A Quantitative Conceptual Site Model Approach for Environmental and Engineering Decision Making

EXECUTIVE SUMMARY

For decades the development and use of a Conceptual Site Model (CSM, **Figure 1**) has been described in the technical literature and regulatory guidance as a sound platform for developing a qualitative (narrative and pictorial) description of contamination sources and groundwater flow conditions at a contaminated site.[1–8] The CSM is used for identifying data needs; for performing very preliminary receptor identification; and for providing a qualitative basis for decision making regarding site cleanup planning and implementation through the application of professional knowledge and experience (often referred to as "professional judgment"). Linkage between the CSM and quantitative analysis of key aquifer and contaminant processes is either not discussed, or mentioned briefly in the context of risk assessment.

In the following paper we describe the benefits of establishing as an objective, at the outset of most groundwater projects, the development and use of a Quantitative Conceptual Site Model (QCSM) that provides a functional tool for project leaders to support data collection, conceptual model testing, receptor impact analysis, and remedy evaluation, selection and design.

Introduction

Environmental professionals are often faced with challenging questions and decisions.

- Where are contaminants from a known or suspected source traveling in groundwater? How fast? Will any receptors be impacted?

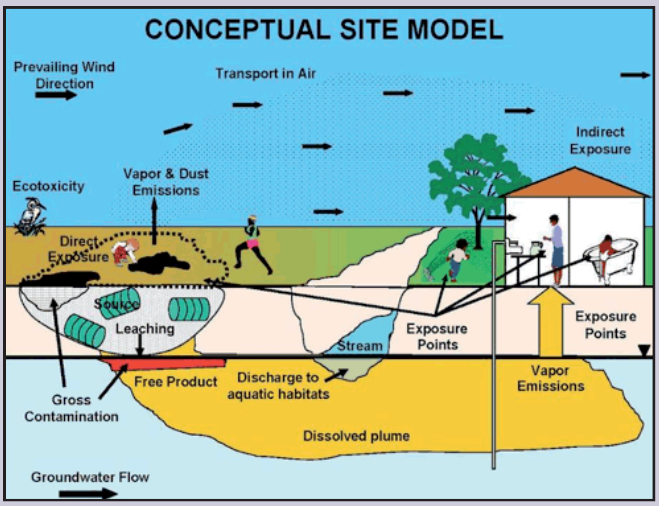

Figure 1. Generic Conceptual Site Model (Source: ITRC 2012 6)

- What is the best remedial action I can design that will be protective and cost effective? What is the best way to establish remedial design parameters and examine performance of various alternatives prior to making the time-consuming and costly investment in one of them?
- Where is the best place to locate a wastewater infiltration system, or a large public water supply system — or possibly both? How to make sure that one does not affect the other? How to examine potential hydraulic impacts or pollutant impacts to sensitive natural hydrologic features?

This is what we do all the time; and frequently in an arena where clients, regulators and stakeholders are joining us in asking these questions.

So how can we develop the answers to these questions, and other similar project-related questions and decisions? One way often described and discussed repeatedly in regulatory and technical guidance doc-

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uments is to begin by developing a Conceptual Site Model (CSM). The CSM is then used to guide the collection of additional information and refined until it can be used for decision making. There are occasional references to the possible need for developing and applying models of various types; but those descriptions are vague. More recently, with the advent of state regulatory programs that vest licensed professionals with major responsibility for site response decision making, the concept of applying one's professional knowledge and experience (often referred to as "professional judgment") has become a recommended approach.

We suggest that the time has come to recognize the need for, and value in, developing and applying a Quantitative Conceptual Site Model (QCSM) approach for hydrologic and environmental projects (**Table 1**).

Table 1. Typical Groundwater and Soil Projects Where a QCSM is Required

The following questions and decisions — which are driven by design considerations or regulatory/permitting requirements — usually cannot be addressed solely by the application of a qualitative Conceptual Site Model and Professional Judgment.

