Emergency use of groundwater as a backup supply: Quantifying hydraulic impacts and economic benefits

Eric G. Reichard,[1] Zhen Li,[1] and Caroline Hermans[2]

Received 22 May 2009; revised 9 January 2010; accepted 22 April 2010; published 21 September 2010.

[1] Groundwater can play an important role in water-supply emergency planning. A framework is presented for assessing the hydraulic impacts and associated costs of using groundwater as a backup supply when imported-water deliveries are disrupted, and for quantifying the emergency benefits of groundwater management strategies that enable better response to such disruptions. Response functions are derived, which relate additional groundwater pumpage during water-supply emergencies to impacts such as increased pumping costs, subsidence, and seawater intrusion. Monte Carlo analysis is employed to estimate the incremental costs of using groundwater as a backup supply. The emergency benefits of alternative groundwater management strategies are computed for different expected durations of imported water disruption, percentages of imported water replaced by groundwater, and threshold drawdowns for subsidence impacts. The methodology is applied to the coastal Los Angeles Basin. For this case study, emergency benefits of artificial recharge strategies are dominated by reduction of potential subsidence costs. The variance of the results also is primarily due to subsidence effects. Incorporation of probability distributions reflecting a larger expected use of groundwater during the imported-water disruption results in higher estimated emergency benefits of artificial recharge strategies. The framework presented for quantifying incremental costs and economic benefits of using groundwater as a backup supply could be applied to a broad range of water emergency planning decisions.

Citation: Reichard, E. G., Z. Li, and C. Hermans (2010), Emergency use of groundwater as a backup supply: Quantifying hydraulic impacts and economic benefits, *Water Resour. Res.*, *46*, W09524, doi:10.1029/2009WR008208.

1. Introduction

[2] Catastrophic events, such as earthquakes, can cause water-supply disruptions that can, in turn, result in large monetary losses. *Brozović et al.* [2007] estimated that the potential costs of a water-supply disruption in the San Francisco Bay area due to an earthquake could be as high as $14 billion, mostly from business losses. Similarly, a study of the potential impacts of an earthquake along the San Andreas Fault in southern California estimated that there could be $50 billion in business losses due to water-supply disruptions [*Jones et al.*, 2008]. Given the enormity of these potential costs, which can result from disruptions in imported water delivery, as well as failure of local infrastructure, there is a strong economic incentive to investigate specific strategies for mitigating the impact of such water-supply emergencies.

[3] In this paper, we focus on the role that groundwater can play in water-supply emergency planning. Groundwater has multiple economic attributes [*National Research Council*, 1997; *Reichard and Raucher*, 2003]. A key economic attribute of groundwater is its buffer or stabilization value; groundwater provides a buffer to the variability in surface water supplies. *Bredehoeft and Young* [1983] noted that the apparent investment in excess well capacity along the South Platte River in Colorado reflected the value that farmers placed on reducing the risks associated with variable surface water supplies. In several studies, Tsur and coworkers have reported that groundwater's stabilization value can be significant [*Tsur*, 1990; *Tsur and Graham-Tomasi*, 1991; *Gemma and Tsur*, 2007]. *Knapp and Olson* [1995] considered conjunctive-use management under conditions of stochastic surface water supplies. They noted that artificial recharge tended to be more likely when there was higher variability in surface supplies. *Cutter* [2007] estimated the buffer value of groundwater in the Los Angeles region by comparing the stock value of groundwater under stochastic versus deterministic conditions, under range of assumptions. He determined that the buffer value of groundwater was significant, in spite of the development of multiple surface storage facilities.

[4] Most studies addressing the stabilization value of groundwater have looked at the overall variability in surface water supplies. This study focuses on the specific role that groundwater can play in emergency planning, and provides a new framework for quantifying incremental costs and emergency benefits. Emergency benefits can be considered a subcategory of stabilization benefits. We consider a future event of an uncertain magnitude that causes a disruption in deliveries of imported surface water, and evaluate alternative scenarios for using local groundwater as a backup supply. We present a framework for estimating the hydraulic

[1]U.S. Geological Survey, San Diego, California, USA.
[2]Advanced Science Research Center, Environmental Cross-Roads Initiative, CUNY, New York, New York, USA.

