

# **The Role of the Exposure Assessment in Ensuring Sustainably Protective Containment of Residual Contamination**

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## **Abstract**

We seek to characterize the role of the exposure assessment in ensuring sustainably protective containment of residual contamination. Exposure assessment is placed in the context of secondary and tertiary preventive actions that seek to ensure that sustainable containment of residual wastes is achieved even when end state land uses or other factors determining successful containment are subjected to change. The defining role of exposure assessment is in the linkage of environmental contamination with activities and events that cause uptake of contaminants by human or ecological receptors. In a post-

remedial situation, exposure assessment helps frame the benchmarks for the originally instituted remedial actions, enables the evaluation of progress on and efficacy of instituted controls, and provides an objective framework for assessing and instituting corrective actions in the event of a changed end state or circumstances that alter previously envisaged exposure pathways. A case study of the Pantex Plant near Amarillo, TX shows how exposure assessment can be used to identify uptake pathways caused by the interplay between regional water use and residual groundwater contamination at the site.

**Key words:** Regional Land Use, Exposure Assessment, Water Resources, Residual Groundwater Contamination, Sustainability

## **1 INTRODUCTION**

Federal and state mandated Health Risk Assessments are used to ensure that corrective actions at contaminated sites are sufficiently protective of human health. Remediation decisions are made after due consideration and prioritization of likely exposure pathways, and any residual contamination is generally assumed to be such that it would not pose a risk under the exposure pathways considered. In other words, clean-up strategies seek to block or remove potential exposure pathways in order to address health risks. Such risk based decision making for remedial action management has been codified and prescribed through federal and state regulations as well as guidances (e.g. Risk Assessment Guidance for Superfund Sites - USEPA, 1989; Risk Based Corrective Action Guidance – USEPA, 1995). However, it may not always be practicable or cost efficient to remove all contamination (Greenberg et al., 2005), and sustainable containment of any residual

contamination requires additional (secondary and tertiary) protective actions. This paper characterizes the role of exposure assessment in such post-remedial actions.

Since remedial strategies depend so critically on understanding of exposure pathways and subsequent actions to block or remove them, any circumstances that change the underlying assumptions about likely exposure pathways are likely to substantially alter the profile of risk posed by residual contamination. The circumstances triggering the change can take many forms: events such as earthquakes, physical containment failures or extreme meteorological happenings; and activities by individuals or populations that cause new pathways to open up or blocked pathways to be reactivated. In particular, Greenberg et al. (2005) consider the human health and ecological risks posed by residual contamination in an asset management context, wherein US Department of Energy (USDOE) and other federal agencies seek to decrease their footprint by transferring federally owned lands to other federal or state agencies, or to private parties. Such a transfer of land could lead to an altered land use that may be different than the end state land use envisaged by original remedial plans, and would therefore be likely to lead to new or renewed risks from residual contamination. The broader lessons are: (a) end state land use is negotiated and therefore alterable rather than frozen for perpetuity; and (b) no land transfers should occur until it has been determined that residual contamination and its potential hazards have been sustainably contained.

The objective of this study is to characterize the role of exposure assessment in ensuring that sustainable systems exist for containing residual contamination. The primary mode

of ensuring sustainability, from a health risk viewpoint, is to ensure that all sets of potential events and activities do not lead to uptake of residual contamination that would pose an unacceptable health risk. Exposure assessment, with its focus on exposure pathway characterization, provides an objective means of considering all potential events and activities that could lead to activation or reactivation of exposure pathways, and for designing and instituting subsequent administrative or engineering controls to ensure the sustainable containment of residual contamination. A case study of the USDOE Pantex Facility will illustrate this role of exposure assessment.

### ***1.1 Exposure Assessment as a Link in the Post-Remediation Risk Management Chain***

Mere existence of a toxic chemical does not constitute contamination – for that, there has to be an existing or current exposure pathway to humans or to the ecosystem. Federal and state regulations designed to protect the environment and human health recognize that environmental emissions from a facility need not constitute contamination that has to be remediated, if the incremental risk posed by the emissions does not exceed the risk posed by “background” environmental levels of contaminants of potential concern (COPCs) (e.g. USEPA, 1989). The corollary to this principle is that efforts should be directed at controlling or remediating incremental risks directly attributable to the operation of a facility.

Identification of the incremental risk hinges on a site-specific characterization of environmental levels of COPCs, as well as measurements (if available) that indicate the amount of contaminants taken up by humans or animals exposed to the contamination.

