The Underground Test Area Project of the Nevada Test Site: The Role of Modeling, Monitoring and Institutional Controls in Establishing Regulatory Protection of the Public - 10349

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ABSTRACT

The Underground Test Area (UGTA) Subproject is an Environmental Restoration activity under the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office Environmental Management Project at the Nevada Test Site. Models of groundwater flow and contaminant transport are used as the central part of an integrated strategy to guide regulatory decisions to protect the public from underground contamination of groundwater by radionuclides produced during nuclear weapons testing. A revised UGTA strategy was developed to better promote scientific discovery during the iterative process of data gathering and modeling, to fully acknowledge uncertainty in modeling studies, and to incorporate risk-informed investigations. The complexity and uncertainty in the hydrogeologic settings of corrective action units (CAUs) on the Nevada Test Site constrains the reliability of model forecasts of radionuclide migration over the next 1,000 years. Risk for UGTA is defined as the likelihood and consequences of future public exposure to contaminated groundwater and is managed through a tripartite combination of characterization and modeling studies, monitoring, and institutional control of areas of contaminated groundwater. **Model development** for flow and transport studies is designed to investigate the effects of statistical and structural uncertainty on multiple alternative representations of contaminant transport used to develop ensembles of contaminant boundaries. The negotiated metric for defining a contaminant boundary perimeter is the 95th percentile of exceeding the radiological standards of the *Safe Drinking Water Act*. **Model evaluation** is conducted during model development, through systematic sensitivity and uncertainty analysis, and during initial monitoring studies designed to test model results/forecasts. The goal of model evaluations is to gain regulatory acceptance that the modeling studies can be used for their intended purpose: aiding and guiding regulatory decisions. **Model application** uses model results to negotiate compliance boundaries between contaminated and uncontaminated groundwater, to achieve CAU closure, and to design a long-term closure monitoring network. Periodic evaluations during closure monitoring are used to evaluate whether the correction action design remains valid.

INTRODUCTION

The Underground Test Area (UGTA) Subproject of the U.S. Department of Energy, National Nuclear Security Administration Nevada Site Office (NSO) is assessing the risk to the public from radioactive contamination produced during past underground testing of nuclear weapons at the Nevada Test Site (NTS). Testing released an estimated 132 million curies of radioactivity (decay corrected to 1992 [1]) above and in the water table, and a component of this radiological source term is moving with local and regional groundwater flow. The considerable depth to groundwater (less than 100 meters [m] to more than 500 m below ground surface), and the large volume of contaminated groundwater extending across hundreds of square kilometers of surface area prohibits cost-effective remediation with current technology.

The original UGTA corrective action unit (CAU) strategy, negotiated in the 1990s as the *Federal Facility Agreement and Consent Order* (FFACO) [2], follows four stages of corrective action activities:

1. Planning of corrective action investigations.

2. Site characterization of subsurface areas contaminated by underground testing supporting development of three-dimensional (3-D) flow and transport models, which are used to forecast areas of future contaminated groundwater over 1,000 years.

3. Negotiation of compliance boundaries for CAUs required to protect the public from contaminated groundwater.

4. Closure in place with combined long-term closure monitoring to ensure compliance with corrective actions.

A fundamental assumption of the corrective action stages is a reliance on modeling to provide the required information to complete the corrective actions. The model results must be accepted to negotiate decisions to protect the public.

Multiple difficulties were encountered in implementing the original UGTA strategy. First, the characterization/modeling approach follows a structured sequence of steps (conventional modeling protocols) and has limited flexibility to adapt to complications and/or surprises in the characterization and modeling process. The strategy assumes sequential progression through planned studies and underestimates the process of scientific discovery inherent in studies of complex environmental systems.

Second, the potential programmatic impacts of uncertainty in the studies were not fully acknowledged, and uncertainty was presumed to be fully reducible through continuing characterization and modeling studies. In actuality, the complex hydrogeologic setting hampers the ability to gather data necessary to build fully reliable models and it is not always possible to reduce uncertainty through data acquisition. Models are uncertain with imperfect abilities to predict future contaminant concentrations of groundwater in space and time. Regulatory actions based on model results must both recognize and accommodate uncertainty in making decisions.

Third, regulatory input/approval was sought only at the end of major stages, and regulator involvement was not integrated into the Subproject. Regulatory decisions required to progress through the corrective action stages did not acknowledge the iterative nature of model building to aid regulatory decision making.

