Nature, Frequency, and Cost of Environmental Remediation at Onshore Oil and Gas Exploration and Production Sites

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This article quantifies the nature, frequency, and cost of environmental remediation activities for onshore oil and gas operations, as determined from over 4,100 environmental remediation cases in Texas, Kansas, New Mexico, and Colorado. For the purpose of this article, "remediation" refers to cleanup efforts that entail longer-term site characterization, monitoring, and remedial action beyond the initial spill cleanup or emergency response stage. In addition, data are also presented regarding short-term spill cleanup activities in two of the four states. © 2011 Wiley Periodicals, Inc.

Over the past two decades, soil impacts from releases of crude oil, natural gas condensate, or produced water have occurred at approximately 9 percent of active oil and gas facilities in the states surveyed. In contrast, groundwater remedial actions have been reported at less than 0.4 percent of oilfield facilities, and surface-water remedial actions at less than 0.03 percent of oilfield facilities. Groundwater impacts requiring remediation occur at only 4 percent of the sites for which soil impacts are reported.

The principal sources of release for remediation projects vary among the states investigated, with crude oil and condensate releases from pipelines reported at 59 percent of sites in Texas, while in Kansas, where the Remediation Site Fund focuses on impacted groundwater sites, produced water releases were reported at 98 percent of sites. The principal remediation technology for soil impacts is excavation and disposal/treatment, with estimated median costs of $13,250 in Colorado. The principal remediation methods for groundwater are monitoring of existing wells or the installation and sampling of new monitoring wells, with median costs of $4,000 and $22,000, respectively, followed by groundwater pumping and treatment, with median costs of approximately $250,000, as reported in Kansas.

INTRODUCTION

Environmental impacts by onshore oil and gas exploration and production (E&P) operations are commonly regulated at the state level in the United States, and each of the ten principal oil-producing states in the United States has established regulations for

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environmental remediation that are specific to oil and gas operations. However, few efforts have been made to compile information on the nature, frequency, and cost of environmental remediation activities at onshore oilfield facilities. In this article, we have surveyed information on remediation projects from four of the ten principal oil-producing states for which electronic records or reports were available. These data will prove useful to environmental professionals for estimating the scope and cost of environmental remediation efforts required for oilfield decommissioning, as well as for policymakers who are interested in identifying the sources of environmental impacts that most commonly require remediation.

This study builds upon information provided in prior studies that have investigated the nature of onshore oilfield releases (Fisher & Sublette, 2005); the costs of specific remediation activities, such as pit closure or tank dismantling (Hesson, 2008; Lewis et al., 2007); or the overall costs of oilfield decommissioning (Kant, 2010). However, in this article, we have sought to characterize the full scope of remediation activities associated with oilfield operations, including the number, nature, and source of environmental conditions that require remediation at oilfield sites, and the type and cost of the remedial actions that are commonly applied.

Fisher and Sublette (2005) provide a comprehensive statistical summary of approximately 17,000 oilfield releases of crude oil or saltwater recorded by the Oklahoma Corporation Commission (OCC) over the period of 1993 to 2003. The data compiled by Fisher and Sublette show that flowlines, followed by tanks and wells, are the principal sources of crude oil and/or produced water releases in the oilfield, with the primary reported causes of these fluid spills being leaks, tank overflows, vandalism, and storm damage.

Lewis et al. (2007) completed a cost analysis for closure of the estimated 1,500 "orphan" reserve pits known to be present in Louisiana in 2007, for which no responsible party could be identified. Based on cost records for pit closures previously conducted on behalf of the Louisiana Department of Natural Resources (LDNR), representative costs were determined to be $1,500 per pit for a "minimal closure" (earthwork only at pits with no contamination), $6,000 per pit for the additional remediation work required for in-place closure of a contaminated pit, and an additional $16,000 for off-site disposal of waste materials at pit locations where in-place closure was not feasible.

The "Inventory of Orphan Facilities" (Hesson, 2008), compiled on behalf of the Division of Oil, Gas, and Geothermal Resources of the California Department of Conservation, specifically addresses the scope and cost of the work required to address tanks, related piping, and affected soils at abandoned oilfield facilities (e.g., well sites, production stations, etc.) in 36 oilfields in California. For a total of 199 tanks at 45 orphan facilities, the study estimated the total cost to dismantle and dispose of the tanks and piping to be approximately $3 million (i.e., $67,000 per facility or $15,000 per tank), with an additional $1 million or less to excavate related oil-affected soils (i.e., up to $22,000 per facility or up to $5,000 per tank).

Kant (2010) provides a case study of the decommissioning of the Schoonebeek Oilfield, which entailed dismantling and remediation of 456 production facilities, 599 oil production wells, and 1,050 kilometers of pipelines in a 50-year-old oilfield in the Netherlands. The total costs for well plugging and abandonment, equipment dismantling, environmental investigation, soil and groundwater remediation, and other activities necessary to convert the former oilfield to agricultural use and other purposes were approximately $261 million, or $1.10 per barrel of oil that had been produced

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(Kant, 2010). Of this, approximately $8 million, or 3 percent of the total budget, pertained to groundwater remediation.

To build upon these prior studies, in this article, we have analyzed electronic databases and reports of remediation sites compiled by four of the principal oil-producing states in the United States (Texas, New Mexico, Kansas, and Colorado) in order to characterize the nature, frequency, and cost of environmental remediation activities in the onshore oilfield sector. Our study focuses on remediation sites where environmental conditions require site assessment and/or remedial actions that extend beyond the scope of a short-term spill response (i.e., requiring months or years to address impacts to soil, groundwater, or surface water in accordance with applicable state regulations and policies). In addition, data are presented for two states (Colorado and Texas) that entail all remedial actions overseen by the state regulatory agency during a period of time, including response measures for both short-term spill cleanups and long-term site-investigation remediation projects.

DATA SOURCES AND METHODOLOGY

For each of the top ten oil-producing states in the United States, records have been reviewed to identify those states for which comprehensive information is available on environmental remediation projects conducted in the oilfield over the past decade or more. Based upon this initial review, four states were found to either maintain electronic databases of remediation sites (Texas and Colorado) or generate reports (Kansas and New Mexico) that would facilitate a comprehensive survey of the nature of soil, groundwater, and surface-water impacts and the associated remedial actions that have been implemented.

Our study focuses on remediation sites where environmental conditions require site assessment and/or remedial actions that extend beyond the scope of a short-term spill response (i.e., requiring months or years to address impacts to soil, groundwater, or surface water in accordance with applicable state regulations and policies).

Exhibit 1 summarizes the principal sources of information that were obtained for the purpose of this study. Two of the five state programs from which we obtained data focused on sites that require significant remedial action beyond the scope of typical spill-response measures, specifically the Texas Operator Cleanup Program (OCP), managed by the Texas Railroad Commission, and the Kansas Remediation Site Fund, managed by the Kansas Corporation Commission (KCC). In contrast, two other state programs maintained databases of all remedial actions undertaken during a specific time period, predominantly including short-term spill response actions (i.e., the Texas State Managed Cleanup Program [SCP], managed by the Texas Railroad Commission, and the Colorado Oil and Gas Conservation Commission [COGCC], which manages the Colorado Oil and Gas Information System [COGIS]). Information on groundwater remediation sites in New Mexico was obtained from a report published by the New Mexico Oil Conservation Division (OCD) in 2005 listing sites with affected groundwater related to leaks, spills, or other releases of oilfield wastes. In total, these data sources provide information on over 4,100 remediation sites for which remedial investigations and cleanup actions are presently under way or have been completed (i.e., "closed") in these states over the past two decades.

Analyses of State Records of Environmental Remediation Cases

The data sources compiled in this study have been analyzed to quantify the following information regarding the nature, frequency, and cost of environmental remediation activities conducted in the upstream oilfield sector:

Exhibit 1. Sources of information on environmental remediation sites in state regulatory programs

State	State Regulatory Agency	Data Source and Associated Time Frame	Description of State Regulatory Program	Sites Analyzed in this Report
Texas	**Operator Cleanup Program (OCP), Railroad Commission of Texas (RRC)**	**Apr. 1992–Feb. 2010** OCP Microsoft Access Database (OCP, 2010)	The Texas Operator Cleanup Program (OCP) oversees oil and gas cleanups by site owners and operators that require long-term or complex remedial action, as well as mercury impacts (which were not addressed in this study).	**1,464 significant remediation sites**
	State Managed Cleanup Program (SCP), Railroad Commission of Texas (RRC)	**Sept. 2000–Feb. 2010** SCP Microsoft Access Database (SCP, 2010)	The Texas State Funded Cleanup Program (SCP) finances and oversees the cleanup of abandoned oil and gas sites including pit closures, decommissioning and remediation of historic tank batteries, and, to a lesser extent, long-term remedial activities associated with significant soil or groundwater impacts (Correa, 2010).	**1,688 routine cleanups; 580 emergencies; 557 assessments** (Sites with routine cleanups may also have emergencies or assessments)
Colorado	**Colorado Oil and Gas Conservation Commission (COGCC)**	**Mar. 2009–Jun. 2010** Form 27s Obtained From COGIS Database (COGCC, 2010a)	Data presented for Colorado was obtained from all Form 27s (Site Investigation and Remediation Workplans) submitted by operators to the COGCC during a 15-month period that addressed spills/releases impacting soil, surface water, or groundwater.	**162 release sites, predominantly spill response actions**
Kansas	**Remediation Site Fund, Kansas Corporation Commission (KCC)**	**1997–2010** Annual Remediation Site Status Reports (KCC, 1997–2010)	Through the Remediation Site Fund (established in 1996), the Kansas Corporation Commission oversees and funds long-term or complicated remedial activities at active and abandoned oil and gas sites, the majority of which entail long-standing monitoring or remediation of affected groundwater.	**124 significant remediation sites**
New Mexico	**New Mexico Oil Conservation Division (NMOCD)**	**1990–2005** Generalized Record of Ground Water Impact Sites (NMOCD, 2005)	Information on groundwater remediation sites in New Mexico originated from the *Generalized Record of Ground Water Impact Sites* report, issued in 2005 by the NMOCD, which provided a list of sites with affected groundwater as a result of leaks, spills, and releases of oilfield wastes prior to 2005.	**700 groundwater remediation sites**

