Kansas Geological Survey

Guidelines for the Application of the Top Specified Boundary Layer (TSBL) Method to Problems of Contaminant Hydrogeology

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Kansas Geological Survey Open File Report 98-43
September 26, 1998

GEOHYDROLOGY

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ABSTRACT

This report presents the basic philosophy and possible uses of the Top Specified Boundary Layer (TSBL) method in studies of contaminant hydrogeology.

The boundary layer (BL) method was originally developed in the beginning of the 20th century, for the approximate analysis of issues of fluid dynamics. Since then it has been useful in a variety of topics associated with fluid flows, heat transfer and mass transfer. Nowadays the BL approach is known as an integral method for the solution of partial differential equations.

The traditional or classical approach of the boundary layer (BL) method considers that a property of interest is distributed within a minor portion of a domain, and that its distribution profiles are similar over its range of occurrence. The property occupies the BL region. In that region its value varies between a prescribed value at the boundary of the domain and a negligible value at the top of the BL region.

The TSBL method separates the definition of the BL region (or regions) of similar distribution profiles of the relevant property, from the region of interest (ROI), which is a TSBL. The ROI occupies the portion of the domain in which the magnitude of the relevant property exceeds an acceptable value. The ROI comprises a portion of the BL, whereas the BL is a region of the overall domain in which distribution profiles are similar.

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Since the presentation of the basic TSBL idea in 1996, it has been employed as a robust approach for the development of quick analyses of issues of contaminant hydrogeology. In this case, the property of interest is typically the contaminant concentration. The TSBL method can be applied to a variety of types of boundary conditions typical of contaminated aquifers.

This report provides background and explanations of the general applications of the TSBL method. It also reviews the various applications of the TSBL method developed by the Kansas Geological Survey for studies of groundwater mineralization in Kansas.

A section in this report lists and describes these applications of the TSBL method. For each application the reader is provided with references and guidelines for appropriate use of the TSBL method.

INTRODUCTION

The boundary layer (BL) concept and its uses date back to von Karman and Pohlhausen, who applied this method in the beginning of the 20th century to phenomena of fluid flow (Schlichting, 1968). Since then the BL concept has been applied to a variety of topics associated with fluid flows, heat transfer and mass transfer (Ozisik, 1993). Basically, the BL approach has been used for the solution of partial differential equations similar to the equation of diffusion-advection. Nowadays the BL approximation is considered to be an integral method for the solution of partial differential equations.

The traditional or classical BL approach incorporates two basic features of the domain and the relevant property, whose transport is to be analyzed: 1) The relevant property is distributed in a portion of the domain, where its concentration varies between a prescribed value at the boundary of the domain and a vanishing value at the top of the BL; and 2) Concentration profiles of the relevant property are similar.

Every case of transport that meets these two conditions can be analyzed by the traditional BL method. Figure 1 (a) describes a domain that can be analyzed by the traditional BL method as well as the TSBL method. In this figure the region incorporating similar contaminant profiles extends between the x-axis and the ordinate $y = \delta_0$. The region of interest (ROI) is the top specified boundary layer (TSBL), in which contaminant concentration exceeds its acceptable value. The ROI extends between the x-axis and the ordinate $y = \delta$. Note that Fig. 1 displays the BLs as originating from a contaminant source at the bottom of the figure (and the aquifer); this is not an essential condition, as the method applies to contaminant plume development independent of the geometry of their origin (see Rubin and Buddemeier, 1996).

In Fig. 1, x and y are the longitudinal and transverse coordinates, respectively; C is contaminant concentration; C_b is contaminant concentration at the boundary; and c_r is the ratio between the value C at $y = \delta_u$ (defined below) and C_b.

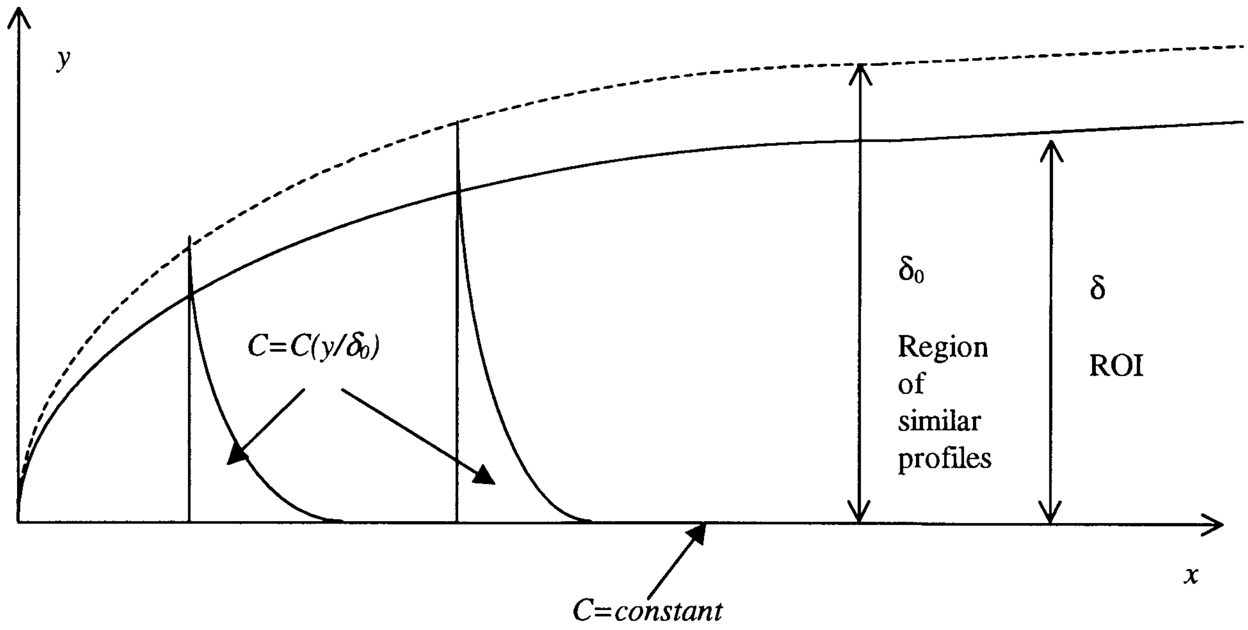

Figure 1a

Illustration of basic BL and TSBL features, and their normalization to demonstrate similarity of profiles.

(a) A contaminant plume originating from a boundary with constant contaminant concentration – case that can be analyzed by traditional BL approach as well as TSBL approach. Parameters of the TSBL are shown; ROI = Region of Interest; C = contaminant concentration; δ = vertical dimension of BL.