Further, environmental monitoring is undertaken to ensure that post-remediation residual levels of COPCs do not pose an unacceptable human health (or ecological) risk. The amount of contamination humans would be exposed to is critically dependent on the kinds of activities that lead to the exposure, as well as the accompanying physiological processes. For example, exposure modeling studies (McCurdy et al., 2000; Georgopoulos et al., 2005) show that inhalation exposures for high energy activities such as exercise are orders of magnitude greater than those for sedentary activities. Hence, characterization and monitoring of exposures requires supplemental observational data or information on populations or sub-populations likely to be exposed to contamination in course of specific activities – typically, these activities are classified in terms of occupational or maintenance activities, agricultural activities, exposure causing activities related to residential use of an environment, and so on.

Characterization of background environmental levels is also of critical importance in linking an increased risk to a distinguishable release. Background levels are defined (USEPA, 2001) as being of two types: naturally occurring levels and anthropogenic levels due to diffuse anthropogenic, non-point sources. They are used in a regulatory context to distinguish contamination due to identifiable site-specific sources and activities from naturally occurring levels or contamination from non-site related diffuse sources and activities. This standard of discrimination between background levels and contamination levels is used to determine whether the threat to human health or environment posed by existing or potential release falls below the risk posed by naturally

occurring substances in the impacted area; to set remediation goals; and to communicate cumulative risks associated with contaminated sites.

Exposure assessment connects environmental monitoring of contaminants and uptake of the contaminants and associated bioindicators through Conceptual Site Models (CSMs) (e.g. Vyas et al., 2006; Mayer et al., 2005). It is important to note that CSMs are also identified in scientific literature as Conceptual Exposure Models, since their main purpose is to articulate potential or existing exposure pathways and depict measures through which these pathways are to be blocked. The exposure pathway in a CSM consists of the mode of environmental release at source, anticipated or possible transport of COPCs through different environmental media, and mode of uptake by human and ecological receptors. Therefore, CSMs are a logical and rigorous way of identifying what to monitor (in terms of COPCs with the greatest potential for human health risk), who to monitor (in terms of human or ecological receptors, e.g. industrial workers, children, farmers) and which environmental medium to monitor (soil, groundwater, air).

Due to its centrality in identifying how contamination leads to hazard, exposure assessment is an integral part of the Risk Assessment paradigm proposed by the National Academy of Sciences (NAS), in an effort, among several additional objectives, “to develop uniform risk assessment guidelines for use by all regulatory agencies.” The conceptual framework proposed by the NAS has four steps: Hazard Identification, Dose Response Assessment, Exposure Assessment, and Risk Characterization (USNAS, 1983). As these steps imply, risk assessment involves gathering all of the necessary agent-

specific toxicity and site-specific exposure information to derive the agent-site-specific potential for adverse human health effects. This culminating derivation, or risk characterization, is the effort “to make sense of the available data and describe what they mean to a broad audience” (Williams and Paustenbach, 2002).

The risk characterization step uses both qualitative and quantitative approaches to arrive at the likelihood and severity (or lack) of health risk due to the offending agents at a site. Specifically, comparisons are made between projected intakes of toxic agents in exposed populations and toxicity reference values to characterize non-carcinogenic health effects. With regard to carcinogenic effects, probabilities that an individual will develop cancer over a lifetime of exposure are estimated from the projected human intakes and dose response slope information.

The US Nuclear Regulatory Commission (USNRC) defines exposure as contact over time and space between an individual (or, by extension, an ecological receptor) and one or more biological, chemical or physical agents (USNRC, 1991). The magnitude and intensity of human exposure are assessed through characterization of environmental release and transport mechanisms; determination of exposure pathways; quantification of duration, frequency and intensity of contact with pollutants; and identification of individual activity patterns and physiological characteristics and population demographics (Lioy, 1990, 1999; WHO, 2000). In other words, a properly executed exposure assessment would: (a) identify the events that would make an environmental release possible and the quantify the magnitude of the associated release; (b) identify the

contaminants with greatest health risk potential due to their known toxicological effects and bioavailability; (c) identify the potential modes of environmental transport and human uptake; (d) identify the human sub-populations at greatest risk as well as their numbers and duration of exposure; (e) characterize the time frames over which the exposure pathways are effective; and (f) identify the exposure pathways that carry the greatest potential for human health (and ecological) risk. If there is one uniquely identifiable characteristic of exposure assessment, it is the linkage of environmental contamination with activities that cause uptake of the contaminant and subsequent health risks to human and ecological receptors. This essential characteristic is applied in risk based decision making to prioritize potential risks and institute appropriate controls. We now describe how this role of exposure assessment fits in a post-remedial risk management chain.