- *frequency of environmental impacts* requiring remediation for soil, groundwater, and surface water, as a percentage of the total number of oilfield facilities in operation in that same time frame;
- *type of affected media* (soil, groundwater, surface water) at each remediation site;
- *source of the release* (wellhead, pit, pipeline, gas plant, saltwater disposal facility, production station, etc.) that required the remedial action;
- *contaminant source material* (crude oil, condensate, produced water, etc.) at each remediation site;
- *type of remedial action* applied for soil or groundwater cleanup at each remediation site;
- *duration of remedial actions* for soil and groundwater remediation; and
- *cost of remediation projects* for soils and groundwater.

In combination, the various data sources reviewed in this study provide information on all of these points of interest. However, the individual data sources may address only some of the parameters identified and/or provide relevant information on only a portion of the sites in their database. Consequently, for each parameter, the statistical distribution of relevant properties was characterized based upon those data sources and sites for which information was available.

Description of Onshore Oilfield Operations

Exhibit 2 provides a general schematic of oilfield operations at onshore oil and gas facilities. Oil wells commonly produce a mixture of crude oil, natural gas, and produced water, while natural gas wells produce a mixture of natural gas, gas condensate, and produced water. As indicated in Exhibit 2, these fluid mixtures are separated into oil, gas, condensate, and produced water streams by a series of separation processes conducted both at the individual well sites and at centralized production stations or gas plants. The separated crude oil is transported from the well site, by means of flowlines or trucks, to a local production station for further removal of produced water and natural gas prior to placement in a crude oil pipeline. Natural gas is similarly transported from the wellhead by flowlines to a central gas processing plant for removal of water, natural gas condensate, and certain impurities prior to placement in a pressurized natural gas pipeline. Produced water, which can be highly saline, is commonly collected at centralized produced water plants for reinjection into deep oil reservoirs by means of injection wells.

Oil wells commonly produce a mixture of crude oil, natural gas, and produced water, while natural gas wells produce a mixture of natural gas, gas condensate, and produced water.

Environmental impacts from oil and gas operations are most commonly associated with spills, leaks, or other releases of one of three principal liquids: crude oil, natural gas condensate, or produced water. Such releases can occur at the individual wellheads (i.e., the oil or gas well, or its associated pits, separators, or tank batteries), from flowlines leading to the central production station or gas plant, from processing equipment or tank farms at the central production stations or gas plants, or from tanks, piping, or injection wells associated with the produced water plants. In this study, we have reviewed available information on environmental remediation projects at oil and gas production sites to determine the most common sources of release, the materials spilled, the environmental media impacted by the release (i.e., soil, groundwater, or surface water), and the nature of the remedial action applied.

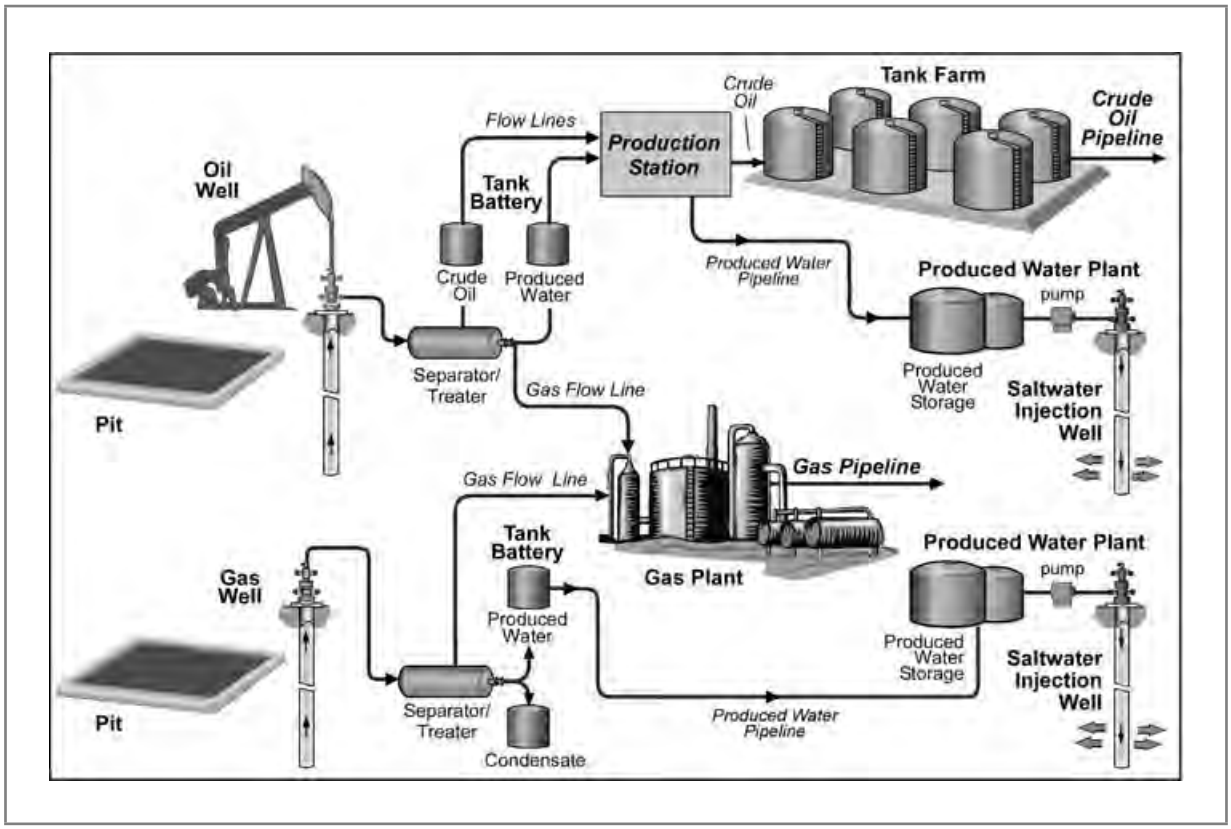

Exhibit 2. Schematic of oilfield infrastructure and possible sources of release of crude oil, condensate, or produced water

RESULTS OF DATA SURVEY

Total Number and Frequency of Remediation Sites at Oilfield Facilities

Frequency of Soil Impacts at Oil and Gas Facilities

Under applicable state regulations, owners and operators of oil and gas facilities are required to report releases of oil, condensate, produced water, or other chemicals in excess of specified threshold volumes (e.g., greater than five barrels of crude oil) that escape containment areas (e.g., concrete pavement) and contact soil, groundwater, or surface water. For each state included in this study, Exhibit 3a summarizes the total number of release incidents reported to the state regulatory agency. In general, it is reasonable to assume that all of these reported spills involve impacts to soils; however, in many cases, the spill volume may not be sufficient to penetrate to the depth of underlying groundwater or to extend to the location of a nearby surface-water body. On this basis, the frequency of soil impacts as a percentage of the total number of oil and gas facilities is presented in Exhibit 3a. As a conservative approach, the total number of oilfield facilities (i.e., wellheads, production stations, gas plants, produced water plants) has been estimated based upon the number of active oil and gas wells, the only facility type for which population records are readily available. Dividing the total number of releases

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Exhibit 3a. Frequency of impacted soil sites as a percentage of active oil and gas wells

State	Source of Information on the Number of Releases at Oil and Gas Sites	Number of Spills/ Release Incidents	Release Reporting Time Period	Number of Active Oil and Gas Wells	Number of Impacted Soil Sites as a Percentage of Total Oil and Gas Well Population
Texas	H-8 forms ("Crude Oil, Gas Well Liquids, or Associated Products Loss Report") submitted by operators to the RRC in the event of a release.	19,043[1]	1989–2009	276,677[4] (2009)	7%
Kansas	"Spill Reports" submitted by operators to KCC district offices in the event of a release.	13,678[2]	1996–2009	71,445[5] (2009)	19%
New Mexico	C-141 forms ("Release Notification and Corrective Action" forms) filed by operators with the NMOCD in the event of a release.	1,374[3]	1990–2005	49,494[6] (2005)	8%
Total	–	**34,095**	**1989–2009**	**397,616**	**9%**

[1]RRC (2010), [2]KCC (2010), [3]NMOCD (2010), [4]RRC (2009), [5]KGS (2010), [6]US EIA (2009).