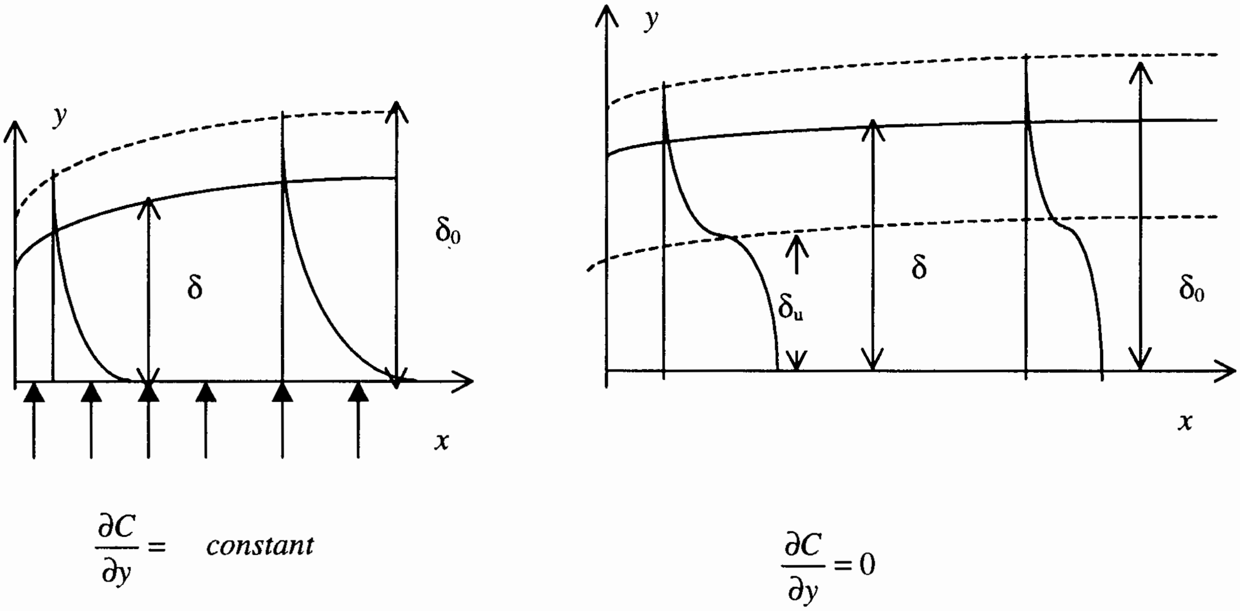

Figure 1b

Illustration of basic BL and TSBL features, and their normalization to demonstrate similarity of profiles.

(b) Cases that can be analyzed by TSBL approach but not by the traditional BL approach – at left, prescribed contaminant flux, and at right, zero contaminant flux at the boundary of the domain.

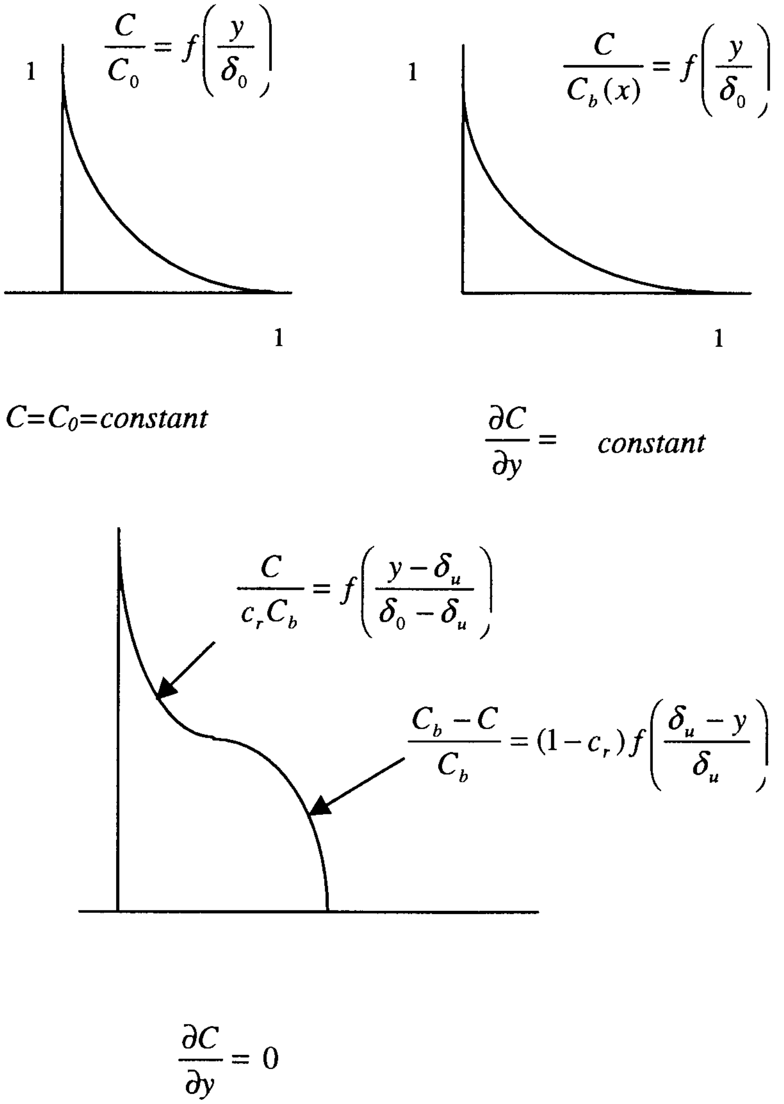

Figure 1c

Illustration of basic BL and TSBL features, and their normalization to demonstrate similarity of profiles.

(c) The fundamental similarity required for a TSBL application – the examples show the single profiles that result from plotting the normalized versions of the multiple profiles within the BL regions of (a) and the two examples of (b), respectively. The equations show the normalization of concentration; the x and y axes are normalized to an appropriate unit length based on the size of the similar profile portion of the domain.

As explained below, the TSBL expands the application of the BL method to cases in which flux is prescribed instead of the contaminant value. Some examples of cases that can be analyzed by the TSBL method are given in Fig. 1. Figure 1(b) represents two examples with flux-prescribed boundaries, where the traditional BL cannot be applied, but the TSBL approach is useful. The left-hand example refers to a prescribed contaminant flux at the boundary of the domain. The right-hand example refers to zero contaminant flux at the boundary of the domain. In this case two types of similar contaminant profiles are identified. Therefore, the contaminated region is divided into two BLs: 1) the inner BL that extends between the x-axis and the ordinate $y = \delta_u$, and 2) the outer BL that extends between the ordinates $y = \delta_u$ and $y = \delta_0$. In both cases of Fig. 1(b), the ROI extends between the x-axis and the ordinate $y = \delta$.

The TSBL method requires appropriate normalization of contaminant concentration and coordinate to identify similar contaminant profiles in the domain. However, there are no clear-cut recipes for the identification of the similar profiles in the domain. The normalization process itself may require specific skills, but applications already developed, such as the cases referred to in these guidelines, can be applied directly if the user takes care to understand and apply the necessary conditions. Figure 1 (c) represents examples of normalized contaminant profiles that represent all of the similar non-normalized profiles in the examples of contaminant distributions of Figs 1(a) and 1(b). More details on the normalization process are provided in each of the cited reports.