It is important to note that since exposure assessment is so critically interwoven into remediation decision making, some kind of exposure assessment would have already taken place at the primary stage of the remediation process, and that target action levels for residual contamination would already take into account potential exposure pathways and vulnerable populations. Subsequent to remediation activities, the exposure assessments conducted during and after remediation would serve as a means for evaluating the progress, and for benchmarking achieved health risk reductions against predetermined targets. In this manner, there would be a significant exposure assessment component to both the primary and secondary preventive remedial actions, as identified by Greenberg et al. (2005).

However, perhaps an even more important role for exposure assessment would be in the secondary and tertiary protective actions conducted in a post-remediation scenario, such as the land transfer scenarios considered by Greenberg et al (2005). Greenberg et al. (2005b) conducted a survey among residents living in vicinity of USDOE facilities that identified the principal concerns of those residents. Surprisingly, hazards posed by transportation of wastes were viewed with far greater concern than those posed by existing or treated contamination. Further work cited in Greenberg et al. (2005b) indicates that residents may not be as concerned by the idea of living on remediated brownfield sites as is generally assumed. This implies that operative assumptions about the inviolable status of land uses would not hold up to the reality of pressures that an attractive brownfields location would generate for alternative land uses. It is therefore important to determine citizen attitudes towards potential land transfers rather than operate on the conservative but misleading assumption that there will be perpetual opposition to the idea of changing land use at remediated sites. This possibility of an altered end state land use creates a situation where exposure pathways that may have been perceived as irrelevant or blocked under the originally conceived remediation plans may be activated or reactivated under the altered land use. Furthermore, as we shall demonstrate through an analysis of potential exposure pathways at a USDOE facility, larger regional dynamics could lead to activation of previously unanticipated exposure pathways. In both cases, exposure assessment would play a vital role in secondary and tertiary preventive actions (as identified in Greenberg et al. 2005) if sustainable containment of residual wastes is to be achieved.

The considerations outlined above indicate that exposure assessment would play a vital role in serving as institutionalized memory of original protective system, in evaluating progress of clean up efforts and containment of residual contamination, and as a means for informing subsequent tertiary protective actions. The place of exposure assessment in the post remediation risk management chain is illustrated in Figure 1.

## **2 USE OF EXPOSURE ASSESSMENT IN IDENTIFYING POST-REMEDIAL CONTROLS FOR RESIDUAL GROUNDWATER CONTAMINATION AT THE US DOE PANTEX FACILITY**

### ***2.1 Background***

#### **2.1.1 Risk Management of Residual Contamination at USDOE Facilities**

USDOE facilities have been mandated to develop End State Vision (ESV) documents that describe the facilities' plans for current and future remediation of contaminated areas (USDOE, 2003). The environmental management plans for USDOE sites, as highlighted in these ESV documents, are based on currently envisaged post-remediation land uses and associated health or ecological risk benchmarks. The facilities are also required to submit any alternative land use plans that would be considered to address the risk posed by contamination, and to use risk informed considerations in framing, evaluating, and selecting future land uses. In framing these documents, the USDOE facilities rely on current projections from their remediation and environmental management plans regarding the future states of different remediated or managed areas, and on currently

formulated and promulgated regulations for future land uses in the surrounding communities. A significant critique of these documents is that they are framed from the inside looking out. In other words, they rely on the USDOE facilities understanding of the broader geographic factors influencing site use and the use of the surrounding areas. In practice, this means that local, state and federal regulations are often considered by the sites to be “written in stone”, and no attempt is made to explore any broader imperative that might cause such regulations to be modified or annulled. The end state documents, therefore, have a blind spot. They miss the impact of the wider geographic forces on the development and use of land in the communities surrounding the USDOE facilities. Consequently, the documents are not able to address, in a holistic manner, the impact of the surrounding community on the environmental resources shared with the site. To put it differently, it would require a complementary study that looks inwards from outside for a complete evaluation of potential exposure pathways to the surrounding community.