Exhibit 3b. Frequency of groundwater remediation sites as a percentage of active oil and gas wells

	Number of Remediation Sites With Groundwater Impacts					Number of Groundwater Remediation Sites as a Percentage of Total Oil and Gas Well Population		
State	Active Sites	Closed Sites	All Sites	Remediation Time Period	Number of Active Oil and Gas Wells	Active Sites	Closed Sites	All Sites
Texas	N/A	N/A	736[1]	1989–2009	276,677[4] (2009)	N/A	N/A	0.3%
Kansas	59	57	116[2]	1996–2009	71,445[5] (2009)	0.08%	0.08%	0.2%
New Mexico	516	184	700[3]	1990–2005	49,494[6] (2005)	1%	0.4%	1.4%
Total	**N/A**	**N/A**	**1552**	**1989–2009**	**397,616**	**N/A**	**N/A**	**0.4%**

[1]TGPC (1990–2010), [2]KCC (1997–2010), [3]NMOCD (2005), [4]RRC (2009), [5]KGS (2010), [6]US EIA (2009).

Exhibit 3c. Frequency of surface-water remediation sites as a percentage of active oil and gas wells

	Number of Remediation Sites With Surface-Water Impacts					Number of Surface-Water Remediation Sites as a Percentage of Total Oil and Gas Well Population		
State	Active Sites	Closed Sites	All Sites	Remediation Time Period	Number of Active Oil and Gas Wells	Active Sites	Closed Sites	All Sites
Texas	N/A	N/A	*100[1]	1992–2010	276,677[3] (2009)	N/A	N/A	0.04%
Kansas	7	11	18[2]	1996–2009	71,445[4] (2009)	0.01%	0.02%	0.03%
Total	**N/A**	**N/A**	**118**	**1992–2010**	**348,122**	**N/A**	**N/A**	**0.03%**

*Estimated based upon a sample of the total site population.

[1]OCP (2010), [2]KCC (1997–2010), [3]RRC (2009), [4]KGS (2010).

recorded from 1989 to 2009 (34,095 releases) in Texas, Kansas, and New Mexico by the number of active oil and gas wells over the same time period (397,616 wells) indicates that soil impacts occurred at approximately 9 percent of the oilfield facilities in the states surveyed. This percentage ranges from approximately 7 percent to 19 percent for the three states for which these data were available. These figures likely overestimate the frequency of soil impacts, as the denominator in this calculation does not include nonproducing wells responsible for historical and ongoing impacts, or other types of oilfield facilities, such as produced water plants, gas plants, and tank farms, at which impacts have occurred.

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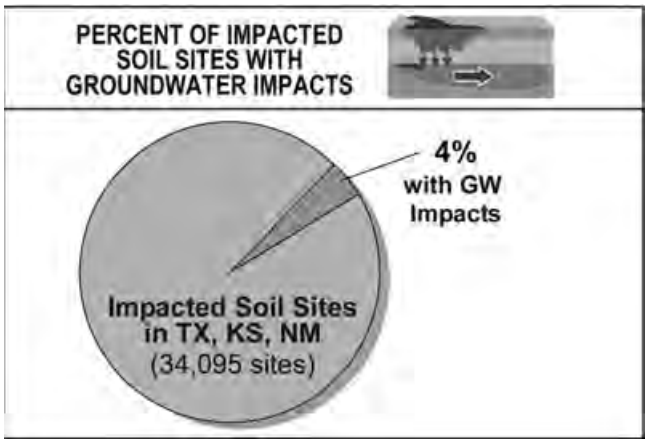

Exhibit 4. Frequency of groundwater impacts at impacted soil sites

Frequency of Groundwater Impacts Requiring Remediation at Oil and Gas Facilities

The frequency of groundwater remediation cases has been estimated in the same manner as soil impacts (i.e., by dividing the total number of reported groundwater remediation cases by the number of active oil and gas wells [as a conservative underestimate of the number of oilfield facilities]). As shown in Exhibit 3b, in Texas, Kansas, and New Mexico (the states for which these data were available), a total of 1,552 groundwater remediation sites have been recorded over the time period of 1989 to 2009, among a total population of 397,616 active oil or gas wells as of 2009, corresponding to an overall frequency of 0.4 percent. This percentage ranges from 0.2 percent to 1.4 percent for the three states for which these data were available. Again, these figures likely overestimate the frequency of groundwater remediation cases as a percentage of the total population of oilfield facilities, due to the underestimate of the number of oilfield facilities used in the calculation. A comparable electronic database was not available for the state of Louisiana. However, discussions with Louisiana Department of Natural Resources personnel indicate that as of 2008 approximately 150 groundwater remediation cases have been identified from the approximately 80,000 oil wells that have been completed since 1900 (K. Brothen, personal communication, 2008; LDNR, 2008; C. Sandoz, personal communication, 2008; G. Snellgrove, personal communication, 2008), corresponding to a frequency of approximately 0.2 percent, which is consistent with our findings for the other states.

The frequency of groundwater impacts as a percentage of soil impacts is shown in Exhibit 4. Out of a total of 34,095 releases resulting in soil impacts in Texas, Kansas, and New Mexico between 1989 and 2009, 1,552 groundwater remediation sites were reported, indicating that groundwater impacts occur at roughly 4 percent of impacted soil sites. This calculation may moderately overestimate the percentage of groundwater impacts associated with soil impact sites, as some groundwater remediation sites may be related to other causes (e.g., produced water injection-well leaks, etc.).

Frequency of Surface-Water Impacts Requiring Remediation at Oil and Gas Facilities

In Texas and Kansas, agency records include a total of 118 remediation sites with impacts to surface-water bodies, which corresponds to 0.03 percent of the 348,122 active oil or

gas well sites in these states in 2009 (see Exhibit 3c). This percentage ranges from 0.03 percent to 0.04 percent for the two states for which these data were available. As noted, these figures likely overestimate the frequency of surface-water impacts as a percentage of the total number of oilfield facilities that could be potential sources of such impacts. For the 18 sites in Kansas designated as surface-water impacts, remedial actions typically consisted of monitoring of surface water, removal of suspected sources (pits and affected soils), and the plugging of flowing and abandoned wells.

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Type of Affected Media at Oilfield Remediation Sites

Exhibit 5 shows the nature of affected media (soil, groundwater, or surface water) reported to be present at remediation sites in the states of Texas, Kansas, and Colorado. As indicated, impacts to groundwater represent the majority of sites in the Texas (77 percent) and Kansas (94 percent) databases, while the Colorado program is dominated by soil impacts (98 percent), with reported groundwater impacts at only half of the sites (51 percent). This contrast most likely reflects a difference in the scope of these regulatory databases rather than a true distinction in the nature of the impacts that occur in these states. In both Texas and Kansas, the statewide remediation site database is reserved for more "complex" remediation sites, such as those that entail groundwater impacts, while smaller-scale soil impacts associated with spills and the like are managed by district offices, and are not recorded in the statewide database. In contrast, the Colorado database incorporates both small-scale soil cleanups and significant remedial actions, with the smaller-scale soil impacts representing the vast majority of the database population. If records of the smaller-scale soil remediation sites were maintained in the statewide databases of Texas and Kansas, soil impacts would likely represent the most frequent impact in these states as well.

Source of Release at Oilfield Remediation Sites

For each remediation site recorded in the Texas, Kansas, Colorado, and New Mexico databases, Exhibit 6 summarizes information regarding the source of the release that resulted in the environmental impact. For this study, these sources have been characterized according to the various components of the oilfield infrastructure, such as wellheads, tank batteries, flowlines, productions stations, gas plants, produced water plants, pipelines, and so on (see Exhibit 2). The results plotted in Exhibit 6 suggest that the principal sources of release vary among the four states based on the scope of the state regulatory programs, as follows:

- *Texas:* In Texas, which has a state regulatory program with full jurisdiction over crude oil pipelines, releases from pipelines are associated with 59 percent of the remediation sites on record, followed by releases from gas plants and well sites, corresponding to 19 percent and 14 percent of the remediation sites, respectively.
- *Kansas:* The Kansas Remediation Site Fund focuses on long-term remediation of affected groundwater sites, which represent 94 percent of the sites in the state database (see Exhibit 5). The principal source of these groundwater impacts, which are primarily associated with produced water releases (see Exhibit 6), are pits (51 percent of sites), followed by releases at wellheads and tank batteries (40 percent of sites),

