4. METHODOLOGY

In this section a detailed description of the methodology developed for modeling agrichemical transport is presented. Two agrichemicals are selected: a nutrient, nitrate plus nitrite as nitrogen, and a herbicide, atrazine. These chemicals are introduced in Section 4.1. Section 4.2 describes two geographic analysis regions: one region used for developing a statistical model, and another smaller region used for GIS model development and its verification. The regression equations that relate chemical concentrations to the chemical application on the field, selected watershed descriptors, climatic variables, and the month of a year, are developed utilizing the USGS data collected in more than 150 watersheds scattered over the Mississippi - Missouri Basin above Thebes, Illinois, and the Ohio Basin above Grand Chain, Illinois. A GIS application of these equations is developed and verified for the Iowa-Cedar River watershed located in Iowa and Minnesota.

A detailed mathematical description of the statistical model is presented in Section 4.3. It provides an overview of the transport equations, introduces the explanatory variables which explain the spatial and seasonal (monthly) variations of the nitrate and atrazine concentrations in surface waters, and explains the concept of spatio-temporal "cascade" modeling within GIS. The watershed parameters of the statistical model are estimated from the 500 m DEM.

The GIS model of agrichemical transport in the Iowa-Cedar River basin is presented in Sections 4.4 - 4.6. Section 4.4 describes the methodology of discretizing the watershed, i.e., subdividing the basin into small (about 30 km^2) hydrologic units and determining the flow connectivity between these units utilizing the 3 arc-sec DEM.

Since the GIS model is designated to estimate the concentrations and loads in all streams, a methodology of redistributing the observed flow rate over ungauged rivers has been developed. Section 4.5 presents details of the monthly flow redistribution technique as well as the application of the GIS capabilities to store and manipulate flow and precipitation time series.

The following flow chart summarizes the methodology developed for the large scale agrichemical transport in the Midwest rivers:

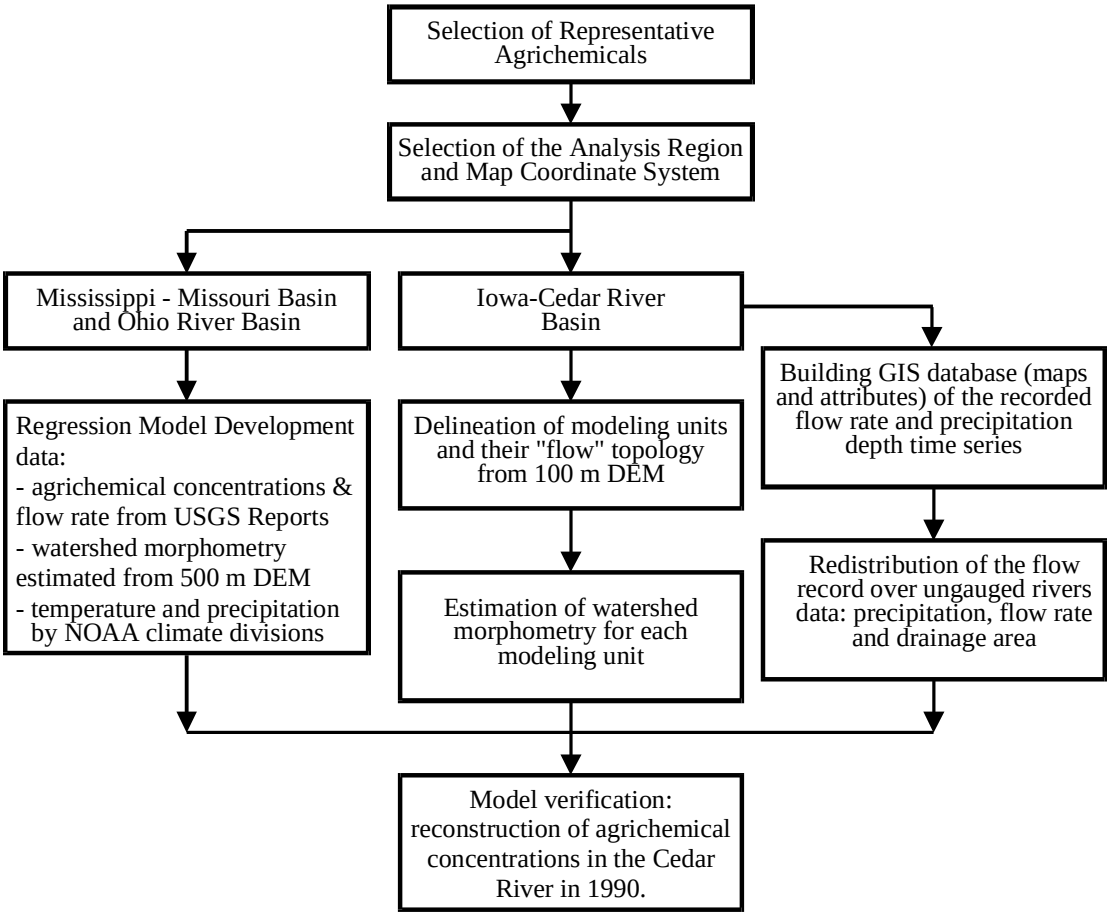

Figure 4.1 Methodology of the large scale modeling of agrichemical concentrations in the Midwest rivers.

An alternative and less successful approach to modeling agrichemical transport to the main one developed in this research is briefly introduced in Section 4.6. This model is based on a first order reaction as well as a method of travel time estimation which is presented there.

In this section and in the following sections, the words *river, stream,* and *stream/river reach* are used interchangeably. Similarly, *drainage area*, *watershed* and *basin* are considered here as equivalent terms. Sometimes one word *nitrate* is used to represent *nitrate plus nitrite as nitrogen*. *Unit watershed, elementary watershed,* and *modeling unit* refer to the smallest drainage area or partial drainage area into which the region under investigation is divided. Each modeling unit is considered as lumped system. Names of maps, computer files, database fields, as well as computer commands are printed in a `Courier` font.

4.1 Representative agricultural chemicals

Two constituents are selected for the study of the transport of agricultural chemicals in surface waters: nitrate plus nitrite as nitrogen, and atrazine. The following factors influenced this selection:

- nitrogen and atrazine are representative of nutrients and herbicides, respectively,
- nitrate plus nitrite as nitrogen and atrazine are present in measurable quantities in many Midwest streams, and

- nitrate plus nitrite as nitrogen was the only nutrient measured during both studies performed by the USGS: the reconnaissance study (Scribner, et al., 1993) and the analysis of agrichemical concentrations in storm runoff (Scribner, et al., 1994).

It is assumed that the nitrate plus nitrite concentrations in Midwest streams are mainly derived from chemical fertilizers.

4.1.1 Nitrate

Nitrogen (N) in soils natural waters occurs as organic or inorganic N. The inorganic forms, include ammonium (NH_4^+), nitrite (NO_2^-), nitrate (NO_3^-), nitrous oxide (N_2O), nitric oxide (NO), and elemental N (N_2). The three most important forms, NH_4^+, NO_2^-,and NO_3^-, usually represent 2 to 5% of the total soil N. The source of NH_4^+ is from mineralization of organic N and from fertilizers. During nitrification, NH_4^+ is converted to NO_2^-, (which is toxic to plant roots) by bacteria *Nitrosomonas* ($2NH_4^+ + 3O_2 = 2NO_2^- + 2H_2O + 4H^+$), and then oxidized to NO_3^- by *Nitrobacter* ($2NO_2^- + O_2 = 2NO_3^-$). The NO_3^- anion is very mobile and subject to leaching losses (Tisdale, et al., 1993).

Nitrate in streams is derived from many anthropogenic and natural resources including chemical fertilizers, animal wastes, domestic sewage, legumes, mineralization of vegetation, soil organic matter, and from the atmosphere through electrical, combustion and industrial processes. NO_3^- is a very soluble and mobile anion. It can be transported from agricultural fields in both overland flow and subsurface flow, and by volatilization into the atmosphere. Ammonium is adsorbed by the soil colloids and moves very little until converted to NO_3^-. The following are typical concentrations in

streams stated in mg/L as nitrogen, where 1 mg N/L = 1.2159 mg NH_3/L = 3.2845 mg NO_2/L = 4.4268 mg NO_3/L): total nitrogen 0.1-10 mg/L, organic nitrogen 0.1-9 mg/L, ammonia 0.01-10 mg/L, nitrite 0.01-0.5 mg/L, nitrate 0.23 mg/L, and nitrogen gas 0-18.4 mL/L (McCutcheon, et al., 1993).

Standard measurements of nitrogen in surface waters include Kjeldahl nitrogen (ammonia plus organic nitrogen), nitrite plus nitrate, nitrite, and nitrogen in plants. The USGS reports utilized in this research (Scribner, et al, 1993, Scribner, et al., 1994) do not contain data about organic nitrogen in surface waters. Only nitrite plus nitrate concentrations were measured during the USGS reconnaissance study of agrichemicals in Midwest rivers (Scribner, et al., 1993). Nitrate, nitrite, and ammonia were measured in two rivers, the West Fork Big Blue River near Dorchester, Nebraska, and the Sangamon River at Monticello, Illinois, during the analysis of agrichemicals in storm runoff from April, 1991 to March 1990 (Scribner, et al., 1994). In most samples of the Sangamon River the concentrations of ammonia were less than 0.1 mg/L, while the nitrate concentrations were 7 - 14 mg/L during the months from November to June and 0.4-3 mg/L during the months from July to October. The concentrations of nitrate in the West Fork River were smaller than the concentrations in the Sangamon River, rarely exceeding 3 mg/L . The September-October concentrations were below the reporting limit. The ammonia levels varied from about 0.1 to 0.4 mg/L except the summer months in which the ammonia concentrations in most samples were less than 0.05 mg/L.

The proportions of the different forms of the nitrogen in Midwest rivers may be illustrated by the samples collected in five sites (Floyd, Carville, Northwood, Cedar Falls, Gilbertville, and Bertram) along the Cedar River, Iowa, from May 1984 to September 1985 (Squillace and Engberg, 1988). The following median concentrations were reported:

- dissolved nitrite plus nitrate as nitrogen	3.5 - 5.1 mg/L
- dissolved ammonia as nitrogen	0.03 - 0.1 mg/L
- dissolved organic nitrogen	0.25 - 0.85 mg/L

Thus it can be seen that most nitrogen in streams of the Midwest is present as nitrate plus nitrite.

In contrast to overland transport, in which nitrate takes minutes or hours to get to a stream, downward vertical leaching and subsequent underground travel is a long process which takes months or years. The soil system has a strong memory with respect to nitrate production and leaching. Jones and Burt (1993) presented a study in which 64% of annual nitrate concentration in streams was explained by a stepwise regression involving the year of measurement, and each of the previous two years. It may take nitrate years or even decades to appear in rivers as a base flow pollutant.

There are some losses of nitrate due to erosion, but for humid temperate climates, erosion is generally an insignificant process compared with leaching and runoff (OECD, 1986). Other authors indicate that the adsorption has no marked influence on the rate of NO_3^- movement (Keeney, 1983; Bailey and Swank 1983). The predominant losses of nitrate in an agricultural field are due to assimilation by row crops and by other terrestrial and aquatic plants.

Although the best time of fertilizer application is at the time of peak N demand of the crop, it is seldom feasible to apply the chemical then. In north central United States most of the N application occurs late summer and fall. It is influenced by the following factors (Tisdale, et al., 1993):

- Temporal and spatial distribution of the rainfall. Because of N mobility in soils, the greater the surplus rainfall, the greater the possibility of loss of N through leaching.

- Temporal and spatial distribution of temperature. Since higher temperatures enhance nitrification, ammonia N applied before planting is more subject to nitrification and leaching.
- Technical factors. In late winter the ground may be to wet for machinery to be operated and spring application is usually too late for small grains to respond in yield to the nitrogen fertilizer applied.

Fall application of nitrogen fertilizers as well as the decrease in temperature during late fall, winter, and early spring, causes high nitrate plus nitrite concentrations in surface waters at those times. These concentrations decrease in late spring and summer when the plant demands for nutrients are high (Goolsby and Battaglin, 1983; Davis and Keller, 1983). In addition, a significant decrease in nitrate concentration in surface water may result from assimilation of nitrate by algae and by instream riparian macrophytes (Heathwaite, 1993; Moore, 1991) as well as nitrate may be converted by the denitrification bacteria and various chemical processes into free nitrogen and nitrogen oxides which escape into the atmosphere. Since these processes are stimulated by high temperatures and low flow rates, the highest loss of nitrate in lakes and rivers occurs during the summer. Lakes and reservoirs act as a "buffer," thus they are less responsive to seasonal changes than are rivers (OECD, 1986).

Denitrification and other processes of biochemical degradation of nitrate can be modeled as a first order reaction with an "overall" decay rate dependent on temperature and carbon content. Some losses may result from infiltration (river water seepage into groundwater).

4.1.2 Atrazine

Atrazine is a herbicide that controls broadleaf weeds in fields of corn and sorghum. It is one of the most widely used herbicides in the United states (Comfort and Roeth, 1996). The EPA has set the drinking water health limit (MCL, Maximum Contamination Level) for atrazine at 3 μg/L (ppb). Conventional water treatment does not remove this herbicide. Recent studies conducted in 29 communities throughout the Midwest, Louisiana, and the Chesapeake Bay detected high concentrations of atrazine in tap water during months from May through July, some of them exceeding EPA MCL of 3 μg/L (EWG, 1996)

Numerous laboratory tests as well as field studies have been performed to determine the behavior of this herbicide in different chemical and physical environments for almost half of the century. Some of the published parameters are as follows: Atrazine (2-chloro-4-ethylamino-6-isopropylamino-s-triazine) is a low solubility herbicide; its water solubility in typical temperature and pH varies from 30 to 35 ppm (mg/L). The volatility of this chemical is very low (vapor pressure = $0.3*10^{-6}$ mm Hg = 0.00004 Pa). Published values of the octanol extrability coefficient (soil sorption coefficient) K_{oc} are from 130 to 172. The octanol-water partition coefficient K_{ow} equals 251 (e.g., Weber, 1972; Hamaker, 1975; Wauchope, 1978; Rao, et al., 1983; Weber, 1988; Plimmer, 1988).

There are two parameters that characterize chemical decay in soil: half-life and chemical persistence. The half-life is the length of time it takes for a sample to reduce to half of its original weight or mass. The chemical persistence is the time for 90% disappearance of chemical from soil. Kruger, et al. (1993) reported half-life of atrazine in soil under unsaturated conditions ranged from 41 d to 231 d, whereas in saturated soil at the 90-120 cm depth, the half-life was 87 d. Similar values were cited by

Goring, et al. (1975). Wauchope (1978) determined that atrazine persistence in soil is 12 months and may vary from 6 to 18 months, which corresponds to a half-life from 55 d to 165 d, depending on climate and soil.

Atrazine decays into many degradation products which can be more persistent and mobile than their parent compound. During a USGS 1991 Mid-continent survey of near-surface aquifers, deethylatrazine, an atrazine metabolite, was the most frequently detected compound followed by atrazine, and then deisopropylatrazine, another atrazine metabolite (Kolpin et al., 1983). The half life of the deisopropylatrazine is much longer in surface water than in soil (Goolsby et al., 1993 pp. 51-62, Comfort and Roeth, 1996). However, Kruger et. al. (1993) found that deisopropylatrazine may be even less persistent under saturated conditions then in saturated soil. Their estimate of the deisopropylatrazine half-life ranged from 32 d to 173 d in the top 30 cm of unsaturated soil, and from 58 d to 173 d in saturated soil at 90 to 120 cm depth.

Weber (1988) presented results of research, which he conducted with J. A. Best, on the effect of pH on the dissipation of atrazine applied to soil. No parent component volatilization was detected; 0.1%-0.2% was found in leachate, plants used two to four percent. Ninety percent of atrazine was retained in the soil layer.