Fourth, there was an overreliance on the ability of characterization and modeling studies to reduce uncertainty, and insufficient reliance on the importance of monitoring studies and institutional controls to compensate for uncertainty and build confidence in model results.

Finally, there was an insufficient recognition of the difficulty of model “validation” in general and specifically “validating” a model with sparse data in a complex hydrogeological setting. The UGTA models should be evaluated for the suitability of their application to the decision problem of long-term protection of the public and the environment from contaminated groundwater.

A decision was made to revise the UGTA strategy, retaining the strong points of the fundamental approach to the corrective action activities but emphasizing the described implementation problems. The strategy revisions were developed with full involvement and critical reviews by the State regulator, the Nevada Division of Environmental Protection (NDEP).
The goals of the revised strategy are to:

1. Develop a strategy with an end state of full protection of human health and the environment.
2. Incorporate risk perspectives into the overall strategy.

3. Follow an iterative process of refining characterization and modeling studies, guided by sensitivity and uncertainty analysis and pragmatic assessments of the cost and likelihood of reducing uncertainty in the model results.
4. Increase reliance on monitoring studies to test, refine, and confirm model results and build confidence that model results can be used in regulatory decisions.
5. Use institutional controls to restrict public access to contaminated groundwater and reduce risk.
6. Recognize modeling as an uncertain tool that guides problem solving and supports environmental decision making.

A critical requirement for successful use of modeling studies for regulatory decisions is ensuring all components of uncertainty are represented in the modeling output. The nomenclature used to describe uncertainty integrates uncertainty terms used in interdisciplinary studies [3-6]. Uncertainty is divided into statistical and structural uncertainty, where statistical uncertainty includes knowledge uncertainty and variability as a subset of knowledge uncertainty. Knowledge uncertainty is represented in UGTA modeling studies through Monte Carlo simulations sampling parameter null space using automated methods of calibration. Structural uncertainty refers to model, conceptual model, and decision or regulatory uncertainty. Structural uncertainty can be separated into model and scenario uncertainty [6], and both forms of uncertainty are discrete/non-continuous and difficult to quantify. Structural uncertainty is represented in UGTA modeling studies through evaluation of matrices of multiple alternative models resulting in ensembles of model outputs. Both statistical and structural uncertainty must be assessed in modeling studies and their impacts accounted for in regulatory decisions.

The remainder of the paper provides an overview of the hydrogeologic setting of the NTS and the constraints this setting places on modeling studies. A simplified risk model for the UGTA strategy is presented with discussion of how risk perspectives guide the corrective action process. The paper concludes with a summary of the approach, decision points, and requirements of the revised four stages of the UGTA strategy.

HYDROGEOLOGICAL SETTING OF THE NEVADA TEST SITE

The NTS is located in the Great Basin physiographic province of southern Nevada, east of the Sierra Nevada range and Death Valley in California, and within an area of basin and range extensional faulting overprinted by strike-slip faulting of the Walker Lane structural system (Figure 1).