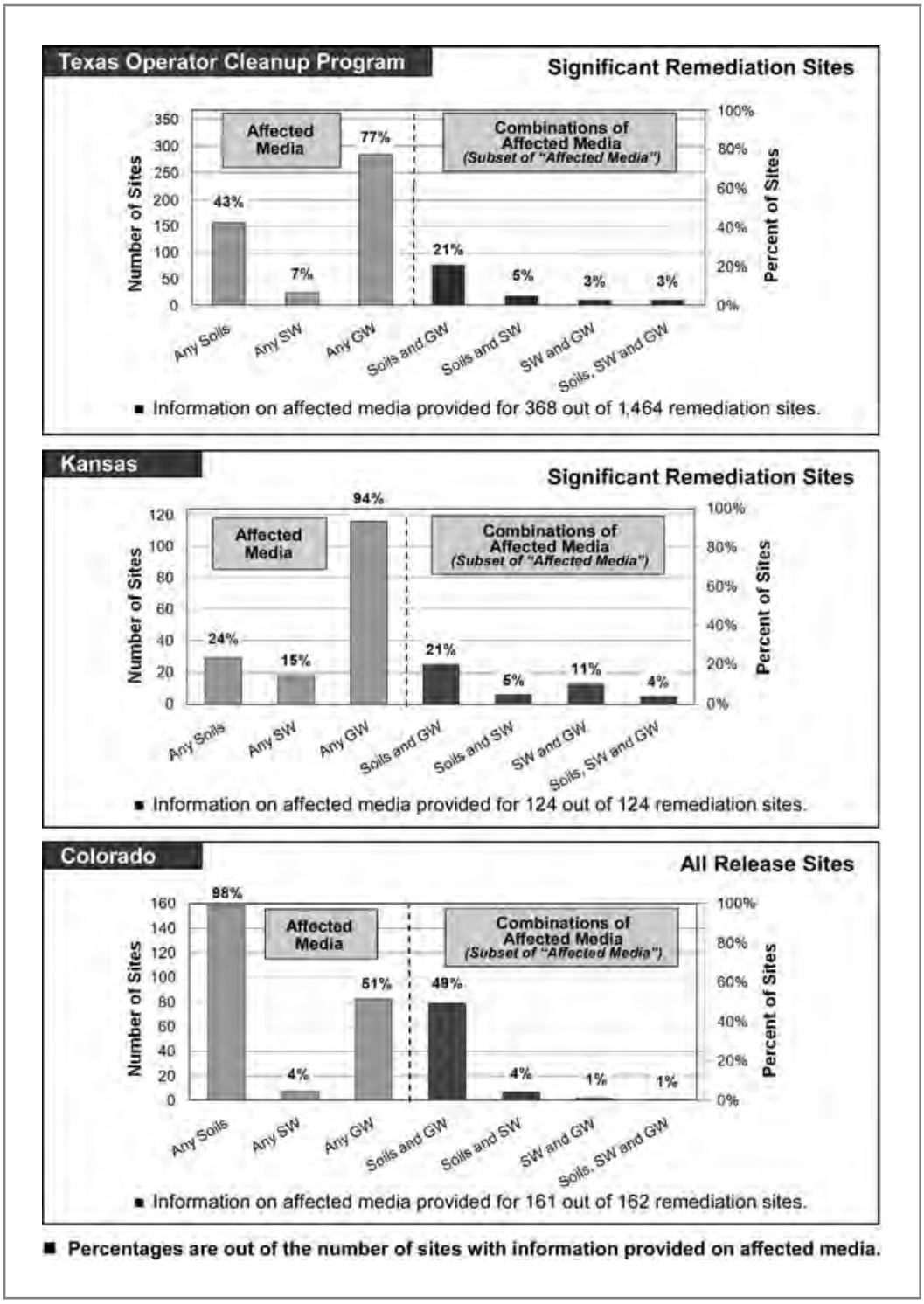

Exhibit 5. Type of affected media at oilfield remediation sites

produced water disposal facilities (31 percent of sites), and flowlines (22 percent of sites). (It is important to note that many sites have been impacted by more than one source of release, which explains why the percentages sum to greater than 100 percent.)

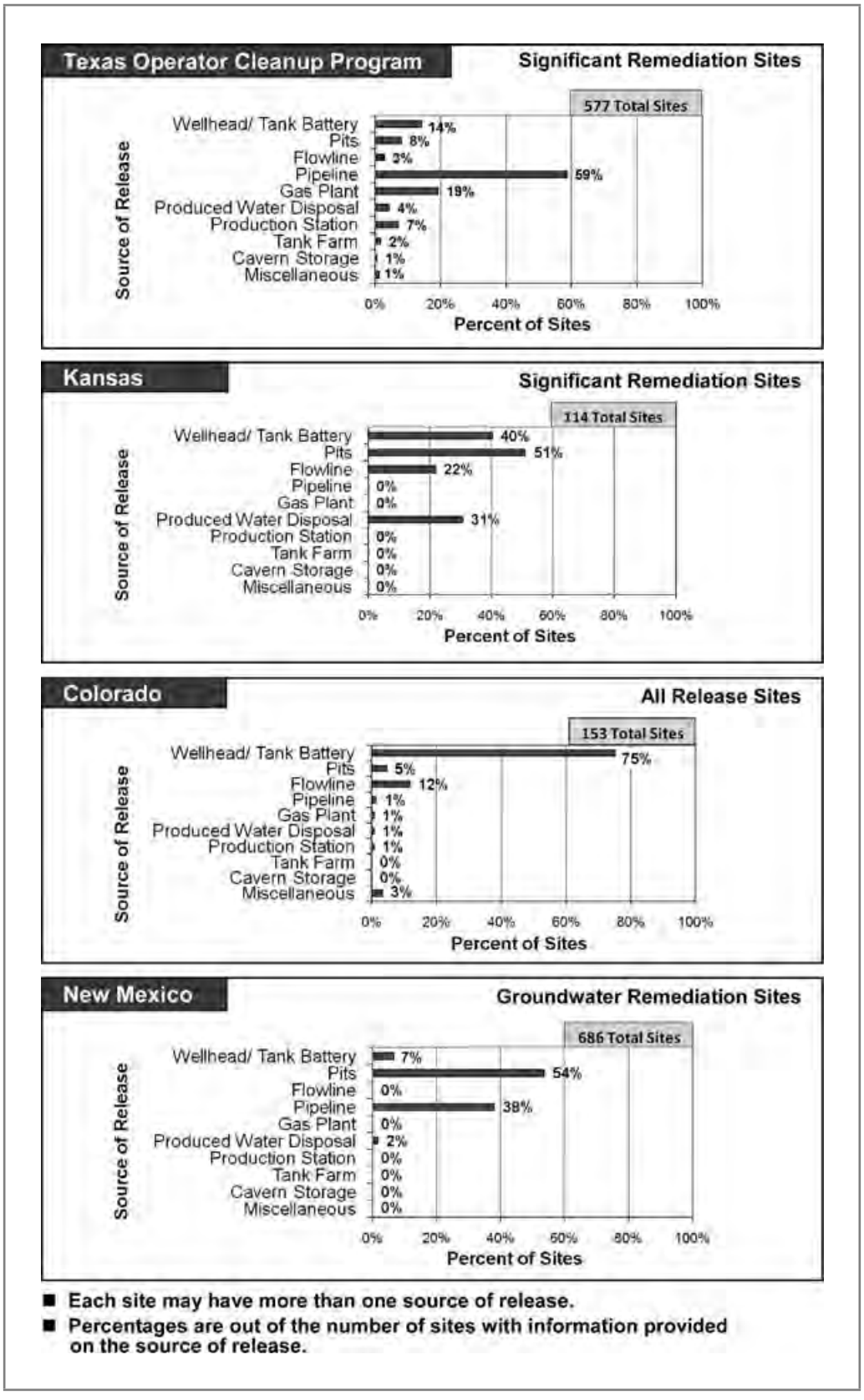

Exhibit 6. Reported source of release impacting oilfield remediation sites

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- *Colorado:* The majority of sites recorded in the Colorado database are smaller-scale soil impacts, which are principally associated with releases from wellheads and tank batteries (75 percent), followed by a smaller number of impacts related to releases from flowlines (12 percent of sites) and pits (5 percent of sites).
- *New Mexico:* In New Mexico, the available reports provide information only for sites with impacted groundwater. The principal sources of these groundwater impacts are pits (54 percent of sites), followed by pipelines (38 percent of sites) and wellheads and tank batteries (a combined 7 percent of sites).

Among the four states surveyed, the principal sources of impacts are pits, pipelines, and wellheads and tank batteries, followed by less frequent impacts at produced water disposal plants, gas plants, and flowlines.

Types of Source Materials at Oilfield Remediation Sites

As indicated in Exhibit 7, the recorded environmental remediation sites have been impacted by releases of one or more of three principal source materials: crude oil, produced water, or natural gas condensate. In Texas and New Mexico, crude oil represents the predominant source material, which is present at 51 percent to 66 percent of remediation sites. In contrast, produced water is the primary source material at remediation sites in both Kansas (98 percent of remediation sites) and Colorado (62 percent), where far fewer sites report impacts by crude oil releases (i.e., 4 percent and 35 percent, respectively, for these two states; see Exhibit 7). Condensate is a less frequent source material than either crude oil or produced water in all of the states surveyed.

Among the four states surveyed, the principal sources of impacts are pits, pipelines, and wellheads and tank batteries, followed by less frequent impacts at produced water disposal plants, gas plants, and flowlines.

