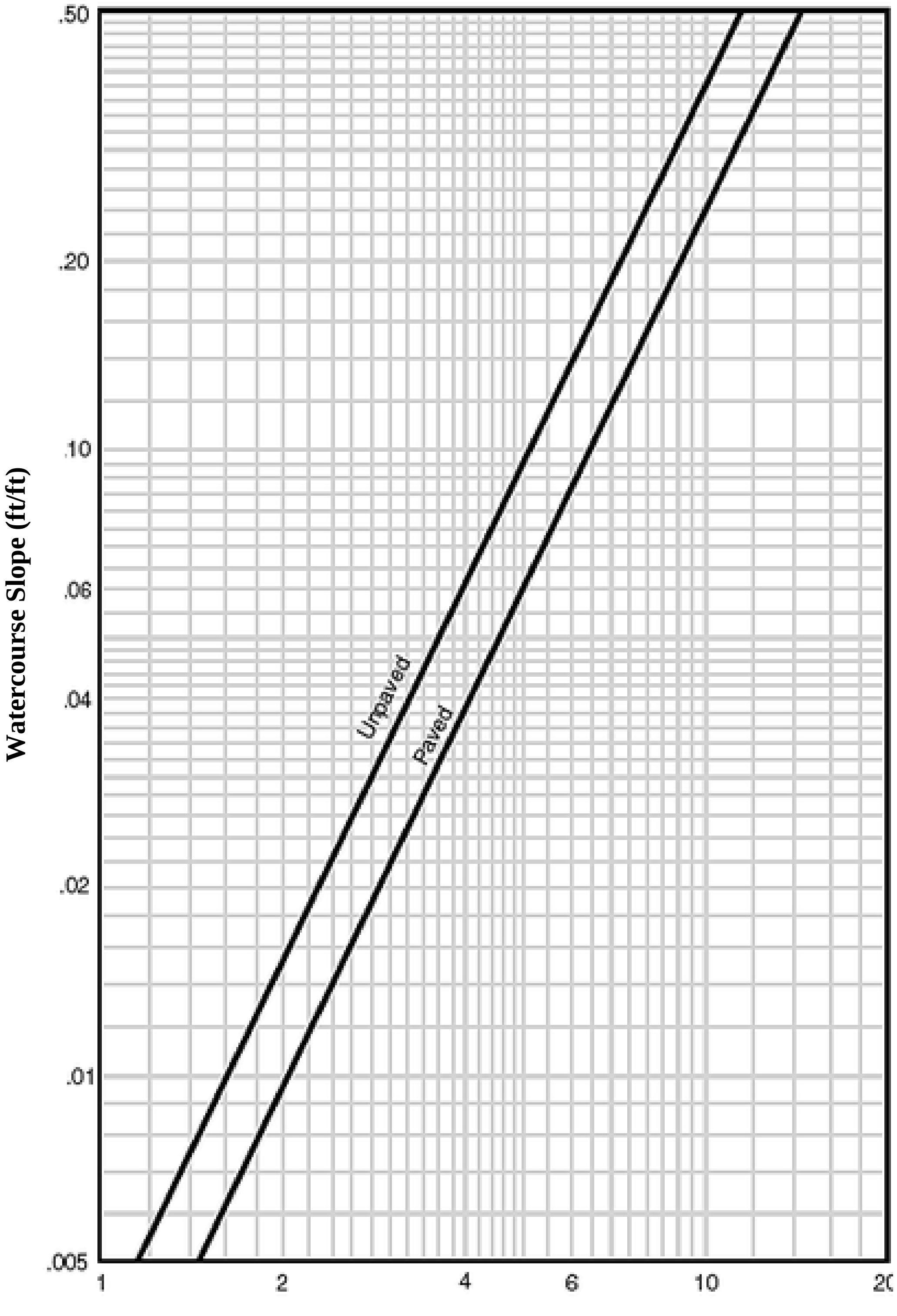
5.2.1 Coastal lagoons

5.2.2 Estuaries

5.2.3 Sea and ocean

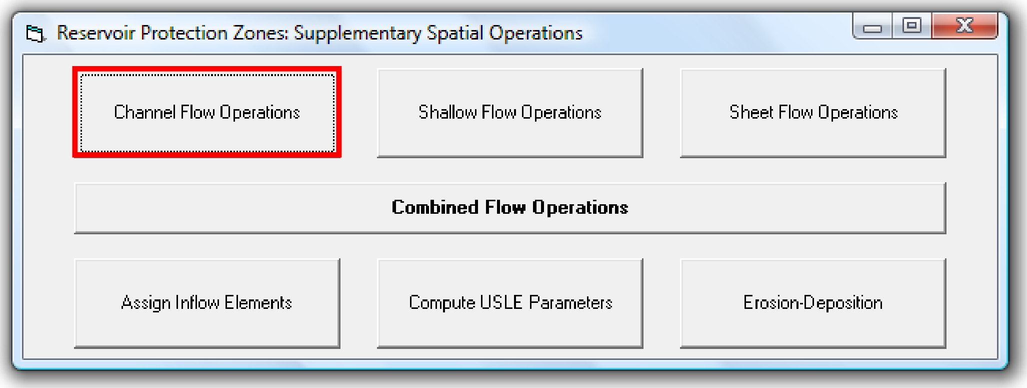
APPENDIX 2

APPENDIX 2.1: Nomograph for estimating average velocities within shallow concentrated flow segments



APPENDIX 3

APPENDIX 3.1: VB code for the spatial operations on channel flow areas



```
Option Explicit
Dim imax, jmax As Long
Dim CF(5000, 5000) As Integer
Dim SCF(5000, 5000) As Integer
Dim SF(5000, 5000) As Integer
Dim FDIR(5000, 5000) As Integer
Dim SLP(5000, 5000) As Double
Dim MANN(5000, 5000) As Double
Dim TT_CF(5000, 5000) As Double
Dim TT_SCF(5000, 5000) As Double
Dim TT_SF(5000, 5000) As Double
Dim BZ(5000, 5000) As Double
Dim BLC(5000, 5000) As Double
Dim TSL(5000, 5000) As Double
Dim BCEL(5000, 5000) As Double
Dim L(5000, 5000) As Double
Dim C(5000, 5000) As Double
Dim K(5000, 5000) As Double
Dim lx2(10) As String
'*****
Private Sub Command1_Click()
LoadChannelFlowAreas
LoadFdirFile
LoadSlopeGrid
Calculate_AS_CF
End Sub
'*****
```

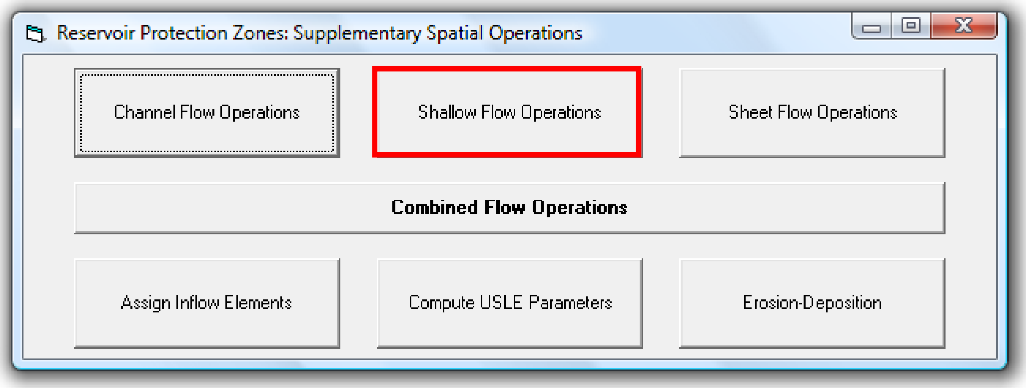
```
Private Sub LoadChannelFlowAreas()
Dim zcf As Integer, icf, jcf As Long, l1cf, l2cf, lx1cf As String
Open "path\cfzones_layer.asc" For Input As #1
Dim arrl1cf(), arrl2cf() As String
Line Input #1, l1cf
arrl1cf() = Split(l1cf, "         ")
jmax = CInt(arrl1cf(1))
Line Input #1, l2cf
arrl2cf = Split(l2cf, "         ")
imax = CInt(arrl2cf(1))
For zcf = 1 To 4
    Line Input #1, lx1cf
Next
For icf = 1 To imax
For jcf = 1 To jmax
    Input #1, CF(icf, jcf)
Next jcf
Next icf
Close #1
End Sub
'*****
Private Sub LoadFdirFile()
Dim zfd As Integer, kfd, lfd As Long
Open "path\fdir_layer.asc" For Input As #4
For zfd = 1 To 6
    Line Input #4, lx2(zfd)
Next
For kfd = 1 To imax
For lfd = 1 To jmax
    Input #4, FDIR(kfd, lfd)
Next lfd
Next kfd
Close #4
End Sub
'*****
Private Sub LoadSlopeGrid()
Dim zs As Integer, xs, ys As Long, lx1s As String
Open "path\slp_layer(as rise/run).asc" For Input As #9
For zs = 1 To 6
```

```
    Line Input #9, lx1s
Next
For xs = 1 To imax
For ys = 1 To jmax
    Input #9, SLP(xs, ys)
Next ys
Next xs
Close #9
End Sub
'*****
Private Sub LoadMannGrid()
Dim zm As Integer, xm, ym As Long, lx1m As String
Open "path\mann_layer.asc" For Input As #5
For zm = 1 To 6
    Line Input #5, lx1m
Next
For xm = 1 To imax
For ym = 1 To jmax
    Input #5, MANN(xm, ym)
Next ym
Next xm
Close #5
End Sub
'*****
Private Sub Calculate_AS_CF()
Dim TSLP(3000, 3000), AVSLP(3000, 3000) As Double, N(3000, 3000) As Long
Dim isl, jsl, isl1, jsl1 As Long
For isl = 1 To imax
For jsl = 1 To jmax
    Debug.Print isl, jsl
    TSLP(isl, jsl) = SLP(isl, jsl): N(isl, jsl) = 1
    If Not CF(isl, jsl) = -9999 Then
        If FDIR(isl, jsl) = 1 Then
        isl1 = isl: jsl1 = jsl + 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 2 Then
        isl1 = isl + 1: jsl1 = jsl + 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 4 Then
        isl1 = isl + 1: jsl1 = jsl: GoTo 10
        ElseIf FDIR(isl, jsl) = 8 Then
```

```
       isl1 = isl + 1: jsl1 = jsl - 1: GoTo 10
       ElseIf FDIR(isl, jsl) = 16 Then
       isl1 = isl: jsl1 = jsl - 1: GoTo 10
       ElseIf FDIR(isl, jsl) = 32 Then
       isl1 = isl - 1: jsl1 = jsl - 1: GoTo 10
       ElseIf FDIR(isl, jsl) = 64 Then
       isl1 = isl - 1: jsl1 = jsl: GoTo 10
       ElseIf FDIR(isl, jsl) = 128 Then
       isl1 = isl - 1: jsl1 = jsl + 1: GoTo 10
       End If
   Else
   AVSLP(isl, jsl) = -9999: TSLP(isl, jsl) = -9999: N(isl, jsl) = -9999
   GoTo 20
   End If
10 If Not CF(isl1, jsl1) = -9999 Then
       If TSLP(isl1, jsl1) <> 0 Then
       TSLP(isl, jsl) = TSLP(isl1, jsl1) + TSLP(isl, jsl): N(isl, jsl) = N(isl1, jsl1) + N(isl, jsl)
       AVSLP(isl, jsl) = TSLP(isl, jsl) / N(isl, jsl)
           If AVSLP(isl, jsl) = 0 Then
           AVSLP(isl, jsl) = Tan(0.1)
           End If
       GoTo 20
       End If
       TSLP(isl, jsl) = SLP(isl1, jsl1) + TSLP(isl, jsl): N(isl, jsl) = N(isl, jsl) + 1
           If FDIR(isl1, jsl1) = 1 Then
           isl1 = isl1: jsl1 = jsl1 + 1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 2 Then
           isl1 = isl1 + 1: jsl1 = jsl1 + 1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 4 Then
           isl1 = isl1 + 1: jsl1 = jsl1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 8 Then
           isl1 = isl1 + 1: jsl1 = jsl1 - 1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 16 Then
           isl1 = isl1: jsl1 = jsl1 - 1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 32 Then
           isl1 = isl1 - 1: jsl1 = jsl1 - 1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 64 Then
           isl1 = isl1 - 1: jsl1 = jsl1: GoTo 10
           ElseIf FDIR(isl1, jsl1) = 128 Then
```

```
            isl1 = isl1 - 1: jsl1 = jsl1 + 1: GoTo 10
            End If
    Else
    AVSLP(isl, jsl) = TSLP(isl, jsl) / N(isl, jsl)
        If AVSLP(isl, jsl) = 0 Then
        AVSLP(isl, jsl) = Tan(0.1)
        End If
    GoTo 20
    End If
20 Next jsl
Next isl
Dim z1, i1, j1As Integer
Open "path\avslp_cf.asc" For Output As #6
For z1 = 1 To 6
    Print #6, lx2(z1)
Next
For i1 = 1 To imax
For j1 = 1 To jmax
    Print #6, AVSLP(i1, j1);
Next j1
    Print #6, ""
Next i1
Close #6
End
End Sub
'*****
```