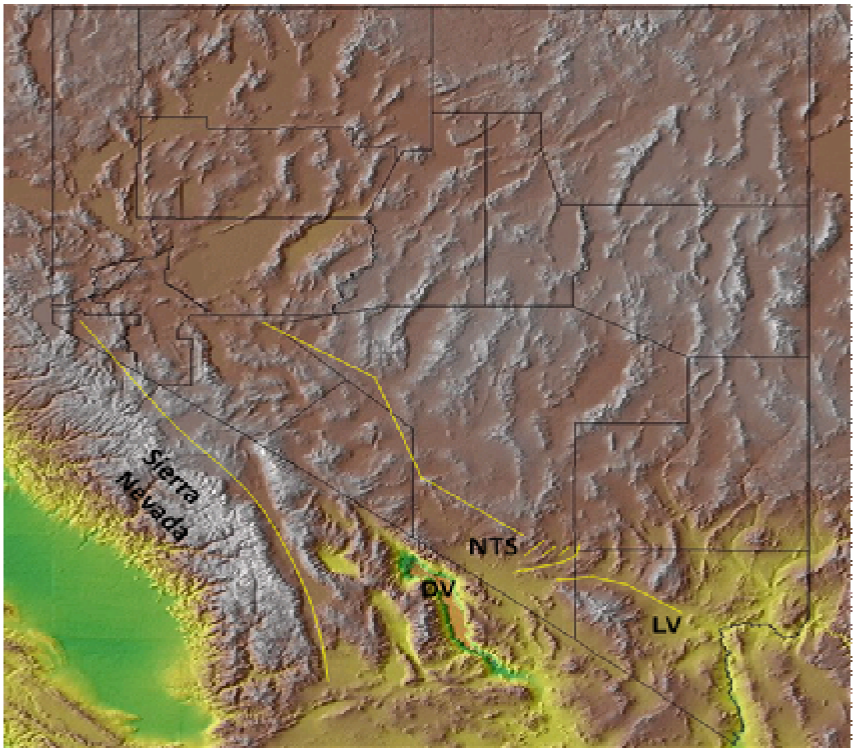

Fig. 1. Shaded-relief map of Southern Nevada and adjacent areas of California. The NTS is located in the southern Great Basin physiographic province, an area of basin and range extensional faulting, and voluminous mid-Cenozoic volcanism (Southwest Nevada Volcanic Field [7]). Extensional deformation in the region is contemporaneous with and overprinted by strike-slip faulting associated within the Walker Lane structural system (area outlined by the yellow lines). Sierra Nevada is the Sierra Nevada mountain range of California; DV is Death Valley; LV is Las Vegas; and NTS is the approximate location of the Nevada Test Site region.

Three major rock sequences are present in the NTS [8]:

1. Late to Mississippian marine carbonate and clastic rocks that are more than 5 kilometers thick and were deposited at the edge of a stable continental margin. Late Paleozoic or Permian thrust faults marking cycles of compressional tectonics offset and redistribute the assemblage of marine sediments. This rock assemblage was also intruded by small granitic stocks during the Late Cretaceous. The carbonate rocks are the primary pathway for groundwater flow in the Death Valley regional groundwater flow system [9-11].
2. Thick sequences of ash flow, lava, and volcaniclastic rocks deposited during episodic volcanic cycles associated with multiple coalesced caldera centers from 17 million to 9 million years (Southwest Nevada Volcanic Field [7]). These rocks uphold ignimbrite plateaus outside the calderas and form thick sequences of volcanic and intrusive rocks inside the calderas. Spatial changes in lithology and thickness of these rocks are significant (laterally heterogeneous), and they are located affected by secondary alteration (zeolitization) and/or hydrothermal activity. Groundwater flow is rapid within zones of higher-density cooling joints and/or fault zones (volcanic aquifers), and slower through zones of zeolization and/or matrix dominated flow (aquitards).

3. Thick sequences of alluvium deposited in sedimentary basins formed by extensional and/or combined extensional and strike-slip faulting associated with Basin and Range tectonism (Yucca, Frenchman, Jackass, and Crater Flats and the Amargosa Valley). This faulting preceded, is contemporaneous with, and followed Miocene volcanic activity. Groundwater flow in the alluvial and volcanic rocks in the basin can be decoupled from the underlying carbonate rocks in basin areas floored by zeolitized volcanic rocks, which form thick aquitards.

The surface geology of the NTS area is documented on a regional scale digital geologic map [12], and the 3-D configuration of rock units is captured in an evolving EarthVision model of the region that is maintained by the UGTA Subproject. The groundwater flow system of the NTS and surrounding areas was described originally by Winograd and Thordarson [13], and was updated in more recent publications describing primarily the Death Valley regional groundwater flow system [9-11]. Surface recharge to the groundwater table is highly variable and ranges from significant at higher elevations (more than 1,500 m) to negligible on the valley floors of alluvial basins (less than 1,000 m). Water balance and groundwater underflow must be established from regional groundwater models with only local information on evapotranspiration and discharge at limited areas of surface springs. Groundwater flow and expected directions of contaminant transport are largely from north to south with locally important discharge areas in Oasis Valley, Ash Meadows, Alkali Flat, and Death Valley. Divergent flow is important in subbasins and near areas of local recharge [9-11; 13].

The complicated assemblages of stratigraphically and structurally diverse rocks on the NTS are difficult to characterize hydrologically, and the volcanic sequences of older caldera complexes are largely buried by volcanic sequences from younger calderas. All rock sequences are buried beneath thick alluvial fill in structural basins. Reconstruction of hydrostratigraphic units at the water table surface is uncertain from spatially heterogeneity in aquifers and aquitards, and complicated by uncertain locations and offsets of thrust faults, stratigraphic and structural complexity near and across caldera structures, and uncertain offsets along basin-range extensional faults.