Project	Groundwater & Soil Zone Flow Modeling	Chemical Fate & Transport Modeling
Well Field Siting & Development	• How can we quantify the aquifer properties? • What is the safe yield? • Will there be any deleterious hydrologic impacts from withdrawals? • How can we delineate a groundwater protection area (WHPA, SWAP, Zone II, etc.) for permitting?	• Will the wellfield draw in contaminants from surrounding areas? • If the wellfield is in a coastal area, will there be any saltwater intrusion?
Municipal & Residential Wastewater Disposal	• How to estimate the allowable infiltration rates and required infiltration areas? • Will the resultant groundwater mounding meet regulatory requirements? • Will treated wastewater flow to any sensitive ecological areas?	• How far will nitrogen or other effluent plumes extend? • Will there be loading of nitrogen or other effluent compounds to sensitive surface water bodies? At what rates?
Hazardous Waste Releases	• Can an analysis of flow paths within delineated contaminant plumes identify sources? • What are the likely flow paths from known or suspected source areas to potential receptors?	• What portion of contamination has each source contributed? • What can the rate of plume movement tell us about the likely release data? • What are the levels of exposure and risk for selected chemicals at the receptors?
Groundwater Remediation	• How can we analyze and compare the performance of remedial alternatives to guide the selection process (extraction wells, trenches, slurry walls, funnel & gate, etc.)? • What is the expected effective capture area? • What are the expected extraction & treatment volumes and rates? • Can we optimize the capture system to ensure plume containment and reduce cost?	• What concentrations will be delivered to the treatment system over time? • What is the expected cleanup time? • Might natural attenuation be an effective remedy? • Can we optimize the mass removal rate to expedite cleanup and reduce cleanup costs?
Soil Remediation	• What is the infiltration rate from contaminated soil to underlying groundwater? • What is the leachate flux rate to underlying groundwater?	• How will leachate impact groundwater with respect to standards? • What soil concentrations can be left in place while providing a protective lower cost remedy?
Dewatering (construction, mining, etc.)	• How many well points will be required to dewater the selected area? • What extraction rates are required to achieve the selected depth(s) of dewatering? • Where should water be reinfiltrated if surface water discharge is not permitted?	• Will contaminants be drawn into the dewatering operation? • Will any chemical constituents present in discharges associated with dewatering operations adversely impact nearby hydrologic or ecological features?
Aquifer Infiltration, Injection or Storage	• What is an achievable infiltration rate? • Will unacceptable groundwater mounding or confined aquifer pressurization occur?	• What are the expected groundwater quality impacts and aquifer geochemical changes caused by infiltration or deep injection?

Definitions

A recent internet search for the phrase "conceptual site model" returned links for over 80,000 documents. A search for "quantitative conceptual site model" returned a dozen documents. Clearly investigators have not been thinking in terms of a QCSM.

For the purposes of this paper, we would like to propose the following definitions:

Definition of Conceptual Site Model –

> *"The conceptual site model is a written and/or illustrative representation of the physical, chemical and biological processes that control the transport, migration and actual/potential impacts of contamination (in soil, air, ground water, surface water and/or sediments) to human and/or ecological receptors." (NJDEP 2011[8])*

Thus, the CSM is laid out in words and pictures. It is qualitative. It describes soil and geologic materials and layers; groundwater depth, aquifer thickness and general flow directions; the distribution of chemicals of concern at sources and in nearby soil and groundwater; and the location and types of potential receptors. It provides a mental picture of what is happening at a site.

Definition of Quantitative Conceptual Site Model –

> *"The merging of quantitative analysis results with the framework of a sound conceptual site model to form a proper basis for high level decision making."*

Or in more simple terms, the QCSM involves "filling in the numbers" that put some useful specificity on the qualitative representations outlined in the CSM.