The adsorption and movement of s-triazines in soil depends upon such factors as soil organic matter, clay minerals, pH, temperature, soil moisture, concentration and species of other ions in the system (Weber, 1972; Weber, 1988; Goring, et al., 1975). In the CREAMS model, pesticide in runoff is partitioned between the solution phase and the sediment phase (Knisel, et al., 1983).

Study by the USGS of the occurrence of herbicides in precipitation in the Midwest and Northeastern United States showed that significant amounts of atrazine were lost through volatilization and subsequently returned to the land through precipitation washout. The amount of atrazine in precipitation washout was

approximately equal to one half the loading found in the Mississippi River flowing into the Gulf of Mexico (Goolsby, et al., 1993, pp. 75-86). Plimmer (1988) discussed reports which described the identification of atrazine in fog. These findings were apparently in contradiction to the findings about negligible volatilization published by Weber (1977, 1988). As was pointed out by Kenaga (1975), volatility of a pesticide is applied to heterogeneous surfaces such as natural water, soil, foliage, wood, or glass, is variable because sorption varies. There is a possibility that atrazine enters the atmosphere adsorbed on particulate matter through dust blowing from the land surface. The process of atrazine volatility is not well understood.

4.2 Selection of analysis region and map coordinate system

The Mississippi - Missouri River basin above Thebes, Illinois (drainage area $1.85*10^6$ km^2) together with the Ohio River basin above Grand Chain, Illinois (drainage area $0.53*10^6$ km^2) constitute the primary region that is used for estimation of statistical model parameters. Its extent is determined by the USGS reconnaissance study of selected herbicides and nitrate in Midwestern United States (Scribner, et al., 1993). This region is one of the most extensive agricultural areas in the country, producing over 80% of all US corn and soybeans (Oberle and Burkart, 1994).

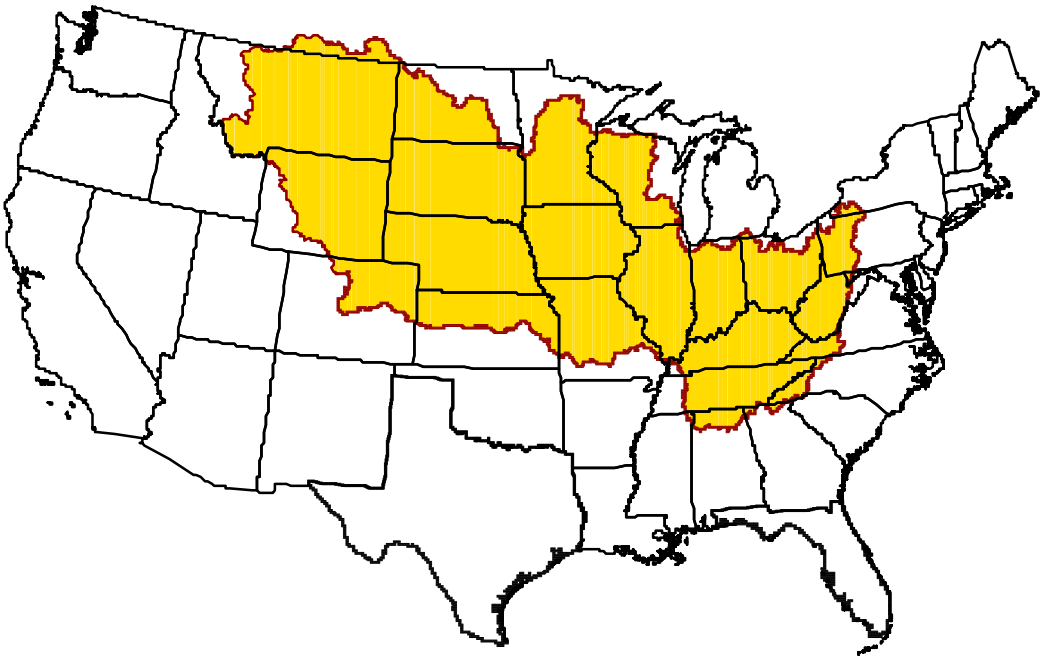

Figure 4.2 The Mississippi-Missouri and Ohio River Basins.

Since processing data for an area that covers almost three million square kilometers requires a computer with adequate operational and storage memory, the final model is built, and verified on a selected subregion, i.e., the Iowa-Cedar River watershed in Iowa (area = 32,000 km^2). There are two sites in the Iowa-Cedar Basin for which measurement of agricultural chemicals are available: Old Man's Creek near Iowa City and Cedar River at Palisades, Iowa. Flow rate is recorded in about 30 USGS gauging stations in the Iowa-Cedar Basin. A diversity of such geographic features as lakes, reservoirs, wetlands, hills, plains, and a wide range of stream sizes makes the Iowa-Cedar Basin a very good representation of the Midwest. Figure 4.3 shows the Iowa and Cedar Rivers, and the location of gauging stations.

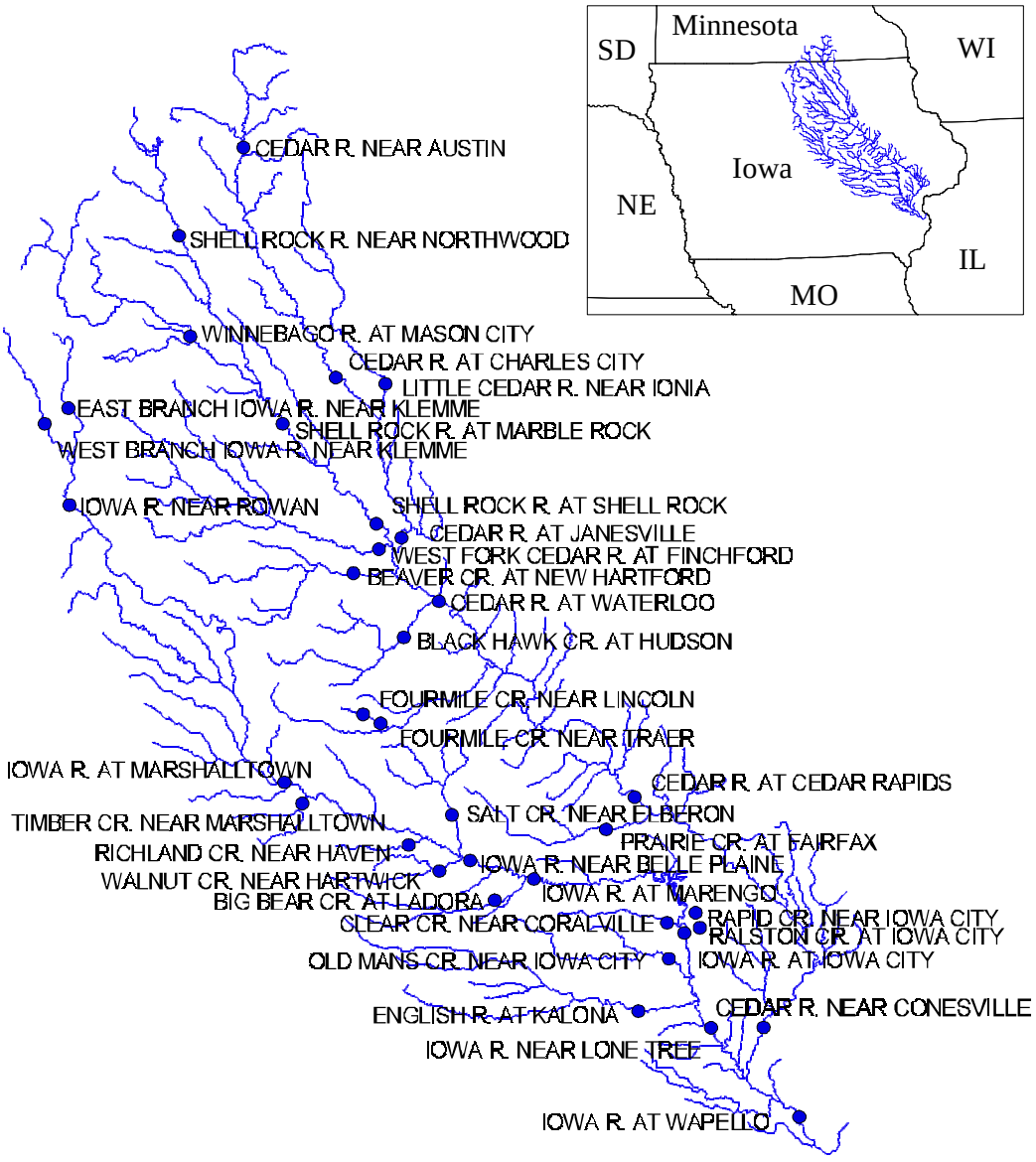

Figure 4.3 The Iowa River with tributaries and the USGS gauging stations.

All maps utilized in this research are represented in Albers Conical Equal Area Projection, generally accepted for large maps of the USA. This projection has the valuable property of equal area representation, combined with a scale error that is practically the minimum attainable in any system covering such a large area in a single sheet.

The following parameters are applied (standard for USA): units = meters, first standard parallel = 29º30'00", second standard parallel = 45º30'00", latitude of projection's origin = 23º00'00", false easting = 0.000 m, false northing = 0.000 m, longitude of central meridian = -96º00'00". Using one common projection for the whole Midwest eliminates the problems associated with merging separately modeling regions into one unit.

The Albers projection is of the conical type, in which the meridians are straight lines meeting in common point beyond the limits of the map, and the parallels are concentric circles, the center of which is at the point of intersection of the meridians. The meridians and the parallels intersect at right angles and the arcs of longitude along any given parallel are of equal length. The spheroid is intersected by a cone at two parallels known as the *standard parallels* for the area to be represented. On the two standard parallels, arcs of longitude are represented by their true lengths, or at an exact scale. Between the standard parallels, the scale along the meridians is too large and beyond them too small (Deetz and Adams, 1969).

The Albers projection is constructed in such a way that the area of the earth's surface between any pair of parallels and meridians is correctly preserved in the flat map representation.

4.3 Mathematical description

4.3.1 Overview of transport equations

There are two basic mechanisms that are responsible for the transport of dissolved and suspended solutes in surface waters: advection and diffusion/dispersion. These two processes are described by the advection-dispersion equation which is the fundamental equation for majority of the pollutant transport models. Equation (4.1) describes one-dimensional advection-dispersion in a reach with a uniform cross-sectional area.

$$\frac{\partial c}{\partial t} = -\frac{\partial vc}{\partial x} + \frac{\partial}{\partial x} E_x \frac{\partial c}{\partial x} + \sum_{i=1}^{n} S_i + \sum_{j=1}^{m} K_j c \qquad (4.1)$$

where:

c = concentration of pollutant [g/m^3]

t = time [s]

x = distance along the river [m]

$-E_x \partial c/\partial x$ = mass flux due to the longitudinal dispersion [g/m^{2}s]

E_x = longitudinal dispersion coefficient [m^2/s]

$-vc$ = mass flux due to advection [g/m^{2}s]

S_i = i-th source/sink of the constituent [g/m^{3}s]

$i = 1...n$, n = number of sources/sinks

K_j = decay rate due to the j-th process [1/s]

v = flow velocity [m/s]

The source/sink term, S_i and reaction term, $K_j c$ represent a wide range of features such as lateral flux, transient storage, biotic and abiotic retention, benthic flux, periphyton retention, sediment retention, reaeration, photosynthesis, and nitrification (U. of Mississippi, 1990, James and Elliot, 1993).

Dynamic models solving (Eq. 4.1) have been used mainly for pollution incidents such as spills and runoff discharges. Their applicability for large scale modeling of nitrate/atrazine transport at the scale attempted in this research is limited, mainly because:

- Numerical solution of the advection-dispersion equation requires subdivision of the time domain into relatively short intervals (minutes, hours), but this is less useful when calculating monthly means of chemical transport in extensive stream networks over large areas;
- It is difficult to write a procedure which solves the dispersion-advection equation using a GIS script language, so such a model has to be solved externally to the GIS.

Lagrangian type transport models, such as a Moving Segment Model (MSM), can be efficiently incorporated into GIS. In MSM (James and Elliot, 1993) the stream is subdivided into series of segments. Within each segment the variations of chemical concentration are calculated by summing, for example, hourly changes due to all the processes involved. The process within the block is described by the following equation:

$$\frac{\partial c}{\partial t} = \pm \sum_{i=1}^{n} S_i + \sum_{j=1}^{m} K_j c \qquad (4.2)$$

where: S_i is the i-th source/sink and K_j is the j-th reaction coefficient.

The segments (blocks) move downstream with travel time τ which may be a function of such parameters as flow rate, cross-sectional area, friction coefficient, slope, and stream curvature. For a detailed representation of the constituent transport in surface water at least the following processes should be represented (O'Connor, et al., 1983; Thomann and Mueller, 1987; O'Connor, 1988a,b; University of Mississippi, 1990):

- Sorption and desorption between dissolved and particulate components in the sediment and water column;
- Settling and resuspension of particles;
- Diffusive exchange between the sediment and water column;
- Loss and gain of the chemical due to the chemical and biochemical reactions such as biodegradation, volatilization, and photolysis;
- Advective and diffusive transport of the chemical in water and as a bed transport;
- Net deposition and loss of chemical to deep sediments.

Figure 4.4 shows these major reaction mechanisms and transfer routes of chemicals and solids in both river water and the river bed.

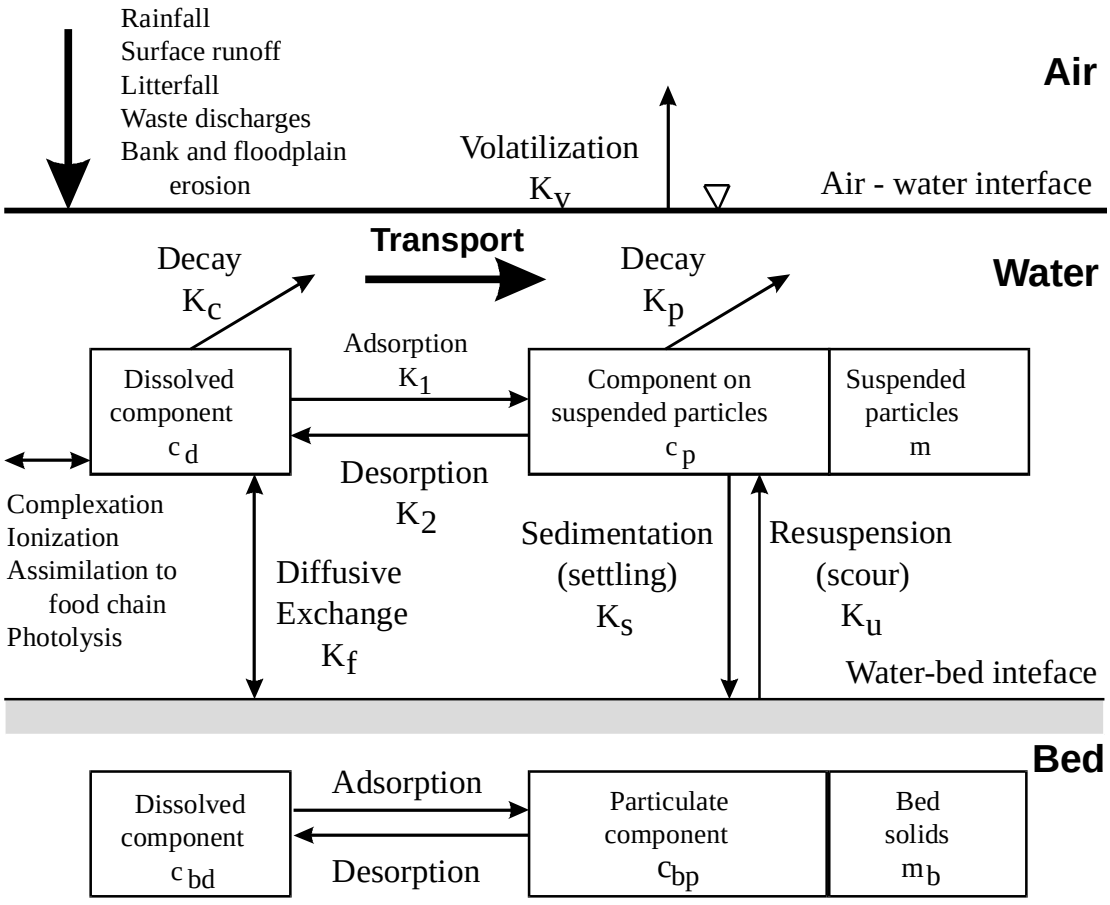

Figure 4.4 Reactions and transfers in a natural water system (after O'Connor, et al, 1983; Thomann and Mueller, 1987; O'Connor, 1988a, b; University of Mississippi, 1990).