The impact of complexity and uncertainty in the geology and hydrology setting of the NTS varies dependent on the geographical location and depth of past underground testing, and the direction and velocity of groundwater flow near the tests. These factors strongly affect the reliability of estimations of future contaminant transport, and these limitations must be represented in the uncertainty of model results used to implement the UGTA strategy. Regulatory decisions may or may not be restricted by modeling uncertainty dependent on the capability of monitoring to test and build confidence in models and institutional controls to restrict access to contaminated groundwater.

RISK INFORMED BASIS FOR THE UGTA STRATEGY

Kaplan and Garrick [14] define the triplet questions for structuring a risk assessment as:

1) What can go wrong?
2) How likely is it?
3) What are the consequences?

Renn [15] emphasizes definitions of risk that contain three elements: outcomes or impacts on valued systems, a likelihood of occurrence, and a specific context in which a hazard may occur. For the UGTA environmental problem, the risk of radiologically contaminated groundwater from underground testing of nuclear weapons is equated to the likelihood and consequences of future public exposure to the contaminated groundwater. What can go wrong is future migration of contaminants to sites where public exposure is possible. The question of how likely it is may be evaluated through modeling of future flow and transport, and developing forecasts of the future locations of contaminated groundwater. What are the consequences is established through evaluating potential exposure to the public should they access contaminated groundwater. The impacts on a valued system are the degradation of a potential groundwater resource now only used for operational activities within the institutionally controlled NTS.

In simplified form, the UGTA risk can be expressed using a standard form of the risk equation:

$$R_k = H_p \times C_h \qquad \text{(Eq. 1)}$$

where R_k is risk, H_p is the probability of contaminated groundwater, and C_h is the consequences of public consumption of the contaminated groundwater. The H_p is established under the FFACO agreement [2] as an evaluation using transport modeling to identify groundwater that exceeds the radiological standards of the *Safe Drinking Water Act* (SDWA) [16]. The C_h is established from the radiological standards of the SDWA and contains two implicit assumptions. First, the probability of exposure is equal to 1 (equivalent to groundwater usage for a municipal water supply); and second, the exposure assumptions are specified in the radiological standards of the SDWA. The first assumption is not applicable to the NTS. Contaminated groundwater on the NTS is well removed from population centers, and the probability of public exposure to contaminated groundwater is less than 1. The second assumption uses standardized exposure parameters for a municipal water supply to calculate maximum contaminant levels. These exposure parameters are not applicable to the rural desert setting of the NTS.

From Equation (1), R_k can be reduced using two alternative approaches or combinations of approaches. The first is by continuing characterization studies and attempting to reduce the uncertainty of forecasts of the future distribution of contaminated groundwater (reduce H_p). The second is to develop administrative controls including land-use restrictions to prevent public access to groundwater, which severs the exposure pathway to the public and results in a C_h of 0 if the land-use restrictions are 100 percent effective. Both approaches can reduce risk, and their relative merits are dependent on the cost and the effectiveness of data gathering in a complex hydrogeologic setting versus the cost and effectiveness of land-use restrictions.

Figure 2 shows the direction of expected migration of contaminated groundwater for the five UGTA CAUs on the NTS. There are two categories of CAUs. The first category is CAUs where contaminant migration will remain within the institutionally control boundaries of the NTS (Yucca Flat/Climax Mine CAU 97 and Rainier Mesa/Shoshone Mountain CAU 99). The second category is CAUs where contaminants already have migrated off (Western Pahute Mesa CAU 102) or may migrate off of the boundaries of the NTS (Central Pahute Mesa CAU 101 and Frenchman Flat CAU 98). There is no public access to groundwater within the NTS, and the boundaries are expected to remain under institutional control in perpetuity. A focus of UGTA studies should be on CAUs where there is potential for migration of contaminants off of the NTS and possible public access to contaminated groundwater.