The differences in the source materials observed in the four states may again reflect the differences in the scope of the regulatory programs and the associated databases. For example, the Texas RRC has full jurisdiction over crude oil and natural gas pipelines, which represent the primary source of release in that state (59 percent of remediation sites; see Exhibit 6). Logically, the materials potentially released from pipeline facilities (i.e., crude oil or condensate) are observed to be the primary source materials at remediation sites in Texas (see Exhibit 7). Similarly, in Kansas, where the Remediation Site Fund focuses on long-term groundwater remediation sites, most of which are associated with pits, wellheads, and produced water facilities (see Exhibit 6), the principal source material is, as could reasonably be expected, produced water, which is present at 98 percent of remediation sites. The higher percentage of Kansas remediation sites associated with produced water than Texas may also reflect the higher salinity of produced water in Kansas (median total dissolved solids [TDS]: 81,000 mg/L; 90th-percentile TDS: 211,000 mg/L; Breit & Otton, 2002). Groundwater impacted by produced water in Kansas was almost exclusively remediated for chloride concentrations above the applicable water-quality criteria. In Colorado, where the majority of remediation sites are associated with wellheads and tank batteries (75 percent of sites; see Exhibit 6), produced water is again the principal source material (62 percent of remediation sites; see Exhibit 7). However, unlike Kansas, the produced water releases in Colorado are mixed with both crude oil and condensate, which, at the wellhead and tank battery, can be present in the produced water in minor quantities prior to more efficient separation of the three fluids. This higher percentage of mixed constituents in produced water in Colorado may also reflect the reporting protocol in COGCC Investigation and Remediation

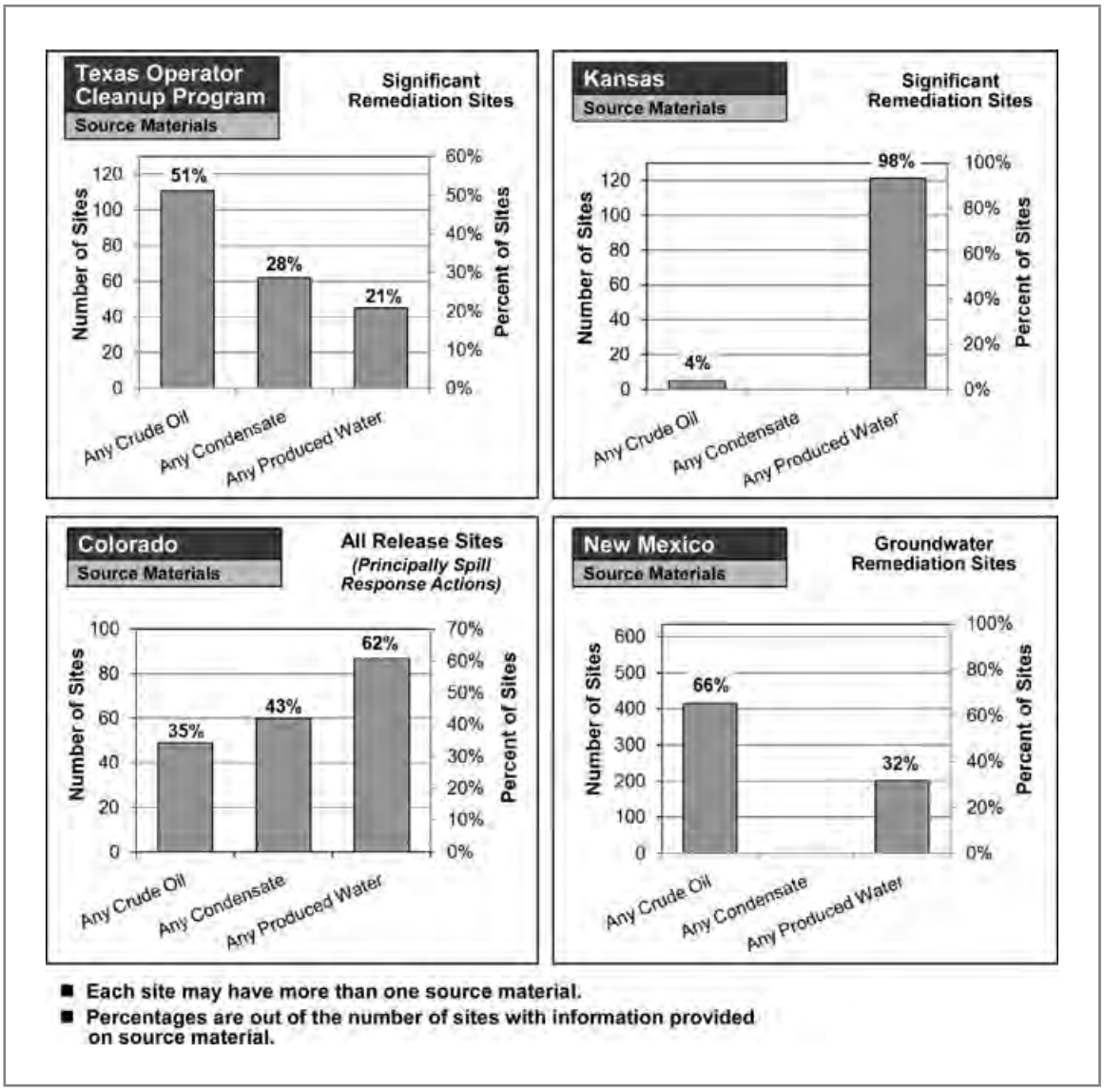

Exhibit 7. Principal source materials reported at oilfield remediation sites

Workplans, where all compounds present or reasonably suspected to be present, even in very minor amounts, are reported.

Relation of Sources of Release to Source Materials at Oilfield Remediation Sites

For remediation sites in Texas and Kansas, Exhibit 8 subdivides the reported source material (crude oil, condensate, produced water) by the related source (wellhead, pit, pipeline, gas plant, etc.). As shown, source materials are strongly associated with specific sources. For example, when they occur, most crude oil impacts in Texas (62 percent) are observed at pipeline facilities; condensate impacts are observed principally at gas plants (43 percent), followed by pipeline facilities (35 percent); and produced water impacts, when observed, occur predominantly (57 percent) at produced water disposal facilities (see Exhibit 8). In Kansas, produced water impacts occur predominantly (53 percent) at

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pits, followed by wellheads and tank batteries (40 percent), and produced water disposal facilities (32 percent) (see Exhibit 8).

Remedial Actions Implemented for Soil and Groundwater Impacts at Oilfield Remediation Sites

Exhibit 9 summarizes available information on the types of remedial actions that have been implemented at environmental remediation sites in Texas, Kansas, and Colorado in response to soil or groundwater impacts at oilfield facilities. The principal technologies employed for these media are as follows:

- *Soil Remediation:* The principal measures employed for remediation of affected soils are excavation and disposal/offsite treatment (78 percent of sites in Texas and 87 percent of sites in Colorado), followed by in-place landfarming (i.e., "soil mixing and tilling," used at 33 percent of sites in Texas and 10 percent of sites in Colorado). The Kansas database includes an insufficient number of soil remediation sites to provide a representative characterization of remediation practices.
- *Groundwater Remediation:* The principal remediation methods reported for groundwater impact sites are monitored natural attenuation (MNA) and/or monitoring at existing wells, which is employed as the sole remediation method at 74 percent of Kansas sites and 42 percent of Texas sites, and groundwater pumping and treatment ("recovery wells"), which is used at 47 percent of sites in Texas and 26 percent of sites in Kansas (see Exhibit 9). In Colorado, whose database addresses all release incidents, including minor spills, the most common remedial response for the localized groundwater impacts that are observed within affected soil excavations is to place either activated carbon granules or Microblaze™ product into the excavation in an effort to immobilize or biodegrade the petroleum contaminants.

In Kansas, plugging and abandonment of inactive oil and gas wells, which can be part of oilfield decommissioning activities, is also recorded in the Remediation Site Fund annual reports and has been implemented at approximately 19 percent of the complex remediation sites.

The Texas Operator Cleanup Program database provides information on the dates that 1,464 remediation sites first entered the regulatory program, as well as the dates upon which 973 of these cases were approved for closure (i.e., no further action).

Duration of Environmental Remediation Projects

The Texas Operator Cleanup Program database provides information on the dates that 1,464 remediation sites first entered the regulatory program, as well as the dates upon which 973 of these cases were approved for closure (i.e., no further action). Of these 1,464 remediation sites, information on the type of affected media was also provided for a subset of sites. Based on this data, Exhibit 10a provides information regarding the period of time that these closed and active (ongoing) groundwater and soil remediation sites have spent in the regulatory program. For active sites, the duration indicated on these figures represents only the time from initial entry in the program to the present day, as further action (e.g., site investigation, remediation, or monitoring) may be required at these sites to achieve case closure.

Exhibit 10b summarizes available information on the duration of closed remediation projects in Kansas. Principal observations regarding these data are in the paragraphs that follow.