This is the <u>critical difference</u> between a CSM and a QCSM. In the CSM, any numbers that may be filled in with respect to the geometry or properties of the physical system (depth, thickness, distance, permeability, gradient, concentration, etc.) come from site measurements. But even with those numbers added to the word-and-picture representation of the system, the CSM does not provide a basis for any more than lower level decision making in most cases. For example, a CSM is valuable for deciding where to collect data; i.e. it can guide (and focus and streamline) the site characterization process. A CSM can also be used in some of the early stages of a risk assessment to eliminate certain pathways that are not likely to be completed given the understanding of the hydrogeologic system. But beyond that, a CSM is very limited in its decision-support capabilities.

In contrast to the CSM, the numbers in the QCSM come from calculations that use the system properties and parameter inputs determined from site characterization to quantify processes and rates in the system (flow volumes, velocities, chemical fluxes or loadings, travel times, concentration trends and durations, capture zones, mounding heights, etc.).

As described in a recent National Groundwater Association (NGWA) Technical White Paper[9], there exists a wide, tiered spectrum of calculational tools that can be applied in a stepwise approach to derive the required quantitative results. These quantitative results, when incorporated into the QCSM, result in a "functional" version of the CSM that can be used to guide investigations, assist in remedial design, and/or evaluate the effectiveness of the remedy (in other words, the QCSM can be integrated and utilized at every stage of the project).

Questions

At this point you might have some questions about this proposed QCSM approach. For example:

Q1: How is this different from what some investigators have referred to as quantitative conceptual site models?

A: *Some investigators have described the development of a quantitative conceptual model using subsurface geophysical techniques and/or by applying the concepts of Environmental Sequence Stratigraphy (ESS) (see for example USEPA 2012[10]). These studies supplement a CSM by providing a more refined spatial picture of the subsurface geology. But they generally do not perform any quantitative analyses of groundwater flow or contaminant fate and transport that allow the CSM to be a functional tool that can be used to guide decision-making.*

Q2: How is this different from what the CSM guidance says about using models?

A: *First of all, much of the regulatory and technical guidance, when talking about the development of a CSM, is very vague about the application of computer models; and the modeling appears to be an ancillary, not integral, process (**Figure 2**). And in most instances the references are to the application of contaminant*

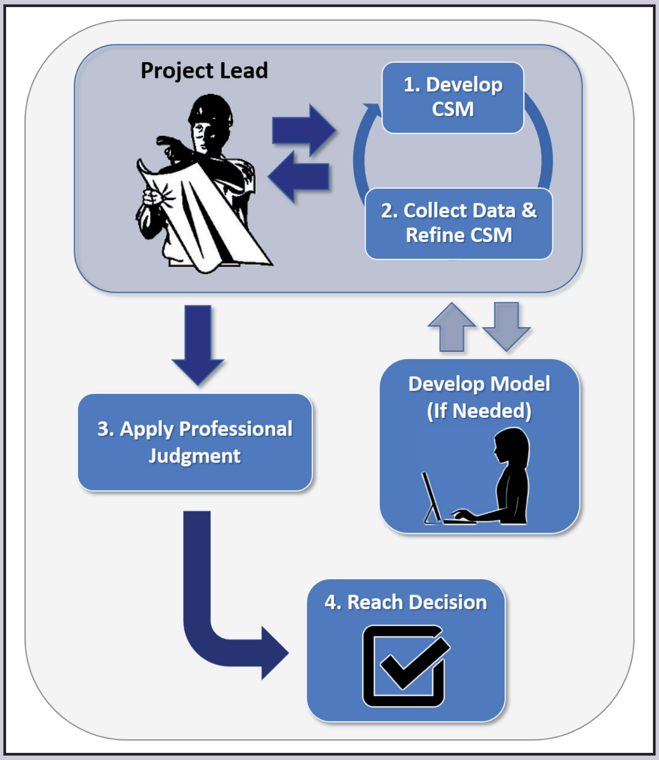

Figure 2. Typical CSM / Decision Approach

fate and transport models for risk assessment, not for hydraulic containment and cleanup.