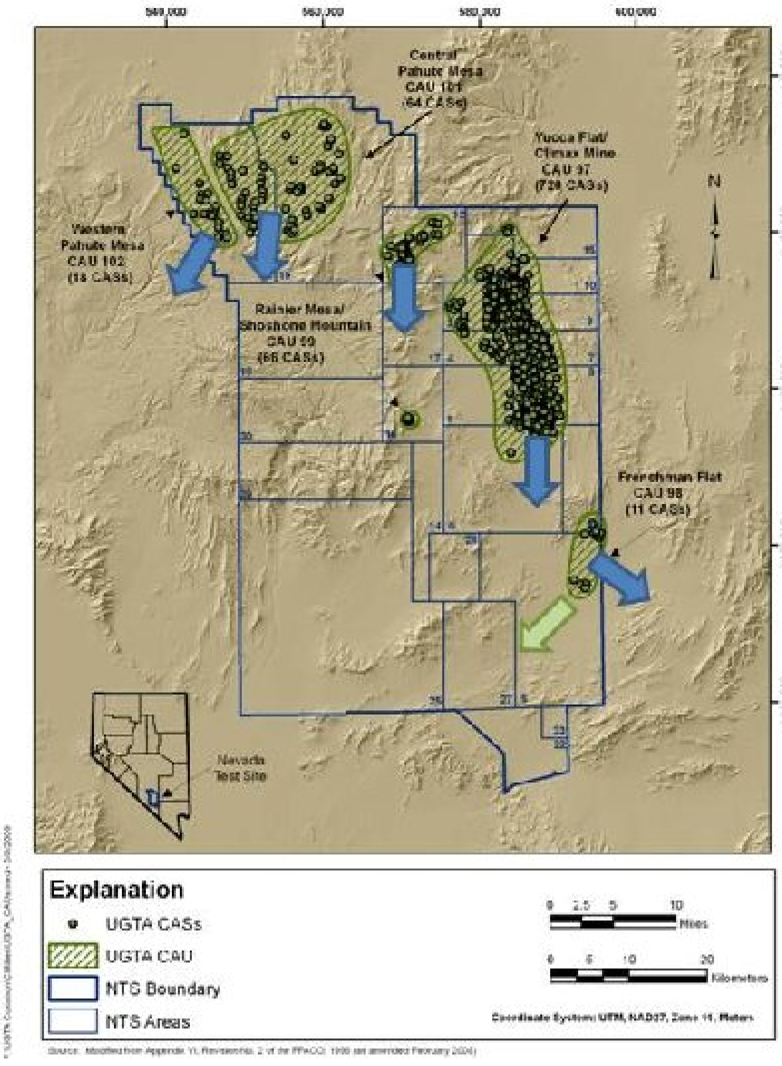

Fig. 2. Site map of the location of CAUs (green shaded areas) and corrective action sites (CASs) (small circles) on the Nevada Test Site. The blue arrows show the direction of local groundwater flow based on the regional groundwater flow model and flow and transport studies at individual CAUs (Frenchman Flat and Pahute Mesa). The southeast-directed arrow showing the transport direction in the Frenchman Flat CAU is in the alluvial and volcanic aquifers; regional flow in the carbonate aquifer is to the south and southwest (southwest-directed green arrow).

Table I shows the predicted curies by corrective action unit for testing areas on the NTS [1]. The Pahute Mesa CAU is the most significant CAU from a risk perspective by virtue of the high potential for offsite migration of contaminants and the high percentage of inventory. The Yucca Flat CAU has the second highest inventory, but there is a small risk of offsite migration. The Frenchman Flat CAU has the lowest inventory but a moderate potential for offsite migration. The Rainier/Shoshone CAU has both a small inventory and a very small risk of offsite migration of contaminants.

Table I. Corrective Action Units, Corrective Action Sites, and Percentage of Estimated Total Unclassified Inventory and Total Curies by Geographical Testing Area on the Nevada Test Site.[a]

Geographical Area	CAU/Sub CAU	CAS	% Inventory	Total Curies
Pahute Mesa		**82**	**60.6**	**8.0e7**
	Pahute Mesa (Area 20)	18	46.1	6.1e7
	Pahute Mesa (Area 19)	64	14.5	1.9e7
Rainier/Shoshone		**66**	**0.7**	**8.9e5**
	Rainier Mesa			
	Shoshone Mountain			
Yucca Flat		**720**	**36.6**	**5.1e7**
	Climax Mine	4		
	Yucca Flat	716		
Frenchman Flat		**11**	**0.14**	**1.9e5**
	Northern Test Cluster	7		
	Southern Test Cluster	4		

[a] From [1]; inventory is decay corrected to September 1992. The unclassified total inventory is only available for designated the geographical areas.

THE REVISED UGTA STRATEGY

This section briefly describes the revised UGTA strategy, which retains the original four stages of the corrective action process described in the FFACO agreement [2], and highlights major changes in the strategy. The revisions emphasize the iterative process of model development and are consistent with guidance by the U.S. Environmental Protection Agency (EPA) on the use of models for environmental decision making [17].