APPENDIX 3.2: VB code for the spatial operations on shallow concentrated flow areas



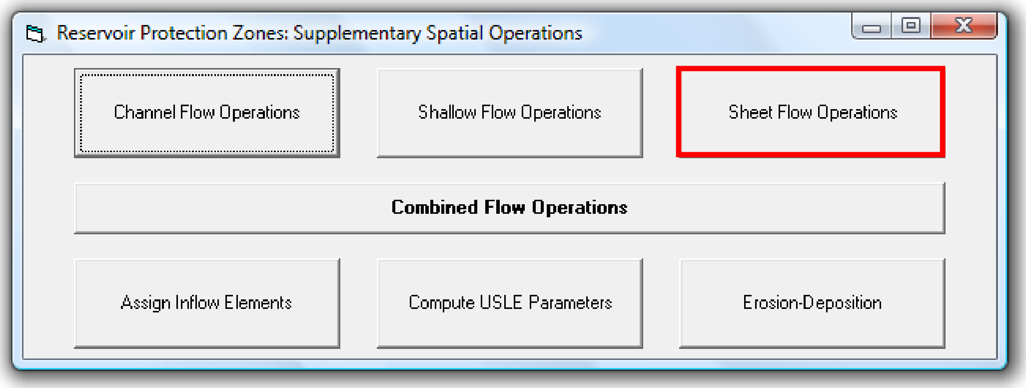
```
Private Sub Command2_Click()
LoadShallowConFlowAreas
LoadFdirFile
LoadSlopeGrid
Calculate_AS_SCF
End Sub
'*****
Private Sub LoadShallowConFlowAreas()
Dim zscf As Integer, iscf, jscf As Long
Dim l1scf, l2scf, lx1scf As String
Open "path\scfzones_layer.asc" For Input As #2
Dim arrl1scf(), arrl2scf() As String
Line Input #2, l1scf
arrl1scf() = Split(l1scf, "         ")
jmax = CInt(arrl1scf(1))
Line Input #2, l2scf
arrl2scf = Split(l2scf, "         ")
imax = CInt(arrl2scf(1))
For zscf = 1 To 4
    Line Input #2, lx1scf
Next
For iscf = 1 To imax
For jscf = 1 To jmax
    Input #2, SCF(iscf, jscf)
Next jscf
Next iscf
Close #2
```

```
End Sub
'*****
Private Sub Calculate_AS_SCF()
Dim TSLP(5000, 5000), AVSLP(5000, 5000) As Double, NSLP(4000, 4000) As Long
Dim isl, jsl, isl1, jsl1 As Long
For isl = 1 To imax
For jsl = 1 To jmax
    Debug.Print isl, jsl
    TSLP(isl, jsl) = SLP(isl, jsl): NSLP(isl, jsl) = 1
    If Not SCF(isl, jsl) = -9999 Then
        If FDIR(isl, jsl) = 1 Then
        "TMANN(ir, jr) = MANN(ir + 1, jr) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl: jsl1 = jsl + 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 2 Then
        "TMANN(ir, jr) = MANN(ir + 1, jr + 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl + 1: jsl1 = jsl + 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 4 Then
        "TMANN(ir, jr) = MANN(ir, jr + 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl + 1: jsl1 = jsl: GoTo 10
        ElseIf FDIR(isl, jsl) = 8 Then
        "TMANN(ir, jr) = MANN(ir - 1, jr + 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl + 1: jsl1 = jsl - 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 16 Then
        "TMANN(ir, jr) = MANN(ir - 1, jr) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl: jsl1 = jsl - 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 32 Then
        "TMANN(ir, jr) = MANN(ir - 1, jr - 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl - 1: jsl1 = jsl - 1: GoTo 10
        ElseIf FDIR(isl, jsl) = 64 Then
        "TMANN(ir, jr) = MANN(ir, jr - 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl - 1: jsl1 = jsl: GoTo 10
        ElseIf FDIR(isl, jsl) = 128 Then
        "TMANN(ir, jr) = MANN(ir + 1, jr - 1) + TMANN(ir, jr): N(ir, jr) = N(ir, jr) + 1
        isl1 = isl - 1: jsl1 = jsl + 1: GoTo 10
        End If
    Else
    AVSLP(isl, jsl) = -9999: TSLP(isl, jsl) = -9999: NSLP(isl, jsl) = -9999
    'AVMANN(ir, jr) = TMANN(ir, jr) / N(ir, jr)
    GoTo 20
```

```
    End If
10  If Not SCF(isl1, jsl1) = -9999 Then
        If TSLP(isl1, jsl1) <> 0 Then
        TSLP(isl, jsl) = TSLP(isl1, jsl1) + TSLP(isl, jsl)
        NSLP(isl, jsl) = NSLP(isl1, jsl1) + NSLP(isl, jsl)
        AVSLP(isl, jsl) = TSLP(isl, jsl) / NSLP(isl, jsl)
            If AVSLP(isl, jsl) = 0 Then
            AVSLP(isl, jsl) = Tan(0.1)
            End If
        GoTo 20
        End If
        TSLP(isl, jsl) = SLP(isl1, jsl1) + TSLP(isl, jsl): NSLP(isl, jsl) = NSLP(isl, jsl) + 1
        If FDIR(isl1, jsl1) = 1 Then
        isl1 = isl1: jsl1 = jsl1 + 1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 2 Then
        isl1 = isl1 + 1: jsl1 = jsl1 + 1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 4 Then
        isl1 = isl1 + 1: jsl1 = jsl1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 8 Then
        isl1 = isl1 + 1: jsl1 = jsl1 - 1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 16 Then
        isl1 = isl1: jsl1 = jsl1 - 1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 32 Then
        isl1 = isl1 - 1: jsl1 = jsl1 - 1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 64 Then
        isl1 = isl1 - 1: jsl1 = jsl1: GoTo 10
        ElseIf FDIR(isl1, jsl1) = 128 Then
        isl1 = isl1 - 1: jsl1 = jsl1 + 1: GoTo 10
        End If
    Else
    AVSLP(isl, jsl) = TSLP(isl, jsl) / NSLP(isl, jsl)
        If AVSLP(isl, jsl) = 0 Then
        AVSLP(isl, jsl) = Tan(0.1)
        End If
    GoTo 20
    End If
20 Next jsl
Next isl
Dim z1s, i1s, j1s As Integer
```

```
Open "path\avslp_scf.asc" For Output As #10
For z1s = 1 To 6
    Print #10, lx2(z1s)
Next
For i1s = 1 To imax
For j1s = 1 To jmax
    Print #10, AVSLP(i1s, j1s);
Next j1s
    Print #10, ""
Next i1s
Close #10
End
End Sub
'*****
```