The processes in surface waters can be described by the mass balance equations for the dissolved and particulate components (Eq. 4.3 and Eq 4.4). For a specific chemical, e.g. nitrate or atrazine, some processes must be included in the transport model whereas some processes may not significant and therefore can be neglected.

$$\frac{dc_s}{dt} = -K_1 c_s + K_2 c_p - K_v c_s + K_f (c_{bs} - c_s) - K_c c_s + K_p c_p - K_q (c_s + c_p) \qquad (4.3)$$

$$\frac{dc_p}{dt} = K_1 c_s - K_2 c_p - K_s c_p + K_u (c_{bp} - c_p) - K_c c_{bs} + K_p c_{bp} \quad (4.4)$$

where:

K_v, K_f, K_s, K_u = the bulk transfer coefficients of volatilization, dissolved exchange, settling and scour respectively;

c_s, c_p = dissolved and particulate concentrations in water, respectively;

c_b, c_{bp} = dissolved and particulate concentrations in bed;

K_c, K_p = decay coefficients of dissolved and particulate form;

K_1 = $K_0 r_c m$; K_0 = adsorption coefficient, r_c = adsorptive capacity, m = concentration of solids;

K_2 = desorption coefficient;

K_q = coefficient of dilution due to the groundwater inflow.

4.3.2 GIS and cascade modeling

GIS technology gives the opportunity to construct versatile “cascade” models. The idea of cascade modeling incorporated here into GIS has been extracted from the methodology used in forecasting the municipal water use (Maidment and Parzen, 1984; Mizgalewicz, 1991).

The GIS cascade structure is two dimensional. It can be applied both in space and time. In the time domain, a general model describes spatial distribution of annual average amounts of agricultural chemicals in rivers. The annual values are then broken into seasonal or monthly values. For example, the annual average concentrations c_y for the Midwest can be estimated by the general function:

$$c_y = f(\mathrm{X}) \tag{4.5}$$

where: X is a vector of explanatory variables such as annual agrichemical application and watershed morphometry (area, land slope, stream slope, stream length, overland flow length) which do not change with time.

The Equation (4.5) can be further extended by adding a seasonal component, as monthly fractions *S(m)*, to break down the annual predictions of concentration c_y into monthly values *c(m):*

$$c(m) = c_y S(m) = f(\mathrm{X})S(m) \tag{4.6}$$

Cascade modeling enables further extending of the Eq. (4.6) by adding such elements as year to year trend and an irregular random component.

Cascade modeling in the spatial domain implies that the modeling process is subdivided into several levels of resolution, i.e., the Upper Mississippi-Missouri and Ohio River can be subdivided into three basins: the Missouri River Basin above junction with the Mississippi River, the Upper Mississippi River Basin, and the Ohio River Basin. The transport of agricultural pollutants in the Upper Mississippi River is estimated by utilizing results of sub-models that describe transport in individual component basins such as the Des-Moines River, the Skunk River, the Iowa-Cedar River, and Wisconsin River Basins.

Additional spatial subdivision of the Midwest can be performed by introduction of climate zones. Each zone is defined, for instance, by a specific range of temperatures and precipitation depths. Thus, the Eq. (4.6) could have the following form:

$$c(m,g) = f(\mathrm{X})S(m)g(\mathrm{T},\mathrm{P},\mathrm{Z}) \tag{4.7}$$

where: *c(m,g)* is the monthly (*m*) agrichemical concentration in rivers modified for the climate zones (*g*) ; *g(*T,P,Z*)* is a function of T - zonal temperature, P - zonal precipitation depth, and Z - zone location.

The diagram shown in Figure 4.5 illustrates the example of spatio-temporal cascade modeling within GIS.

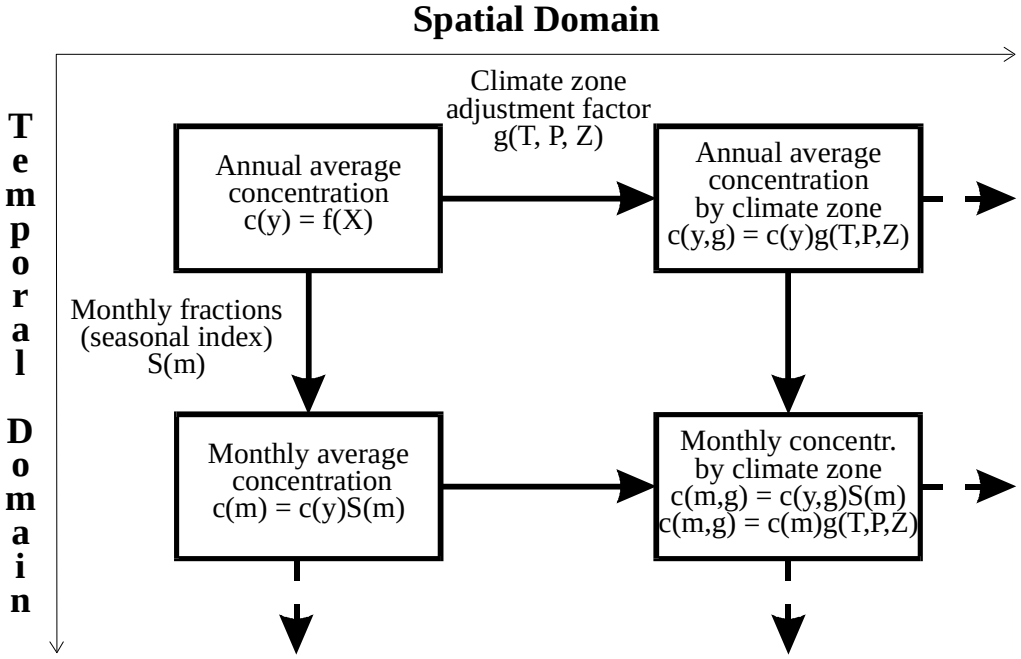

Figure 4.5 Example of the cascade modeling within the GIS.

Parameters of the mathematical description of the chemical application-runoff process and chemical losses in streams are stored in a GIS attribute table. Moreover, the equations are stored as objects in a database table. Storing equations as a database objects not only permits one to fully implement the cascade modeling technique into the GIS but also it simplifies the structure of the model, allows one to test and compare an unlimited number of equations, and permits changes to the mathematical

description by simple record editing operations. The model prototype is constructed within ArcView, a GIS application (ESRI, 1995).

4.3.3 Regression equation development

There is no complete and consistent data base of parameters required for comprehensive modeling the agrichemical runoff from the field and its transport in surface waters of the Midwest. The runoff and transport parameters have to be estimated from such data as:

(1) The observed flow rate and the measured agrichemical concentrations in the variety of watersheds scattered over the upper Mississippi-Missouri and Ohio River basins;

(2) The DEM from which a watershed morphometry can be calculated; and

(3) Parameters that describe the climatic conditions of the sampled watershed.

Thus, a model based on statistical analysis of observed concentration data is used in this research.

Watershed morphometry, annual agrichemical rate, normal annual temperature, and normal precipitation depth do not depend on the month of the year. These parameters are used here to explain the average annual agrichemical concentration c_y in Midwest rivers. The following linear relationship is tested by the regression analysis (A detailed discussion of the set of explanatory variables that have potential application in the large scale model of agrichemical runoff from the field and transport in the river network is presented in Section 4.3.4 and Section 4.3.5):

$$c_y = \beta_0 + \beta_1 A_p + \beta_2 S_L + \beta_3 L_L + \beta_4 A + \beta_5 E_S + \beta_6 S_S + \beta_7 Q + \\ + \beta_8 T + \beta_9 T_{avg} + \beta_{10} P + \beta_{11} P_{avg} + error \quad (4.8)$$

where:

c_y = average annual constituent concentration (concentration with removed seasonal component) [mg/L nitrate, μg/L atrazine];

A_p = annual chemical application rate [kg/km^2/yr];

S_L = average slope of the land [dimensionless];

L_L = average length of the constituent travel path, from the point of application to the stream network within a given watershed to the sampling point [km];

A = drainage area [km^2];

E_S = average of the exponent of negative flow distance in streams

$= \frac{1}{n_s} \sum_{i=1}^{n_s} \exp(-L_{ik})$;

n_s = number of cells that constitute the stream network within a sampled watershed;

L_{ik} = length of the flow path from the *i*-th stream cell to the watershed outlet *k* [10^2 km] (since the Missouri River is a very long river, units 10^2 km are applied to enhance the Arc/Info-GRID calculations);

S_S = average slope of the stream network [dimensionless];

Q = flow rate at a given stream location [m^3/s];

T = normal annual temperature at sampling site [°C]

T_{avg} = normal annual temperature, average over sampled watershed [°C]

P = normal annual precipitation depth at sampling site [mm]

P_{avg} = normal annual precipitation depth, average over sampled watershed [mm]

β_0, β_1, β_2 ... = regression coefficients.

The right hand side of Eq. (4.8) represents two major components of the transport process: runoff from the field and losses in the stream, as well as the climatic conditions that affect the transport processes:

1) $\beta_1 A_p + \beta_2 S_L + \beta_3 L_L + \beta_4 A$ describe changes in mass applied U_R on a field as it travels from the point of application to a stream;

2) $\beta_5 E_S + \beta_6 S_S + \beta_7 Q$ reflect the losses of agrichemical in rivers; and

3) $\beta_8 T + \beta_9 T_{avg} + \beta_{10} P + \beta_{11} Pavg$, incorporates into the model the effects of the climate zone on the agrichemical transport.

More details on each of the model variables are now presented.

4.3.4 Agrichemical runoff from the field

Agrichemical application rate A_p. Since it is a common practice to put more chemical on the field than the amount that can be completely utilized by the vegetation and the chemical - microbiological processes, some of the nutrients and herbicides are transported in runoff from the field. Many studies show that the more chemical is applied on fields, the higher are chemical loads carried by rivers (e.g., Battaglin, et al., 1993).

Land slope S_L. The higher the slope of the land S_L, the chemicals are more susceptible to washout, therefore greater losses of the chemical from the field can be expected. This complex process is influenced by gravitational forces. Since vegetation has a smaller chance to uptake nutrient or herbicide when the land slope is higher (due to the shorter residence time), a greater portion of the mass applied on the field should reach

the stream network. Models of erosion and sediment transport include a slope parameter.

Distance to a stream L_L. The influence of the average distance L_L between the point of herbicide or nutrient application and the location of the stream network on the amount of mass that enters the stream is not as obvious as watershed slope. (Here, the L_L is an average distance measured along the flow path between all cells that do not represent a stream network and the cells that constitute the streams, within a given watershed). Intuitively it may be expected that since the longer the average travel path is, the larger the chemical losses are and thus the coefficient β_3, from Eq. (4.8), estimated by the regression analysis should be negative. But, since the predictor variable L_L represents complex watershed features, the coefficient β_3 does not necessarily have to be negative. The average length of the land-flow path depends on the stream density, i.e., on the length of the streams per unit area of watershed. The more streams there are within a given watershed, the shorter the length of the overland flow. The density of the stream network influences the amount of chemical that enters a unit length of the stream. Therefore, for watersheds characterized by a higher value of L_L , the amount of chemical that enters a stream (mass per unit length) is higher than the amount reaching the stream network which is located in a watershed with smaller L_L.

Climate. Both precipitation (P, P_{avg}) and temperature (T, T_{avg}) have an impact on vegetation growth. Moreover, the greater the water surplus (precipitation minus potential evaporation), the greater the possibility of loss of agrichemical through leaching if the crop is not growing vigorously or through washout if the land is not protected by a plant cover. Denitrification depends on the amount of water in soil, whereas nitrification rate is highly correlated with the temperature (Tisdale, et al., 1993).

The influence of climate on the concentrations in surface waters can be illustrated by comparison of studies performed in different climatic regions. For example, the largest number of atrazine detections in Swedish stream waters was in July, August and September (Kreuger and Brink, 1993), whereas in the Midwestern United States the major atrazine runoff occurs in May and June (Scribner, et al., 1994). The Swedish vegetation period is short (6-8 months) and cold (3º-17º C)

Since the region under scrutiny extends from about 37º N to 50º N (latitude) and from 79º W to 114º W (longitude) the spatial distribution of the average temperature and the average precipitation influences not only the spatial distribution of the chemical runoff from the field but it also causes spatially different agrichemical application times. The difference in climate conditions within the studied region could be represented by a spatially distributed adjustment coefficient as well as a time shift introduced into periodic functions that describe seasonal variation of agrichemical concentration in the surface water. The time-shifting of periodic functions is not studied in this research.

4.3.5 Transport in rivers

Exponent of negative stream-flow distance E_S. The explanatory variable E_S has been introduced to represent agrichemical losses in streams. It is defined by the following formula (excerpted from Eq. 4.8):

$$E_S = \frac{1}{n_s} \sum_{i=1}^{n_s} \exp(-L_{ik}) \tag{4.9}$$

where:

n_s = number of cells that constitute the stream network within a sampled watershed;

L_{ik} = length of the flow path from the *i*-th stream cell to the watershed outlet *k* [10^2 km]

Equation (4.9) is a simplified version of the discrete model of exponential losses of chemical as it travels downstream. The following paragraph explains the development of the explanatory variable E_S.

The losses of agrichemical in streams can be described by an exponential function of the travel time (the traditional approach) or by an exponential function of the travel distance (Smith. et al., 1993). Although it is possible to estimate the travel time from the observed flow time series, in this research the agrichemical decay has been related to the travel distance, i.e., the amount of chemical that enters the stream in point *i* (cell *i* in raster representation of river) decays as it travels downstream according to the following equation:

$$R_k = \sum_{i=1}^{n} R_i \exp(-k_S L_{ik}) \qquad (4.10)$$

where:

R_k = total agrichemical mass in a runoff from *k*-th watershed [kg/m^3];

k.. = index of sampled watershed outlet (cell *k*);

R_i = chemical load that enters the stream in point *i* (cell *i*) [kg/m^3];

n = number of all cells that constitute the stream network located within *k*-th watershed;

k_S = overall distance decay coefficient [1/10^2 km];

L_{ik} = length of the flow path from stream cell *i* in which the chemical runoff from a

field enters the stream network to the watershed outlet located in cell k [10^2 km].

Since application of the Eq. (4.10) is very computationally intensive, the following assumptions have been made to construct it's simplified form, i.e., equation (4.9):

- a unit mass of chemical enters the stream network ($\Sigma R_i = 1$ within sampled watershed);
- the chemical that enters surface water is uniformly distributed over all stream cells, i.e., the amount of chemical that enters the stream at each cell of the stream network within sampled watershed equals $1/n_s$;
- the overall distance decay coefficient is equal one, $k_S = 1$ (the chemical losses depend only on the chemical travel distance L)

Stream slope S_s. The stream slope parameter is introduced into the agrichemical transport equation to represent two physical features: flow velocity that is directly related to the chemical travel time, and stream power that affects sedimentation and resuspension of deposits as well as their transport.