Implementation of a corrective action strategy for UGTA includes four stages:

1) The Corrective Action Investigation Plan (CAIP) stage
2) The Corrective Action Investigation (CAI) stage
3) The Corrective Action Decision Document (CADD)/Corrective Action Plan (CAP) stage
4) The Closure Report (CR) stage

The **CAIP stage** uses existing information from the weapons testing program combined with the regional flow model and one-dimensional transport simulations to assess the potential for alternative characterization options to reduce statistical uncertainty and uncertainty in estimations of contaminant boundaries (both statistical and structural uncertainty). A value-of-information analysis is conducted to identify high-priority characterization activities. The resulting information is used to evaluate site characterization options which are described in the Corrective Action Investigation Plan. The CAIP stage has been completed for all CAUs of the UGTA Subproject, and the investigation plans have been approved by NDEP.

The **CAI stage** is the primary stage for evaluating existing data, collecting new information identified in the CAIP stage, and developing CAU-specific models of flow and transport. The modeling studies assume significant uncertainty and are constructed to consider at a minimum:

1) Alternative hydrologic framework models of the CAU modeling domain.
2) Uncertainty in the radiological and hydrological source term.
3) Alternative models of recharge.
4) Alternative boundary conditions and groundwater flows.
5) Multiple permissive sets of calibrated flow models.
6) Probabilistic simulations of transport using plausible sets of alternative framework and recharge models, and boundary and groundwater flows from calibrated flow models.
7) Ensembles of forecasts of contaminant boundaries for the CAU.
8) Sensitivity and uncertainty analysis of the model outputs.

The primary results of the **CAI stage** are the development of models of groundwater flow and transport, and the use of the models to forecast contaminant boundaries for 1,000 years. The term *forecast* is used instead of *prediction* for the model results to reflect the uncertainty of evaluating contaminant boundaries over long time intervals. Three-dimensional concentration data from Monte Carlo transport simulations are post-processed to develop probabilistic forecasts of the likelihood of groundwater exceeding or remaining below the radiological standards of the SDWA [16]. These contaminant boundaries are not discrete *predictions* of the location or concentration of contaminants but instead are spatial representations of the probability of exceeding the SDWA radiological standards.

A contaminant boundary is defined as the model-forecast perimeter that delineates the extent of radionuclide-contaminated groundwater from underground testing over 1,000 years. Monte Carlo transport simulations are used to identify a volume of contaminated groundwater (exceedance volume), and this volume is projected upward to the ground surface to define a two-dimensional contaminant boundary perimeter. Contaminated groundwater is defined as water exceeding *any* of the radiological standards of the SDWA. The negotiated metric for defining the contaminant boundary perimeter is the 95th percentile of exceeding the radiological standards of the SDWA (Figure 3).

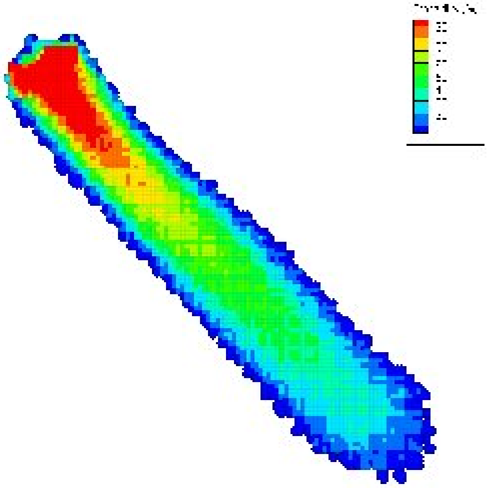

Fig. 3. Example of a contaminant boundary forecast for a single underground test in a groundwater flow field (test located at the upper left top of the diagram). The color contours represent the probability of exceeding the radiological standards of the SDWA over 1,000 years. The probability of not exceeding these standards (groundwater outside an individual contour) is equal to or less than $1 - P$ where P is the contour value of the probability of exceedance (probability contours shown on the figure legend).

Two important changes in the **CAI stage** were made in the strategy revisions. First, the new strategy emphasizes the iterative process of model development and refinement, and recognizes that the goals of model development are not to develop the best or a preferred model(s) but to develop sets or ensembles of model results and build confidence that the model results can be used for regulatory decisions. The emphasis of the modeling process is an examination of the range of permissive model results (the concept of mapping the model output space of Beven [18]). This is accomplished through a combination of Monte Carlo simulations that sample uncertain model inputs (primarily statistical uncertainty), and replicate model runs using multiple sets of combinations of alternative conceptual model components (hydrostratigraphic framework models; alternative representations of source term and source term release; and alternative models of recharge incorporated with alternative boundary conditions and groundwater flows, all representing structural or conceptual model uncertainty).