*The QCSM approach, (1) explicitly calls for the use of groundwater and soil zone flow models to develop a quantitative representation of the flow system, and to provide an answer for problems that are primarily hydraulic in nature (e.g. capture zone, mounding, etc.) along with contaminant transport models for receptor or cleanup analyses, and (2) the QSM approach brings the model results into the CSM framework as a basis for decision making (**Figure 3**). All models require a certain level of simplification, and If the quantitative site model (i.e. the numerical model) is not evaluated in light of the underlying CSM, the results may be erroneously interpreted and applied.*

Q3: How does the QCSM concept apply to states (like New Jersey) with licensed environmental professional programs?

A: The New Jersey Department of Environmental Protection (NJDEP) has issued guidance[8] for site remediation investigators including Licensed Site Remediation Professionals (LSRPs) on the preparation of a CSM. The guidance does not mention computer modeling, but does say (in a single instance) that the information from a groundwater CSM can be useful for fate and transport analysis, especially when it requires a quantitative approach. The guidance does not describe the quantitative analysis, nor does it identify the many other beneficial uses of modeling in groundwater projects.

In a related NJDEP training document[11], the author noted that a CSM "provides a scientific and technical basis to support Professional Judgment", and that the CSM model is in the form of a "diagram, text, mapping" and "not necessarily a computer model."

There does not appear to be any New Jersey guidance for LSRPs and other investigators that attempts to integrate quantitative analysis into the basic CSM to form a QCSM. In contrast, there have been entire workshops presented on the concept of environmental professionals applying professional judgment.

Q4: What is wrong with developing a good CSM to qualitatively understand the general nature of the site and then applying professional judgment?

A: While there is certainly nothing wrong with applying professional judgment — or common sense, or prudent

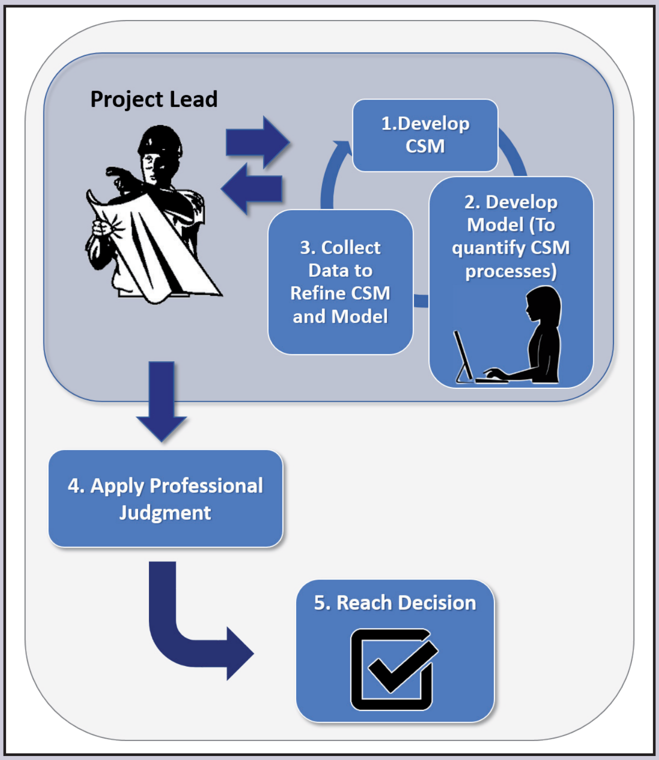

Figure 3. QCSM / Decision Approach

but reasonable conservatism, or many years of experience, or any of a number of other qualitative traits that the environmental professional may wish to bring to bear — this is no substitute for quantitative analysis based on a sound CSM and adequate site data. To our knowledge there are no codified definition or standards for professional judgment in environmental practice.