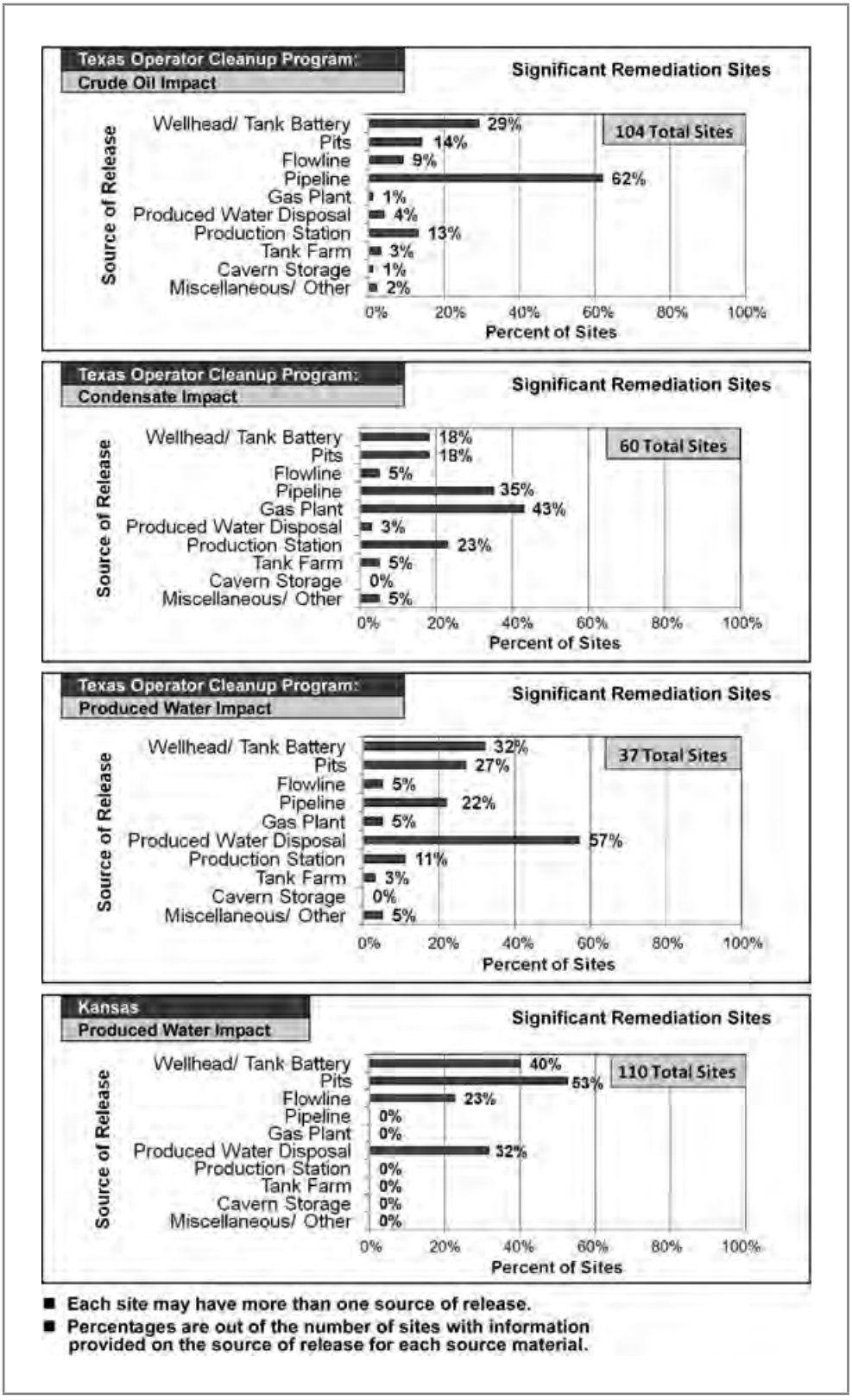

Exhibit 8. Source material vs. source of release at oilfield remediation sites

Remediation DOI: 10.1002/rem

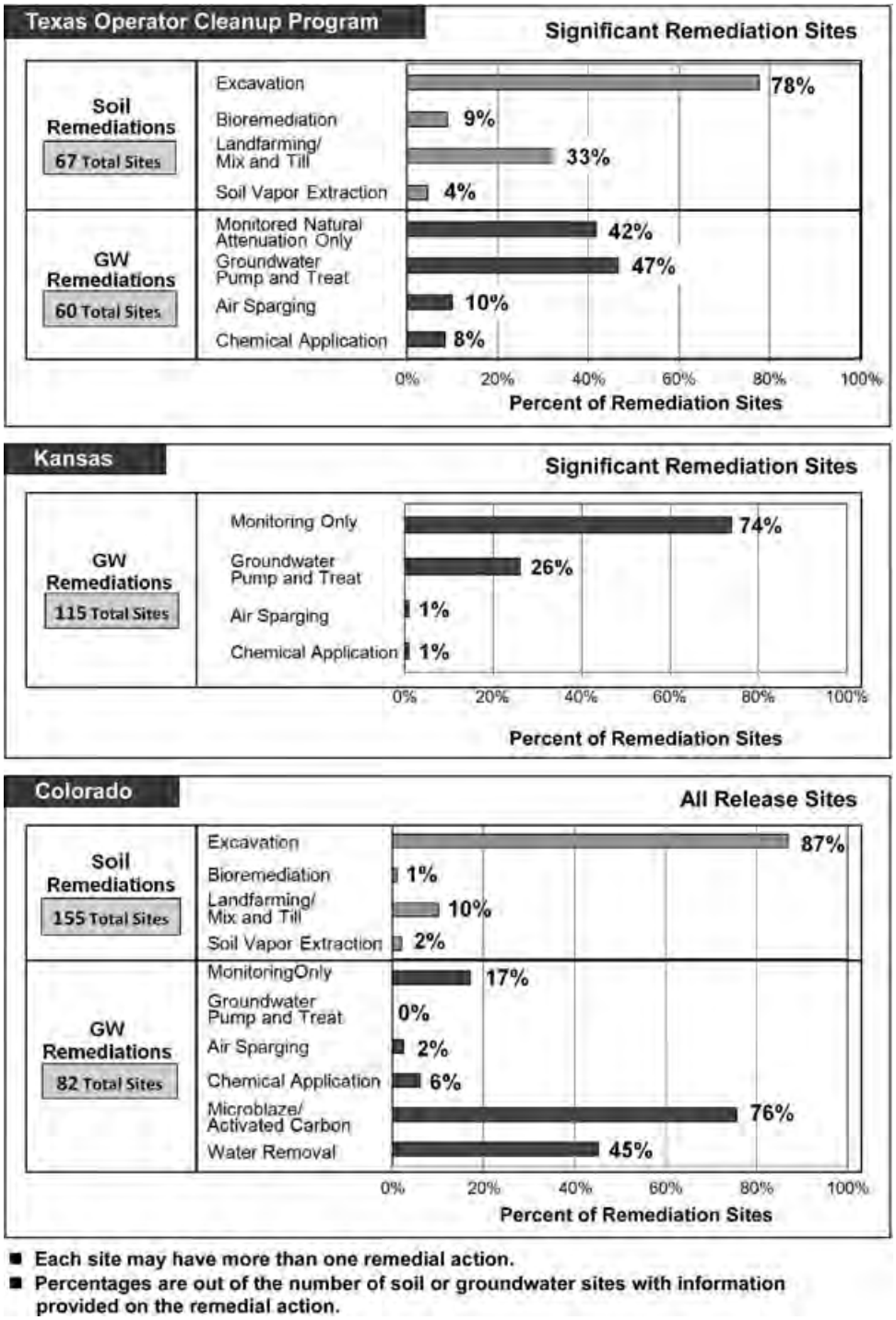

Exhibit 9. Remedial actions employed for affected soil and groundwater at oilfield remediation sites

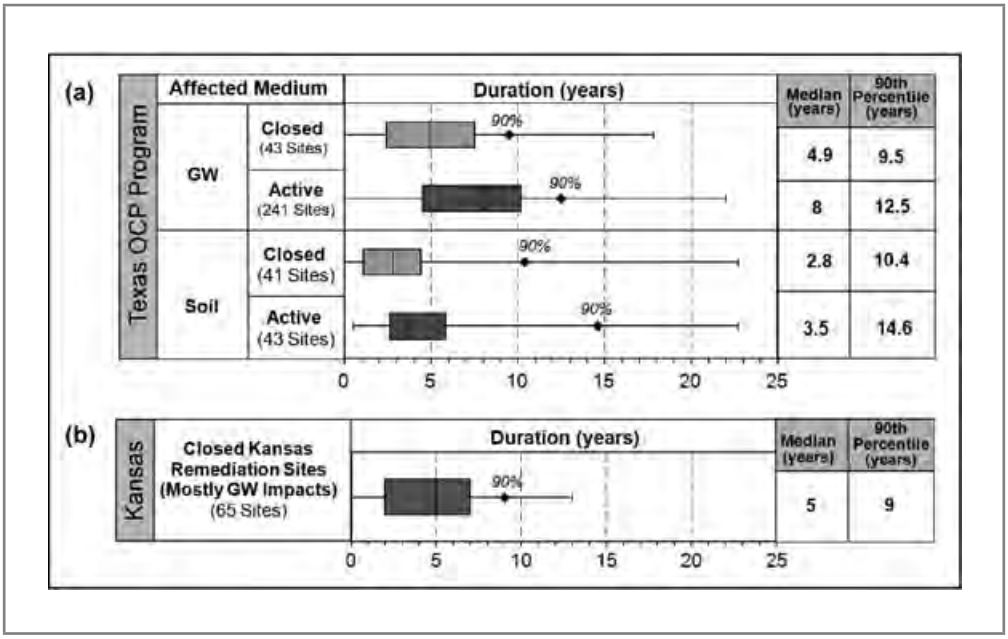

Exhibit 10. (a) Duration of environmental remediation projects in the Texas Operator Cleanup Program by type of affected medium; (b) Duration of environmental remediation projects in the Kansas program