Calibration of flow models is an intermediate step in the model development process. Flow models must achieve acceptable model calibrations, but multiple acceptable calibration fits of flow models using a matrix of alternative conceptual models is expected. Moreover, the UGTA strategy requires model optimization for regulatory decisions based on forecasts of contaminant transport; optimization of calibrated models does not necessarily result in optimized results for contaminant transport.

The second major revision in the model development process is the incorporation of the concept of model acceptance. Model acceptance is defined as a joint judgment by the UGTA Subproject and NDEP that there is sufficient credibility/reliability of model forecasts to use the data as the basis for regulatory decisions. It is comparable to answering the question whether a model and its model results adequately represent the reality of a modeled system (the variable hydrogeological setting of transport in the UGTA CAUs) and can be used for decision making [17].

There are two decision points in the **CAI stage** of the revised UGTA strategy. The first occurs at the completion of the development of the flow and transport model for each CAU. The UGTA Subproject and NDEP jointly decide whether the data and the model results are adequate where adequacy is based on the definition of model acceptance. If the data and the model results are inadequate, a revised corrective action characterization plan is developed leading to a new phase of data collection and model development. If the data and model results are adequate, a peer review by external reviewers of the results of the **CAI stage** is conducted, and NDEP assesses model acceptance. This step of model acceptance is based on the question of whether there is sufficient confidence in the model results to start a monitoring program.

The **CADD/CAP stage** is the third stage of the UGTA strategy. For the previous strategy version, this was envisioned as a monitoring program with a required five-year proof-of-principle monitoring interval. In the revised strategy, this stage includes developing and negotiating an initial compliance boundary, developing monitoring programs for model testing and closure, and identifying institutional controls.

Monitoring studies and institutional controls are now recognized as a balanced component of a tripartite approach that forms the foundation of the revised UGTA strategy (Figure 4). The tripartite approach recognizes that there will be significant uncertainty in model results, and this uncertainty can be accommodated by combining modeling studies with site monitoring designed to evaluate model forecasts and ensure compliance and institutional controls to restrict public access to groundwater. The relative emphasis of the three components of the tripartite strategy for each CAU is dependent on:

1. The uncertainty in the model results.
2. The potential for uncertainty reduction with iterative cycles of data gathering.

3. The ease of gathering groundwater monitoring data for model testing and for verifying closure requirements and long-term compliance.

The ability to maintain long-term institutional controls for areas of identified contaminated groundwater.

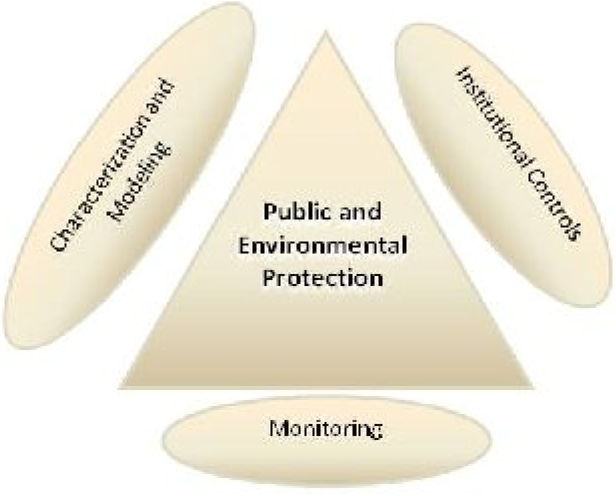

Fig. 4. Schematic diagram of the tripartite approach that forms the foundation of the revised UGTA strategy. The revised strategy does not assume that continuing modeling studies can or will succeed in fully reducing uncertainty necessary to achieve protection of the public and the environment. Instead, the three components of the revised strategy (characterization/modeling, monitoring, institutional controls) are used in combination to compensate for uncertainty and adapt to the uncertainty and decision requirements of individual UGTA CAUs.