APPENDIX 3.3: VB code for the spatial operations on sheet flow areas



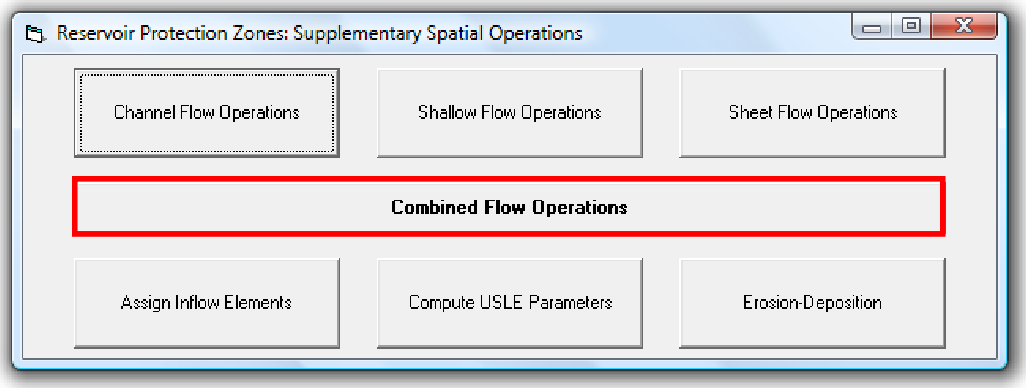
```
Private Sub Command3_Click()
LoadSheetFlowAreas
LoadFdirFile
LoadSlopeGrid
LoadMannGrid
Calculate_ASR_SF
End Sub
'*****
Private Sub LoadSheetFlowAreas()
Dim zsf As Integer, isf, jsf As Long
Dim l1sf, l2sf, lx1sf As String
Open "path\ sfzones_layer.asc" For Input As #3
Dim arrl1sf() As String
Dim arrl2sf() As String
Line Input #3, l1sf
arrl1sf() = Split(l1sf, "        ")
jmax = CInt(arrl1sf(1))
Line Input #3, l2sf
arrl2sf = Split(l2sf, "        ")
imax = CInt(arrl2sf(1))
For zsf = 1 To 4
    Line Input #3, lx1sf
Next
For isf = 1 To imax
For jsf = 1 To jmax
    Input #3, SF(isf, jsf)
Next jsf
Next isf
```

```
Close #3
End Sub
'*****
Private Sub Calculate_ASR_SF()
Dim TSLP(5000, 5000), AVSLP(5000, 5000) As Double
Dim TMANN(5000, 5000) AVMANN(5000, 5000) As Double, NSR(5000, 5000) As Long
Dim isr, jsr, isr1, jsr1 As Long
Dim i_old(2), j_old(2) As Long
Dim i_old1, j_old1 As Long
For isr = 1 To imax
For jsr = 1 To jmax
    Debug.Print isr, jsr, FDIR(isr, jsr)
    TSLP(isr, jsr) = SLP(isr, jsr): TMANN(isr, jsr) = MANN(isr, jsr): NSR(isr, jsr) = 1
    If Not SF(isr, jsr) = -9999 Then
    i_old(1) = isr: j_old(1) = jsr
        If FDIR(isr, jsr) = 1 Then
        isr1 = isr: jsr1 = jsr + 1: GoTo 10
        ElseIf FDIR(isr, jsr) = 2 Then
        isr1 = isr + 1: jsr1 = jsr + 1: GoTo 10
        ElseIf FDIR(isr, jsr) = 4 Then
        isr1 = isr + 1: jsr1 = jsr: GoTo 10
        ElseIf FDIR(isr, jsr) = 8 Then
        isr1 = isr + 1: jsr1 = jsr - 1: GoTo 10
        ElseIf FDIR(isr, jsr) = 16 Then
        isr1 = isr: jsr1 = jsr - 1: GoTo 10
        ElseIf FDIR(isr, jsr) = 32 Then
        isr1 = isr - 1: jsr1 = jsr - 1: GoTo 10
        ElseIf FDIR(isr, jsr) = 64 Then
        isr1 = isr - 1: jsr1 = jsr: GoTo 10
        ElseIf FDIR(isr, jsr) = 128 Then
        isr1 = isr - 1: jsr1 = jsr + 1: GoTo 10
        End If
    Else
    AVSLP(isr, jsr) = -9999: TSLP(isr, jsr) = -9999
    AVMANN(isr, jsr) = -9999: TMANN(isr, jsr) = -9999: NSR(isr, jsr) = -9999
    GoTo 20
    End If
10  If Not SF(isr1, jsr1) = -9999 Then
        If TSLP(isr1, jsr1) <> 0 Then
```

```
    TSLP(isr, jsr) = TSLP(isr1, jsr1) + TSLP(isr, jsr)
    TMANN(isr, jsr) = TMANN(isr1, jsr1) + TMANN(isr, jsr)
    NSR(isr, jsr) = NSR(isr1, jsr1) + NSR(isr, jsr)
    AVSLP(isr, jsr) = TSLP(isr, jsr) / NSR(isr, jsr)
    AVMANN(isr, jsr) = TMANN(isr, jsr) / NSR(isr, jsr)
        If AVSLP(isr, jsr) = 0 Then
        AVSLP(isr, jsr) = Tan(0.1)
        End If
    GoTo 20
    End If
TSLP(isr, jsr) = SLP(isr1, jsr1) + TSLP(isr, jsr)
TMANN(isr, jsr) = MANN(isr1, jsr1) + TMANN(isr, jsr)
NSR(isr, jsr) = NSR(isr, jsr) + 1
i_old(2) = isr1: j_old(2) = jsr1
    If FDIR(isr1, jsr1) = 1 Then
    isr1 = isr1: jsr1 = jsr1 + 1
    ElseIf FDIR(isr1, jsr1) = 2 Then
    isr1 = isr1 + 1: jsr1 = jsr1 + 1
    ElseIf FDIR(isr1, jsr1) = 4 Then
    isr1 = isr1 + 1: jsr1 = jsr1
    ElseIf FDIR(isr1, jsr1) = 8 Then
    isr1 = isr1 + 1: jsr1 = jsr1 - 1
    ElseIf FDIR(isr1, jsr1) = 16 Then
    isr1 = isr1: jsr1 = jsr1 - 1
    ElseIf FDIR(isr1, jsr1) = 32 Then
    isr1 = isr1 - 1: jsr1 = jsr1 - 1
    ElseIf FDIR(isr1, jsr1) = 64 Then
    isr1 = isr1 - 1: jsr1 = jsr1
    ElseIf FDIR(isr1, jsr1) = 128 Then
    isr1 = isr1 - 1: jsr1 = jsr1 + 1
    End If
    If isr1 = i_old(1) And jsr1 = j_old(1) Then
    TSLP(isr, jsr) = TSLP(isr, jsr) - SLP(i_old(2), j_old(2))
    TMANN(isr, jsr) = TMANN(isr, jsr) - MANN(i_old(2), j_old(2))
    NSR(isr, jsr) = NSR(isr, jsr) - 1
    AVSLP(isr, jsr) = TSLP(isr, jsr) / NSR(isr, jsr)
    AVMANN(isr, jsr) = TMANN(isr, jsr) / NSR(isr, jsr)
        If AVSLP(isr, jsr) = 0 Then
        AVSLP(isr, jsr) = Tan(0.1)
```

```
            End If
        GoTo 20
        Else
        i_old(1) = i_old(2): j_old(1) = j_old(2)
        GoTo 10
        End If
    Else
    AVSLP(isr, jsr) = TSLP(isr, jsr) / NSR(isr, jsr)
    AVMANN(isr, jsr) = TMANN(isr, jsr) / NSR(isr, jsr)
        If AVSLP(isr, jsr) = 0 Then
        AVSLP(isr, jsr) = Tan(0.1)
        End If
    GoTo 20
    End If
20 Next jsr
Next isr
Dim z1s, i1s, j1s As Integer
Open "path\avslp_sf.asc" For Output As #13
Open " path \avmann_sf.asc" For Output As #14
For z1s = 1 To 6
    Print #13, lx2(z1s)
    Print #14, lx2(z1s)
Next
For i1s = 1 To imax
For j1s = 1 To jmax
    Print #13, AVSLP(i1s, j1s);
    Print #14, AVMANN(i1s, j1s);
Next j1s
    Print #13, ""
    Print #14, ""
Next i1s
Close #13
Close #14
End
End Sub
'*****
```

APPENDIX 3.4: VB code for combining the travel times of different flow types



```
Private Sub Command4_Click()
LoadCFTravelTimes
LoadSCFTravelTimes
LoadSFTravelTimes
LoadFdirFile
Combine_CF_SCF_SF
End Sub
'*****
Private Sub LoadCFTravelTimes()
Dim zcft As Integer, icft, jcft As Long
Dim l1cft, l2cft, lx1cft As String
Open "path\cf_traveltimes_layer.asc" For Input As #18
Dim arrl1cft(), arrl2cft() As String
Line Input #18, l1cft
arrl1cft() = Split(l1cft, "         ")
jmax = CInt(arrl1cft(1))
Line Input #18, l2cft
arrl2cft = Split(l2cft, "         ")
imax = CInt(arrl2cft(1))
For zcft = 1 To 4
    Line Input #18, lx1cft
Next
For icft = 1 To imax
For jcft = 1 To jmax
    Input #18, TT_CF(icft, jcft)
Next jcft
Next icft
```

```
Close #18
End Sub
'*****
Private Sub LoadSCFTravelTimes()
Dim zscft As Integer, iscft, jscft As Long
Dim l1scft, l2scft, lx1scft As String
Open " path\scf_traveltimes_layer.asc" For Input As #19
Dim arrl1scft(), arrl2scft() As String
Line Input #19, l1scft
Line Input #19, l2scft
For zscft = 1 To 4
    Line Input #19, lx1scft
Next
For iscft = 1 To imax
For jscft = 1 To jmax
    Input #19, TT_SCF(iscft, jscft)
Next jscft
Next iscft
Close #19
End Sub
'*****
Private Sub LoadSFTravelTimes()
Dim zsft As Integer, isft, jsft As Long
Dim l1sft, l2sft, lx1sft As String
Open " path\sf_traveltimes_layer.asc" For Input As #20
Dim arrl1sft(), arrl2sft() As String
Line Input #20, l1sft
Line Input #20, l2sft
For zsft = 1 To 4
    Line Input #20, lx1sft
Next
For isft = 1 To imax
For jsft = 1 To jmax
    Input #20, TT_SF(isft, jsft)
Next jsft
Next isft
Close #20
End Sub
'*****
```