4.3.6 Seasonal variations

The seasonal variations of the nitrate concentration as well as the atrazine concentration in surface waters are modeled by two sets of 12 values, calculated by the following formula:

$$S(m) = \frac{\exp\left(\sum_{k=1}^{5}\left(a_k \sin(2k\pi m/12) + b_k \sin(2k\pi m/12)\right)\right)}{\sum_{i=1}^{12}\exp\left(\sum_{k=1}^{5}\left(a_k \sin(2k\pi i/12) + b_k \sin(2k\pi i/12)\right)\right)} \qquad (4.11)$$

where:

S(m) = the seasonal factor of month *m* (average *S(m)* = 1)

sin(2*k*π*m*/12), and cos(2*k*π*m*/12) = components of the Fourier series (the cycle corresponding to k = 1 has a 12-month period, k = 2, 3, 4, and 5 are harmonics of period 12/*m* months;

m = month of a year (1 for January);

i = index of the month (*i* = 1, 2, ... 12);

k = index of the harmonics;

a_k and b_k = regression coefficients.

The exponent of the periodic function in Eq. (4.11) is a result of the agrichemical transport model specification in which a linear function that describes the average concentration in a stream is multiplied by a seasonal factor. To estimate the coefficients a_k and b_k from the concentration data the logarithmic transformation of concentration data is necessary. Two models have been selected to determine the variation of the constituent concentration in sampled rivers. The first one explains monthly changes by selected harmonics of the Fourier series (Eq. 4.12), whereas the other model, in addition to the sine-cosine components, embodies the flow rate to isolate the flow effect from the systematic seasonal the variations (Eq. 4.13):

$$\ln\left[c(j,d)\right] = w_j + \sum_{k=1}^{5}\left(a_k \sin(2k\pi m/12) + b_k \sin(2k\pi m/12)\right) \qquad (4.12)$$

and

$$\ln[c(j,d)] = w_j + a_0 \ln[Q(j,d)] + \sum_{k=1}^{5} \left(a_k \sin(2k\pi m/12) + b_k \sin(2k\pi m/12)\right) \quad (4.13)$$

where:

ln[...] = natural logarithm;

c(j,d) = concentration measured at site *j* on day *d* (μg/L or mg/L);

Q(j,d) = flow rate measured at site *j* on day *d* (m^3/s);

w_j = an intersect specific for the *j*-th sampled watershed, determined by the regression analysis;

a_0, a_k and b_k = regression coefficients;

j = index of the sampling site;

d = day of sample collection;

k = harmonics number;

m = month of the year.

By combining (Eq. 4.11) with (Eq. 4.12) and (Eq. 4.11) with (Eq. 4.13) the relation between the average annual concentration in a sampled stream can be given by the following equations:

$$c_y(j) = \exp(w_j) \sum_{i=1}^{12} \exp\left(\sum_{k=1}^{5} \left(a_k \sin(2k\pi i/12) + b_k \sin(2k\pi i/12)\right)\right) \quad (4.14)$$

and the model including the flow rate is specified by:

$$c_{yQ}(j) = \exp(w_j) Q^{a_0} \sum_{i=1}^{12} \exp\left(\sum_{k=1}^{5} \left(a_k \sin(2k\pi i/12) + b_k \sin(2k\pi i/12)\right)\right) \quad (4.15)$$

The flow rate is introduced into analysis to examine the effects of the flow rate on the concentration level. However, the data utilized in this research may be biased by extreme flow conditions. At least one third of the reconnaissance data (Scribner, et. al., 1993) contain measurements made during the first major runoff after application of herbicides (33% of atrazine samples collected in 1989, and 50% of atrazine samples taken in 1990). Twenty five percent of nitrate plus nitrite as N measurements were collected in May and June of 1989 and 50% of nitrate samples represent concentrations in major runoff events after fertilizer application in 1990. Also, the gathering of samples in nine rivers of Midwest (Scribner, et. al., 1994) was designed to study the concentrations of selected herbicides and nutrients in storm runoff rather than to investigate the seasonal changes of agrichemicals in the Midwest rivers.

The general relation between flow rate and the chemical concentration is as follows: When flow increases, concentration increases. This is a result of the "washout effect". If the flow increases above a level at which the chemical washout is in balance with the chemical dilution, the concentration does not increase. Further increase in flow may produce further chemical dilution and therefore decrease in concentration. Figure 4.6 shows an example of such a nitrate concentration pattern observed in the Sangamon River at Monticello, Illinois, in May 1990 (Scribner, et al., 1994). As flow increases up to about 40 m^3/s, the nitrate concentration level rises. A further increase of the flow, up to 80 m^3/s, does not produce a change of the concentration level. For flows larger than 80 m^3/s the dilution effect becomes significant and the nitrate concentration decreases when the flow rate increases.

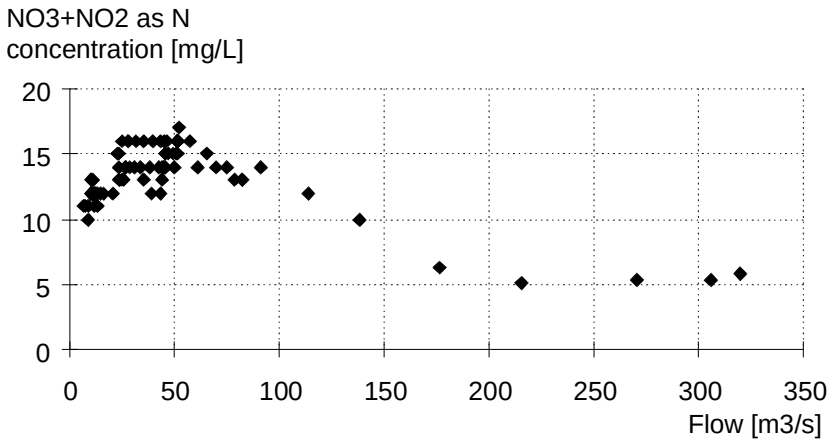

Figure 4.6 Nitrate plus nitrite as nitrogen concentrations measured in the Sangamon River at Monticello, Illinois, in May 1990 (Scribner, et al., 1994).

Research performed by Walling and Webb (1984, work cited by Jones and Burt, 1993) shows that in most streams the annual nitrate variations do not have a perfectly symmetrical sinusoidal form; the annual minimum and maximum occur 4-6 weeks later and 2-3 weeks earlier then the timing suggested by a single harmonic. Furthermore, no clear seasonal variations of nitrate concentration exist in catchments where groundwater with a consistently high nitrate concentration mixes with quick flow of varying origin and concentration (Jones and Burt, 1993).

4.3.7 Extracting values of explanatory variables for the regression analysis

The estimation of values of explanatory variables such as agrichemical application rate, total application, average stream slope, average land slope, exponent

of the negative flow length, and average distance from the field to the closest stream is performed in two steps: (1) Grids of spatially distributed parameters are constructed for the Upper Mississippi - Missouri River and the Ohio River basins, and (2) for each cell that represents a sampled watershed outlet the value of the explanatory variable is extracted.

Here, the grid of spatially distributed parameters means a grid which each cell contains average or sum calculated for the total drainage area upstream to the given cell. Figure 4.7 shows selected cells that contain a value that characterize the upstream watershed. This concept is supported by Arc/Info-Grid commands such as `flowaccumulation` and `flowlength`.

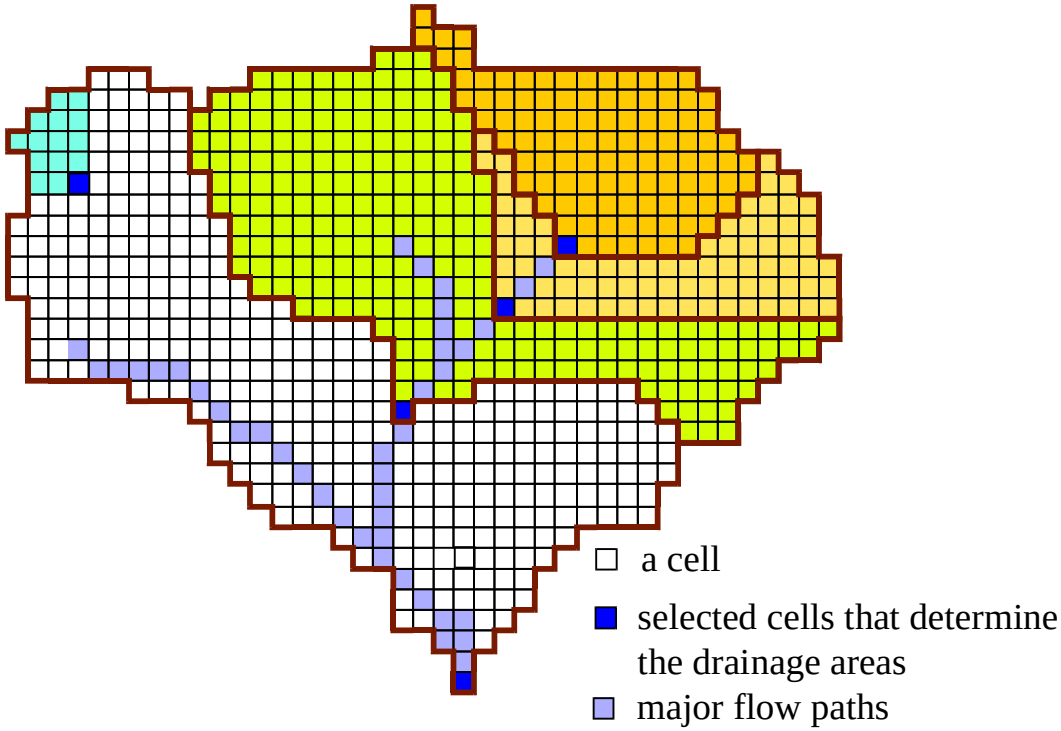

Figure 4.7 Example of a grid of spatially distributed values of explanatory variables.

4.3.8 Application of the regression models

Once their parameters have been determined, the agrichemical transport models (Eq. 4.6) can be used in the following way:

- Estimation of average monthly and average annual concentrations in rivers of the Upper Mississippi-Missouri basin, including the Ohio River basin. The calculations are made using grid-map algebra. The calculations are estimated in all cells ($9.6 * 10^6$ cells of size 500 m) that constitute the basin. The equations that describe chemical concentration in rivers require only a map of distribution of the total agricultural chemical use, the parameters of watersheds that can be easily determined from digital elevation model, and the maps of annual temperature and precipitation depth. Only models that do not utilize the flow rate can be applied. Since the calculation of the concentrations over such a large area is very computationally and computer disk space intensive, it is not presented in this dissertation.

- Calculation of average monthly agrochemical concentrations in the Iowa-Cedar River basin. The map of flow rate is required for obtaining a spatial picture of atrazine and nitrate concentrations in surface waters. The estimation is performed for the watershed subdivided into 1032 subwatersheds of average area 31.6 km^2 utilizing maps in a vector format. The regression equations are applied to each subwatershed utilizing the data from an attribute table that characterizes the upstream drainage area. A GIS approach to model the concentrations in rivers is discussed in the following Section 4.4. The procedure of the spatial distribution of the historical flow record is presented in Section 4.5.

4.4 GIS model description

4.4.1 Subdivision of study region into modeling units

Elementary watersheds, i.e., modeling units that are considered lumped systems, constitute the smallest units into which a region is subdivided. Each unit is characterized by set of parameters such as area, agricultural chemical application, slope, depth of precipitation, water runoff, average elevation, and an equation that relates the mass of chemical applied and the mass of chemical runoff.

Since the GIS offers very convenient tools for data storage and manipulation, all attributes can be stored and extracted by models that operate on different spatial scales. The order of processing the individual watersheds is the researcher's choice. Moreover, each watershed does not need to be divided into modeling units of the same size. To make the modeling process efficient, such features as density of spatial information and diversity of terrain should influence the assumed size of the elementary unit.

A watershed is explicitly defined by its outlet point. This hydrologic property is utilized here to subdivide the region under investigation into elementary drainage areas. Three types of watershed outlet locations are considered:

1) Points in which the drainage area exceeds a threshold value. Streams originate at these points. In this research a threshold value of 25 km^2 drainage area has been assumed;

2) Points located immediately upstream of a stream junction; and

3) Gauging station sites.

Figure 4.8 shows example of selected watershed outlets and corresponding modeling units:

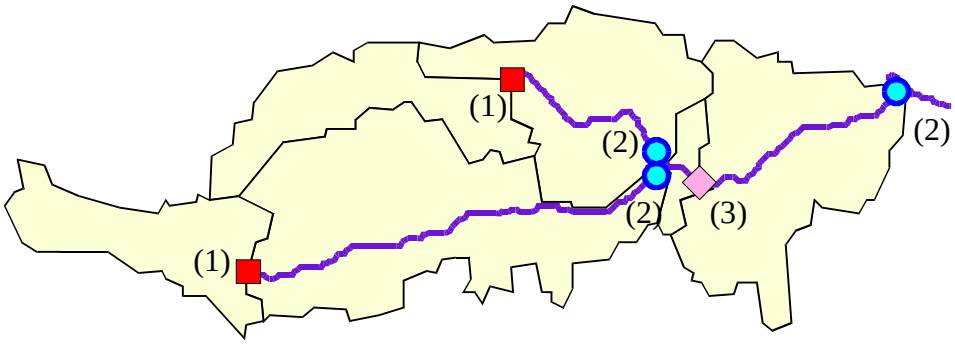

Figure 4.8 Example of watershed outlets: (1) beginning of the river, (2) stream junction, and (3) gauging station.

The watershed structure, developed by Maidment (1993) for hydrologic modeling utilizes type (2) and (3) watershed outlets which are positioned at the stream junctions and at the gauging station locations. In this study, this set of watershed outlets has been extended by adding the points in which the stream network, delineated from DEM, begins (type 1 outlet). A test has been performed to determine the influence of additional unit watersheds on the uniformity of region subdivision and the control on the unit area. The Iowa-Cedar River basin has been subdivided using two sets of outlets. Full set: Median unit watershed area = 25.8 km^2 and mean = 31.6 km^2, reduced set (type 1 outlets not included): median = 37.9 km^2 and mean = 46.7 km^2. By including the outlets of type 1, the median of unit watershed drainage areas is very close to the threshold drainage area (25 km^2). Figure 4.9 compares the frequencies of modeling unit area.

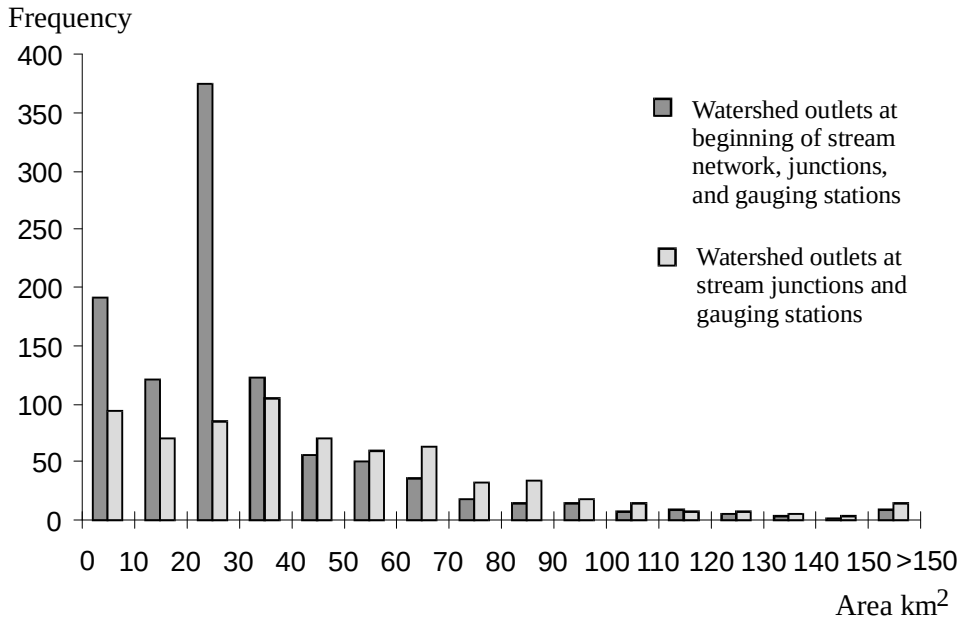

Figure 4.9 Comparison of the frequency of modeling unit area subdivided using different sets of watershed outlets.