The **CADD/CAP stage** requires negotiation of an initial CAU compliance boundary. The compliance boundary represents a regulatory-based distinction between groundwater contaminated or not contaminated by the effects of underground testing. The ensemble of contaminant boundary forecasts for a CAU developed from the **CAI stage** provides the initial technical basis for negotiation of the compliance boundary. The NNSA/NSO must demonstrate with an acceptable level of confidence (reasonable expectation), gained through implementation of the UGTA corrective action strategy, that groundwater *outside* the compliance boundary meets the radiological standards of the SDWA [16]. The initial compliance boundary will not be a compulsory boundary. It is a preliminary boundary negotiated to promote communication between the UGTA Subproject and its regulator, and as a guide to developing the monitoring program.

A monitoring network will then be developed and installed in two phases. The first phase will install well-to-model results including multiple aspects of the matrix of alternative models used to develop ensembles of contaminant boundary forecasts. Data from these wells will *not* emphasize measurement of radionuclide concentrations in groundwater because of the uncertainty in time and space of model estimates of contaminant concentrations and potentially long time intervals for contaminants to migrate to potential monitoring sites. Sensitivity and uncertainty analysis from the flow and transport modeling studies will be used to identify requirements that could be assessed through focused monitoring studies. The **CADD/CAP stage** is a hypothesis-testing stage used to interrogate model results, test model stability, and build confidence that the modeling can be used for regulatory decisions. The stage is comparable to the model evaluation requirements of the EPA guidance for the use of environmental models [17]. The second phase of monitoring will install wells for the long-term closure monitoring network.

Model development does not end with the **CAI stage**. Model results under the **CADD/CAP stage** will be continually reviewed by the UGTA Subproject and NDEP to assess the level of confidence in the model results. With completion of individual cycles of monitoring results and/or completion of new monitoring wells, the next step of model acceptance under the revised UGTA strategy is assessed. Is there sufficient confidence in the model and monitoring results to move to the closure stage of the UGTA strategy? If the answer is no, additional monitoring evaluations will be designed to address critical uncertainties in the model results, and the flow and transport modeling will be refined if required. If the answer is yes, the UGTA Subproject will move to the final stage of the strategy.

The **CR stage** is the final stage of the UGTA Subproject and includes negotiating the final compliance boundary for CAU closure; developing a closure report, which must be approved by NDEP; and developing and initiating a long-term closure monitoring program. The emphasis of the UGTA Subproject at this stage shifts from model development and evaluation to model application. Once the monitoring program is accepted and the monitoring network established, the UGTA Subproject concludes and program responsibilities are transitioned to long-term stewardship. Under the CR stage and after transition to long-term stewardship, there will be periodic evaluations jointly with NDEP to evaluate whether the corrective action design established in the closure report remains valid. If the answer is yes, the long-term closure monitoring program continues. If the answer is no, the feasibility of monitoring studies are evaluated and model refinements are considered. If the modeling studies can be refined and the monitoring studies refocused, the long-term monitoring program will continue. If the studies cannot be refocused, the UGTA strategy will conclude and alternative strategies considered.

OVERVIEW

The revised UGTA strategy reduces reliance on modeling as the primary means of achieving corrective action goals. Modeling of flow and contaminant transport remains the primary tool to investigate the processes of flow and transport, to forecast transport, to develop contaminant boundaries over 1,000 years, and to assess uncertainty. The required confidence in model results are dependent on the hydrogeologic setting of CAUs, the percentage of radionuclides in each CAU, the likelihood of contaminant migration off of the institutionally controlled NTS, the ability to monitor efficiently for model evaluation and long-term closure, and the ability to establish land-use restriction for off-NTS areas. Each CAU requires a balanced appraisal of the decision problem of protecting the public and environment and the technical- and cost-effectiveness of relying on each component of the tripartite approach.

The revised strategy allows model development and refinement to occur through all stages of the UGTA strategy with overlap but evolving changes in the emphasis of each stage. The **CAIP stage** is primarily a planning stage. The focus of the **CAI stage** is data collection/evaluation and model development with some model evaluations conducted as a necessary part of building and developing models. The goal of the **CAI stage** is to develop sufficient confidence in the reliability of model results to achieve the first step of model acceptance and move into the monitoring stage. The **CADD/CAP stage** is concerned primarily with model evaluations through focused monitoring and building confidence required to achieve the second stage of model acceptance and progress to the **CR stage**. Model refinements, if required by stage goals, can continue in both the **CADD/CAP** and **CR stages**. Final compliance boundaries are negotiated during the **CR stage**; closure plans are developed; long-term closure monitoring networks are designed and implemented; and the work is transitioned to long-term stewardship, concluding the UGTA Subproject.

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