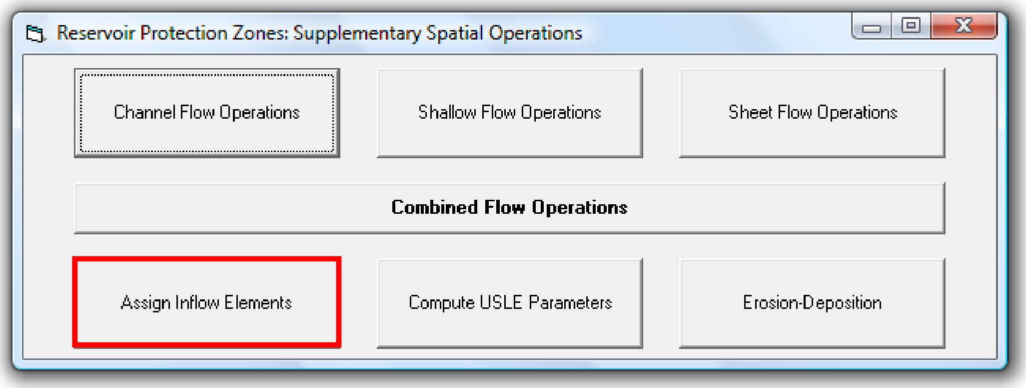
```
Private Sub Combine_CF_SCF_SF()
Dim TT_CF_SCF(5000, 5000), TT_CF_SCF_SF(5000, 5000) As Double
Dim it, jt, it1, jt1, itt, jtt, itt1, jtt1 As Long
For it = 1 To imax
For jt = 1 To jmax
    Debug.Print it, jt, "CF+SCF"
    If TT_CF(it, jt) <> -9999 Or TT_SCF(it, jt) <> -9999 Then
        If TT_CF(it, jt) <> -9999 Then
        TT_CF_SCF(it, jt) = TT_CF(it, jt): GoTo 20
        End If
        If FDIR(it, jt) = 1 Then
        it1 = it: jt1 = jt + 1: GoTo 10
        ElseIf FDIR(it, jt) = 2 Then
        it1 = it + 1: jt1 = jt + 1: GoTo 10
        ElseIf FDIR(it, jt) = 4 Then
        it1 = it + 1: jt1 = jt: GoTo 10
        ElseIf FDIR(it, jt) = 8 Then
        it1 = it + 1: jt1 = jt - 1: GoTo 10
        ElseIf FDIR(it, jt) = 16 Then
        it1 = it: jt1 = jt - 1: GoTo 10
        ElseIf FDIR(it, jt) = 32 Then
        it1 = it - 1: jt1 = jt - 1: GoTo 10
        ElseIf FDIR(it, jt) = 64 Then
        it1 = it - 1: jt1 = jt: GoTo 10
        ElseIf FDIR(it, jt) = 128 Then
        it1 = it - 1: jt1 = jt + 1: GoTo 10
        End If
    Else
    TT_CF_SCF(it, jt) = -9999: GoTo 20
    End If
10  If Not TT_SCF(it1, jt1) = -9999 Then
        If FDIR(it1, jt1) = 1 Then
        it1 = it1: jt1 = jt1 + 1: GoTo 10
        ElseIf FDIR(it1, jt1) = 2 Then
        it1 = it1 + 1: jt1 = jt1 + 1: GoTo 10
        ElseIf FDIR(it1, jt1) = 4 Then
        it1 = it1 + 1: jt1 = jt1: GoTo 10
        ElseIf FDIR(it1, jt1) = 8 Then
        it1 = it1 + 1: jt1 = jt1 - 1: GoTo 10
```

```
        ElseIf FDIR(it1, jt1) = 16 Then
        it1 = it1: jt1 = jt1 - 1: GoTo 10
        ElseIf FDIR(it1, jt1) = 32 Then
        it1 = it1 - 1: jt1 = jt1 - 1: GoTo 10
        ElseIf FDIR(it1, jt1) = 64 Then
        it1 = it1 - 1: jt1 = jt1: GoTo 10
        ElseIf FDIR(it1, jt1) = 128 Then
        it1 = it1 - 1: jt1 = jt1 + 1: GoTo 10
        End If
    Else
        If Not TT_CF(it1, jt1) = -9999 Then
        TT_CF_SCF(it, jt) = TT_SCF(it, jt) + TT_CF(it1, jt1): GoTo 20
        Else
        TT_CF_SCF(it, jt) = TT_SCF(it, jt): GoTo 20
        End If
    End If
20 Next jt
Next it
For itt = 1 To imax
For jtt = 1 To jmax
    Debug.Print itt, jtt, "CF+SCF+SF"
    If Not TT_SF(itt, jtt) = -9999 Then
        If FDIR(itt, jtt) = 1 Then
        itt1 = itt: jtt1 = jtt + 1: GoTo 30
        ElseIf FDIR(itt, jtt) = 2 Then
        itt1 = itt + 1: jtt1 = jtt + 1: GoTo 30
        ElseIf FDIR(itt, jtt) = 4 Then
        itt1 = itt + 1: jtt1 = jtt: GoTo 30
        ElseIf FDIR(itt, jtt) = 8 Then
        itt1 = itt + 1: jtt1 = jtt - 1: GoTo 30
        ElseIf FDIR(itt, jtt) = 16 Then
        itt1 = itt: jtt1 = jtt - 1: GoTo 30
        ElseIf FDIR(itt, jtt) = 32 Then
        itt1 = itt - 1: jtt1 = jtt - 1: GoTo 30
        ElseIf FDIR(itt, jtt) = 64 Then
        itt1 = itt - 1: jtt1 = jtt: GoTo 30
        ElseIf FDIR(itt, jtt) = 128 Then
        itt1 = itt - 1: jtt1 = jtt + 1: GoTo 30
        End If
```

```
    Else
    TT_CF_SCF_SF(itt, jtt) = TT_CF_SCF(itt, jtt)
    GoTo 40
    End If
30  If Not TT_SF(itt1, jtt1) = -9999 Then
        If FDIR(itt1, jtt1) = 1 Then
        itt1 = itt1: jtt1 = jtt1 + 1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 2 Then
        itt1 = itt1 + 1: jtt1 = jtt1 + 1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 4 Then
        itt1 = itt1 + 1: jtt1 = jtt1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 8 Then
        itt1 = itt1 + 1: jtt1 = jtt1 - 1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 16 Then
        itt1 = itt1: jtt1 = jtt1 - 1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 32 Then
        itt1 = itt1 - 1: jtt1 = jtt1 - 1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 64 Then
        itt1 = itt1 - 1: jtt1 = jtt1: GoTo 30
        ElseIf FDIR(itt1, jtt1) = 128 Then
        itt1 = itt1 - 1: jtt1 = jtt1 + 1: GoTo 30
        End If
    Else
        If TT_SCF(itt1, jtt1) <> -9999 Or TT_CF(itt1, jtt1) <> -9999 Then
        TT_CF_SCF_SF(itt, jtt) = TT_SF(itt, jtt) + TT_CF_SCF(itt1, jtt1): GoTo 40
        Else
        TT_CF_SCF_SF(itt, jtt) = TT_SF(itt, jtt): GoTo 40
        End If
    End If
40 Next jtt
Next itt
Dim z2t, i2t, j2t As Integer
Open "path\tot_cf_scf_sf_asc.asc" For Output As #22
For z2t = 1 To 6
    Print #22, lx2(z2t)
Next
For i2t = 1 To imax
For j2t = 1 To jmax
    Print #22, TT_CF_SCF_SF(i2t, j2t);
```

```
Next j2t
    Print #22, ""
Next i2t
Close #22
End
End Sub
'*****
```

APPENDIX 3.5: VB code for selecting the inflow cells from the boundaries



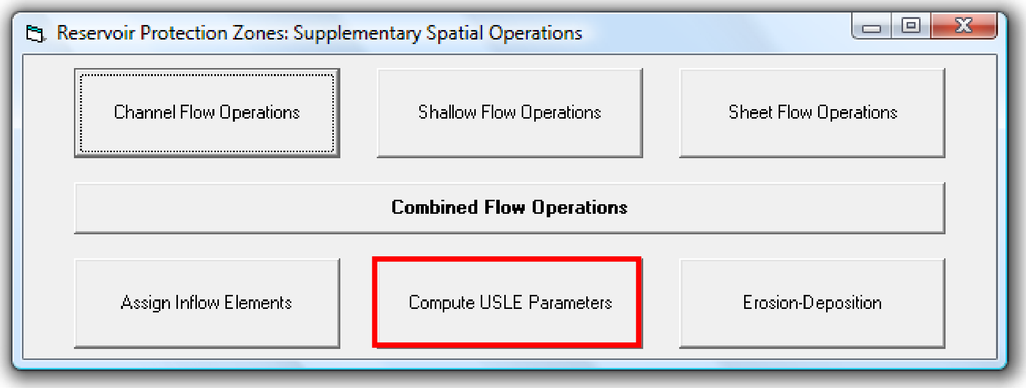
```
Private Sub Command5_Click()
LoadBufferZonesGrid
LoadBufferBoundaryPixels
LoadFdirFile
ComputeBufferInflowPixels
End Sub
'*****
Private Sub LoadBufferZonesGrid()
Dim zbz As Integer, xbz, ybz As Long
Dim l1bz, l2bz, lx1bz As String
Open "path\buffer_segments_layer.asc" For Input As #24
Dim arrl1bz(), arrl2bz() As String
Line Input #24, l1bz
arrl1bz() = Split(l1bz, "         ")
jmax = CInt(arrl1bz(1))
Line Input #24, l2bz
arrl2bz = Split(l2bz, "         ")
imax = CInt(arrl2bz(1))
For zbz = 1 To 4
    Line Input #24, lx1bz
Next
For xbz = 1 To imax
For ybz = 1 To jmax
    Input #24, BZ(xbz, ybz)
Next ybz
Next xbz
Close #24
End Sub
```

```
'*****
Private Sub LoadBufferBoundaryPixels()
Dim zbp As Integer, xbp, ybp As Long
Dim lx1bp As String
Open "path\buffer_boundary_cells_layer.asc" For Input As #25
For zbp = 1 To 6
    Line Input #25, lx1bp
Next
For xbp = 1 To imax
For ybp = 1 To jmax
    Input #25, BLC(xbp, ybp)
Next ybp
Next xbp
Close #25
End Sub
'*****
Private Sub ComputeBufferInflowPixels()
Dim BIP(4000, 4000) As Double
Dim ib, jb, ib1, jb1 As Long
For ib = 1 To imax
For jb = 1 To jmax
    Debug.Print ib, jb
    If Not BLC(ib, jb) = -9999 Then
        If FDIR(ib, jb) = 1 Then
        ib1 = ib: jb1 = jb + 1: GoTo 10
        ElseIf FDIR(ib, jb) = 2 Then
        ib1 = ib + 1: jb1 = jb + 1: GoTo 10
        ElseIf FDIR(ib, jb) = 4 Then
        ib1 = ib + 1: jb1 = jb: GoTo 10
        ElseIf FDIR(ib, jb) = 8 Then
        ib1 = ib + 1: jb1 = jb - 1: GoTo 10
        ElseIf FDIR(ib, jb) = 16 Then
        ib1 = ib: jb1 = jb - 1: GoTo 10
        ElseIf FDIR(ib, jb) = 32 Then
        ib1 = ib - 1: jb1 = jb - 1: GoTo 10
        ElseIf FDIR(ib, jb) = 64 Then
        ib1 = ib - 1: jb1 = jb: GoTo 10
        ElseIf FDIR(ib, jb) = 128 Then
        ib1 = ib - 1: jb1 = jb + 1: GoTo 10
```

```
        End If
    Else
    BIP(ib, jb) = -9999
    GoTo 20
    End If
10  If Not FDIR(ib1, jb1) = -9999 Then
        If BZ(ib1, jb1) > BZ(ib, jb) Or BZ(ib1, jb1) = BZ(ib, jb) Then
        BIP(ib, jb) = -9999: GoTo 20
        End If
        If FDIR(ib1, jb1) = 1 Then
        ib1 = ib1: jb1 = jb1 + 1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 2 Then
        ib1 = ib1 + 1: jb1 = jb1 + 1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 4 Then
        ib1 = ib1 + 1: jb1 = jb1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 8 Then
        ib1 = ib1 + 1: jb1 = jb1 - 1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 16 Then
        ib1 = ib1: jb1 = jb1 - 1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 32 Then
        ib1 = ib1 - 1: jb1 = jb1 - 1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 64 Then
        ib1 = ib1 - 1: jb1 = jb1: GoTo 10
        ElseIf FDIR(ib1, jb1) = 128 Then
        ib1 = ib1 - 1: jb1 = jb1 + 1: GoTo 10
        End If
    Else
    BIP(ib, jb) = 1
    GoTo 20
    End If
20 Next jb
Next ib
Dim z1b, i1b, j1b As Integer
Open "path\camli_buffer_inflow_grid.asc" For Output As #26
For z1b = 1 To 6
    Print #26, lx2(z1b)
Next
For i1b = 1 To imax
For j1b = 1 To jmax
```

```
    Print #26, BIP(i1b, j1b);
Next j1b
    Print #26, ""
Next i1b
Close #26
End
End Sub
'*****
```