The following list summarizes the advantages of the addition of type(1) outlets:

- The watershed is subdivided into more uniform (similar area) modeling units and one has more control on the area of units;
- It makes possible the determination of the flow and the constituent load in all nodes of the stream network. Each node has a defined contributing area; and
- The representation of all streams can be standardized. Each reach has input (inflow or load that enters the reach at the upstream end), lateral loss or gain, and output (outflow or load that leaves the reach at its end).

The threshold area of 25 km^2 was selected after many tests with different threshold areas were performed. A smaller threshold area results in very dense stream network and thus large number of areas of size of 1-2 cells. After Arc/Info conversion of these small units from raster format (grid) into vector format many of them disappeared. In addition, smaller than 25 km^2 threshold areas are not justified by the data used in the research. For example, the agrichemical application rate is published with a county-size spatial resolution. The stream network delineated from a 3" DEM using 25 km^2 areas, is slightly more dense that the one represented by the RF1 (1:500,000 digital map of rivers).

A larger threshold value than 25 km^2 resulted in very coarse subdivision of studied region and a low density stream network. Figure 4.10 presents the Iowa-Cedar River watershed divided into modeling units of different sizes.

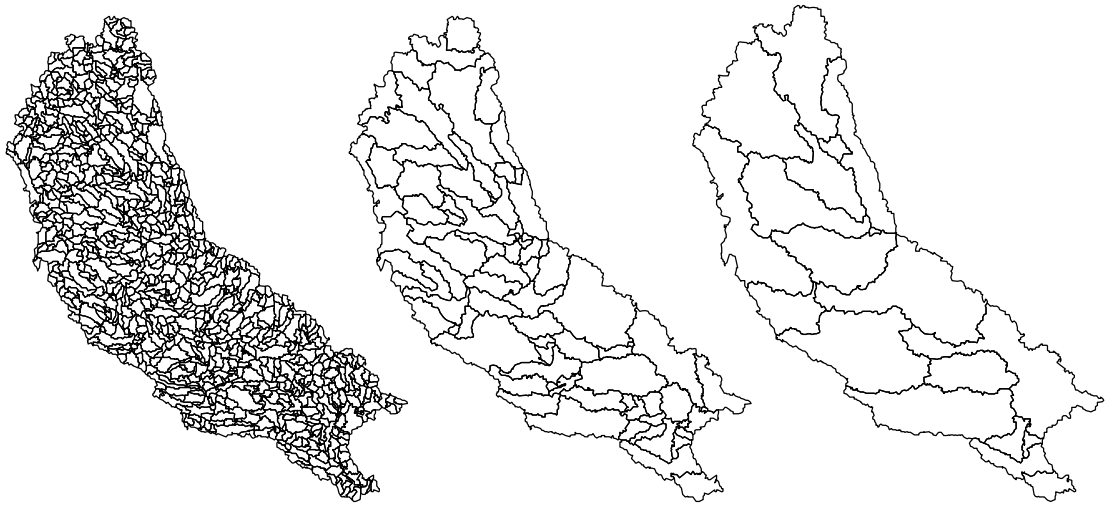

Figure 4.10 Division of the Iowa-Cedar River into modeling units using different threshold drainage areas: 25 km^2, 400 km^2, and 2500 km^2.

4.4.2 Unit watershed flow system

The network flow system is common function in vector GIS (Maidment, 1993). Here the flow system has been extended: instead of arcs, unit watersheds (polygons) compose the flow system. The flow topology is described by two numbers: the modeling unit ID and the ID of the downstream unit, i.e., the next unit on the flow path. The ID = 0 of the next unit indicates that there are no more downstream units. Figure 4.11 shows an example of the description of the flow topology of the modeling units.

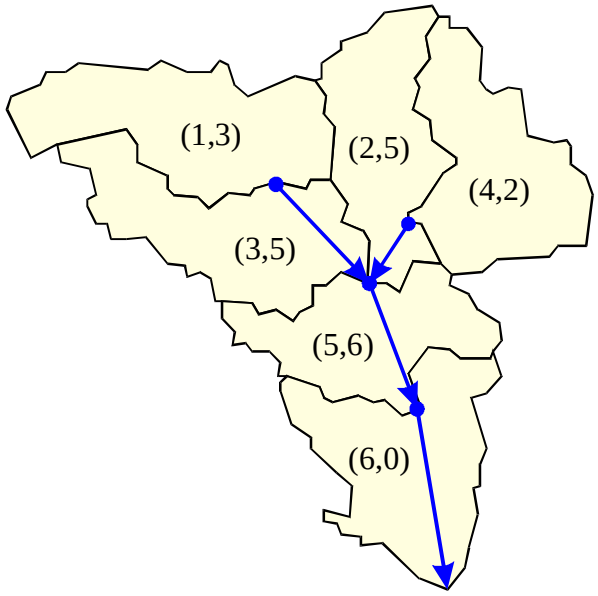

Figure 4.11 An example of the flow topology of the unit watersheds; (*x*,*y*), *x* is the unit ID, *y* is the ID of downstream to *x* unit.

The flow direction indicator is the basic concept in the raster-based hydrologic modeling. For example, Arc/Info Grid denotes the next cell in the flow path by one of eight numbers: 1 represent flow into E (East) neighbor cell, 2 in SE cell, 4 in S cell,

8 in SW cell, 16 in W cell, 32 in NW cell, 64 in N cell, and 128 in NE cell. These numbers are called “flow direction”. Since modeling units are not regular spatial shapes, as the cells are, it is not possible to create an uniform numbering system of the flow direction. The method proposed here describes the flow connectivity by specifying the ID of the next unit on the flow path.

Addition of an item that describes the flow direction into the unit watershed attribute table makes it possible to utilize most of the concepts of hydrologic modeling, so far used in raster GIS, in the vector environment. Such functions as flow accumulation, basin delineation, and flow length can be applied for any shapes and thus for unit drainage areas. The flow system described here may be adopted for all models in which the conditions in a modeling unit do not influence the conditions in an upstream unit such as kinematic wave routing and constituent decay as a pollutant flows downstream.

In this study, the flow connectivity of the unit watersheds is used to calculate cumulative or average parameters of drainage area upstream of a given point. These values are applied to the regression equation to estimate agricultural chemical concentration in the runoff. The following list presents selected examples of application of the unit watershed flow system that have been programmed in the Arc/View script language:

- weighted average of a feature (for example agrichemical application) for the total drainage area upstream of each (or selected) modeling unit (like the Grid function `zonalaverage`);
- accumulated value over total upstream drainage area going along the flow path (vector version of the Grid `flowaccumulation` function); and

- difference between the inputs and the output for each modeling unit, flow difference or “flow-decumulation”.

The unit watershed approach of modeling agrichemical transport can be considered as a semantic data model:

> *... semantic data modeling --- creating abstractions of geographic data layers which map one to one with their geographic representation but which are simplified in a functional description to the level needed for hydrologic modelling.* (Maidment, 1993)

Figure 4.12 shows examples of the conceptual stream network. The links have been developed by connecting the cells immediately below each modeling unit outlet. Thus, although the system is conceptual, each node is located on the river represented in Grid format.

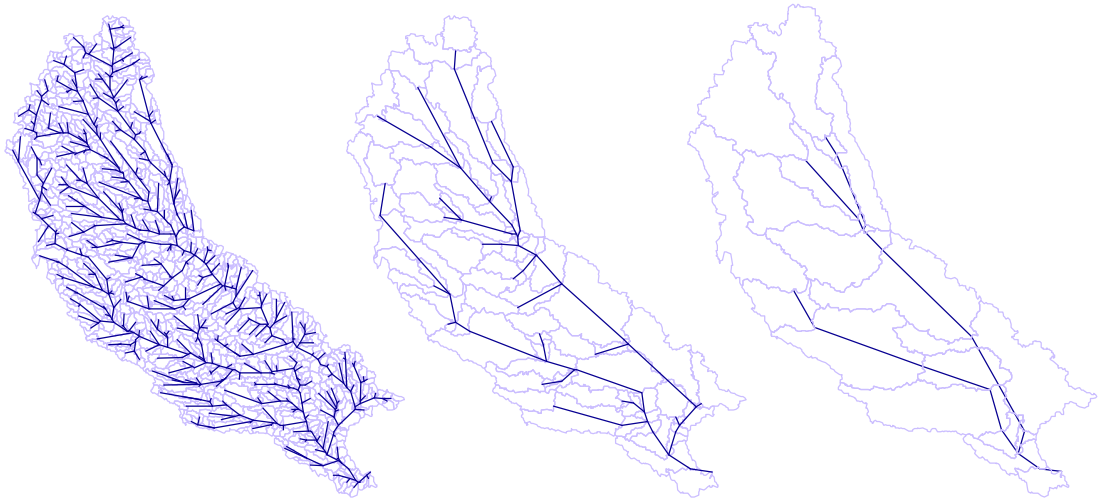

Figure 4.12 Flow system in the Iowa-Cedar River basin subdivided into modeling units of different sizes (threshold drainage area: 25 km^2, 400 km^2, and 2500 km^2).

In this system, the outflow from the source watershed (first order watershed) is a point inflow into the stream. The outflow from an intermediate watershed can be represented as a lateral inflow applied on the stream length or can contribute directly to the outflow from the reach, as applied in this research. Thus the conceptual stream network attribute table contains three items that describe the water or agrichemical mass flow conditions:

- Inflow (sum of inflows from upstream units);
- Lateral inflow; and
- Outflow.

In addition, the arc attribute table can contain wide range of items that describe the links (length, slope, RF1-ID, agrichemical decay coefficient, travel time) as well as the parameters of the beginning node and the ending node (elevation, coordinates, and length from the watershed outlet). In this research only the conceptual stream network represented by unit watersheds is utilized. Since the unified system of hydrologic unit IDs is developed in this research, the attributes of unit watersheds and the attributes of stream reaches can be linked, i.e., stream parameters such as actual flow length or stream slope can be attributed to modeling units.

4.4.3 Ordering system of the modeling units

To enhance the calculations performed by the GIS model, the following system of ordering modeling units has been utilized: The most upstream units are assigned an order one. An interior unit has the order equal to the maximum order of the upstream units increased by one. Figure 4.13 compares this ordering method with the Strahler

and the Shreve ordering systems (ESRI, 1992). The proposed ordering system allows one to perform calculations in consecutive manner: initially all the first order units are processed, then the order is increased by one and all units of order two are evaluated. The routing is performed until the unit of the highest order is calculated.

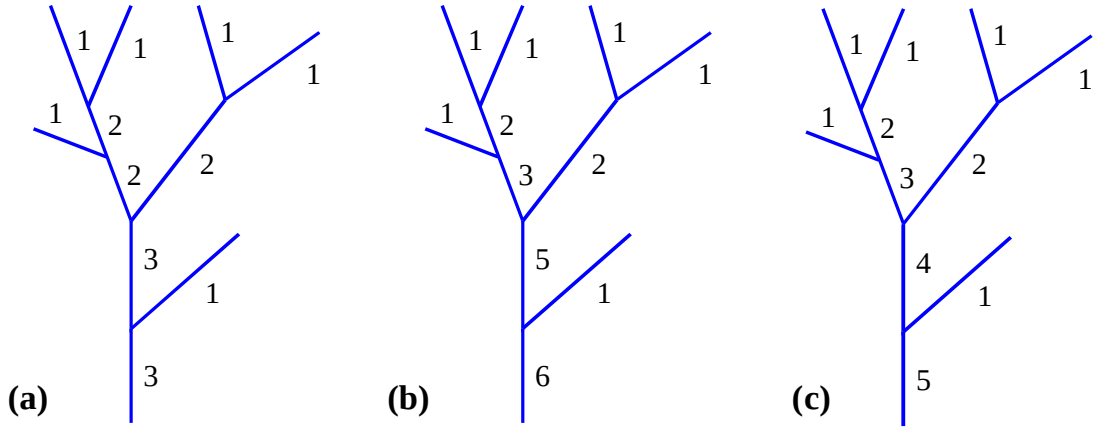

Figure 4.13 Comparison of the stream ordering systems: (a) Strahler, (b) Shreve, and (c) utilized in the agrichemical transport model.

4.4.4 Enhancement of the stream delineation process

The grid that describes the cell-to-cell flow (flowdirection) is crucial for all hydrologic analysis that is performed in a rasterized environment. Procedures such as stream and watershed boundary delineation, dividing a basin into modeling units, stream slope calculation, length of the flow path estimation, and connection of hydrologic units, are examples of operations that cannot be performed without the map of flow direction. Moreover, the accuracy of all derived information depends on the precision of the flow direction grid. Therefore, an effort has been made to develop a method to improve the map that represents the flow paths. The RF1-digital 1:500,000 map of the US rivers has been selected as a basis for the spatial framework

of the entire flow system. The following explanations support the application of a map of existing rivers to correct the flow system determined from a DEM:

- Since the location of a stream that is delineated from elevation data depends on the cell size, the stream networks determined from the DEMs of different resolutions are not compatible. Thus, the gauging stations linked to one grided river system will not be in agreement with other grided river systems derived from DEM grids of different cell sizes.
- The stream system constitutes the best framework for the spatial flow. It took hundreds of thousands of years for a river bed to develop to its current form. Since the river location practically does not change, other information such as position of gauging stations may be related to the location of the stream reach.
- In flat regions, the streams delineated from the DEM tend to be straight lines, whereas, in reality the rivers have a tendency to meander. This causes an overestimation of the stream slope and an underestimation of the river length in purely DEM-derived streams.
- RF1 represents the true river system, whereas, the stream network delineated from the DEM just approximates the same system.

The process of the DEM adjustment is based on the converting the RF1 into grid form and then increasing the elevation of all DEM cells, that do not represent gridded RF1, by an arbitrary value (e.g., 10,000 m). This operation forces the Grid GIS to create a map of flow direction that is compatible with the flow system represented by the vector map of rivers (RF1). The method of enhancing the flow system development has the following disadvantages:

- Since the elevations of the DEM are changed, the modified DEM can not be used for other tasks than the flow direction estimation.
- The stream network has to be represented by a single line. A double line description of rivers can be utilized if the distance between the lines is smaller than the cell size.
- All existing loops in the river network have to be removed or opened to eliminate the ambiguous flow paths.
- All lakes have to be converted into line representations or to polygons.
- The cell width applied for the adjustment process should be smaller than half of the distance between any streams in RF1, to avoid connections of stream networks from different basins that may be created when converting from vector format into raster format.

If the river network does not fulfill the above mentioned requirements, some editing after converting into grid format is necessary.

Incorporating the RF1 into a grid has an additional advantage. By assigning the reach ID from RF1 to the raster river representation, the attribute table of RF1 can be linked with the attribute table of derived grids. Thus, such information as the average flow velocity, average flow rate or stream names that are in the RF1 attribute table can be used for grid models and vice versa, the parameters estimated in grid such as reach slope, drainage area and flow length can be assigned to the streams in vector RF1. The RF1 - Grid link extends the grid-network procedure for hydrologic modeling developed by Maidment (1992).