The traditional BL method usually refers to two-dimensional domains, where the diffusion-advection equation is integrated in the direction representing the major portion of diffusion of the relevant property.

Practical needs led Rubin and Buddemeier (1996) to the development of the TSBL method. Although the traditional BL method can be very useful in cases where the contaminant value is prescribed at the boundaries of the domain, very often contaminant flux rather than contaminant concentration is prescribed at the boundary of the domain. Furthermore, the definition of a vanishing or very small concentration of the relevant property can be variable, or a vague concept. For example, it is well known that with regard to various types of contaminants concentrations on the order of 1 ppb may be high, whereas for certain water quality parameters, concentrations on the order of ppt are acceptable. Application of the BL approach for contaminant hydrogeology issues therefore requires both extension of the approach to incorporate flux-prescribed domains, and easier definition of the region subject to contamination. Both issues are resolved by the TSBL approach.

Mineralization of inland aquifers can generally be described as a process of contaminant diffusion-advection. However, there are some particular characteristics of aquifer mineralization which require adaptation of the TSBL method to the specific site conditions. Such cases occur in south central Kansas, the location of the phenomena that stimulated development of these approaches.

The following sections concern: 1) the basic conceptual approach leading to the TSBL method, 2) examples of TSBL method applications, 3) specific TSBL methods developed for the evaluation of aquifer mineralization in Kansas, and 4) summary information and guidelines for using the TSBL method.

THE CONCEPTUAL APPROACH LEADING TO THE TSBL METHOD

Rubin and Buddemeier (1996) presented the conceptual approach to the TSBL method, including numerical experiments which indicated that many cases of flux-prescribed domains can be shown to have similar concentration profiles if coordinates and concentration are appropriately normalized. Whenever similar concentration profiles are identified an adaptation of the TSBL approach can be used, and if the flux of the contaminant is prescribed at the boundary of the domain, it is possible to normalize the contaminant concentration to the concentration value at the boundary of the domain. However, the spatial coordinates used for the presentation of the similar profiles also require appropriate normalization. Figure 1 presents some examples of this process, which is discussed in more detail in each of the cited reports.

Rubin and Buddemeier (1996) used concentration values to determine the size of the region of interest (ROI). As stated in the previous section, the ROI incorporates the portion of the domain in which the concentration is larger than some defined acceptable value of the property. The ROI comprises part of the region of similar profiles of the property distribution, and usually extends between the boundary of the domain where the property value (concentration) or its flux is prescribed and the other boundary of the ROI where the acceptable value of the concentration is defined. Therefore, the ROI is termed as a top specified boundary layer (TSBL). The term "top" refers the position of δ relative to the contaminant source, and does not imply any specific spatial orientation.

The basic simulation of property transport in a two dimensional domain is provided by the solution of differential equations similar to the diffusion-advection equation. Solution of the diffusion-advection equation requires specification of an initial condition of the domain and two boundary conditions of Dirichlet (prescribed value of the property at the boundary) and/or Neumann (prescribed property gradient at the boundary) type with regard to each one of the coordinates (usually in the longitudinal and transverse directions). The transformation of the transport problem (from its basic presentation as the diffusion-advection equation to a BL problem) results in a decrease in the number of boundary conditions needed to obtain the appropriate simulation. Diffusion in the longitudinal direction, parallel to streamlines, can usually be neglected, so only a single boundary condition at the upstream of the domain (e.g., at $x = 0$ in Fig. 1a) is required. The downstream of the domain comprises an open boundary. Due to the integration of the diffusion-advection equation in the direction of dominant diffusion (which is usually perpendicular to streamlines), a single boundary condition is required in that direction for the solution of the BL problem. This boundary condition is provided by the prescribed property value or its flux at the boundary of the domain (e.g., y = 0 in Fig.1).

The separation of the ROI from the larger region of similar concentration profiles represents the major advantage of the TSBL method compared to the traditional BL method. The ROI is a portion of the region of similar contaminant profiles. However, its size is determined only by criteria of the contaminant values. Its thickness is not used for the determination of any normalized coordinate in the domain. In some cases the ROI thickness incorporates several types of similar contaminant profiles. The TSBL approach provides more flexibility in using the BL method under different boundary conditions for the domain. Examples presented below show how this flexibility is implemented and used in a variety of practical cases.

GENERAL TSBL APPLICATIONS

The TSBL method is helpful in quick quantification and evaluation of contaminant hydrogeology phenomena. As indicated in the preceding section, so far the TSBL has been used in cases of prescribed value of the property or its flux at a boundary of the domain, and the examples shown involved contaminant input from the bottom of the aquifer. It can be used in other geometries and in more complex cases where the boundary of the domain combines portions of prescribed values of the property and of specified portions of the prescribed flux of the property. Figure 2 provides schematics of different cases in which the TSBL method can be applied. Both examples of Fig. 2 assume steady state flow in the aquifer, and show a contaminant source at the top of the aquifer (Rubin and Buddemeier, 1996). However, example (a) shows a prescribed constant value of the contaminant concentration over a portion of the top of the free surface aquifer, and a combination of that situation with a portion of the top of the aquifer having prescribed zero contaminant flux. Example (b) concerns possible prescribed contaminant flux, or a combination of prescribed contaminant flux and prescribed zero contaminant flux.

The TSBL method has been so far applied successfully to cases of steady flow, steady boundary conditions of various types and combinations, steady and unsteady contaminant transport in the domain. The method can be applied with minor changes to cases of aquifer heterogeneity in the flow direction. It can also be adapted to incorporate simple cases of heterogeneity in the direction perpendicular to the flow direction.

One of the major objectives of the TSBL method is to provide quick evaluation of contaminant transport originating from a small-scale penetration of contaminant into groundwater. However, as the examples below indicate, estimates of large-scale contamination can also be obtained by using this method.