### **2.1.2 The Pantex Plant**

The USDOE Pantex Plant is located in the Texas Panhandle, about 17 miles to the northeast of Amarillo, Texas (Figure 2). The Pantex Plant was a World War II munitions factory, and was converted for nuclear weapons assembly in the early 1950s (USDOE, 2004). Currently, it is the sole facility for nuclear weapons assembly/disassembly in the entire nation, and is expected to continue in that role in the foreseeable future. The land use within the plant is designated as industrial use (USDOE, 2004), which is expected to continue into the foreseeable future.

Industrial and weapons testing operations at the plant caused the discharge of TCE, High Explosives (HE, including RDX) and metals including hexavalent chromium into the onsite playas, which are shallow, ephemeral lakes. The contamination from playa beds seeped into the underlying perched aquifer, which is a part of and likely to be in physical connection with the larger underlying Ogallala system. It was announced in 2000 that TCE from onsite operations and sources had migrated into the Ogallala aquifer (USDOE, 2000a; USDOE 2000b), but subsequent investigations indicated that the elevated concentrations were introduced due to improperly constructed monitoring well (USDOE, 2002). The episode raised fears that private or public water supply wells sunk into the Ogallala aquifer through the perched aquifer would lead to the opening of a rapid connection between the two closely aligned formations, leading to leakage of residual contamination into the Ogallala formation. The perched aquifer plume is expected to cross the site boundary on its east and southeast (USDOE, 2004 - Figure 3.1b). In this general direction, there are about 16 private wells drilled into the Ogallala aquifer within one mile of the site boundary (USDOE, 2004 - Figures 3.1b and 3.2a2).

The subsequent remedial action plan focused on the following (USDOE 2002):

1. Containing and cleaning up the contamination in the perched aquifer through pump and treat methods. This was initially started as a pilot study, and operations were ramped up around 2003
2. Detailed characterization (such as thickness, areal extent and hydrogeological properties) of the aquifer systems below the plant in order to establish the extent of contamination

3. Monitoring of contamination in the perched aquifer and the underlying main Ogallala system.

### **2.1.3 The Surrounding Region**

The closest big city, Amarillo, has about 220,000 people, and has grown about 10% between 1991 and 2001 (USBC, 2005). Amarillo is located in Potter and Randall Counties, while the Pantex Plant is located in the adjacent Carson County. Carson County is sparsely populated with about 9000 people (TWDB, 2000); the biggest community is Panhandle which has a population of about 4500. The major land use for Carson County is agriculture and raising livestock; other industrial developments and an oil and gas field are also present in the County.

The Texas Panhandle is a semi-arid region with an annual rainfall of 48.5 cm (19 inches) (USDOE, 2004). Carson, Potter and Randall counties rely heavily on groundwater for their water supply needs (USGS, 2005); the region is underlain by the massive Ogallala Aquifer System which stretches all the way from South Dakota to Southern Texas. The Ogallala is a sole source aquifer for the Texas Panhandle, and supplies more than 90% of the region's total water demand.

The Panhandle region falls in the Texas Panhandle Water Planning Area, which is charged with developing long term water management policies for the region. The planning area board has developed population and water usage projections for all counties in the area (TWDB, 2000).

## ***2.2 Population and Water Use Projections for the Panhandle Region***

The Panhandle is one of the most intensive water consuming regions of Texas. It has about 1.9% of the state's total population, but accounts for almost 13% of the total water use. According to year 2000 figures (TWDB, 2000), more than 90% of the water was used for agricultural purposes - 91% for irrigation of crops, and 2.5% for livestock demands. The municipal demand consumed about 4% of the total supply, and industrial operations (manufacturing, mining, power plants) accounted for about 2.2% of the total water use. In the period 2000 to 2050, the population in the Panhandle region is expected to increase from about 280,000 to about 550,000; census data indicate that most of the projected increases will be in urban areas, while rural areas and smaller communities will decline in population (TWDB, 2000). Potter and Randolph, the two counties containing the principal city in the region, Amarillo, will likely increase their population from about 233,000 to 392,000, thus accounting for the bulk of the population and population increase in the region (TWDB, 2000; USBC, 2005).

The per capita municipal use was assumed to reduce from an average of 223 gallons per capita per day (gpcd) for Amarillo, to an average of about 195 gpcd through water conservation measures (TWDB, 2000). Even with this, municipal demand is projected as the fastest rising demand for the region (and for the state in general) in the coming years.