4.5 Redistribution of the flow record over ungauged rivers

The flow rate is essential to estimate the agrichemical concentration and load in all rivers of the area under investigation. In this study, the historical flow record is utilized instead of synthetic values. The high or low flow conditions are modeled by selecting a year from the past that had the high or low flow rate recorded. The flow measurements are available only in locations in which the USGS gauging stations are located. Therefore, a procedure that calculates the flow rate in ungauged stations has been developed. This section describes this procedure.

4.5.1 GIS database of monthly flow rate and the precipitation depth

To make the model of transport of agrichemicals capable of reconstructing historical conditions, a database of the recorded average monthly flow rate and a database of the observed average monthly precipitation depth must be constructed. Since the model is developed within the GIS, the data structure of the flow and precipitation time series must be incorporated into the geographic system. The advantages of this approach are as follows:

- Compactness of the system. Spatial and temporal data are stored in one format that is specified by the GIS;
- Efficiency of the system. The spatio-temporal features can be viewed, queried, and processed directly by the procedures built into such GIS software as Arc/Info or ArcView;
- Easy to maintain. Data can be organized by spatial units (e.g., political or hydrologic units) and/or by temporal unit (e.g., year, month or decade);

- Simple to understand. Data are stored in attribute tables, records represent the spatial domain whereas the columns (items) represent the time domain.

The GIS database of monthly flow rate and the database of the average monthly precipitation depth is developed in two steps: first a map of monitoring stations is created and then, for each map, the attribute table with the measurements is built.

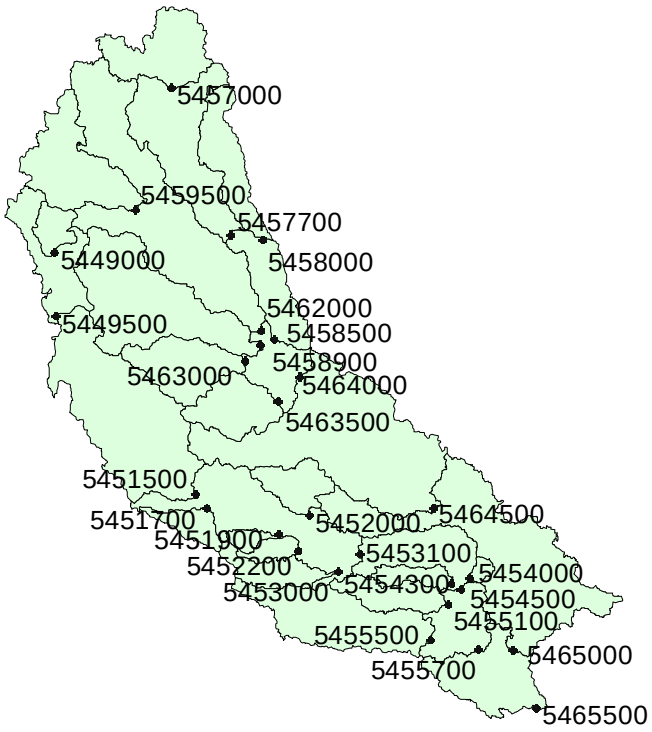

Figure 4.14 The Iowa-Cedar River basin: subwatersheds and selected USGS gauging stations (numbers represent station ID).

The gauging station maps are created utilizing the latitude and longitude of gauging sites published by Hydrosphere (1993 a, b; 1994). Although there are 38

USGS stations in the Iowa-Cedar River basin only the 28 stations with complete flow record for period from 1960 to 1992 have been used for analysis. Figure 4.14 shows the map of the USGS gauging stations selected for modeling the spatial distribution of recorded flow rate.

The map of National Weather Service Climate stations contains 86 stations that are located within the Iowa-Cedar River basin and within the 50-km buffer zone outside the basin. Figure 4.15 shows the map of the climate stations. All climate stations are utilized to create precipitation maps.

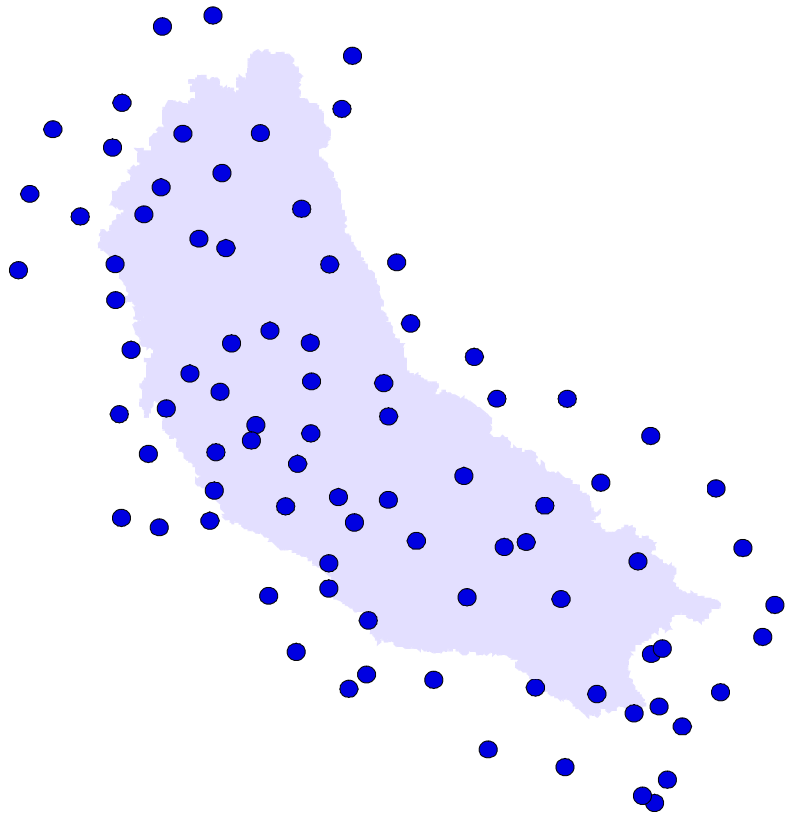

Figure 4.15 Weather stations applied to analysis of the hydrologic conditions in the Iowa-Cedar River watershed.

A fragment of the point attribute table that contains average monthly flow rates is presented in Table 4.1.

Table 4.1 An example of PAT--point attribute table of the USGS gauging station coverage (e.g., item M199001 contains average flow rate in year 1990, month 01). Full table contains monthly flow record for 38 stations, for period from 1940 to 1992 in m^3/s.

GSFLOW_	GSFLOW_ID	STATION_ID	M199001	M199002	M199003	M199004	M199005
1	1	5457000	1.339	1.419	13.111	15.036	18.519
2	3	5459500	0.292	0.357	3.228	2.274	6.513
3	4	5457700	2.444	3.596	22.201	23.390	31.630
4	5	5458000	0.165	0.294	5.239	3.143	4.955
5	6	5449000	0.004	0.020	0.697	0.413	0.445
6	9	5449500	0.154	0.204	1.481	1.141	2.917
7	10	5462000	1.444	1.855	15.150	12.601	26.618

4.5.2 Average precipitation depth in modeling units

The process of spatial redistribution of the measured monthly average flow requires the average precipitation depth for each modeling unit. GIS water quality models such as SWAT-GRASS utilize the rainfall depth observed in the closest weather station to the subbasin (Ramanarayan, et al., 1996, Krysanova, et al., 1996). The methods commonly used in hydrology for spatial estimation of rainfall from rain gauges are the Thiessen polygon method (Chow, et al., 1988) and the inverse distance-squared method (Smith, 1993). There are two other functions available in Arc/Info GIS: kriging and trend (fitting a polynomial regression surface). In this research the Arc/Info IDW function (inverse distance-squared method) has been applied. It creates a grid of spatially distributed values extracted from the attribute table of point

coverage. The calculations are very fast, thus it was feasible to create maps of spatial distribution of monthly average precipitation depth for the Iowa-Cedar River basin for the period from 1950 to 1992. Figure 4.16 presents the map of precipitation depth estimated for June 1990.

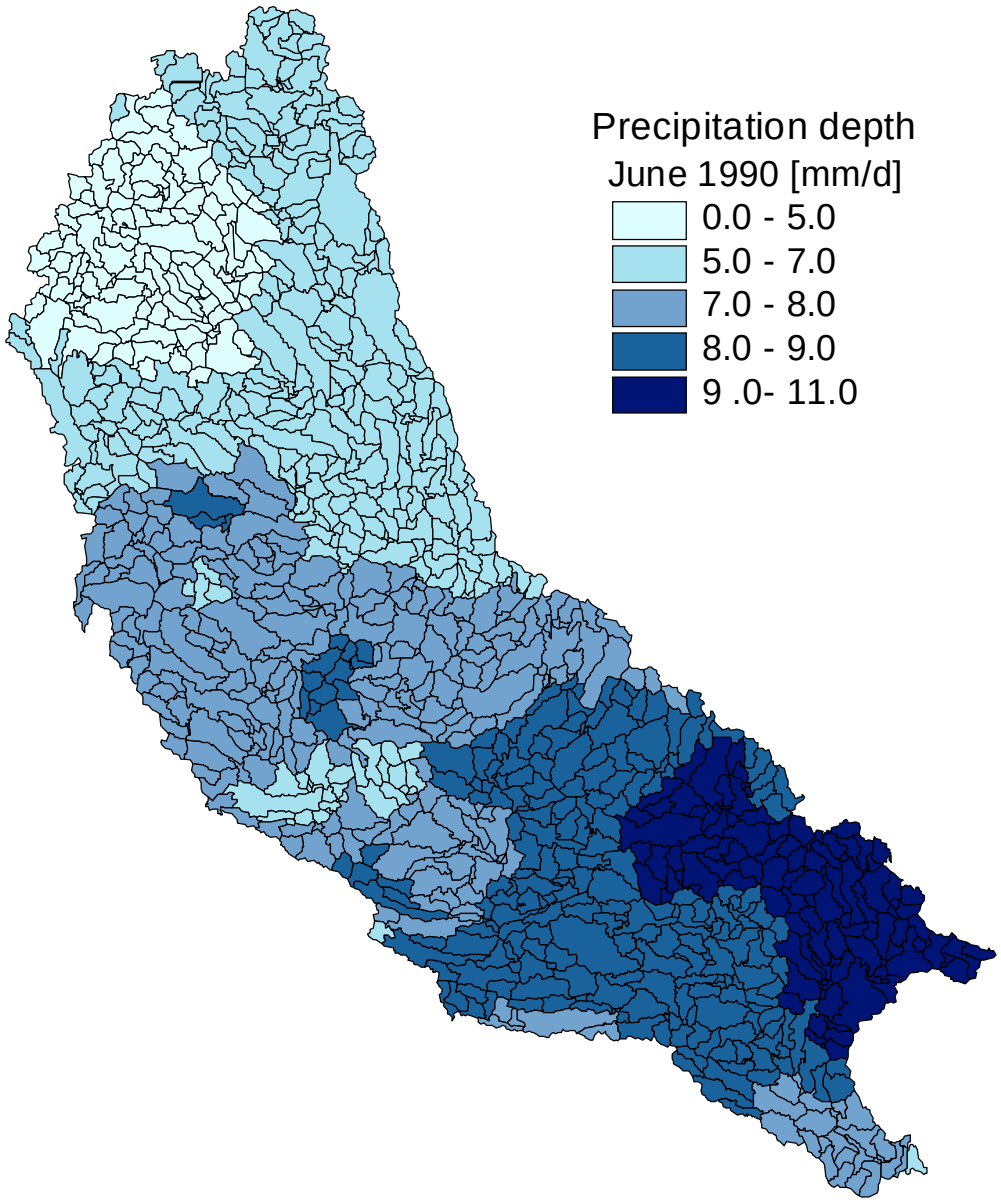

Figure 4.16 Spatial distribution of monthly precipitation depth [mm/d] in the Iowa-Cedar River watershed in June 1990.

4.5.3 Mathematical description

There are about 38 USGS gauging stations in the Iowa-Cedar River basin (some of them are not in service). One or more gauging stations determine a drainage area (or partial drainage area), referred to as a gauging station zone or zone. The gauging station constitutes a point through which a known amount of water flows from one zone to an other zone. The runoff from each modeling unit depends on two factors: 1) the water balance calculated for the unit's respective zone and 2) the distribution of the precipitation depth over the gauging zone. Figure 4.17 illustrates an example of a gauging zone and modeling units.

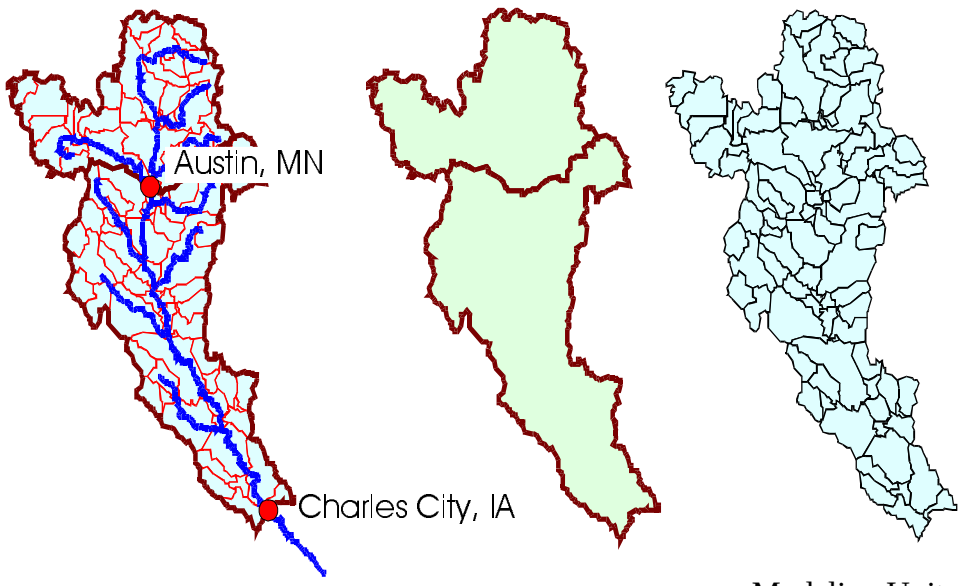

Figure 4.17 Cedar River watershed above Charles City, Iowa: An example of gauging station zones and modeling units.

The process of spatial redistribution of the measured monthly average flow is performed in four steps. Each step is performed separately for a given month. Since the method only redistributes observed values using drainage area and precipitation as a weight, the effect of the snow accumulation and the evaporation on the spatial distribution of the flow is included in the flow record for the gauging zones. Within each zone neither the snow accumulation nor evaporation or groundwater transfer are explicitly taken into consideration but they are considered implicitly by using varying runoff coefficient in each month of each year. The precision of data used for the agrichemical transport such as county level chemical application do not justify construction of a very detailed flow model that would require information about spatially distributed temperature, snow depth, land use, aspect, solar radiation etc. The steps of the flow rate interpolation are as follows:

1) Estimation of an average runoff coefficient relating monthly precipitation to discharge;
2) Approximation of the flow in streams;
3) Evaluation of error between estimated flow and gauged flow;
4) Correction of estimated flow rate at the gauge and over all modeling units within gauged zone.

Estimation of average runoff coefficient. Using recorded outflow from the first order zones, i.e. watersheds determined by the most upstream gauging stations, an average runoff coefficient C_f is calculated according to the following equation:

$$C_f(m) = \frac{\sum_j Q_j(m)}{a \sum_j A_j(m) * P_j(m)} \tag{4.16}$$

where:

$C_f(m)$ = average runoff coefficient for the m-th month [dimensionless]

$Q_j(m)$ = average flow recorded in j-th gauging station during m-th month [m^3/s]

$P_j(m)$ = average monthly precipitation depth [mm/d]

$A_j(m)$ = j-th watershed area [km^2]

m = month

j = index of the first order watersheds

a = units conversion factor.