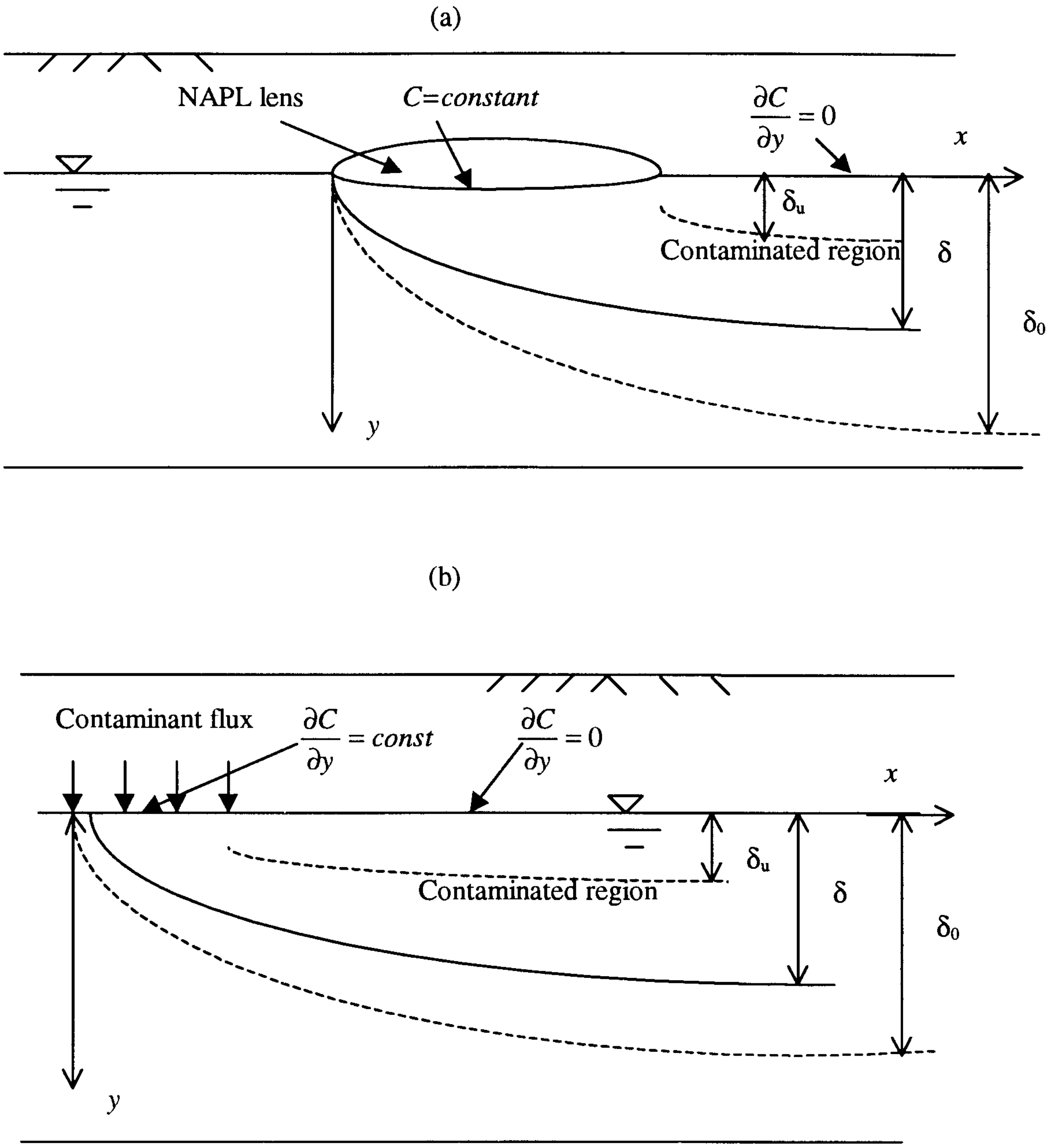

Figure 2

Schematics of complex domain boundaries that can be evaluated by using the TSBL method

(a) Combination of prescribed property value and prescribed zero flux

(b) Combination of prescribed flux value and prescribed zero flux

Phenomena connected with groundwater contamination very often depend on the scale of reference, i.e. coefficients of dispersion obtained on the laboratory scale are usually different from those of field scale. However, in the situations considered here, sources of groundwater contamination may not be well defined in terms of location, size, or rate of contaminant discharge. Under such conditions, the TSBL method can be very useful for preliminary evaluation of the possible sources of contamination. Use of the different types of TSBL modeling approaches can be justified on the basis of the scale of the contamination phenomenon, as show in the examples presented below. The TSBL model adapted to a thick aquifer should be used if the contaminated region is smaller than the aquifer thickness, and another adaptation of the TSBL model should be used if the entire thickness of the aquifer is contaminated.

Due to its applicability to a variety of types of boundary conditions relevant to contaminant transport in aquifers, the TSBL method has been so far useful for obtaining the following specific goals:

- Prediction of contaminant distribution in very thick aquifers due to prescribed contaminant concentration or contaminant flux.
- Prediction of contaminant distribution in very thick aquifers due to penetration of contaminant through a minor portion of the aquifer boundary, owing to either prescribed contaminant concentration or flux.
- Prediction of contaminant distribution in an aquifer of limited thickness.
- Evaluation of field data to obtain major properties and contaminant transport coefficients of the aquifer.
- Design of field monitoring systems in locations of aquifer contamination or risk of contamination.

Figures 2 and 3 illustrate some of these possibilities. If estimates of the vertical salinity distributions and total salt loads can be obtained down-gradient from a probable source of contamination (e.g., the concentration profiles along the plume), the approximate location and strength of the source or sources can be estimated, and the shape and rate of change in the BL can help to identify the most sensitive and informative areas for additional sampling or monitoring. It is important to note that if some information is available about the probable location and/or size of the source, then the source flux can be more accurately estimated, and predictions of plume development can be used to refine estimates of other aquifer characteristics. Examples of this situation might include contamination from improperly abandoned wells or boreholes (source size approx. one meter), from sinkholes or collapse features defined by surveying, seismic, or drilling studies (Garneau, 1995), or from erosional bedrock exposure surfaces of specific strata (Buddemeier et al., 1994).

Complete understanding of the various types of uses of the TSBL method can be obtained by reading the various publications listed in the references of this report. However, the brief review of these studies in the following section of this report should provide the reader with enough information to decide on the possible use of the TSBL method for particular cases of interest. It should be noted that the case studies presented and discussed in the following section exemplify only some of the possible uses of the TSBL method, which is applicable to other questions.

USE OF THE TSBL METHOD FOR THE EVALUATION OF GROUNDWATER MINERALIZATION IN KANSAS

Bedrock in the western part of Kansas consists largely of marine sediments, and the freshwater aquifers are generally separated from the deep saline bedrock formations of Cretaceous and Permian age by the thick Dakota formation. Therefore, saline water and brines, which saturate the deep bedrock, cannot penetrate into the freshwater aquifers of western Kansas. On the other hand, at the eastern edge of the Dakota formation, salinity emanates into the surface aquifers in various locations due to lack of a continuous impermeable formation separating the freshwater aquifers and the saline bedrock. In a series of publications issued by KGS, Rubin and Buddemeier (see References section) adapted and applied the TSBL method to provide quick evaluations of the types of aquifer mineralization phenomena that may take place in south-central Kansas, especially in the Great Bend Prairie aquifer. In the following paragraphs a brief review of the general approach of each study and its outcomes are presented.