APPENDIX 3.6: VB code for computing the USLE parameters averaged along the slope length



```
Private Sub Command7_Click()
LoadBeginCellGrid
LoadKGrid
LoadCGrid
LoadLGrid
LoadSlopeGrid
LoadFdirFile
ComputeUSLEparameters
End Sub
'*****
Private Sub LoadBeginCellGrid()
Dim zbc As Integer, xbc, ybc As Long
Dim l1bc, l2bc, lx1bc As String
Open "path\start_cells_layer.asc" For Input As #29
Dim arrl1bc(), arrl2bc() As String
Line Input #29, l1bc
arrl1bc() = Split(l1bc, "        ")
jmax = CInt(arrl1bc(1))
Line Input #29, l2bc
arrl2bc = Split(l2bc, "        ")
imax = CInt(arrl2bc(1))
For zbc = 1 To 4
    Line Input #29, lx1bc
Next
For xbc = 1 To imax
For ybc = 1 To jmax
    Input #29, BCEL(xbc, ybc)
```

```
Next ybc
Next xbc
Close #29
End Sub
'*****
Private Sub LoadKGrid()
Dim zk As Integer, xk, yk As Long
Open "path\K_grid_layer.asc" For Input As #30
For zk = 1 To 6
    Line Input #30, lx2(zk)
Next
For xk = 1 To imax
For yk = 1 To jmax
    Input #30, K(xk, yk)
Next yk
Next xk
Close #30
End Sub
'*****
Private Sub LoadCGrid()
Dim zc As Integer, kc, lc As Long
Open "path\C_grid_layer.asc" For Input As #31
For zc = 1 To 6
    Line Input #31, lx2(zc)
Next
For kc = 1 To imax
For lc = 1 To jmax
    Input #31, C(kc, lc)
Next lc
Next kc
Close #31
End Sub
'*****
Private Sub LoadLGrid()
Dim zlen As Integer, klen, llen As Long
Open "path\L_grid_layer.asc" For Input As #34
For zlen = 1 To 6
    Line Input #34, lx2(zlen)
Next
```

```
For klen = 1 To imax
For llen = 1 To jmax
    Input #34, L(klen, llen)
Next llen
Next klen
Close #34
End Sub
'*****
Private Sub ComputeUSLEparameters()
Dim KK(5000, 5000), CC(5000, 5000) As Double
Dim SUMC(5000, 5000), SUMK(5000, 5000) As Double
Dim SSLP(5000, 5000) , SUMS(5000, 5000) As Double
Dim ius, jus, ius1, jus1 As Long
For ius = 1 To imax
For jus = 1 To jmax
KK(ius, jus) = K(ius, jus): CC(ius, jus) = C(ius, jus)
SUMC(ius, jus) = 1: SUMK(ius, jus) = 1
SSLP(ius, jus) = SLP(ius, jus) * 100: SUMS(ius, jus) = 1
Next jus
Next ius
For ius = 1 To imax
For jus = 1 To jmax
Debug.Print ius, jus
If BCEL(ius, jus) <> -9999 Then
If BCEL(ius, jus) = 1 Then
CC(ius, jus) = C(ius, jus): KK(ius, jus) = K(ius, jus)
SSLP(ius, jus) = SLP(ius, jus) * 100: GoTo 20
Else
'The following controls consider the orthogonal and diagonal lengths of 5 m and 7.071 m,
'respectively, between the two neighbor cells for a cell size of 5 m.
If (ius - 1 >= 1 And jus - 1 >= 1) And FDIR(ius - 1, jus - 1) = 2 And (L(ius, jus) - L(ius - 1, jus - 1) >
7 And L(ius, jus) - L(ius - 1, jus - 1) < 7.1) Then
ius1 = ius - 1: jus1 = jus - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
```

```
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf ius - 1 >= 1 And FDIR(ius - 1, jus) = 4 And (L(ius, jus) - L(ius - 1, jus) > 4.9 And L(ius, jus) -
L(ius - 1, jus) < 5.1) Then
ius1 = ius - 1: jus1 = jus
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf (ius - 1 >= 1 And jus + 1 <= jmax) And FDIR(ius - 1, jus + 1) = 8 And (L(ius, jus) - L(ius - 1,
jus + 1) > 7 And L(ius, jus) - L(ius - 1, jus + 1) < 7.1) Then
ius1 = ius - 1: jus1 = jus + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
```

```
ElseIf jus + 1 <= jmax And FDIR(ius, jus + 1) = 16 And (L(ius, jus) - L(ius, jus + 1) > 4.9 And L(ius, jus) - L(ius, jus + 1) < 5.1) Then
ius1 = ius: jus1 = jus + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf (ius + 1 <= imax And jus + 1 <= jmax) And FDIR(ius + 1, jus + 1) = 32 And (L(ius, jus) - L(ius + 1, jus + 1) > 7 And L(ius, jus) - L(ius + 1, jus + 1) < 7.1) Then
ius1 = ius + 1: jus1 = jus + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf ius + 1 <= imax And FDIR(ius + 1, jus) = 64 And (L(ius, jus) - L(ius + 1, jus) > 4.9 And L(ius, jus) - L(ius + 1, jus) < 5.1) Then
ius1 = ius + 1: jus1 = jus
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
```

```
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf (ius + 1 <= imax And jus - 1 >= 1) And FDIR(ius + 1, jus - 1) = 128 And (L(ius, jus) - L(ius + 1, jus - 1) > 7 And L(ius, jus) - L(ius + 1, jus - 1) < 7.1) Then
ius1 = ius + 1: jus1 = jus - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf jus - 1 >= 1 And FDIR(ius, jus - 1) = 1 And (L(ius, jus) - L(ius, jus - 1) > 4.9 And L(ius, jus) - L(ius, jus - 1) < 5.1) Then
ius1 = ius: jus1 = jus - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
```

```
End If
GoTo 10
End If
End If
10 If BCEL(ius1, jus1) = 1 Then
CC(ius, jus) = CC(ius, jus) / SUMC(ius, jus): KK(ius, jus) = KK(ius, jus) / SUMK(ius, jus): SSLP(ius, jus) = SSLP(ius, jus) / SUMS(ius, jus): GoTo 20
Else
If (ius1 - 1 >= 1 And jus1 - 1 >= 1) And FDIR(ius1 - 1, jus1 - 1) = 2 And (L(ius1, jus1) - L(ius1 - 1, jus1 - 1) > 7 And L(ius1, jus1) - L(ius1 - 1, jus1 - 1) < 7.1) Then
ius1 = ius1 - 1: jus1 = jus1 - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf ius1 - 1 >= 1 And FDIR(ius1 - 1, jus1) = 4 And (L(ius1, jus1) - L(ius1 - 1, jus1) > 4.9 And L(ius1, jus1) - L(ius1 - 1, jus1) < 5.1) Then
ius1 = ius1 - 1: jus1 = jus1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
```

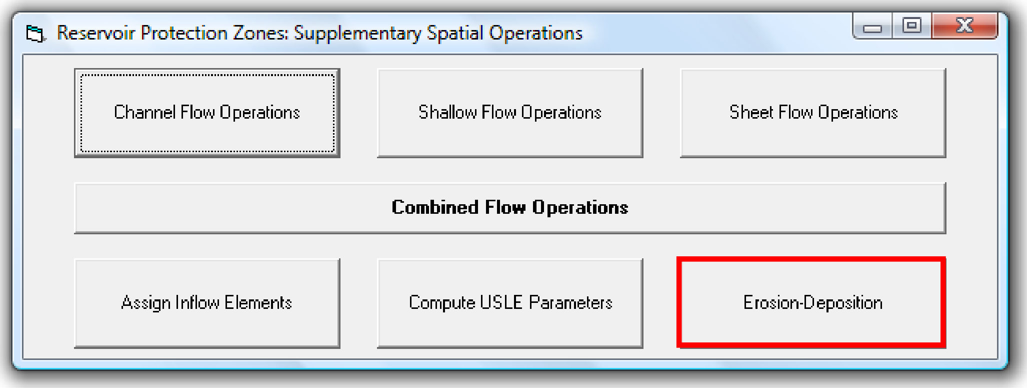
```
GoTo 10
ElseIf (ius1 - 1 >= 1 And jus1 + 1 <= jmax) And FDIR(ius1 - 1, jus1 + 1) = 8 And (L(ius1, jus1) - L(ius1 - 1, jus1 + 1) > 7 And L(ius1, jus1) - L(ius1 - 1, jus1 + 1) < 7.1) Then
ius1 = ius1 - 1: jus1 = jus1 + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf jus1 + 1 <= jmax And FDIR(ius1, jus1 + 1) = 16 And (L(ius1, jus1) - L(ius1, jus1 + 1) > 4.9 And L(ius1, jus1) - L(ius1, jus1 + 1) < 5.1) Then
ius1 = ius1: jus1 = jus1 + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf (ius1 + 1 <= imax And jus1 + 1 <= jmax) And FDIR(ius1 + 1, jus1 + 1) = 32 And (L(ius1, jus1) - L(ius1 + 1, jus1 + 1) > 7 And L(ius1, jus1) - L(ius1 + 1, jus1 + 1) < 7.1) Then
ius1 = ius1 + 1: jus1 = jus1 + 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
```

```
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf ius1 + 1 <= imax And FDIR(ius1 + 1, jus1) = 64 And (L(ius1, jus1) - L(ius1 + 1, jus1) > 4.9
And L(ius1, jus1) - L(ius1 + 1, jus1) < 5.1) Then
ius1 = ius1 + 1: jus1 = jus1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf (ius1 + 1 <= imax And jus1 - 1 >= 1) And FDIR(ius1 + 1, jus1 - 1) = 128 And (L(ius1, jus1) -
L(ius1 + 1, jus1 - 1) > 7 And L(ius1, jus1) - L(ius1 + 1, jus1 - 1) < 7.1) Then
ius1 = ius1 + 1: jus1 = jus1 - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
```

```
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
ElseIf jus1 - 1 >= 1 And FDIR(ius1, jus1 - 1) = 1 And (L(ius1, jus1) - L(ius1, jus1 - 1) > 4.9 And L(ius1, jus1) - L(ius1, jus1 - 1) < 5.1) Then
ius1 = ius1: jus1 = jus1 - 1
If SLP(ius1, jus1) <> -9999 Then
If SSLP(ius, jus) = -9999 Then SSLP(ius, jus) = 0
SSLP(ius, jus) = SSLP(ius, jus) + (SLP(ius1, jus1) * 100): SUMS(ius, jus) = SUMS(ius, jus) + 1
End If
If C(ius1, jus1) <> -9999 Then
If C(ius, jus) = -9999 Then CC(ius, jus) = 0
CC(ius, jus) = CC(ius, jus) + C(ius1, jus1): SUMC(ius, jus) = SUMC(ius, jus) + 1
End If
If K(ius1, jus1) <> -9999 Then
If KK(ius, jus) = -9999 Then KK(ius, jus) = 0
KK(ius, jus) = KK(ius, jus) + K(ius1, jus1): SUMK(ius, jus) = SUMK(ius, jus) + 1
End If
GoTo 10
End If
End If
Else
SSLP(ius, jus) = -9999: CC(ius, jus) = -9999: KK(ius, jus) = -9999
GoTo 20
End If
20 Next jus
Next ius
Dim z1us, i1us, j1us As Integer
Open "path\KK_grid.asc" For Output As #32
Open " path\CC_grid.asc" For Output As #33
Open " path\SSLP_grid.asc" For Output As #34
For z1us = 1 To 6
Print #32, lx2(z1us)
Print #33, lx2(z1us)
Print #34, lx2(z1us)
Next
For i1us = 1 To imax
For j1us = 1 To jmax
Print #32, KK(i1us, j1us);
```

```
Print #33, CC(i1us, j1us);
Print #34, SSLP(i1us, j1us);
Next j1us
Print #32, ""
Print #33, ""
Print #34, ""
Next i1us
Close #32
Close #33
Close #34
End
End Sub
'*****
```