First approximation of the flow in streams. The runoff from the modeling units is summed along the flow path, moving downstream from a first order stream toward the outlet of the basin. The mass balance for the i-th unit is described by the following formula:

$$Q_i'(m) = \sum_k Q_k'(m) + aC_f(m)P_i(m)A_i(m) \qquad (4.18)$$

where:

$Q'_i(m)$ = estimated cumulative flow at the outlet point of the i-th unit [m^3/s]

$Q'_k(m)$ = estimated cumulative flow at the outlet point of the k-th unit [m^3/s]

k = index of units in the immediate upstream vicinity of the i-th unit

$C_f(m)$, $P_i(m)$, $A_i(m)$, = average runoff coefficient, average monthly precipitation depth in unit i, and i-th unit area, respectively

To make calculations more efficient, when the flow path crosses the border of the gauging station zone, i.e. at a gauging station, the calculated cumulative flow $\Sigma Q'_k(m)$ is substituted by the measured value $Q_j(m)$. This substitution of values ensures

that the observed inflow is used to calculate accumulated flow in each zone, and the resulting error at the zone outlet is due only to inaccuracy of water balance estimated within the zone (errors do not propagate from zone to zone). Thus, the water balance in unit downstream to the gauging station is:

$$Q_i'(m) = Q_j(m) + aC_f(m)P_i(m)A_i(m) \tag{4.18}$$

where:

$Q'_i(m)$, $C_f(m)$, $P_i(m)$, $A_i(m)$, = same as for (Eq. 4.17)

$Q_j(m)$ = observed inflow into modeling unit i, from zone j. This value equals to the outflow from zone j [m^3/s]

Error evaluation. In this step, the difference between estimated and observed flow, $\Delta Q_j(m)$, is calculated for each zone j:

$$\Delta Q_j(m) = Q_j(m) - Q_i'(m) \tag{4.19}$$

where:

$Q_j(m)$ = observed outflow from zone j

$Q'_i(m)$ = estimated cumulative flow at the outlet point of the i-th unit that is also the outlet point of the j-th gauging station zone.

Correction of the cumulative flow. The correction of the estimated cumulative flow is the crucial process of the flow distribution method. Two weighting coefficients k_1 and k_2 are applied. The coefficient k_2 redistributes error according to the cumulative runoff calculated for each zone separately - the flow in rivers is created only by the estimated runoff $C_fP(m)A(m)$. There are no inflows from the upstream zones. Thus the coefficient k_2 redistributes error according to the drainage area and the

precipitation depth within each zone separately. It is calculated for each modeling unit as a proportion of the runoff $Q^x_i(m)$ from the drainage area upstream of the given, *i*-th unit outlet (within the zone *j*) to the total runoff $Q^x_j(m)$ from the zone *j* (at the beginning of the flow path it is very small, at the zone outlet it equals one):

$$k_{2i} = \frac{Q_i^x(m)}{Q_j^x(m)} \tag{4.20}$$

To put more burden of the error correction on the major rivers rather than small streams, the coefficient k_1 has been introduced. There is a higher probability that the estimated error is due to the losses/gains of the river between the two gauging stations than to the losses/gains in small streams located far from measurement points. In another words, the further from the gauged reach a stream is located, the higher is the uncertainty of the flow is and therefore, the more appropriate it is to apply the average basin runoff coefficient to estimate the stream flow rate.

The coefficient k_1 is calculated using total cumulative flow, i.e., the approximated flow in the streams of the whole basin as a proportion of the estimated cumulative flow $Q'_i(m)$ at the outlet point of the *i*-th modeling unit to the cumulative flow $Q'_j(m)$ at the outlet of zone *j* in which the *i*-th unit is located:

$$k_{1i} = \frac{Q_i'(m)}{Q_j'(m)} \tag{4.21}$$

The adjustment of estimated flow (Eq. 4.18 and Eq. 4.19) can be represented by the following formula:

$$Q_i''(m) = Q_i'(m) + k_{1i}k_{2i}\Delta Q_j(m) \tag{4.22}$$

where:

$Q''_i(m)$ = corrected cumulative flow at the outlet point of the *i*-th modeling unit;

$Q'_i(m)$ = estimated cumulative flow at the outlet point of the *i*-th modeling unit;

$\Delta Q_j(m)$ = error, difference between observed and estimated cumulative flow at the outlet of zone *j*;

k_1, k_2 = weighting coefficients.

4.5.4 Example of flow redistribution

This section shows an example of the redistribution of the recorded flow rate in the gauged zone 6565500 in which the Iowa River joins the Cedar River for June 1990. The location of this zone is shown in Figure 4.18.

The average runoff coefficient for the June 1990 is calculated using recorded outflow and redistributed measured precipitation depth in the first order gauged zones of the Iowa-Cedar basin from Eq. (4.17):

$$C_f(m) = \frac{345.4}{891.6} = 0.387$$

where *m* indicates June 1990, 345.4 m^3/s is the cumulative discharge from the first order basins, and 891.6 m^3/s is the product of monthly precipitation and drainage area over all first order basins.

The outflow from the zone, station 5465500 (the Iowa River at Wapello), equals to 827.621 m^3/s. The measured inflows at stations 5455700 (the Iowa River near Lone Tree) and 5465000 the Cedar River near Conesville) are 285.039 m^3/s and 491.895 m^3/s respectively.

Figure 4.18 Location of the gauged zone 5465500, its subdivision into modeling units, and the USGS gauging stations.

The estimated outflow from the zone is equal to the sum of inflows from upstream zones plus the runoff from zone due to the precipitation (40.034 m^3/s):

$$Q'_{5465500}(m) = Q_{5455700}(m) + Q_{5465000}(m) + aC_f(m)P_{5465500}(m)A_{5465500}(m)$$
$$= 285.039 + 491.895 + 40.034 = 816.968 \quad m^3/s$$

The error of estimated flow is calculated according to the equation (4.19):

$$\Delta Q_{5465500}(m) = 827.621 - 816.968 = 10.653 \quad m^3 / s$$

The correction coefficients k_{1i} and k_{2i} are calculated according to the equations (4.20) and (4.21) respectively. k_{1i} is calculated by dividing column $Q_i'(m)$ by $Q_j'(m)$ = 816.968 m^3/s and k_{2i} is calculated by dividing column $Q_i^x\ (m)$ by $Q_j^x\ (m)$ = 40.03 m^3/s.

Table 4.2. Steps of the recorded flow rate redistribution in gauged zone 5465500 for June 1990.

Unit	Next	Order	Area	P	$C_i P_i A_i$	$Q_i^x\ (m)$	$Q_i'\ (m)$	k_{2i}	k_{1i}	$Q_i''\ (m)$
ID	unit ID		km^2	mm/d	m^3/s	m^3/s	m^3/s	-	-	m^3/s
100644	644	1	29.29	9.1	1.198	1.198	1.198	0.0299	0.0015	1.198
644	675	2	69.53	8.9	2.773	3.970	3.970	0.0992	0.0049	3.975
100666	666	1	25.96	8.8	1.027	1.027	1.027	0.0256	0.0013	1.027
663	671	58	28.22	8.5	1.076	1.076	286.115	0.0269	0.3502	286.216
657	665	74	11.59	9.1	0.475	0.475	492.370	0.0119	0.6027	492.446
665	680	75	64.89	8.5	2.469	4.066	495.961	0.1016	0.6071	496.618
100664	664	1	25.03	9.5	1.065	1.065	1.065	0.0266	0.0013	1.065
100668	668	1	30.68	8.3	1.139	1.139	1.139	0.0285	0.0014	1.139
668	667	2	19.56	8.3	0.727	1.866	1.866	0.0466	0.0023	1.867
666	671	2	10.85	8.4	0.409	1.436	1.436	0.0359	0.0018	1.437
667	671	3	36.08	8.2	1.333	4.192	4.192	0.1047	0.0051	4.197
664	665	2	1.39	9.2	0.057	1.122	1.122	0.0280	0.0014	1.123
100673	673	1	25.08	8.3	0.933	0.933	0.933	0.0233	0.0011	0.933
100676	676	1	26.31	8.3	0.977	0.977	0.977	0.0244	0.0012	0.978
671	675	59	20.17	8.2	0.738	7.442	292.481	0.1859	0.3580	293.190
670	667	2	1.41	8.2	0.052	0.993	0.993	0.0248	0.0012	0.993
673	681	2	64.83	8.2	2.379	3.312	3.312	0.0827	0.0041	3.315
100672	672	1	25.09	9.0	1.008	1.008	1.008	0.0252	0.0012	1.008
100670	670	1	25.66	8.2	0.941	0.941	0.941	0.0235	0.0012	0.941
100678	679	1	29.79	8.1	1.087	1.087	1.087	0.0271	0.0013	1.087
100674	674	1	30.8	8.0	1.110	1.110	1.110	0.0277	0.0014	1.110
675	677	60	6.4	7.9	0.227	11.639	296.679	0.2907	0.3631	297.803
674	677	2	42.37	7.8	1.478	2.587	2.587	0.0646	0.0032	2.590
672	679	2	47.07	8.4	1.764	2.772	2.772	0.0692	0.0034	2.775
676	681	2	59.99	8.2	2.216	3.194	3.194	0.0798	0.0039	3.197
681	685	3	73.53	7.8	2.565	9.071	9.071	0.2266	0.0111	9.097
677	680	61	1.37	7.7	0.047	14.274	299.313	0.3566	0.3664	300.705
680	682	76	27.33	7.7	0.949	19.289	796.223	0.4818	0.9746	801.225
5465500	684	78	62.05	7.8	2.173	40.034	816.968	1.0000	1.0000	827.621
100683	683	1	25.13	8.0	0.904	0.904	0.904	0.0226	0.0011	0.904
679	5465500	3	11.98	7.9	0.427	4.285	4.285	0.1070	0.0052	4.291
685	682	4	57.49	7.8	2.001	14.168	14.168	0.3539	0.0173	14.234
682	5465500	77	3.36	7.9	0.118	33.576	810.510	0.8387	0.9921	819.373
683	685	2	63.18	7.7	2.193	3.096	3.096	0.0773	0.0038	3.100

For example, consider modeling unit number 663 which is located on the Iowa River just downstream of the Lone Tree gauge (station 5455700). The January 1990 precipitation on this model unit was 8.5 mm/d on average, thus with a drainage area of 28.22 km^2 and a runoff coefficient C_f of 0.3874, the runoff from this modeling unit is 28.22 * 8.5 * 0.3874 = 92.926 km^2mm/d = 92.926/86.400 m^3/s= 1.076 m^3/s.

The outflow from unit 663 is a sum of inflow and estimated outflow:

$Q_i'(m)$ = 285.039 + 1.076 =286.115 m^3/s.

The correction coefficients are:

k_1 = 286.115/816.968 = 0.3502, and k_2 = 1.076/40.034 = 0.0269,

thus, the adjusted flow in the Iowa River at the outlet point of the unit 663 is:

$Q_i''(m)$ = 286.115 + 0.3502*0.0269*10.653 = 286.216 m^3/s.

4.6 Exponential decay model

This section discusses a model which estimates loads in rivers assuming the chemical losses in rivers are governed by a first order reaction, i.e., the agrichemical mass exponentially decays as it travels from one modeling unit to the next downstream unit. The preliminary model has been developed to calculate the concentrations in rivers utilizing the results of a CEEPS (Comprehensive Environmental Economic Policy Evaluations System) metamodel developed by the Iowa State University's Center for Agricultural and Rural Development (Bouzaher and Monale, 1993).

The CEEPS applies two models of chemical runoff from the field: PRZM (Mullins, et al., 1993) for pesticides and EPIC for nutrients. These results specify the proportion of agrichemical mass applied that leaves the field as runoff. Unfortunately, the author of this dissertation was unable to obtain the spatial distribution of these chemical application-loss relations over the Iowa-Cedar river to estimate the rate of agrichemical losses in rivers necessary to develop and test the complete GIS model with CEEPS data as input. Since it is not in the scope of the research to develop such a CEEPS model, only its outline for the completeness of discussion, is included below.

4.6.1 Exponential decay model overview

The spatial model frame is based on the watershed divided into modeling units described in previous sections. The mass that enters the stream in a unit watershed is calculated using export factors:

$$M_i = U_i Z_i \tag{4.23}$$

where:

M_i = agrichemical mass that enters surface water in the *i*-th modeling unit;

U_i = total agrichemical application in the *i*-th unit; and

Z_i = export factor that depends, e.g., on agricultural management practices. This factor also includes all chemical losses in *i*-th unit.

As the agrichemical mass load travels along the flow path it decays. The decay process can be related to travel time or to travel distance. It is assumed here that the time decay coefficient or distance decay coefficient represent such processes as decay,

sorption, desorption, volatilization, exchange between sediment and water column, settling, scour, and dilution. The equations (4.24 and 4.25) describe this process utilizing a travel time and a time decay coefficient:

$$M_{in,i} = \sum_{j} M_{out,j} \tag{4.24}$$

and

$$M_{out,i} = M_{in,i} \exp(-k_{T,i} t_i) + M_i \tag{4.25}$$

where:

$M_{in,i}$ = agrichemical mass that enters *i*-th modeling unit;

$M_{out,j}$ = output mass from the *j*-th unit;

j = indicator of units that are immediate upstream of the unit *i*;

$M_{out,i}$ = agrichemical mass that leaves *i*-th modeling unit;

M_i = agrichemical mass in runoff from *i*-th unit;

$k_{T,i}$ = time loss coefficient, applied to the mass that enters *i*-th unit;

t_i = time that takes the constituent to travel through *i*-th unit.

To describe the agrichemical losses by an exponential function of river reach length the $k_{T,i}\ t_i$ component of the equation (4.25) must be substituted by a distance loss coefficient $k_{L,i}$ and a travel distance L_i (Eq. 4.26).

$$M_{out,i} = M_{in,k} \exp(-k_{L,i} L_i) + M_i \tag{4.26}$$

where:

$k_{L,i}$ = distance loss coefficient, applied to the mass that enters *i*-th unit;

L_i = travel distance through *i*-th unit.

Since the database of the average monthly precipitation depth, the monthly water runoff from the field as well as the average monthly flow rate in river for all modeling units it is feasible to apply concentrations (traditional approach: $c_1 = c_0^{-k_T t}$) instead of loads.

4.6.2 Travel time approximation

Since no information about the river cross sections is available as yet, a special procedure has been developed to determine the distribution of time of travel and flow velocity. The visual analysis of daily flow record along the flow path has revealed that there is a time shift between flow time series. Figure 4.19 presents an example of the flow rate time series along the flow path from the gauging station "Winnebago River at Mason City, Iowa" to the gauging station "Iowa River at Wapello, Iowa".

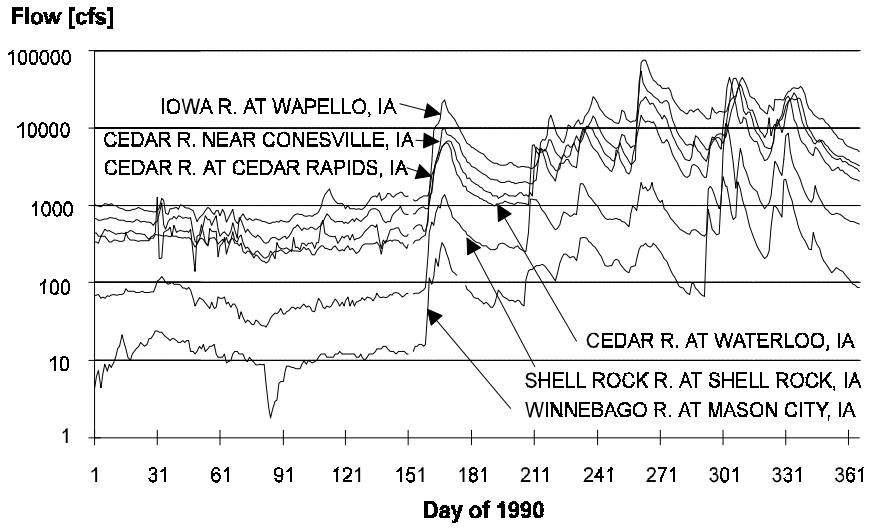

Figure 4.19 Example of time series recorded in gauging stations located along the Cedar River. The data are for the water year 1990. The logarithmic scale is used to show all time series in one picture.