One environmental setting may look like another from the professional's recent memory, but may behave differently due to an interaction of subtle influencing factors. And most, if not all, environmental settings are complex; especially if three-dimensional flow and/or the transport of chemicals of concern are involved. As a colleague once remarked, "It's not wise to attempt to pre-guess the processes that are the result of second order partial differential equations."

Application of only professional judgment, based on the qualitative information and graphical representation of a typical CSM will rarely be accepted in support of a permit application, does not provide the quantitation necessary to evaluate complex remedial alternatives, and is insufficient to properly size and design engineered groundwater systems.

Q5: What are the benefits of moving to a QCSM approach? Isn't that going to be more costly? Where is the pay off?

A: In most projects with which we have been associated, the development of a Quantitative Conceptual Site Model (with the attendant data reduction and computer modeling) represents no more than a few percent of the overall project budget. The benefits of that to the project and the professional occur in several areas.

A QCSM:

- *Yields greater gained insight and deeper understanding of key processes and behavior of the system (i.e., the groundwater flow system and movement of any contaminant plume[s]). This is beneficial in identifying data needs during the site characterization phase, and in developing and explaining the solution during the design, permitting and implementing phase.*
- *Provides a documented basis for decisions, designs, and determinations. As licensed site professionals take on greater responsibility for remedial decisions, this can be beneficial to the smooth operation and prolonged tenure of their careers. The same can be said for engineers who are responsible for designs in the area of water supply and wastewater engineering that have the potential to cause costly problems if not formulated correctly.*
- *Supports a better outcome for the project and the client than could have been obtained with site field data alone. We have seen quantitative analyses that ensured the smooth and timely issuance of permits; allowed for the selection of optimal locations for the placement of monitoring wells; limited the need for excavation of impacted soils; increased projected wellfield yield by 50%; protected water supplies from the influx of harmful chemicals; winnowed the list of possible remedial alternatives to the proper selection; identified and segregated contaminant sources in areas of complex geology and multiple commingled plumes; and clarified the patterns of flow in highly complex three-dimensional flow fields beneath contaminated sites. A standard CSM, regardless of the amount of data collected, could not have achieved those outcomes.*

Conclusions

We have attempted to explain the nature and benefits of a Quantitative Conceptual Site Model for hydrogeologic, engineering, and environmental projects. We would suggest that the objective of most site characterization and analysis programs should be to move beyond a CSM to the development of a QCSM.

A standard CSM:

- represents a description of the system being investigated (hydrogeologic features, sources, pathways, and receptors);
- forms a framework that guides data collection; and
- provides the necessary fundamental data for the analyses that are required to support higher level decision making.

A CSM alone cannot provide a sufficient basis for higher level decision making in all but the most rudimentary of cases.

A QCSM:

- merges the results of quantitative analyses into a functional tool, with the framework of the CSM;

- "fills in the numbers" to provide a credible, scientific basis for decisions that affect the health of the public and/or the hydrogeologic and environmental system;
- provides documented support for the investigator (e.g. contractor or licensed site professional) whose responsibility it is to develop the best solution for problems in which complex hydrogeologic and contaminant fate and transport processes are at play.

A QCSM can be integrated and utilized at every stage of the project, and provides a strong clear basis for higher level decision making in a manner that is scientifically supported and transparent. Key processes are identified and explained; results are clearly and, in most cases, visually presented to facilitate understanding on the part of stakeholders; and questions can be framed and addressed in a quantitative and internally consistent manner within the QCSM. And equally as importantly, the decision makers are led to decisions and engineered responses that align with, refine, and support their professional experience and judgment.

The time has come to move beyond the idea that a basic CSM can form the basis for high level decision making in projects where public health is at issue, and where millions of dollars will be required to implement engineering or remediation systems. A QCSM is required. And the approach from the outset of most projects should be to begin with a CSM, and then to collect the data that form the basis for the calculations and quantitative analyses that are incorporated back into an integrated QCSM to provide documented, scientifically-based information for decision making.

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