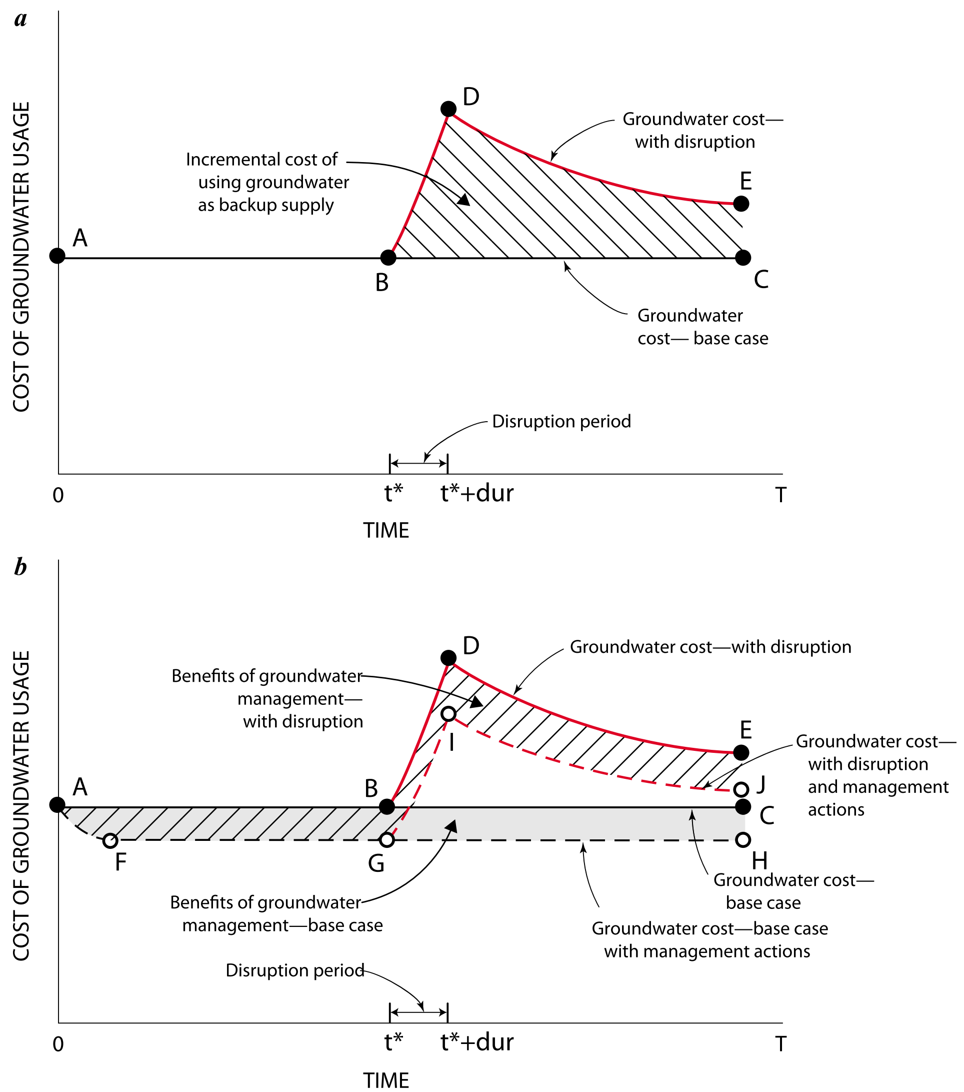

Figure 1. Conceptual framework: schematic representation of (a) the incremental costs of using groundwater as backup supply and (b) the benefits of groundwater management actions.

impacts of replacing different portions of imported water with groundwater, quantifying the costs of these impacts, and quantifying the cost reductions that can be brought about by implementing groundwater management strategies. We refer to these cost reductions as the emergency benefits.

[5] The paper is organized in the following manner. First, we present an overview of the framework. Second, we describe the study area used for the example case study. Third, we demonstrate how the hydraulic impacts of different water emergency scenarios are estimated with a simulation model, and represented by response functions. Finally, we apply Monte Carlo analysis to estimate the incremental costs of using groundwater as a backup supply during emergencies and the emergency benefits of alternative groundwater management strategies.

2. Overview of Framework

[6] Water managers must plan for the possibility of an emergency that would cause a disruption in delivery of imported water for some period of time. In a region with available groundwater supplies, some percentage of imported-water deliveries could be made up by additional groundwater pumping. Water managers may consider this additional use of groundwater, along with other options, including utilizing available storage in local reservoirs and implementation of water conservation measures. In order to make sound decisions, these managers need information on the likely hydraulic impacts of additional groundwater pumpage occurring during the disruption, and the benefits of alternative groundwater management strategies in reducing the costs of these impacts. This study presents a quantitative framework for providing this information.

[7] The framework employed in the analyses is illustrated schematically in Figure 1. Figure 1 shows the direct and indirect costs of groundwater usage under different scenarios during the planning period from time 0 to time *T*. There is a potential disruption of imported-water delivery of given duration (*dur*) that may occur at time *t**. If the disruption occurs, additional groundwater can be pumped to replace some portion of the lost imported water. In Figure 1a, curve ABC represents the expected costs of groundwater use for

base case conditions: no disruption. For simplicity, curve ABC is shown as a horizontal line, implying that groundwater costs are constant. This would be the case for steady state conditions. In reality, the expected base case costs of groundwater use could be changing with time. The curve ABDE represents the costs if a disruption occurs and additional groundwater is pumped. The shape of curve ABDE schematically illustrates that the costs of groundwater use increase sharply during the disruption period (BD), and that residual costs are incurred after the additional groundwater pumpage ceases (DE). The area between curves ABDE and ABC in Figure 1a represents the total incremental costs associated with using groundwater as a backup supply. The costs can be compared with costs of alternative sources of backup supply.