Lagged cross-correlation coefficients can be applied to test the linear relationship between flow time series recorded in the gauging stations located on the same flow path. Six gauging stations along the Cedar River shown in Figure 4.20 have been selected for preliminary analysis.

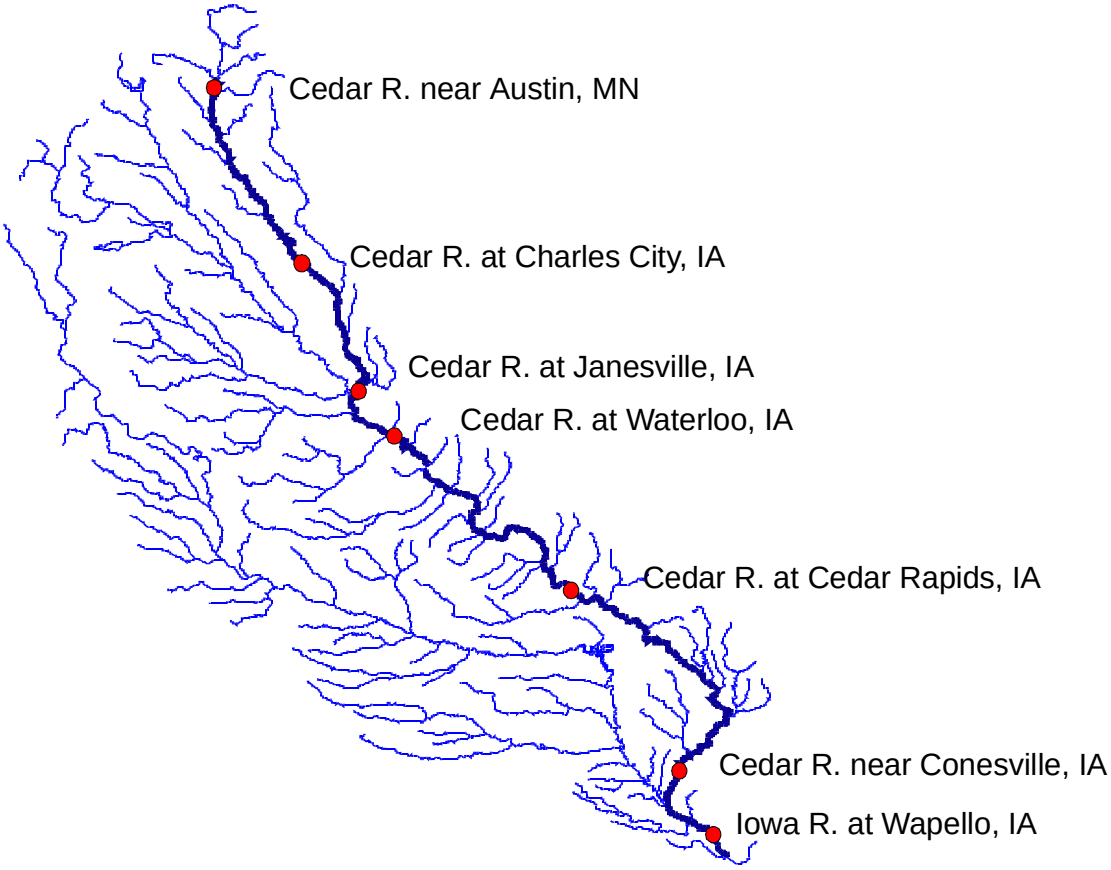

Figure 4.20 Flow path and location of gauging stations which have been used to illustrate the potential method for time of travel estimation.

The cross-correlation coefficients between the time series recorded at the gauging station "Cedar River near Conesville, IA" and the time series recorded in remaining gauging stations have been calculated. Figure 4.21 shows the estimated

coefficients. For example, the cross-correlation between the flow recorded in gauging station "Cedar River near Conesville" and the flow recorded in gauging station "Cedar River at Cedar Rapids" has the maximum value for a two-day lag. This suggests that it takes about two days for the water to flow from Cedar Rapids to Conesville.

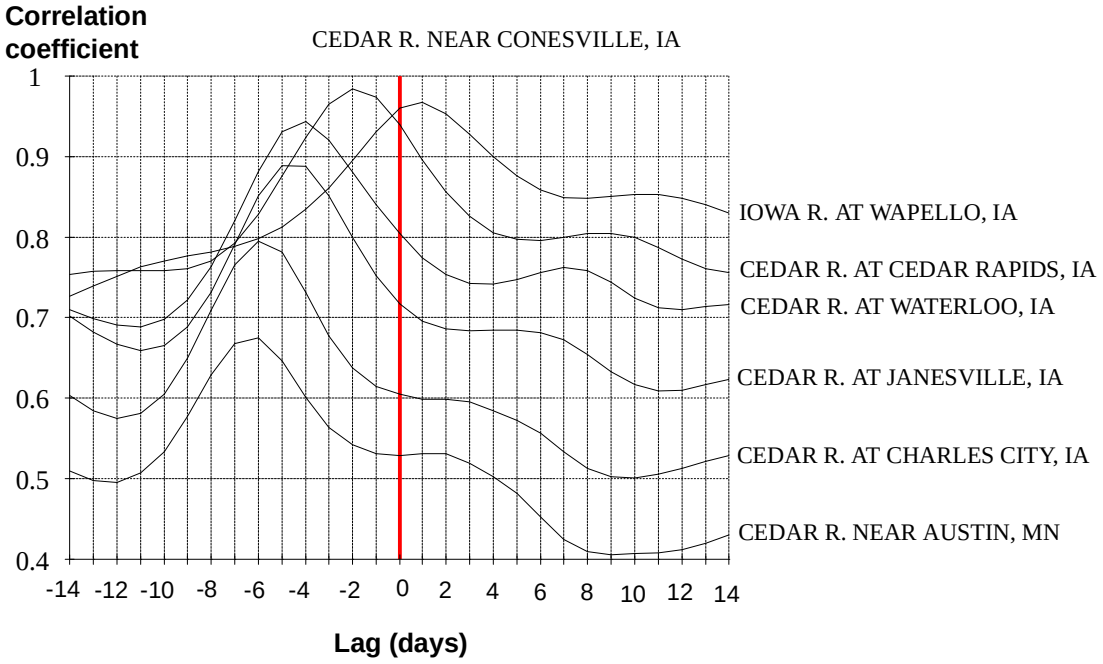

Figure 4.21 Cross-correlation coefficients: the strength of the linear relationship between the flow rate in the Cedar River recorded near Conesville, IA, and the flow rate recorded at indicated locations. All gauging stations are on one flow path (shown in Figure 4.20).

The projection of the travel time over the ungauged regions is much more difficult than the projection of the flow velocity, except the case when a simple relation between the travel time and the travel distance is applied. Figures 4.22a and 4.22b show such a relationship which indicates that the travel time can be substituted by the

travel distance. Figure 4.22c presents the flow velocity as a function of the square root of the stream slope.

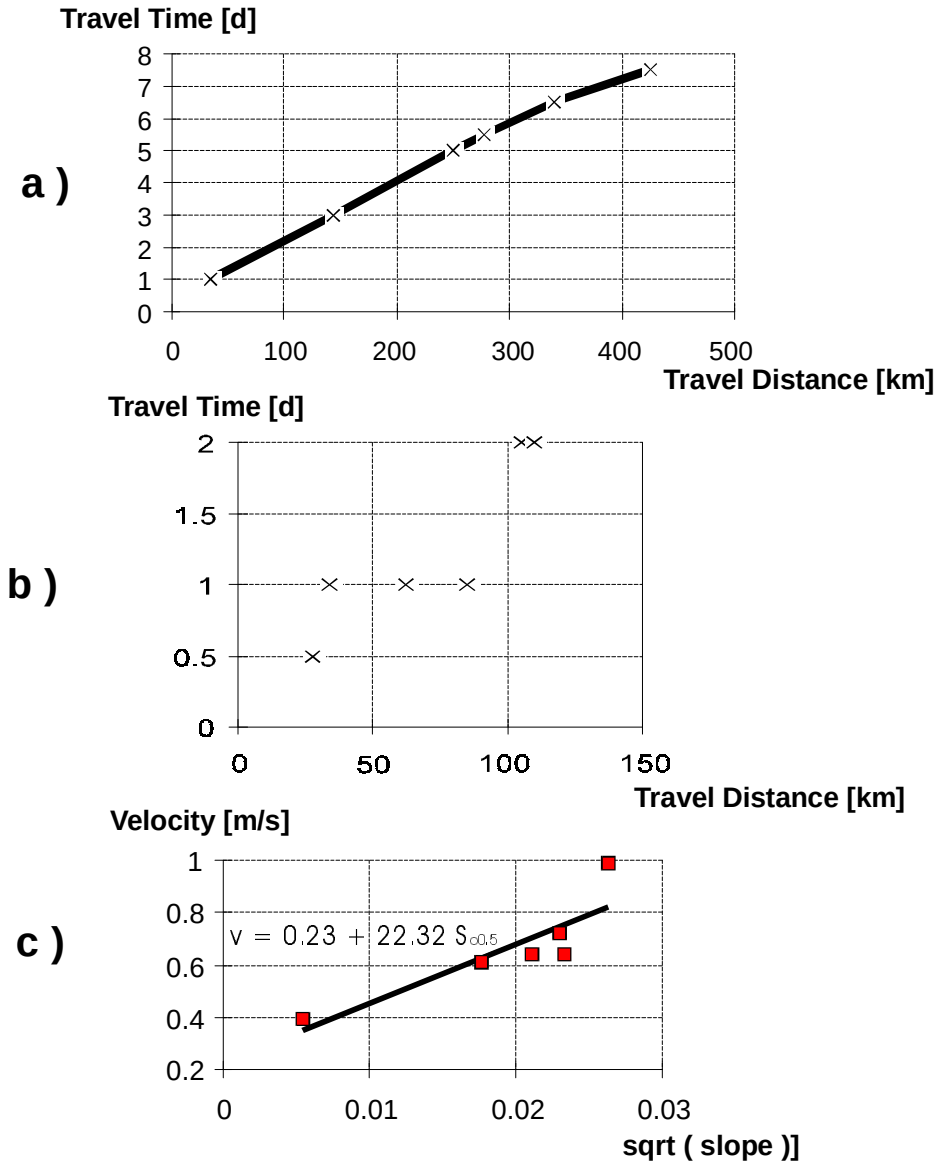

Figure 4.22 Analysis of travel time and flow velocity:
a) cumulative travel time versus cumulative flow distance;
b) travel time vs. flow distance;
c) velocity vs. square root of stream slope.

The travel time shown in Figure 4.22 represents the lag time for which the cross-correlation coefficient has the maximum value. The slope for each stream reach has been calculated from the digital elevation model (DEM). The flow length has been calculated by the Arc/Info function `flowlength`.

The same exercise has been repeated for the Iowa River. Two river sections have been excluded from the analysis: one between Rowan and Marshalltown (maximum correlation between no-lagged series) and other between Marengo and Iowa City (the Lake Coralville causes that the maximum correlation coefficient to be estimated for nine-day lagged series). The following relationship between "travel time", the stream slope, and the stream length has been estimated for both the Iowa River and the Cedar River:

$$t = \frac{L}{0.3 + 20.0So^{0.5}} \tag{4.27}$$

where:

t = travel time [d]

So = stream slope

L = stream length [km]

The Equation (4.27) gives a good approximation of the "travel time" in the Iowa River and the Cedar River. Figure 4.23 shows that the error of prediction for all stream reaches is below 0.5 day (the precision of determining a lag time of the maximum correlation is 0.5 day.)

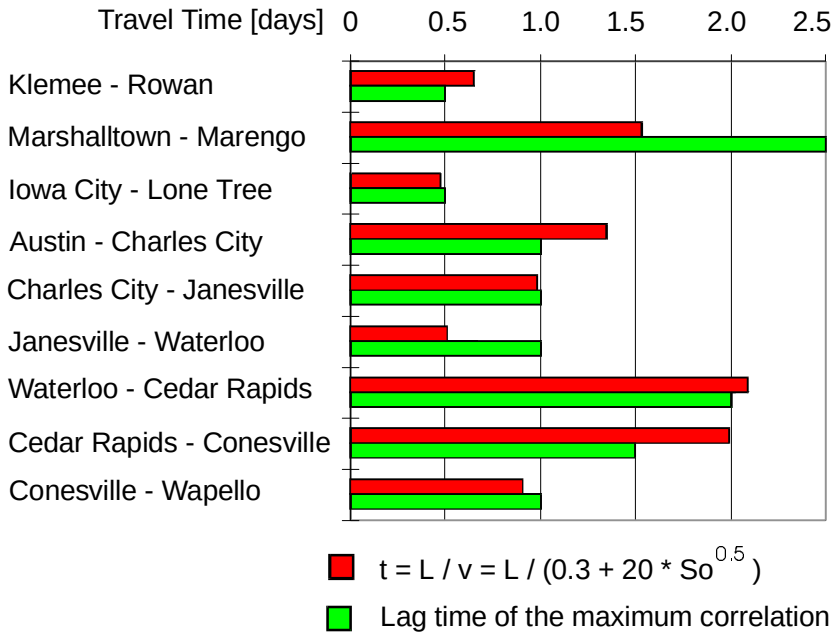

Figure 4.23 Estimation of the "travel time" for major reaches of the Iowa River and the Cedar River, IA.

Figure 4.24 compares the flow velocity extracted from the RF1 database with the flow velocity estimated by the correlation analysis. There is no visible relation between these two data sets. The flow velocity estimated from the correlation of flow record is about three times higher then the one published with RF1. According to the RF1 velocities, it takes constituent almost a month to travel from Austin, MN to Wapello, IA. Further analysis is needed to clarify the reasons for this discrepancy.

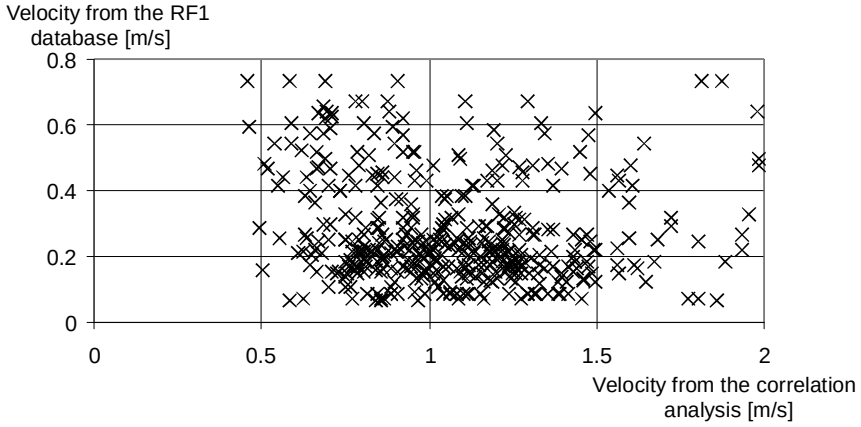

Figure 4.24 Comparison of the velocity from the RF1 database with the velocity estimated from a correlation analysis of the flow record in the Iowa River and tributaries