The projections for agricultural demand, which is the major driver of total water demand, are more problematic. While the Texas Water Development Board (TWDB) does put out its projections, the projected demand is contested by those who claim that improved

agricultural practices and conservation measures would significantly reduce demands. In conjunction with expected population declines in rural areas and farm labor, the demographics indicate that the agricultural demand may level off or decline. On the other hand, the issue of ground-water marketing (also referred to as water ranching or ground water mining) would significantly raise water demand for withdrawals that would normally be defined as agricultural uses. This issue is discussed in greater detail in a subsequent section.

After aggregating demands for different uses, TWDB projects that counties in the Panhandle Area with intensive agricultural water demands will begin to experience deficits by the year 2020; notably, one county would start experiencing deficits by 2010 (Figure 3). The burgeoning population in Potter and Randolph counties (containing Amarillo) has led to projections that these counties will start experiencing across the board deficits by about 2020. These deficits will be exacerbated and accelerated by diminished supplies, since the region has already started experiencing declines in water table levels (Harkins, 1998). The region as a whole will start experiencing a deficit between known supplies and projected total demand sometime between 2020 and 2050. These deficits will, very rapidly, start placing strain on groundwater resources of those areas within the region that are expected to have surplus groundwater capacities. Carson County, which contains the Pantex Plant, is expected to have surplus groundwater supplies well past 2050; however, the City of Amarillo has already bought rights to groundwater resources within the county. It is expected that these rights would have to

be exercised in the near future, as the city begins to run out of capacity from existing sources (TWDB, 2000).

### ***2.3 State Regulations and their Impact on Groundwater Resources Exploitation***

The Texas Supreme Court adopted the English Rule of Capture in a 1904 decision, *Houston & Texas Central Railway v. East* (Glennon, 2002). This rule permits landowners to pump groundwater in spite of eventual effects to one's neighbors' groundwater supply and/or on surface water availability and flow. The Texas legislature has been extremely slow and largely ineffective in regulating groundwater use. In 1949, the Texas Legislature authorized the formation of underground water conservation districts, but this act resulted in the establishment of only a few districts (Urban, 1992). Legislation enacted in 1985 allowed for conservation districts to be defined by political instead of aquifer boundaries resulting in the formation of twenty-two (22) underground water conservation districts. Although districts were permitted to set both well spacing and withdrawal requirements, no district in the Ogallala/ High Plains area has set withdrawal restrictions and three districts have set special siting requirements (Roberts, 1992).

Recently in 1999 the Texas Supreme Court upheld the Rule of Capture in *Sipriano v. Great Water Springs of America*. This case was originally brought to the lower court by residents living in the area of Roher Springs, northeast of Dallas, against Ozarka Natural Spring Water Company (a subsidiary of Perrier). Ozarka began pumping 90,000 gallons per day (gpd) of groundwater for its bottling plant in 1996, resulting in immediate depletion of neighboring wells (Glennon, 2002). The Texas High Court found "compelling reasons for groundwater use to be regulated". However, they did not

abandon the rule of capture because Senate Bill 1, enacted by the Texas legislature in 1997, created a statewide water management system. This system, while requiring the creation and management of priority groundwater districts, has been promulgated without adequate enforcement regulations (Glennon, 2002).

This state of legal and regulatory affairs has promoted a “water ranching” industry wherein holders of agricultural tracts can install powerful pumps and deep wells on their properties to extract and sell ground water. The Pantex Plant falls in the Red River Groundwater Conservation District, which gets almost 85% of its total water supply from the Ogallala and related aquifers. This district is currently witnessing a high profile and controversial initiative for marketing ground water. In this initiative, landowners’ water rights for Roberts County (which is adjacent to Carson County and to its North East) are being marketed by a private water corporation that wants to pipe the water and sell it to the City of San Antonio, TX. Mesa Water Corporation has purchased or leased approximately 150,000 acres of land from which it is estimated that he could pump and pipe as much as 60 billion gallons of groundwater per year to San Antonio (Glennon, 2002). The case for water marketing for Roberts County is that its soil is not conducive to agriculture, and that it has a readily available surplus groundwater capacity that can be used commercially by landowners exercising their rightful claims under current Texas regulations (Mesa Water, 2005). The San Antonio Water System (SAWS) has rejected the proposal for the time being citing the high cost and effects at the production site.