Closed vs. Active Remediation Sites

In both Texas and Kansas, the median duration of activity at closed remediation sites is significantly less than that of active remediation sites (see Exhibits 10a and 10b). For example, in Texas, the median time period that closed groundwater remediation sites remained in the regulatory program is 4.9 years, while the active groundwater remediation sites have been in the program for a median time period of 8 years and have yet to satisfy requirements for closure. Similarly, in Kansas, for which 94 percent of the remediation sites entail groundwater impacts (see Exhibit 5), closed sites spent a median time of 5 years in the program. The duration of time that active sites have spent in the Kansas Remediation Site Fund is not shown in Exhibit 10b because over half of the sites entered the program during its inception 13 years ago, and are still under active monitoring and remediation. The much shorter time periods recorded for sites that have already been closed likely reflects the fact the closed sites entailed smaller impacts that were simpler to remediate, while the open sites represent the more complex, time-consuming projects.

Variation of Project Duration by Affected Medium

As indicated in Exhibit 10a, the median time frames for management of groundwater remediation sites exceeds that of soil remediation sites for the cases recorded in the Texas OCP database. For those groundwater remediation sites for which project duration is reported (41 closed sites and 243 active sites), closed and active cases have been in the regulatory program for median times of 4.9 and 8 years, respectively. For the soil

Remediation DOI: 10.1002/rem

remediation sites for which project duration is reported (41 closed and 43 active sites), the closed and active cases have been in the regulatory program for median times of 2.8 and 3.5 years, respectively. This difference in project duration can be reasonably expected, given that the remediation method most commonly employed for affected soils is excavation and disposal (see Exhibit 9), which is relatively rapid compared to the remediation methods most commonly employed for groundwater remediation sites (i.e., MNA and/or monitoring at existing wells, or groundwater pumping and treatment). The median duration among all closed remediation sites in the Texas database (973 sites, including those for which there was no information provided on the type of affected media) is only 0.6 years, which suggests that many remediation cases, most likely soil cleanup sites, have been completed in much shorter time periods than suggested by the records for sites where the type of affected media was reported.

Cost of Oilfield Remediation Activities

Information on the costs of environmental remediation activities was available from: (1) the Texas State Managed Cleanup Program, which is funded by the state to address decommissioning and/or remediation of oilfield sites for which no responsible operator or owner has been identified, and (2) the Kansas Remediation Site Fund, which supports long-term remediation and monitoring activities at both abandoned and active leases. In addition, the volume of soil excavated at soil remediation sites in Colorado was compiled from Spill/Release Reports submitted to the COGCC, and costs for soil excavations were estimated based on typical unit costs reported for excavation, disposal, and backfill at petroleum-impacted excavation sites in the United States. Key information regarding the costs of remediation activities under the Texas, Kansas, and Colorado programs is in the paragraphs that follow.

Assuming a nominal cost of $50/cubic yard, the median cost for excavation, disposal, and backfill of soil in Colorado is $13,250, with 90th-percentile costs of $73,400.

Cost of Soil Excavation for Soil Remediation in Colorado

Under applicable Colorado regulations, soils exceeding allowable concentrations, as stipulated in Rule 910, Table 910-1, are required to be treated and/or removed (COGCC, 2010b). The volume of soil excavated for the purpose of soil remediation was reported at 131 release sites in Colorado. The median reported soil volume excavated at these remediation sites is 265 cubic yards, with a 90th-percentile excavated soil volume of 1,468 cubic yards. Typical unit costs for excavation, nonhazardous landfill disposal, and backfill of petroleum-contaminated soils in the United States are in the range of $50/cubic yard (Colorado Department of Labor and Employment [CDLE], 2010; Veil, 1997), although unit rates may be less in some jurisdictions. Assuming a nominal cost of $50/cubic yard, the median cost for excavation, disposal, and backfill of soil in Colorado is $13,250, with 90th-percentile costs of $73,400.

Texas State Managed Cleanup Program

The Texas SCP addresses site assessment and decommissioning activities for abandoned sites, principally involving pit closures, removal of tank batteries and other equipment, and, to a lesser extent, remediation of groundwater impacts (A. Correa, personal communication, 2010). For the approximate 9.5-year period of September 2000 through

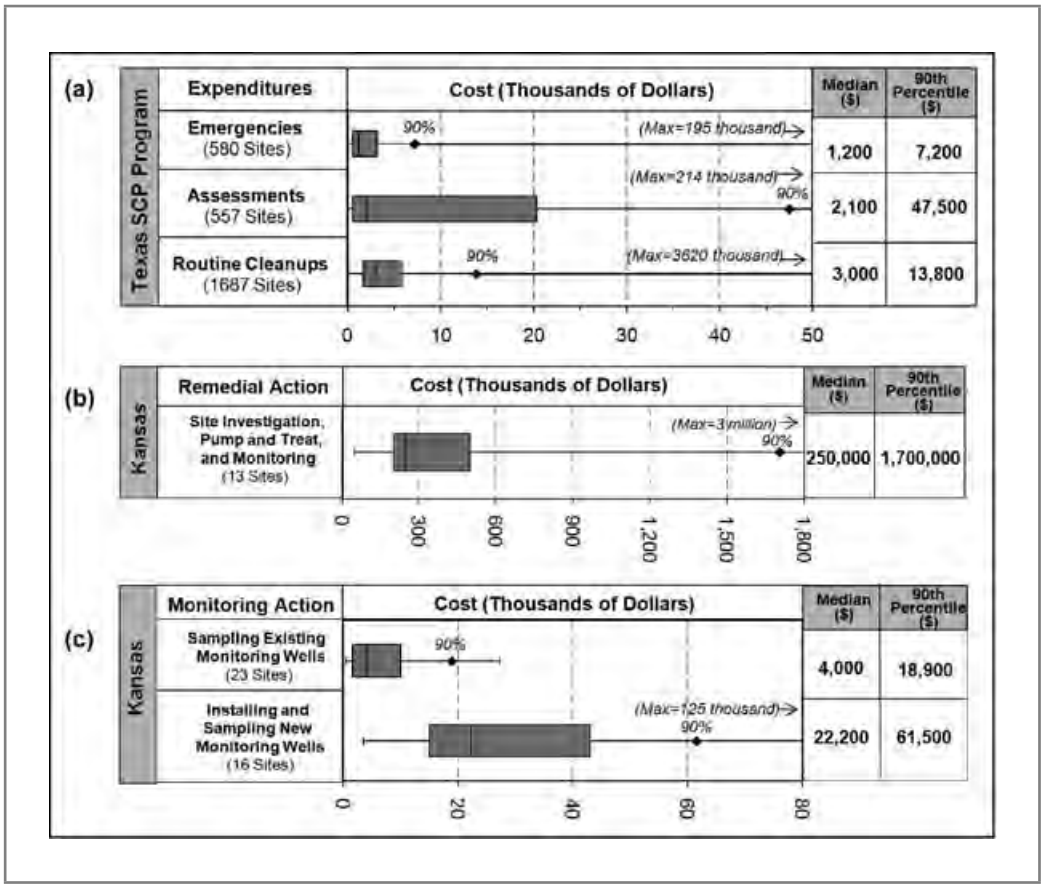

Exhibit 11. (a) Texas State Cleanup Program expenditures; (b) Cost of investigation, pump-and-treat remediation, and monitoring at impacted groundwater sites in Kansas; (c) Cost of monitoring existing wells at impacted groundwater sites in Kansas

February 2010, the SCP database recorded a total of 2,825 site expenditures, which were classified according to the following three categories (see Exhibit 11a):

Emergencies: Immediate actions to address potential threats to human health, safety, or the environment, which are typically completed in a short time period, as needed to mitigate an urgent threat.

Assessments: Activities related to characterization of affected sites, including sampling and lab analysis, delineation of pits, and installation of groundwater monitoring wells.

Routine Cleanups: Short-term or long-term decommissioning or remediation actions for which there is time to complete site evaluation, scoping, and the bid process.

For most sites, both assessments and routine cleanups will be conducted, for which the combined median total costs per site are approximately $5,100 (see Exhibit 11a). This total cost is comparable to the average cost of pit closures at orphaned sites in Louisiana ($4,000), as reported by Lewis et al. (2007).

Remediation DOI: 10.1002/rem

Kansas Remediation Site Fund

The annual Status Reports issued by the KCC provide total estimated costs for site assessments and remedial actions for a portion of the significant remediation projects included in the state database. These costs may be incurred by either the Kansas Remediation Site Fund or by the operator, if a responsible party is identified. As indicated in Exhibit 5, the vast majority of remediation sites in the Kansas database (94 percent) entail groundwater remediation.