APPENDIX 3.7: VB code for differentiating between the areas of erosion and deposition, and for computing the sedimentation rates



```
Private Sub Command6_Click()
LoadSoilLossGrid
LoadFdirFile
LoadLGrid
ComputeErosionDeposition
End Sub
'*****
Private Sub LoadSoilLossGrid()
Dim ztsl As Integer, xtsl, ytsl As Long
Dim l1tsl, l2tsl, lx1tsl As String
Open "path\usle_layer.asc" For Input As #27
Dim arrl1tsl(), arrl2tsl() As String
Line Input #27, l1tsl
arrl1tsl() = Split(l1tsl, "         ")
jmax = CInt(arrl1tsl(1))
Line Input #27, l2tsl
arrl2tsl = Split(l2tsl, "         ")
imax = CInt(arrl2tsl(1))
For ztsl = 1 To 4
Line Input #27, lx1tsl
Next
For xtsl = 1 To imax
For ytsl = 1 To jmax
Input #27, TSL(xtsl, ytsl)
Next ytsl
Next xtsl
Close #27
```

```
End Sub
'*****
Private Sub ComputeErosionDeposition()
Dim ERODEP(3000, 3000) As Double
Dim cellincome As Double
Dim ied, jed As Long
For ied = 1 To imax
For jed = 1 To jmax
Debug.Print ied, jed
If Not TSL(ied, jed) = -9999 Then
If (ied - 1 >= 1 And jed - 1 >= 1) And TSL(ied - 1, jed - 1) <> -9999 And FDIR(ied - 1, jed - 1) = 2 And (L(ied, jed) - L(ied - 1, jed - 1) > 7 And L(ied, jed) - L(ied - 1, jed - 1) < 7.1) Then
cellincome = TSL(ied - 1, jed - 1)
ElseIf ied - 1 >= 1 And TSL(ied - 1, jed) <> -9999 And FDIR(ied - 1, jed) = 4 And (L(ied, jed) - L(ied - 1, jed) > 4.9 And L(ied, jed) - L(ied - 1, jed) < 5.1) Then
cellincome = TSL(ied - 1, jed)
ElseIf (ied - 1 >= 1 And jed + 1 <= jmax) And TSL(ied - 1, jed + 1) <> -9999 And FDIR(ied - 1, jed + 1) = 8 And (L(ied, jed) - L(ied - 1, jed + 1) > 7 And L(ied, jed) - L(ied - 1, jed + 1) < 7.1) Then
cellincome = TSL(ied - 1, jed + 1)
ElseIf jed + 1 <= jmax And TSL(ied, jed + 1) <> -9999 And FDIR(ied, jed + 1) = 16 And (L(ied, jed) - L(ied, jed + 1) > 4.9 And L(ied, jed) - L(ied, jed + 1) < 5.1) Then
cellincome = TSL(ied, jed + 1)
ElseIf (ied + 1 <= imax And jed + 1 <= jmax) And TSL(ied + 1, jed + 1) <> -9999 And FDIR(ied + 1, jed + 1) = 32 And (L(ied, jed) - L(ied + 1, jed + 1) > 7 And L(ied, jed) - L(ied + 1, jed + 1) < 7.1) Then
cellincome = TSL(ied + 1, jed + 1)
ElseIf ied + 1 <= imax And TSL(ied + 1, jed) <> -9999 And FDIR(ied + 1, jed) = 64 And (L(ied, jed) - L(ied + 1, jed) > 4.9 And L(ied, jed) - L(ied + 1, jed) < 5.1) Then
cellincome = TSL(ied + 1, jed)
ElseIf (ied + 1 <= imax And jed - 1 >= 1) And TSL(ied + 1, jed - 1) <> -9999 And FDIR(ied + 1, jed - 1) = 128 And (L(ied, jed) - L(ied + 1, jed - 1) > 7 And L(ied, jed) - L(ied + 1, jed - 1) < 7.1) Then
cellincome = TSL(ied + 1, jed - 1)
ElseIf jed - 1 >= 1 And TSL(ied, jed - 1) <> -9999 And FDIR(ied, jed - 1) = 1 And (L(ied, jed) - L(ied, jed - 1) > 4.9 And L(ied, jed) - L(ied, jed - 1) < 5.1) Then
cellincome = TSL(ied, jed - 1)
Else
cellincome = 0
End If
ERODEP(ied, jed) = TSL(ied, jed) - cellincome
```

```
cellincome = 0
Else
ERODEP(ied, jed) = -9999
End If
Next jed
Next ied
Dim z1ed, i1ed, j1ed As Integer
Open "path\erodep_grid.asc" For Output As #28
For z1ed = 1 To 6
Print #28, lx2(z1ed)
Next
For i1ed = 1 To imax
For j1ed = 1 To jmax
Print #28, ERODEP(i1ed, j1ed);
Next j1ed
Print #28, ""
Next i1ed
Close #28
End
End Sub
'*****
```