#### ***2.4 Potential Consequences of Increased Regional Groundwater Demands on Legacy Contamination at the Pantex Plant***

The geographic trends in the Panhandle region indicate a convergence of projected demands and existing regulations that points to increasing and unprecedented exploitation of groundwater resources within the Texas Panhandle. The overall impact of these demands would lead to further declines of water tables in the region surrounding the Pantex Plant. Furthermore, as water supplies become scarcer, water prices are likely to rise. Consequently, there will be much greater economic incentive for property holders living or farming near the plant to start marketing the rights to their groundwater wells drilled into the Ogallala Aquifer.

The increased groundwater exploitation near the Pantex Plant is a credible and highly probable scenario that can lead to the formation of an entirely different conceptual exposure model than the one articulated by the plant in its End States Vision Document (USDOE, 2004). The currently articulated conceptual site models do not take into account that well drilling can cause fractures into the aquiclude separating the contaminated perched aquifer from the underlying Ogallala system, and thereby open up rapid migration pathways into the Ogallala formation for any residual contamination. The scenario of groundwater mining near the boundaries of the plant, probably in the coming decades, is in sharp contrast to time frames of hundreds or thousands of years that most health risk and performance assessment studies related to USDOE facilities and their legacy contamination usually refer to. Furthermore, the point of exposure would be at a location that would pose a significant health risk, a risk that is not mitigated by

dilution over space or degradation over time. There are already about 16 private wells drilled into the Ogallala, in close proximity of the perched aquifer plume leaking into the Ogallala formation. The delivery of contaminated water to users in the wider region would spread the health risk impacts over a far larger cohort than would be considered by the health risk studies conducted on behalf of the facility – these typically use population projections for a much more restricted region, say of 50 miles, and would thus miss the impact due to distribution of water over a much larger region than envisaged. Any consequent discovery of contamination in water sources would result in great pressure on the Pantex facility to clean up any residual contamination to even lower concentrations, and thereby result in significant additional costs to the onsite environmental management program.

### **3 DISCUSSION**

The objective of this paper is to characterize the role of exposure assessment in ensuring that sustainable systems exist for containing residual contamination. Since remedial strategies depend so critically on understanding of exposure pathways and subsequent actions to block or remove them, any circumstances that change the underlying assumptions about likely exposure pathways are likely to substantially alter the profile of risk posed by residual contamination. The circumstances triggering the change can take many forms: events such as earthquakes, physical containment failures or extreme meteorological happenings; and activities by individuals or populations that cause new pathways to open up or blocked pathways to be reactivated. The primary mode of ensuring sustainability, from a health risk viewpoint, is to ensure that all sets of potential events and activities do not lead to uptake of residual contamination that would pose an

unacceptable health risk. The defining role of exposure assessment is in the linkage of environmental contamination with activities and events that cause uptake of contaminants by human or ecological receptors. Exposure assessment therefore provides an objective means of considering all potential events and activities that could lead to activation or reactivation of exposure pathways, and for designing and instituting subsequent administrative or engineering controls to ensure the sustainable containment of residual contamination. It would play a vital role in serving as institutionalized memory of original protective system, in evaluating progress of clean up efforts and containment of residual contamination, and as a means for informing subsequent tertiary protective actions.

The case study of residual contamination at the USDOE Pantex Plant demonstrates how exposure assessment can be used to identify important but overlooked uptake pathways caused by the interplay between regional geography (represented by water usage patterns) and residual environmental contamination. The Pantex facility can use a post remedial exposure assessment such as the one described in this case study to evaluate whether its containment plans for residual groundwater contamination are sustainable under regional water use conditions that have a high probability of occurrence in the near future. In this case, the exposure assessment enables the incorporation of geographic imperatives that are common knowledge in the Texas Panhandle, and shows how these imperatives would lead to exposure scenarios that are not currently anticipated under the envisaged end state at the site. Once the facility and USDOE become aware of the potential hazards that such exposure scenarios could pose, they can move to implement appropriate institutional

controls such as buying up of all groundwater rights in the immediate vicinity of the site. Such institutional controls are not considered under the original system of protective actions, and therefore, they can be characterized as a tertiary actions resulting from the exposure evaluation under the primary-secondary-tertiary actions paradigm articulated by Greenberg et al. (2005). Hence, in the context of sustainable containment of residual contamination and management of potential risks posed by it, exposure assessment reveals itself as an tool that can not only evaluate the progress and effectiveness of originally envisaged remedial actions (clean up of original contamination through pump and treat methods), but also as a guiding framework for instituting additional (tertiary) actions (buying up of water rights to prevent potential commercial extraction of contaminated water) to ensure the sustainable containment of residual contamination.