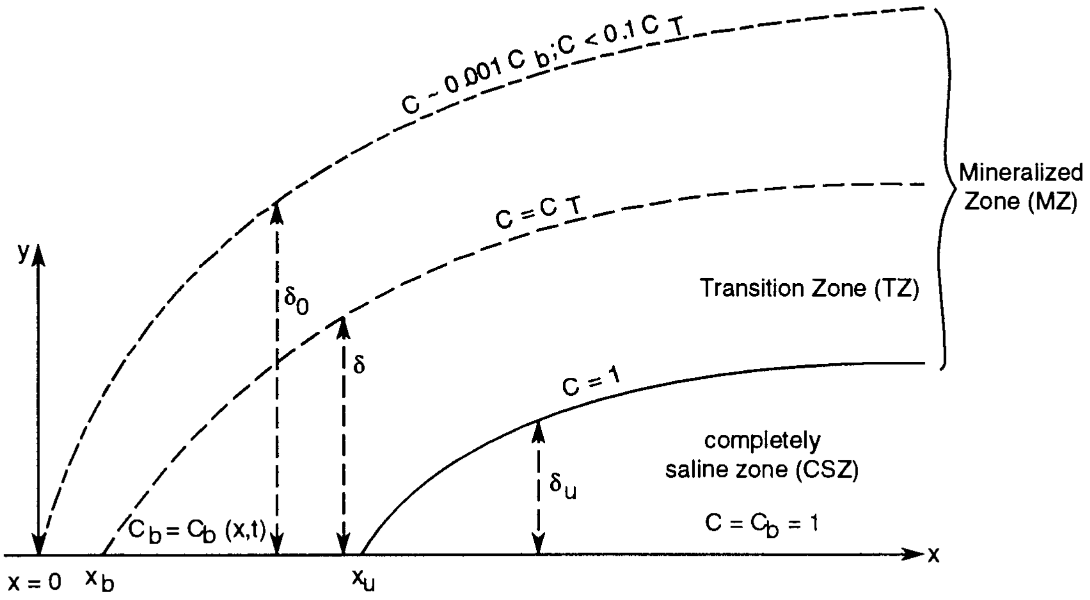

Figure 3a

Illustrations of the features of TSBL applications discussed:

(a) Extended interface in a thick aquifer, with a semi-permeable layer between the salt- and freshwater (Rubin and Buddemeier, 1998b). For the case of direct contact (Rubin and Buddemeier, 1998a), there would be no Completely Saline Zone (CSZ), and a mirror-image freshwater plume would develop in the saline layer of the aquifer below the interface.

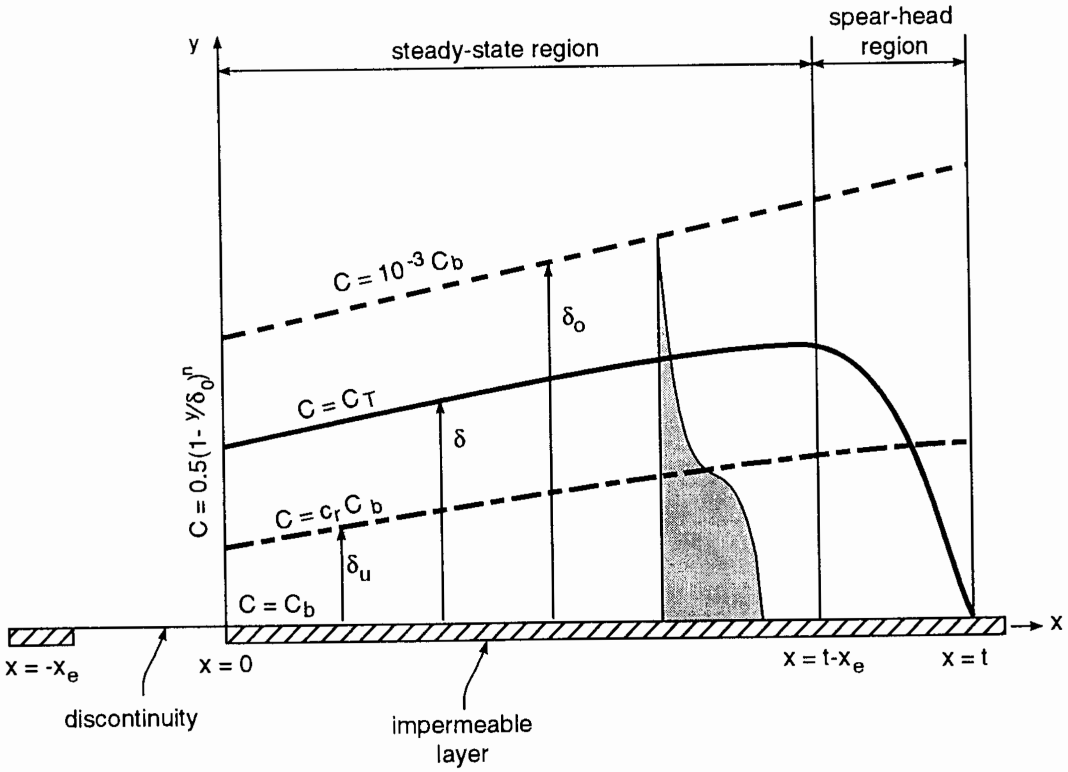

Figure 3b

Illustrations of the features of TSBL applications discussed:

(b) Development of TSBL approach for contamination due to a limited length of minor seepage of saltwater or direct contact between salt- and freshwater at the base of a thick aquifer (Rubin and Buddemeier, 1998c).

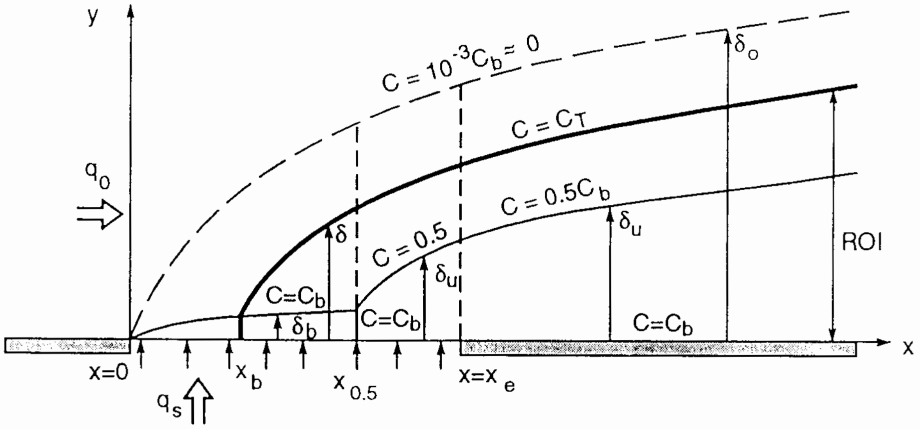

Figure 3c

Illustrations of the features of TSBL applications discussed:

(c) Seepage of water through a semi-permeable discontinuity in the confining layer at the base of a thick aquifer (Rubin and Buddemeier, 1998d).