APPENDIX 4

APPENDIX 4.1: AML script for computing the USLE LS-factor (prepared by Rick D. Van Remortel)

```
/*
/**************************************************************
/*
/*RUSLE_LS_4_PC.AML
/*
/*Calculates LS Factor using DEM data according to RUSLE-based criteria.
/*
/*Code prepared by: Rick D. Van Remortel, Lockheed Martin Environmental
/*Services, Las Vegas, NV, latest draft dated Dec 2003.  Other primary
/*contributors are: Robert J. Hickey, Central Washington University,
/*Ellensburg, WA;  Mathew E. Hamilton and Robert W. Maichle, Lockheed
/*Martin Environmental Services, Las Vegas, NV.
/*
/*RUSLE Version 4
/*Corrects computational order of operations for S-constituent elements from
/*previous versions, which results in a more accurate LS factor estimate for RUSLE.
/*
/*RUSLE Version 3 (May 2002; revised Aug 2003 to correct rounding problem in final
/*LS grid) increased speed by inverting order of slope-length re-initialization code;
/*adjusted slope angle code to get more consistent results on assignment of minimum
/*slope gradients; adjusted cell length code to make more generic and solve ESRI's
/*ArcInfo 7 error with "in" function and resultant portability to ArcInfo 8 on PC.
/*
/*RUSLE Version 2 added more caveats about watershed catchment configuration of
/*input DEM, and modified number of nodata check grids that were produced in the
/*initial RUSLE Version 1.
/*
/*Original USLE-based AML code written by Robert Hickey, USLE Version 1 documented by
/*Hickey et al. (1994) and USLE Version 2 by Hickey (2000). The USLE Version 2 code
/*was modified by Rick Van Remortel and Matt Hamilton, Lockheed Martin Environmental
/*Services, Las Vegas, NV, with a RUSLE focus, to change a few of the assumptions
/*about filled sinks and flat areas, and to address the handling of any residual
/*nodata strips near the watershed boundary, allow assignment of separate slope
/*cutoff factors for different slope ranges, and utilize LS-calculation algorithms
```

```
/*in accordance with numerous RUSLE improvements documented in McCool et al. (1997)
/*as Chapter 4 within the RUSLE Handbook (Renard et al. (1997). A journal article
/*describing the RUSLE-based AML has been published with the following citation:
/*Van Remortel, R.D., M.E. Hamilton, and R.J. Hickey.  2001.  Estimating
/*the LS factor for RUSLE through iterative slope length processing of digital
/*elevation data within ArcInfo Grid.  Cartography Vol. 30, No. 1, Pg. 27-35.
/*
/*Tested on: ArcInfo Workstation 8.2 on WinXP
/*
/*Notes for the user:
/*
/*Steeper, longer slopes produce higher overland flow velocities, but soil loss
/*is much more sensitive to changes in S than to changes in L.  The RUSLE effects
/*of irregular and segmented slope shapes are not addressed within the AML.
/*
/*LS calculation algorithms are based on the RUSLE research of McCool et al. (1997)
/*which corrects slope length for horizontal projection; useful in GIS where slope
/*lengths are measured off grid cells or maps (x,y) instead of in the field (x,y,z).
/*
/*The AML calculates slope length from high points (e.g., ridgetops) towards low points
/*such as the watershed pour point or other outlet.  An administratively-defined
/*watershed (e.g., HUC) may not be suitable unless it's also a hydrologically defined
/*catchment area.  The ideal input for generating an LS-factor grid is a DEM dataset
/*(e.g., NED) of suitable extent that has been either clipped or enlarged to encompass
/*the zone of interest plus any additional relevant catchment area. To avoid any
/*scale-induced edge effects, the mapextent should be slightly larger than the area of
/*interest.  Make sure DEM elevation units are the same as horizontal distance units
/*(the default is meters).
/*
/*The output from the L and S calculations should be closely examined to ensure
/*that the calculations are being applied properly and that there are no significant
/*format problems with the input DEM data.  If processing difficulties occur with the
/*use of a floating-point format, truncating or rounding to an integer format may be
/*advisable as many DEM product suppliers will not attest to the significance of
/*decimal digits in their data sets.  The presence of horizontal or vertical stippling,
/*corn-rowing, or edge-matching anomalies in the DEM can yield erratic or discontinuous
/*slope length features.  There are smoothing algorithms available that may correct
/*some of the DEM irregularities but will also result in unwanted smoothing
/*or generalization of other DEM elevation cells that did not require any such
```

```
/*correction.  If utilized, DEM-enhancement algorithms should be well-documented and
/*applied with caution to avoid gross over-extension of slope lengths.
/*
/*Define slope angle (theta) in degrees (inverse tangent of %slope gradient).  The
/*slope cutoff factor (a value between 0 and 1) is the relative change in slope
/*angle that will cause the slope length cumulation to end and start over with the
/*next downslope cell; a high factor value will cause the slope length cumulation
/*to end more easily than a small factor value, i.e., a smaller slope differential
/*between cells is required to end cumulation when using a factor of 0.7 versus
/*using a factor of 0.5 (the opposite of what one would initially think).  This
/*is a very important consideration for the initial settings, so use care.
/*
/*The routine periodically uses 1-cell buffer grid to avoid nodata around edges;
/*this will often be sufficient to prevent edge errors for many accurately clipped
/*input DEMs; however, adding a buffer of about 10 cells to the input watershed DEM
/*is recommended to ensure that possible "trapped pools" or strips of nodata
/*cells near the outer border of the watershed can later be clipped out of the
/*LS-factor grid using the actual watershed boundary.
/*
/***************************************************************************

&echo &off

/*define a root prefix name (4 characters or less) for study area.
&type
&sv sa = [response 'Enter a study area root prefix name, 4 characters or less']

/*identify the workspace containing DEM and study area boundary grids.
&type
&sv ws = [response 'Enter full path to workspace holding DEM and boundary grids']
&if [exists %ws% -workspace] &then
  &goto skipto11
&if ^ [exists %ws% -workspace] &then
  &do
    &type
    &type NOTE: Wrong path identified!
    &sv ws = [response 'Re-enter full path to workspace holding DEM and boundary grids']
  &end
&label skipto11
```

```
/*specify input dem elevation grid name.
&type
&sv dem_input = [response 'Enter name of the input DEM grid']

/*specify watershed boundary grid for clipping final LS grid.
&type
&sv wshed = [response 'Enter name of study area boundary grid']

/*identify DEM units, ensure vertical & horizontal are same.
&type
&sv demunits = [response 'Enter DEM measurement units, meters or feet ']
&if [null %demunits%] &then
  &sv demunits = meters
&if %demunits% eq meters or %demunits% eq feet &then
  &goto skipto12
&if %demunits% ne meters or %demunits% ne feet &then
  &do
    &type
    &type NOTE: Wrong DEM vertical/horizontal units!
    &sv demunits = [response 'Re-enter DEM measurement units, meters or feet ']
    &if [null %demunits%] &then
      &sv demunits = meters
  &end
&label skipto12

/*set slope cutoff factors for ending/beginning slope length cumulation; use
/*different factors for lt or ge 5 percent slope gradients.
&type
&sv scf_lt5 = [response 'Enter slope cutoff factor for slopes < 5% : suggested = .7']
&if [null %scf_lt5%] &then
  &sv scf_lt5 = .7
&if %scf_lt5% lt 1.1 &then
  &goto skipto13
&if %scf_lt5% ge 1.1 &then
  &do
    &type
    &type NOTE: Erroneous factor value!
    &sv scf_lt5 = [response 'Re-enter slope cutoff factor for slopes < 5% : suggested = .7']
```

```
    &if [null %scf_lt5%] &then
      &sv scf_lt5 = .7
  &end
&label skipto13
&type
&sv scf_ge5 = [response 'Enter slope cutoff factor for slopes >= 5% : suggested = .5']
&if [null %scf_ge5%] &then
  &sv scf_ge5 = .5
&if %scf_ge5% lt 1.1 &then
  &goto skipto14
&if %scf_ge5% ge 1.1 &then
  &do
    &type
    &type NOTE: Erroneous factor value!
    &sv scf_ge5 = [response 'Re-enter slope cutoff factor for slopes >= 5% : suggested = .5']
    &if [null %scf_ge5%] &then
      &sv scf_ge5 = .5
  &end
&label skipto14

w %ws%
&if ^ [exists ls_rusle -workspace] &then
  cw ls_rusle
w ls_rusle

&wat runspecs.log
&type %sa%
&type %ws%
&type %dem_input%
&type %wshed%
&type %demunits%
&type %scf_lt5%
&type %scf_ge5%
&wat &off

grid
setwindow ..\%dem_input%
setcell ..\%dem_input%
```

```
/*create filled dem grid using Hickey's alternative to the Grid fill command; this
/*one uses a sliding 1-cell donut annulus applied to an individual sink cell
/*to adopt the minimum value of its octagonal neighbors, thus filling the sink.
&if [exists dem_fill -grid] &then
  kill dem_fill all
&if [exists dem_fill2 -grid] &then
  kill dem_fill2 all
dem_fill = ..\%dem_input%
finished = scalar(0)
&do &until [show scalar finished] eq 1
  finished = scalar(1)
  rename dem_fill dem_fill2
  if (focalflow(dem_fill2) eq 255) {
    dem_fill = focalmin (dem_fill2, annulus, 1, 1)
    test_grid = 0
    }
  else {
    dem_fill = dem_fill2
    test_grid = 1
    }
  endif
  kill dem_fill2 all
  /*test for no more sinks filled
  docell
    finished {= test_grid
  end
  kill test_grid all
&end

/*create inflow and outflow direction grids which assign possible inflow or
/*outflow direction values within a cell's immediate octagonal neighborhood;
/*these grids may legitimately include a few cells with values corresponding to
/*other than the primary orthogonal or diagonal directions.
&if [exists flowdir_in -grid] &then
  kill flowdir_in all
flowdir_in = focalflow (dem_fill)
/*create outflow direction grid
&if [exists flowdir_out -grid] &then
  kill flowdir_out all
```

```
flowdir_out = flowdirection (dem_fill)

&describe dem_fill
/*reset window to include a 1-cell buffer around input DEM boundary.
setwindow [calc [show scalar $$wx0] - [show scalar $$cellsize]] ~
    [calc [show scalar $$wy0] - [show scalar $$cellsize]] ~
    [calc [show scalar $$wx1] + [show scalar $$cellsize]] ~
    [calc [show scalar $$wy1] + [show scalar $$cellsize]]
/*create 1-cell buffer dem to change nodata (nd) on edge cells to a value
&if [exists dem_fill_b -grid] &then
  kill dem_fill_b all
dem_fill_b = con (isnull(dem_fill), focalmin(dem_fill), dem_fill)
kill dem_fill all

/*set cell length for orthogonal and diagonal flow directions.
&sv cell = [show scalar $$cellsize]
&sv cellorth = (1.00 * %cell%)
&sv celldiag = (1.4142 * %cellorth%)

/*calculate downslope angle in degrees for each cell; amended previous code to reset
/*groups of "flat" cells (0.0-degree slope by default, where flowdir_out ^= octagonal
/*direction) to a value >0.00 and <0.57 (inv. tan of 1% gradient); suggested value
/*is 0.1; new assumption is that all cells, even essentially flat areas such as dry
/*lakes, have slope > 0.00 degrees; this ensures that all cells remain connected to
/*the flow network, and therefore are assigned a slope angle and final LS factor
/*value, however small it might be; the () below prevents problems that occur with
/*using whole numbers.
&if [exists down_slp_ang -grid] &then
  kill down_slp_ang all
if (flowdir_out eq 64)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(0, -1)) div %cellorth%)
else if (flowdir_out eq 128)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(1, -1)) div %celldiag%)
else if (flowdir_out eq 1)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(1, 0)) div %cellorth%)
else if (flowdir_out eq 2)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(1, 1)) div %celldiag%)
else if (flowdir_out eq 4)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(0, 1)) div %cellorth%)
```

```
else if (flowdir_out eq 8)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(-1, 1)) div %celldiag%)
else if (flowdir_out eq 16)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(-1, 0)) div %cellorth%)
else if (flowdir_out eq 32)
  down_slp_ang = deg * atan((dem_fill_b - dem_fill_b(-1, -1)) div %celldiag%)
else
  down_slp_ang = 0.1
endif
&if [exists down_slp_ang2 -grid] &then
  kill down_slp_ang2 all
down_slp_ang2 = con (down_slp_ang eq 0, 0.1, down_slp_ang)
kill down_slp_ang all
rename down_slp_ang2 down_slp_ang

/*reset window to normal extent and clip downslope grid, rename as original name.
setwindow ..\%dem_input%
&if [exists down_slp_ang2 -grid] &then
  kill down_slp_ang2 all
down_slp_ang2 = down_slp_ang
kill down_slp_ang
rename down_slp_ang2 down_slp_ang

/*calculate cell slope length considering orthogonal & diagonal outflow dir.