Exhibit 11b summarizes the estimated total costs of investigation and remediation at 13 sites where the chosen remedial technology is pumping and treatment (or disposal) of affected groundwater. Estimated expenditures encompass costs associated with site investigation (including the installation of monitoring wells), assessment of potential remedial solutions, and annual monitoring, in addition to that incurred during the installation and maintenance of extraction wells. The median and 90^{th}-percentile total costs for affected groundwater sites undergoing pumping and treatment (or disposal) are $250,000 and $1.7 million, respectively.

Exhibit 11c shows the estimated total costs for 39 affected groundwater sites in Kansas where monitoring was the only response action taken by the state or responsible party. The costs are divided into the costs incurred for sampling at existing monitoring wells (including local domestic wells), with median and 90^{th}-percentile total costs of $4,000 and $18,900, respectively, and the costs incurred for both the installation and sampling of new monitoring wells, with median and 90^{th}-percentile total costs of $22,200 and $61,500, respectively.

The annual Status Reports issued by the KCC provide total estimated costs for site assessments and remedial actions for a portion of the significant remediation projects included in the state database.

SUMMARY OF PRINCIPAL FINDINGS

The data obtained from the state regulatory databases reviewed in this study support the following principal conclusions regarding the frequency, nature, and cost of remedial actions conducted for environmental impacts associated with oilfield operations:

Frequency of Occurrence of Impacts Requiring Remedial Action: Soil impacts have been reported at approximately 9 percent of oil and gas facilities. Impacts to groundwater or surface water requiring remedial action occur less frequently, corresponding to only 0.4 percent and 0.03 percent, respectively, of the total number of oil and gas facilities in the states for which these data were available for the past 10 to 20 years. Groundwater remediation projects are conducted at approximately 4 percent of the sites where soil impacts occur.

Sources of Release for Remediation Sites: The principal sources of release vary among the states investigated, likely due to the differing jurisdictions of the state programs. For example, in Texas, 59 percent of remediation sites are related to crude oil or condensate releases from pipelines, while in Kansas the vast majority of remediation sites (98 percent) are associated with elevated chloride and TDS concentrations related to produced water releases.

Relation of Source Materials to Sources of Release: Source materials (i.e., principally crude oil, produced water, and condensate) are strongly associated with specific operations. When they occur, most crude oil impacts in Texas (62 percent) are observed at pipeline facilities; and condensate impacts in Texas are observed principally at gas plants

(43 percent) and pipeline facilities (35 percent). Produced water impacts, when observed, occur predominantly at produced water disposal facilities (57 percent) in Texas and predominantly at pits (53 percent), wellheads and tank batteries (40 percent), or produced water disposal facilities (32 percent) in Kansas.

Soil Remediation Methods: The principal measures employed for remediation of affected soils are excavation and disposal/off-site treatment (78 percent of sites in Texas and 87 percent of sites in Colorado), followed by in-place landfarming (i.e., "soil mixing and tilling," used at 33 percent of sites in Texas and 10 percent of sites in Colorado). The median soil volume excavated, as reported for remediation sites in Colorado, is 265 cubic yards, with a 90th-percentile soil volume of 1,468 cubic yards.

Groundwater Remediation Methods: For significant groundwater remediation sites, the principal remediation methods reported are: (1) MNA and/or monitoring at existing wells, which is employed as the sole remediation method at 74 percent of Kansas sites and 42 percent of Texas sites, and (2) groundwater pumping and treatment, which is used at 47 percent of sites in Texas and 26 percent of sites in Kansas.

Duration of Environmental Remediation Projects: The median duration of site assessment and remediation activities at closed groundwater remediation sites (4.9 years in Texas, 5 years in Kansas) is significantly less than that of active groundwater remediation sites (8 years in Texas, greater than or equal to 13 years in Kansas), likely due to the fact that the closed sites were simpler to remediate, while the open sites represent the more complex, time-consuming problems. Groundwater impacts entail longer remediation periods than soil impacts. However, it should be pointed out that many of these sites with groundwater impact are still in remediation and eventually the medians may rise.

Cost of Oilfield Remediation Projects: Data from Texas show the median and 90th-percentile total costs for site assessment and decommissioning and/or cleanup activities to be $5,100 and $61,300, respectively. Estimated median and 90th-percentile costs of soil excavation in Colorado are $13,250 and $73,400, assuming a $50/cubic yard unit cost of excavation, disposal, and backfill of soil. In Kansas, the median and 90th-percentile costs for specific actions taken to address affected groundwater are: (1) monitoring existing wells: $4,000 and $18,900, respectively; (2) installation and sampling of monitoring wells: $22,200 and $61,500, respectively; and (3) groundwater pumping and treatment: $250,000 and $1.7 million, respectively.

REFERENCES

Breit, G. N., & Otton, J. K. (2002). USGS produced waters database. Retrieved from http://energy.cr.usgs.gov/prov/prodwat/data2.htm

Colorado Department of Labor and Employment (CDLE). (2010). 4-3-1 rates for activities associated with the excavation, transportation and disposal of petroleum-contaminated soils. Retrieved from http://oil.cdle.state.co.us/archive_old%20items/fund/excvdisp.asp

Colorado Oil and Gas Conservation Commission (COGCC). (2010a). Colorado Oil and Gas Information System (COGIS) "inspection/incident inquiry" database. Retrieved from http://cogcc.state.co.us/cogis/IncidentSearch.asp

Colorado Oil and Gas Conservation Commission (COGCC). (2010b). COGCC Webpage, rules, 900 series exploration and production waste management. Retrieved from http://cogcc.state.co.us/

Fisher, J., & Sublette, K. (2005). Environmental releases from exploration and production operations in Oklahoma: Type, volume, causes, and prevention. Environmental Geosciences, 12(2), 89–99.

Hesson, B. (2008). An inventory of orphan facilities within oil fields in the state of California: Potential costs and recommendations. California Department of Conservation—Division of Oil, Gas, and Geothermal Resources. Retrieved from ftp://ftp.consrv.ca.gov/pub/oil/publications/Open-file6.pdf

Kansas Corporation Commission (KCC). (1997–2010). Annual remediation site status report 1997–2010. Environmental Protection and Remediation Section of the Conservation Division. Topeka, KS: Author.

Kansas Corporation Commission (KCC). (2010, December 17). Open records request: Total number of spills reported by district offices between 1996 and 2009. Topeka, KS: Legal Dept., KCC.

Kansas Geological Survey (KGS). (2010). State production and historical info. Kansas Geological Survey, Kansas State University. Retrieved from http://www.kgs.ku.edu/PRS/petro/state.html

Kant, A. (2010). Oilfield abandonment and soil restoration in the Netherlands: Experiences for the future. Presented at the SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production, Rio de Janeiro, Brazil.

Lewis, A., Webre, T., & Wojtanowicz, A. (2007). Louisiana orphaned reserve pit cost assessment. Presented at the SPE E&P Environmental and Safety Conference, Galveston, Texas.

Louisiana Department of Natural Resources (DNR). (2008). Strategic Online Natural Resources Information System (SONRIS) database, Louisiana Department of Natural Resources. Retrieved from http://sonris.com/

New Mexico Oil Conservation Division (NMOCD). (2005, September 30). Generalized record of ground water impact sites. Santa Fe, NM: Energy, Minerals and Natural Resources Department.

New Mexico Oil Conservation Division (NMOCD). (2010). OCD online database, administrative and environmental orders issued prior to 2006. Santa Fe, NM: Energy, Minerals and Natural Resources Department.

Operator Cleanup Program (OCP), Railroad Commission of Texas (RRC). (2010). OCP database obtained through an open records request submitted to the site remediation section of the RRC.

Railroad Commission of Texas (RRC). (2009). Distribution of wells monitored by the Railroad Commission as of March 28, 2009. Railroad Commission of Texas, Data and Statistics. Retrieved from http://www.rrc.state.tx.us/data/wells/welldistribution/welldistribution032809.pdf

Railroad Commission of Texas (RRC). (2010). Open records request: Number of H8 forms filed between 1989 and 2009, Office of General Counsel, RRC.

State Funded Cleanup Program (SCP), Railroad Commission of Texas (RRC). (2010). SCP database obtained through an open records request submitted to the site remediation section of the RRC.

Texas Groundwater Protection Committee (TGPC). (1990–2010). Joint groundwater monitoring and contamination report 1990–2010. Prepared by the Texas Groundwater Protection Committee. Retrieved from http://www.tceq.state.tx.us/comm_exec/forms_pubs/pubs/sfr/056_08_index.html

US Energy Information Administration (US EIA). (2009b). New Mexico 2005 distribution of wells by production rate bracket. US Energy Information Administration—Independent Statistics and Analysis. Retrieved from http://www.eia.doe.gov/pub/oil_gas/petrosystem/nm_table.html

Veil, J. A. (1997, April). Costs for off-site disposal of nonhazardous oil field wastes: Salt caverns versus other disposal methods. Prepared by Argonne National Laboratory for the US Department of Energy.

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