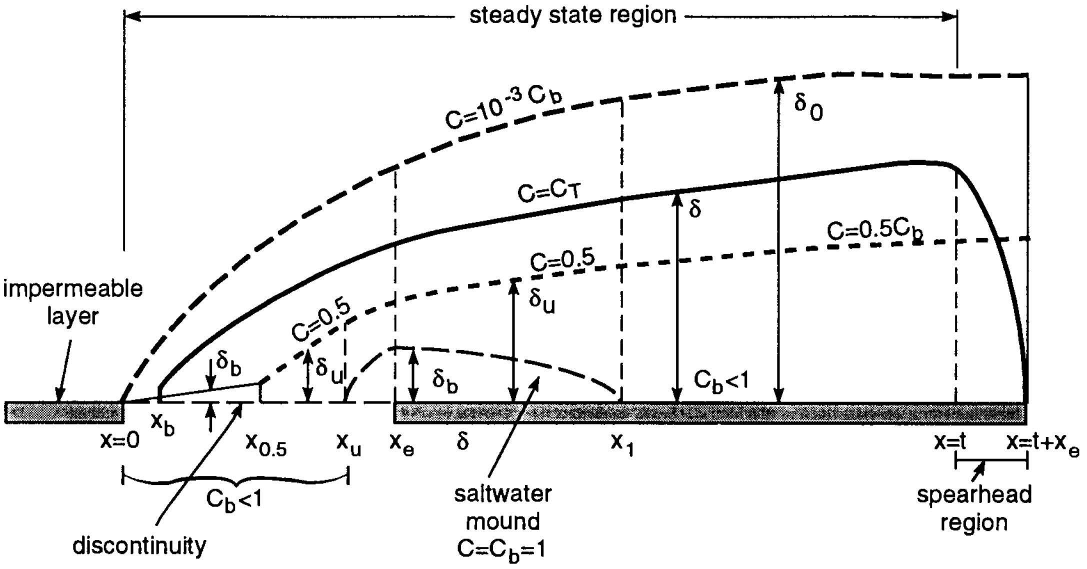

Figure 3d

Illustrations of the features of TSBL applications discussed:

(d) As in (c.), but with low dispersivity values leading to the formation of a saltwater mound immediately downgradient from the discontinuity (Rubin and Buddemeier, 1998f).

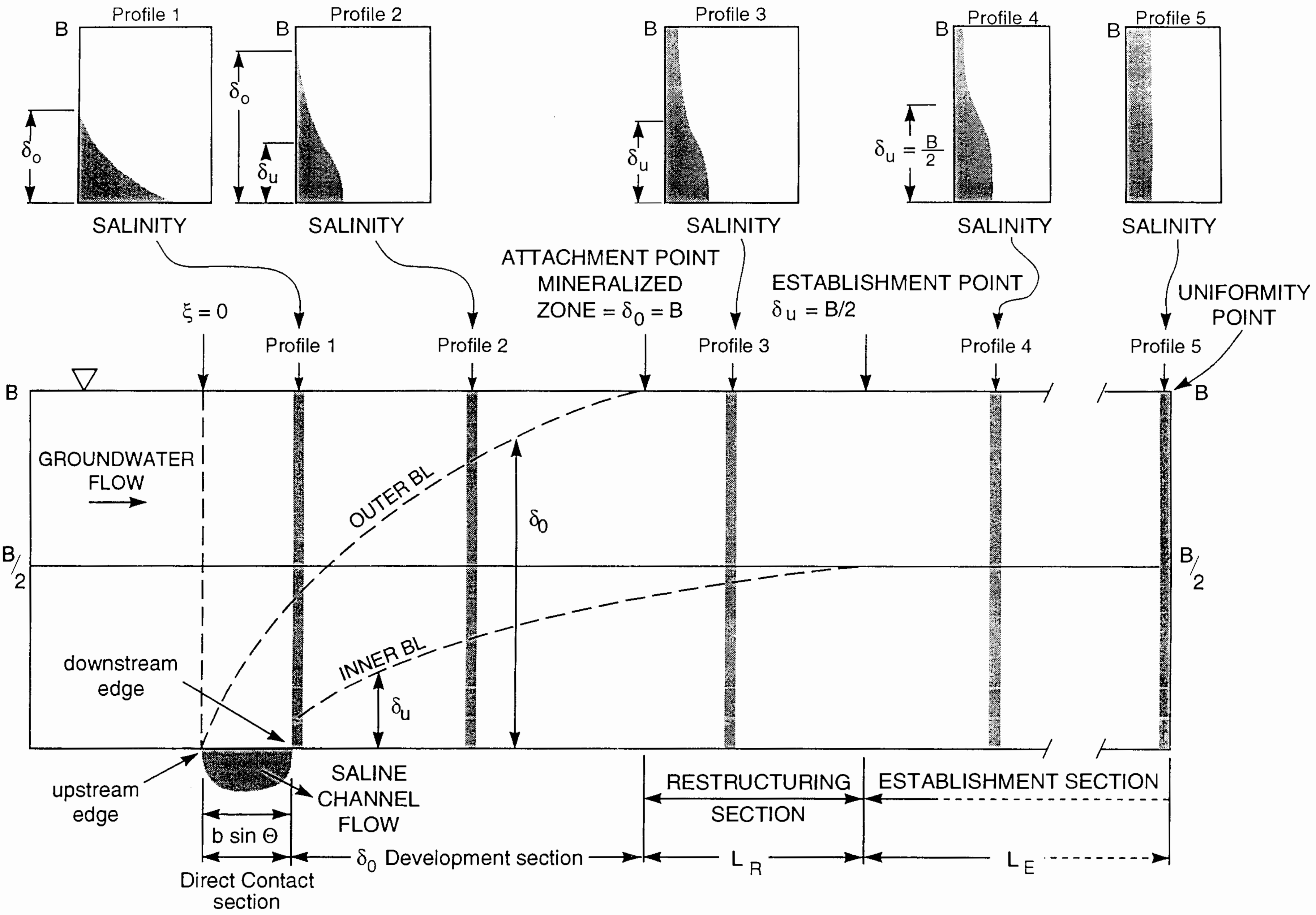

Figure 3E. **Illustrations of the features of TSBL applications discussed:** Composite figure illustrating the development of horizontal transport in a thin aquifer, to the right of the attachment point (Rubin and Buddemeier, 1998e), and the case of aquifer mineralization by salt transfer from a paleodrainage channel (entire figure) (Rubin and Buddemeier, 1998g).

Figure 3 presents cross sections of the major features of the TSBL models used in the applications described. All of the studies assume a homogeneous porous medium within each of the defined regions, and the range of characteristics assumed for aquifer and groundwater properties are generally appropriate to the High Plains aquifer and other aquifers of primarily alluvial origin. However, sensitivity tests for the ranges of applicability are discussed in most of the reports. Furthermore, the methods developed in each of the studies can easily be extended to particular cases of domain heterogeneity.

Continuous Supply of Salinity into the Freshwater Aquifer

(Rubin and Buddemeier, 1998a, b)

The goal of this two-part study was to evaluate the possible intensity of salinity intrusion into the freshwater aquifers of south central Kansas if there are no barriers to the migration of saltwater.