&if [exists slp_lgth_cell -grid] &then
  kill slp_lgth_cell all
if (flowdir_out eq 2)
  slp_lgth_cell = %celldiag%
else if (flowdir_out eq 8)
  slp_lgth_cell = %celldiag%
else if (flowdir_out eq 32)
  slp_lgth_cell = %celldiag%
else if (flowdir_out eq 128)
  slp_lgth_cell = %celldiag%
else
  slp_lgth_cell = %cellorth%
endif

/*reset window to buffer extent, create outflow dir grid w/ buffer cells eq 0.
```

```
setwindow dem_fill_b
&if [exists flowdir_out_b -grid] &then
  kill flowdir_out_b all
flowdir_out_b = con (isnull(flowdir_out), 0, flowdir_out)
kill flowdir_out all

/*create initial cumulative slope length grid and do bitwise compare of flowdir_in
/*with flowdir_out to find normally flowing cells, set these to nodata, then
/*calculate high points (includes filled sinks) to 1/2 cell length.
&if [exists slp_lgth_cum -grid] &then
  kill slp_lgth_cum all
if ((flowdir_in && 64) and (flowdir_out_b(0, -1) eq 4))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 128) and (flowdir_out_b(1, -1) eq 8))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 1) and (flowdir_out_b(1, 0) eq 16))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 2) and (flowdir_out_b(1, 1) eq 32))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 4) and (flowdir_out_b(0, 1) eq 64))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 8) and (flowdir_out_b(-1, 1) eq 128))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 16) and (flowdir_out_b(-1, 0) eq 1))
 slp_lgth_cum = setnull(1 eq 1)
else if ((flowdir_in && 32) and (flowdir_out_b(-1, -1) eq 2))
 slp_lgth_cum = setnull(1 eq 1)
else
 slp_lgth_cum = 0.5 * slp_lgth_cell
endif

/*set beginning slope length points (high points and filled sinks) to be added back
/*in later after slope lengths for all other cells have been determined for each
/*iteration; beginning points will have a value of 1/2 their cell slope length;
/*a beginning point is a cell that has no points flowing into it or if the only
/*cells flowing into it are of equal elevation; amended previous code to change
/*assumption that "flat" high points get a value of zero cell slope length to
/*1/2-cell slope length; the new assumption is that the minimum cumulative
/*slope length is 1/2 cell slope length even for filled sinks and "flat" high
```

```
/*points, thereby ensuring the LS factor value for every cell > 0.00.
&if [exists slp_lgth_beg -grid] &then
  kill slp_lgth_beg all
slp_lgth_beg = con (isnull(slp_lgth_cum), %cell%, slp_lgth_cum)

/*assign slope-end factor where slope length cumulation is ended; amended previous
/*code to use RUSLE guidelines suggesting that a slope break of 5% (2.8624 deg angle)
/*separates two different erosion/deposition regimes for gentle and steep slopes;
/*this is also a convenient break to address concentration dependency issues, where
/*the effects of relative changes in slope are inordinately amplified at lower gradients;
/*for slope gradients of < 5%, use a higher factor than for >= 5%; this makes it easier
/*on shallower slopes to end erosion and begin deposition; i.e., a higher cutoff factor
/*means that less slope reduction is needed to end cumulation.
&if [exists slp_end_fac -grid] &then
  kill slp_end_fac all
if (down_slp_ang lt 2.8624)
  slp_end_fac = %scf_lt5%
else if (down_slp_ang ge 2.8624)
  slp_end_fac = %scf_ge5%
endif

/*remove any residual directional grids if present from a previous run.
&if [exists fromcell_n -grid] &then
  kill fromcell_n all
&if [exists fromcell_ne -grid] &then
  kill fromcell_ne all
&if [exists fromcell_e -grid] &then
  kill fromcell_e all
&if [exists fromcell_se -grid] &then
  kill fromcell_se all
&if [exists fromcell_s -grid] &then
  kill fromcell_s all
&if [exists fromcell_sw -grid] &then
  kill fromcell_sw all
&if [exists fromcell_w -grid] &then
  kill fromcell_w all
&if [exists fromcell_nw -grid] &then
  kill fromcell_nw all
```

```
/*amended previous code to set up additional nodata tests that create a series of
/*nodata grids to track progress of run; reset window to normal extent, use filled
/*dem grid to mask testing of buffer cells.
setwindow ..\%dem_input%
setmask ..\%dem_input%
ndcell = scalar(1)
/*amended previous code to set iterative nodata cell count grids to zero.
&if [exists slp_lgth_nd2 -grid] &then
  kill slp_lgth_nd2 all
slp_lgth_nd2 = 0
&sv warn = .FALSE.

/*begin iterative loop to calculate cumulative slope length for every cell.
&sv finished = .FALSE.
&sv n = 1
&do &until %finished%

  /*keep copy of previous iterations's max cumulation grid to check progress.
  &if [exists slp_lgth_prev -grid] &then
    kill slp_lgth_prev all
  copy slp_lgth_cum slp_lgth_prev

  &sv counter = 0
  &do counter = 1 &to 8
    /*set variables for the if that follows.
    &select %counter%
      &when 1
      &do
        &sv fromcell_dir = fromcell_n
        &sv dirfrom = 4
        &sv dirpossto = 64
        &sv cellcol = 0
        &sv cellrow = -1
      &end
      &when 2
      &do
        &sv fromcell_dir = fromcell_ne
        &sv dirfrom = 8
        &sv dirpossto = 128
```

```
  &sv cellcol = 1
  &sv cellrow = -1
&end
&when 3
&do
  &sv fromcell_dir = fromcell_e
  &sv dirfrom = 16
  &sv dirpossto = 1
  &sv cellcol = 1
  &sv cellrow = 0
&end
&when 4
&do
  &sv fromcell_dir = fromcell_se
  &sv dirfrom = 32
  &sv dirpossto = 2
  &sv cellcol = 1
  &sv cellrow = 1
&end
&when 5
&do
  &sv fromcell_dir = fromcell_s
  &sv dirfrom = 64
  &sv dirpossto = 4
  &sv cellcol = 0
  &sv cellrow = 1
&end
&when 6
&do
  &sv fromcell_dir = fromcell_sw
  &sv dirfrom = 128
  &sv dirpossto = 8
  &sv cellcol = -1
  &sv cellrow = 1
&end
&when 7
&do
  &sv fromcell_dir = fromcell_w
  &sv dirfrom = 1
```

```
      &sv dirpossto = 16
      &sv cellcol = -1
      &sv cellrow = 0
    &end
    &when 8
    &do
      &sv fromcell_dir = fromcell_nw
      &sv dirfrom = 2
      &sv dirpossto = 32
      &sv cellcol = -1
      &sv cellrow = -1
    &end
  &end

  /*test flow source cell for nodata using n-notation, control downslope cell
  /*advance. First test inflow and outflow direction grids for possible flow
  /*source cell.
  if (not(flowdir_in && %dirpossto%))
    %fromcell_dir% = 0
  else if (flowdir_out_b(%cellcol%, %cellrow%) <> %dirfrom%)
    %fromcell_dir% = 0
  /*then test current cell with respect to source cell slope-end factor cutoff
  /*criteria; if met, set to 0 to start cumulation at and below the cell.
  else if (down_slp_ang lt (down_slp_ang(%cellcol%, %cellrow%) * slp_end_fac))
    %fromcell_dir% = 0
  else if (down_slp_ang ge (down_slp_ang(%cellcol%, %cellrow%) * slp_end_fac))
    %fromcell_dir% = slp_lgth_prev(%cellcol%, %cellrow%) + ~
        slp_lgth_cell(%cellcol%, %cellrow%)
  else if (isnull(slp_lgth_prev(%cellcol%, %cellrow%)))
    %fromcell_dir% = setnull(1 eq 1)
  else
    %fromcell_dir% = 0
  endif
&end

/*select max cumulative slope length in fromcell dir grids, else beg. cell value.
&if [exists slp_lgth_cum -grid] &then
  kill slp_lgth_cum all
slp_lgth_cum = max(fromcell_n, fromcell_ne, fromcell_e, fromcell_se, ~
```

```
    fromcell_s, fromcell_sw, fromcell_w, fromcell_nw, slp_lgth_beg)

/*test for the last iteration filling in all cells with data.
&sv nodata = [show scalar ndcell]
&if %nodata% eq 0 &then
  &sv finished = .TRUE.
/*test for any residual nodata cells.
&if [exists slp_lgth_nd -grid] &then
  kill slp_lgth_nd all
if (isnull(slp_lgth_cum) and not isnull(flowdir_out_b))
  slp_lgth_nd = 1
else
  slp_lgth_nd = 0
endif
ndcell = scalar(0)
docell
  ndcell }= slp_lgth_nd
end

/*amended previous code to allow monitoring of whether nodata cells decrease with
/*each iteration; if no more decrease after 2 iterations, end the iterative loop
/*and proceed to creation of LS grid; in this event the likelihood is that there
/*are one or more small nodata strips along outer boundary, probably within the
/*10-cell buffer area of the input DEM and not within the actual study area.
&if [exists nd_chg2 -grid] &then
  kill nd_chg2 all
if (slp_lgth_nd eq slp_lgth_nd2)
  nd_chg2 = 0
else
  nd_chg2 = 1
endif
  ndchg2 = scalar(0)
docell
  ndchg2 }= nd_chg2
end
&sv nd2 = [show scalar ndchg2]
&if %nd2% eq 0 &then
  &do
    &sv finished = .TRUE.
```

```
      &sv warn = .TRUE.
    &end

  /*remove temporary directional grids from the latest iteration.
  kill (!fromcell_n fromcell_ne fromcell_e fromcell_se fromcell_s fromcell_sw ~
    fromcell_w fromcell_nw!)
  /*amended previous code to move nodata-test grid 1 notch to prepare for next loop.
  &if [exists slp_lgth_nd2 -grid] &then
    kill slp_lgth_nd2 all
  copy slp_lgth_nd slp_lgth_nd2
  kill slp_lgth_nd all

  &sv n = %n% + 1
  &type This begins slope length iteration %n%

&end

/*change name of cumulation grid from final iteration to max, clip, rename back again.
rename slp_lgth_cum slp_lgth_max
/*resetting window to normal extent.
setwindow ..\%dem_input%
&if [exists slp_lgth_max2 -grid] &then
  kill slp_lgth_max2 all
rename slp_lgth_max slp_lgth_max2
slp_lgth_max = slp_lgth_max2
kill slp_lgth_max2 all

/*convert slope length in meters to feet if necessary.
&if [exists slp_lgth_ft -grid] &then
  kill slp_lgth_ft all
&if %demunits% eq meters &then
  slp_lgth_ft = slp_lgth_max div 0.3048
&else
  slp_lgth_ft = slp_lgth_max

/*amended previous code to assign RUSLE slope length exponent (m) from rill/interrill
/*ratio; assuption is that rangeland/woodland has low susceptibility; used guidelines
/*in Table 4-5 in McCool et al. (1997) with minor extrapolation for end members.
&if [exists m_slpexp -grid] &then
```

```
  kill m_slpexp all
if (down_slp_ang le 0.1)
  m_slpexp = 0.01
else if ((down_slp_ang gt 0.1) and (down_slp_ang lt 0.2))
  m_slpexp = 0.02
else if ((down_slp_ang ge 0.2) and (down_slp_ang lt 0.4))
  m_slpexp = 0.04
else if ((down_slp_ang ge 0.4) and (down_slp_ang lt 0.85))
  m_slpexp = 0.08
else if ((down_slp_ang ge 0.85) and (down_slp_ang lt 1.4))
  m_slpexp = 0.14
else if ((down_slp_ang ge 1.4) and (down_slp_ang lt 2.0))
  m_slpexp = 0.18
else if ((down_slp_ang ge 2.0) and (down_slp_ang lt 2.6))
  m_slpexp = 0.22
else if ((down_slp_ang ge 2.6) and (down_slp_ang lt 3.1))
  m_slpexp = 0.25
else if ((down_slp_ang ge 3.1) and (down_slp_ang lt 3.7))
  m_slpexp = 0.28
else if ((down_slp_ang ge 3.7) and (down_slp_ang lt 5.2))
  m_slpexp = 0.32
else if ((down_slp_ang ge 5.2) and (down_slp_ang lt 6.3))
  m_slpexp = 0.35
else if ((down_slp_ang ge 6.3) and (down_slp_ang lt 7.4))
  m_slpexp = 0.37
else if ((down_slp_ang ge 7.4) and (down_slp_ang lt 8.6))
  m_slpexp = 0.40
else if ((down_slp_ang ge 8.6) and (down_slp_ang lt 10.3))
  m_slpexp = 0.41
else if ((down_slp_ang ge 10.3) and (down_slp_ang lt 12.9))
  m_slpexp = 0.44
else if ((down_slp_ang ge 12.9) and (down_slp_ang lt 15.7))
  m_slpexp = 0.47
else if ((down_slp_ang ge 15.7) and (down_slp_ang lt 20.0))
  m_slpexp = 0.49
else if ((down_slp_ang ge 20.0) and (down_slp_ang lt 25.8))
  m_slpexp = 0.52
else if ((down_slp_ang ge 25.8) and (down_slp_ang lt 31.5))
  m_slpexp = 0.54
```

```
else if ((down_slp_ang ge 31.5) and (down_slp_ang lt 37.2))
  m_slpexp = 0.55
else if (down_slp_ang ge 37.2)
  m_slpexp = 0.56
endif

/*amended previous code to calculate L constituent by slopelength/72.6 to the
/*mth power as defined by McCool et al. (1997).
&if [exists %sa%_ruslel -grid] &then
  kill %sa%_ruslel all
docell
  %sa%_ruslel = pow((slp_lgth_ft div 72.6), m_slpexp)
end

/*amended previous USLE code to calculate S constituent using different algorithms
/*for lt or ge sin of 9% slope as defined by McCool et al. (1997), where:
/*radian = 57.2958 deg (factor = 6.2832);  deg (theta) = inv tan of % gradient;
/*(e.g., 0.09 slope gradient = 5.1428 deg angle = 0.0898 radians).
/*NOTE: RDV 12/03 Fixed previous computational order-of-operations problem below
&if [exists %sa%_rusles -grid] &then
  kill %sa%_rusles all
%sa%_rusles = con (down_slp_ang ge 5.1428, 16.8 * (sin(down_slp_ang div deg)) - .50, ~
    10.8 * (sin(down_slp_ang div deg)) + .03)

/*multiply L and S constituents to produce LS-factor integer grid clipped to the
/*watershed boundary, use .vat to perform statistical analysis as necessary;
/*define grid value as * 100 to retain significant digits for future calculations.
/*NOTE: RDV 8/03 Fixed previous rounding problem in integer function below
setwindow ..\%wshed%
setmask ..\%wshed%
&if [exists %sa%_ruslels2 -grid] &then
  kill %sa%_ruslels2 all
%sa%_ruslels2 = int (((%sa%_ruslel * %sa%_rusles) * 100) + .5)
buildvat %sa%_ruslels2

q

/*define actual LS-factor attribute as "value/100" rounded to 2 decimal places.
additem %sa%_ruslels2.vat %sa%_ruslels2.vat ls_factor 8 8 n 2
```

```
tables
sel %sa%_ruslels2.vat
calc ls_factor = value / 100
q

w

&echo &off
&return
```