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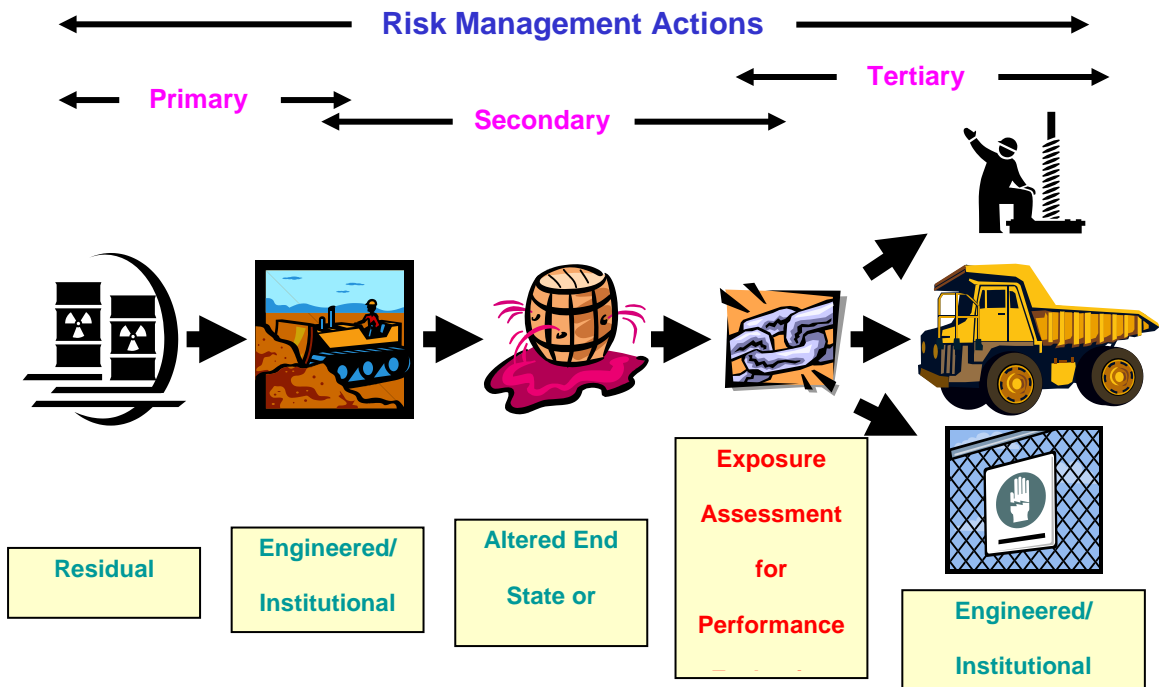
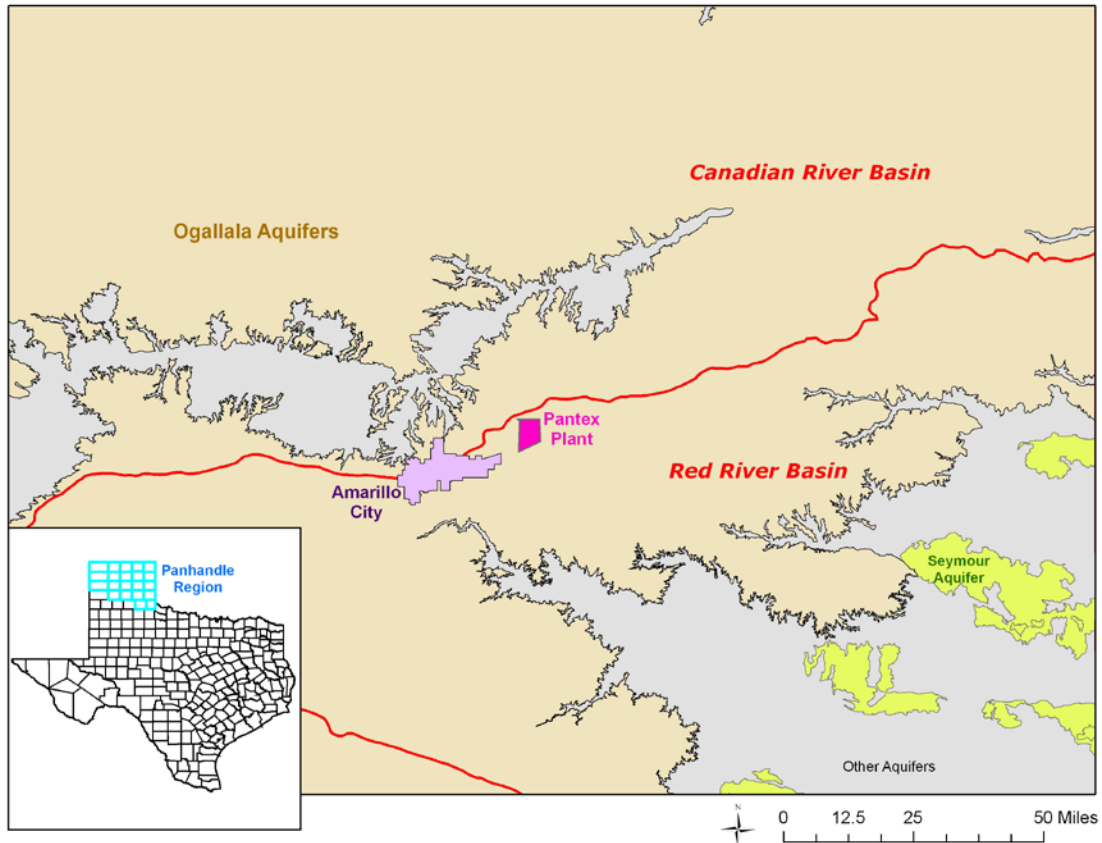