If there is no impermeable formation between the bedrock formation and the freshwater aquifers, then a conceptual model of a two-layer aquifer can be adopted. The bottom layer is saline, the top layer is saturated with freshwater, and the length of the contact is very much greater than the saturated thickness of the top layer (this is referred to elsewhere as the "thick aquifer" case). A transition zone, which can be treated as a BL, develops at the boundary between the two layers. However, field data imply that in some locations there are differences between the potentiometric heads in the saline bedrock and in the freshwater aquifers. Therefore, the possible presence of a semi-confining layer between the two aquifers must also be taken into account. Cases of both direct contact between fresh and saline groundwater (Rubin and Buddemeier 1998a), and head-driven seepage of saltwater into the freshwater aquifer through a semi-permeable layer (Rubin and Buddemeier (1998b) were quantified by applying the TSBL method. Figure 3(a) illustrates the BLs developed in this study. These studies also included some preliminary estimates of the possible effects of pumping and recharge on the contaminant plume development.

The models developed considered a situation in which the interface of salinity transfer was indefinitely long (much longer than the vertical dimensions of either the saturated freshwater aquifer or the contaminant plume). Subsequent studies (Rubin and Buddemeier 1998c, d, discussed below) considered other situations.

Application of the traditional or classical BL approach could simulate the buildup of the transition zone between the two layers of fresh and saltwater aquifers. However, application of the TSBL method provided results of better accuracy. The traditional BL method cannot be used to describe saltwater seepage into the freshwater aquifer, which is a particular case of prescribed contaminant and solvent fluxes. Special adaptation of the TSBL method is needed for this case. Two different approaches to this adaptation were developed (Rubin and Buddemeier, 1998b and 1998d). These studies indicated that continuous seepage of saltwater into the freshwater aquifer may create completely saline regions at the bottom of the freshwater aquifer, which could also be simulated with the TSBL method. The saline region developments are illustrated in Figs. 3(a), where CSZ = Completely Saline Zone, and 3(d), where a saltwater mound develops.

The extended-interface and the extended saltwater seepage options for groundwater mineralization evaluated using the TSBL method showed that neither of the two-layer aquifer models could represent a widespread mechanism of groundwater mineralization, since either model implied that all the groundwater resources of south central Kansas should already be mineralized. As such an extreme phenomenon has not occurred, the penetration of salinity must generally be a local phenomenon limited to particular locations.

Supply of Salinity into the Freshwater Aquifer through Discontinuities in the Impermeable formations (Rubin and Buddemeier, 1998c, d)

Results of the studies described above led Rubin and Buddemeier (1998c, d) to consider the possible migration of salinity into the freshwater aquifer through discontinuities in an impermeable layer consisting of lenses of clay and shale, which separates the freshwater aquifers from the deep saline bedrock. Again, two options of mineralization were considered: a) mineralization due to direct contact between the fresh and saltwater at the discontinuity in the impermeable layer, and b) head-driven seepage of saltwater through a semi-permeable discontinuity in the impermeable layer.

Aquifer mineralization due to direct contact between fresh and saltwater in the region of the discontinuity in the impermeable layer is represented by a conceptual model of a domain subject to a combination of two types of boundary conditions similar to those of Fig. 2(a). One portion of the aquifer is subject to boundary condition of prescribed salinity value, and another portion is subject to boundary condition of prescribed zero salinity flux. Regions of prescribed zero salinity flux incorporate two BLs of similar salinity profiles. Fig. 3(b) depicts the TSBL development downstream from a direct contact at a discontinuity, or minor seepage of saltwater into the freshwater aquifer through a semi-permeable discontinuity in an impermeable layer.

The option of saltwater seepage through the discontinuity in the impermeable layer is schematically fully represented by the combination of boundary conditions of Fig. 3(c). The TSBL analysis and calculations showed that in some cases, a high rate of seepage and a small rate of transverse dispersion could create a saltwater mound in the freshwater aquifer (discussed below).

Both of these studies showed that downstream of the discontinuity in the impermeable layer, the mineralized aquifer portion consists of two successive horizontal regions. The horizontally-penetrating salt front is called "the spearhead region" (illustrated in Figs. 3 (b) and (d)); its length is identical to the length of the discontinuity in the impermeable layer. Upstream of the spearhead region, there is a steady state region. The studies also indicated that, at some significant distance downstream from the discontinuity in the impermeable layer, the BL should reach the top of the aquifer. At this point, the "thick aquifer" assumption is no longer valid, and another adaptation of the TSBL method is required to describe the situation.

Horizontal Penetration of Salinity into an Aquifer (Rubin and Buddemeier 1998e)

At some distance downstream from the discontinuity in the impermeable layer, the entire thickness of the aquifer contains similar salinity profiles, which can be represented by two BLs. Rubin and Buddemeier (1998e) used the TSBL approach to analyze the phenomena of expansion of these two BLs and the transfer of salinity between them.

The calculations indicated that the mineralized portion of the aquifer can be divided into several sections:

- Section of expansion of the mineralized region;
- Restructuring section;
- Establishment section.

A particular set of similar salinity profiles and features of salinity transfer identify each of these sections. These are illustrated on the right-hand side of Fig. 3(e). In the section of expansion of the mineralized region, the thickness of the mineralized portion of the aquifer is smaller than the aquifer thickness, so the method of the preceding (thick aquifer) section can be applied. In the restructuring section, the mineralized portion occupies the entire aquifer thickness; salinity profiles incorporate two BLs whose thicknesses change due to the salinity gradient, but there is no salinity transfer between them. In the establishment section, each BL occupies half of the aquifer thickness, and salinity is transferred from one BL to the other until uniformity of the salinity profile is obtained.

These results can be applied to calculations of salinity transfer to neighboring aquifers from an aquifer subject to saltwater intrusion.

Development of Saltwater Mounds in a Mineralized Aquifer
(Rubin and Buddemeier, 1998f)

As indicated above, a saltwater mound may develop in a freshwater aquifer subject to seepage of saltwater. Saltwater mounds can develop under any of the following conditions: the discontinuity in the impermeable layer is wide; the rate of seepage of saltwater into the freshwater aquifer is comparatively high; or, the aquifer dispersivity is low.

Rubin and Buddemeier (1998f) adapted the TSBL method to analyze and evaluate cases of saltwater mound development in an aquifer subject to saltwater seepage through a discontinuity in an impermeable layer. Such cases feature an accumulation of a saltwater layer with very minor vertical salinity gradients at the bottom of the freshwater aquifer. This situation is illustrated in Fig. 3(d). The horizontal extent of the layer (or mound) will depend on the details of discharge rates and aquifer characteristics.

Effects of Paleodrainage Channels on Aquifer Mineralization

(Rubin and Buddemeier, 1998g)

Sophocleous (1991) reported that in the Great Bend Prairie aquifer a number of highly transmissive topographic features, termed "paleodrainage channels", exist at the aquifer-bedrock interface. Most of these "channels" emanate from the present day course of the Arkansas River in the western part of the area. Rubin and Buddemeier (1998g) adapted and applied the TSBL method to analyze the possible transfer of bedrock-derived salinity from such channels into the overlying aquifer.