Figure 1. Exposure assessment as a link in the post-remediation Risk Management chain



**Figure 2. Map of the Pantex Facility and the Texas Panhandle. The Ogallala aquifer underlies most of the region, which has been divided up into ground water conservation districts – in this area, the Canadian River Basin and Red River Basin correspond to the Canadian River and Red River groundwater conservation districts**

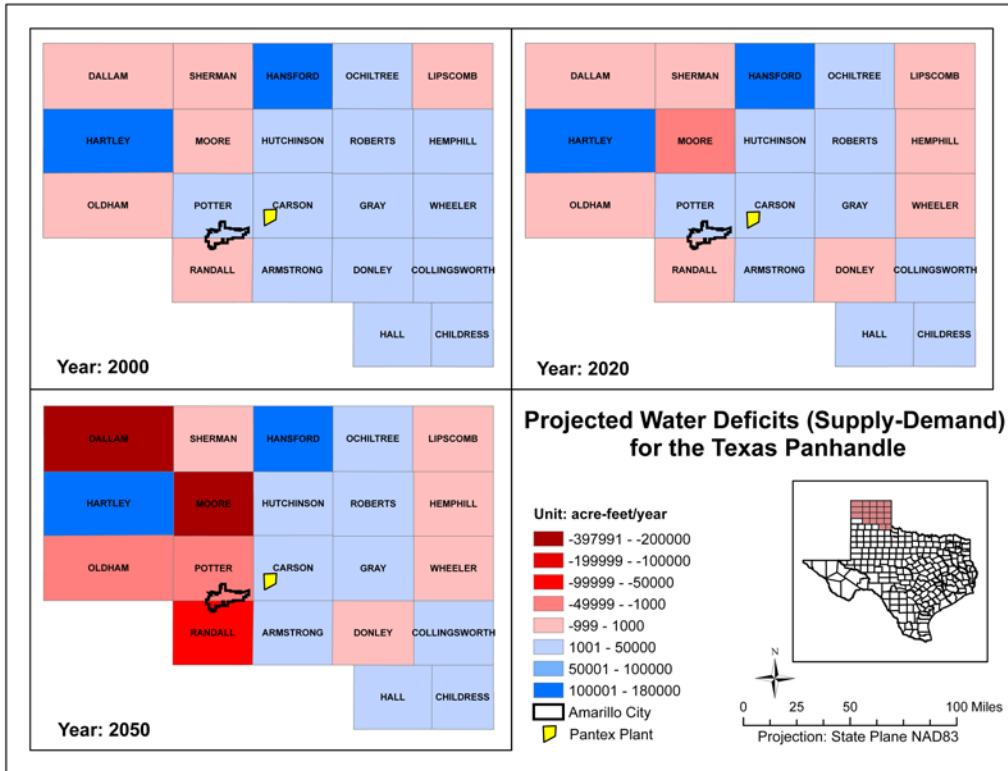


Figure 3. Projected water deficits in the Texas Panhandle counties (data from TWDB, 2000)