Paleodrainge channels are classified into two categories: a) curved channels, and b) winding channels. Curved channels transfer salinity only once to flowlines of freshwater overlying aquifer. Winding channels may transfer salinity to some flowlines carrying groundwater already mineralized as a result of a previous channel transfer. The basic process is illustrated in Fig. 3(e).

Calculation and evaluation of the aquifer mineralization due to paleodrainage channels requires: 1) determination of the course of the channel(s) of interest, b) calculation of salinity transfer into the aquifer flowlines, and c) calculation of changes in salinity profiles along the course of the aquifer flowlines.

The calculations indicate that the effect of the paleodrainge channels on aquifer mineralization may be significant if the aquifer dispersivity is small. Then the channels may transfer salinity to a significant number of successive aquifer flowlines. Depending on the rate of salinity transfer and the criteria for an acceptable concentration, some flowlines may remain saline indefinitely, while others may carry significant salinity only a limited distance along their course. The latter are characterized by an average salinity smaller than the acceptable value. Each paleodrainage channel transports saltwater with a diminishing concentration until dispersion and exchange with the overlying groundwater finally results in its complete dilution.

IMPORTANT FACTS AND ADVICE

Potential applications of the TSBL method include:

- Quick evaluation of large scale contaminant transport phenomena;
- Evaluation of phenomena associated with migration of contaminants from line sources and point sources;
- Identification and calculation of contaminant transport coefficients, based on accumulated field data;
- Identification of locations of line and point sources of contaminants from accumulated field data;
- Design of monitoring systems based on limited field data.

Each one of these uses requires completion of several of the major tasks enumerated below.

Major Tasks Associated with TSBL Method Applications

- Adopt a conceptual model of the contamination process;
- Check suitability of the TSBL method by comparing the similarity of normalized profiles;
- Make necessary adaptations of the BL formulations;
- Develop the appropriate equations;
- Evaluate the possible contaminant transport phenomena;
- Extend the calculations to specific objectives of the project.

The following paragraphs present some examples and of incorporation of these major tasks into the framework of a well designed and targeted study.

Adopt a conceptual model of the contamination process

Field data usually are collected based on some preliminary assumptions about groundwater contamination. Prior to drilling monitoring wells and starting the collection of field data it can be both useful and cost-effective to perform an initial evaluation of the possible sources and phenomena of contamination in the domain of interest. Such analysis and calculations are usually based on the development and use of a conceptual model. An example is the two part study of

Rubin and Buddemeier (1998a, b), which is based on a conceptual model of a two layer aquifer, where the top freshwater layer is mineralized by saltwater from the bottom layer.

Check the suitability of the TSBL method

The similarity of profiles of the relevant property is a criterion for applicability of the TSBL method. Appropriate normalization of the property values and coordinates should be performed relative to specific, well defined contours of the relevant property. Such contours are either of prescribed values of the property, or contours of the normalized property value. The normalization effort addresses the possible structure of BLs developed in the domain. An example of this process is the study of Rubin and Buddemeier (1998d), in which the prescribed contaminant flux at the boundary of the domain invites normalization of that property value to its value at that boundary. Wherever the contaminant flux at the boundary of the domain vanishes, the study considers that two BLs develop in the domain. Therefore, normalized coordinates of such two adjacent BLs must be established.

Make necessary adaptations

Each of the studies of Rubin and Buddemeier (1998a,b,c,d,e) incorporates a specific adaptation of the TSBL method to make it relevant to the specific cases of contaminant hydrogeology problems that are considered. In general, this means division of the domain to several portions of similar profiles, and spatial assignment af BL formulations in such a way as to adequately reproduce the expected contaminant distributions.

Two studies (Rubin and Buddemeier, 1998b,d) exemplify the adaptation of the TSBL method to accommodate flux-prescribed boundaries, at which a prescribed contaminant flux penetrates into the aquifer along with a flux of water. Rubin and Buddemeier (1998c,d,f) illustrate adaptation of the TSBL method to boundaries of zero contaminant flux, in this case an impermeable layer separating major portions of the fresh- and saltwater aquifers. Figs. 3(a), (c), and (d) illustrate the development of BL formulations for those cases.

Develop the appropriate equations

Following adaptation of the TSBL method to the specific needs of the study, an appropriate mathematical formulation of the conceptual model must be developed. The resulting basic formulation is usually a first order hyperbolic differential equation if unsteady-state conditions are considered. Under steady-state conditions, the appropriate formulation is represented by an ordinary first order differential equation. Solution of such equations can often be obtained by using software packages like Maple and Mathamatica.

Evaluate the possible contaminant transport phenomena

From the solution of the basic formulation of the BL problem, it is possible to evaluate and quantify particular features of the contaminated domain. As an example, Rubin and Buddemeier (1998g) calculated specific aspects of salinity transport into the aquifers of south central Kansas from paleodrainage channels. This quantification was accomplished by combining a variety of types of adaptations of the TSBL method to describe the range of possible scenarios involved in a complex salinity transfer and transport process.

Extend the calculations to specific objectives of the project

The solutions to the mathematical formulations provided by the TSBL method can be directly applied to calculate spatial distributions and transport rates relevant to the problem at hand. Such results can often be extended to, and can prove useful for, the achievement of objectives that were not identified in the original study. As an example, Garneau (1995) applied the preliminary verisions of the studies of Rubin and Buddemeier (1998a,b) to evaluate collected field data and identify possible values of transverse dispersivity and local sources of contaminant. He applied the relationships between the structure of contour lines and coefficients of mass diffusion, which were provided by the TSBL method, to obtain values of the dispersivity. By extrapolating contour lines to their possible origin, he could also identify potential sources of contaminant.

SUMMARY AND CONCLUSIONS

The TSBL method is robust, and useful for quick evaluation of a variety of issues in the field of contaminant hydrogeology. Its major feature is the separation of the region of interest (ROI), in which the contaminant concentration exceeds an acceptable value, from those regions of the aquifer subject to contamination which are identified by similar contaminant concentration profiles.

The TSBL method was originally developed as a general method for the evaluation of aquifer contamination processes. However, all studies reviewed in the present report address applications of the TSBL method to quantification of aquifer mineralization processes in Kansas. The case studies in Kansas demonstrate the potential for applying the TSBL method to specific problems, and for extending its uses beyond the initial objectives.

Use of the TSBL method for the evaluation of aquifer contamination leads to simplified differential equations which have analytical solutions, and are easy to calculate. These solutions provide immediate information about the sensitivity of aquifer contamination to variability of various features of the domain. Such expressions can be also useful in the evaluation of inverse problems, in which field monitoring data are applied to calculate properties of the domain and for the design of field monitoring systems when field data are limited.

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