[8] Implementing groundwater management actions, such as artificial recharge, increases the amount of groundwater in storage, thereby reducing the costs of future groundwater use. As described below, costs reductions may include reduced pumping lifts, reduced subsidence, and reduced seawater intrusion. In Figure 1b, curve AFGH represents the costs of groundwater use with groundwater management for base case conditions (no imported-water disruption), and curve AFGIJ represents the costs of groundwater use with groundwater management if a disruption occurs. The area between curves ABC and AFGH (the gray area in Figure 1b) represents the benefits of groundwater management for base case conditions. The area between curves ABDE and AFGIJ (the hachured area in Figure 1b) represents the benefits of groundwater management if a disruption occurs. To quantify the emergency benefits of a groundwater management strategy, it is necessary to take the benefits it provides with a disruption (the hachured area in Figure 1b), and subtract the benefits that would be provided in the base case when there is no disruption (the gray area in Figure 1b). The magnitude of emergency benefits will depend on many factors, including the timing and duration of the imported-water disruption, the amount of additional groundwater that is used during the disruption, the hydraulic functioning of the groundwater system, the attributes of the groundwater management actions, and economic parameters. While the focus of this paper is on quantifying benefits, it is important to emphasize that the benefits of groundwater management actions, such as artificial recharge, must be compared with the costs of implementing and operating these management actions.

[9] The incremental costs of additional groundwater pumpage during the imported water disruption are due to the greater volumes of water being pumped and the direct and indirect impacts of water-level drawdowns. These drawdowns will be greatest during the disruption period, but will continue to have an impact after imported-water supplies are restored. The drawdowns result in increased pumping lifts and may cause additional hydraulic impacts such as land subsidence and seawater intrusion. The relation between the additional groundwater pumpage and the resulting hydraulic impacts is a function of the distribution of wells, and the physics of groundwater flow, solute transport, and land subsidence. These impacts can be estimated with a groundwater simulation model. The net present value of the costs of these hydraulic impacts can be computed by applying cost coefficients (costs of pumpage per unit pumping lift, and cost/unit area affected by land subsidence or seawater intrusion) and a discount rate.

[10] There are multiple uncertainties associated with a possible future imported-water disruption. The analyses presented here explicitly consider the uncertainty regarding the likely percentage of current imported-water deliveries that will be made up by additional groundwater pumping. Monte Carlo analysis is employed to estimate the expected impacts of different management strategies under different probabilistic expectations regarding the likely percentage of imported-water supplies that is replaced by groundwater, the expected duration of the disruption, and the threshold drawdown for subsidence impacts.

[11] Note that this study focuses on disruptions in the delivery of imported water through aqueducts or pipelines. It is assumed that the local water distribution systems and the existing wells remain functional. It also is assumed that there is sufficient well capacity to extract additional groundwater.

3. Description of Study Area

[12] The framework outlined above is applied to the Central and West Coast Basins of the coastal Los Angeles Basin (Figure 2). It is an appropriate area for a case study, because it has significant groundwater resources, but also relies heavily on imported water deliveries that could be disrupted. In order to meet the water demands of over four million people in the region, about 308 million m^3/yr (250,000 acre-ft/yr (af/yr)) are pumped from groundwater, and about 382 million m^3/yr (310,000 af/yr) are provided by imported surface water. In addition to the direct delivery of imported surface water, about 148 million m^3/yr (120,000 af/yr) of additional surface water (imported, recycled, and local runoff) are applied in spreading ponds in the Montebello Forebay northeastern portion of the study area, and about 37 million m^3/yr (30,000 af/yr) of imported and recycled water are injected into wells in three barrier projects–the West Coast Basin Barrier Project, the Dominguez Gap Barrier Project, and the Alamitos Barrier Project–along the coast for control of seawater intrusion (Figure 2). Artificial recharge via spreading and injection provides the largest component of recharge to the regional groundwater system. Imported water comes from three sources: the California State Water Project, Owens Valley, and the Colorado River. Most of the water purveyors in the Central and West Coast Basins have the ability to use both imported water and groundwater. Some rely strictly on one or the other.

[13] Delivery of imported water to the coastal Los Angeles area could be disrupted by a range of events, including an earthquake in southern California that damages one or more of the main aqueducts entering the region, or a breach in the levees in the Sacramento-San Joaquin Delta in northern California. A recent study concluded that the breach of multiple levees due to an earthquake could result in an extended disruption in water-supply exports through the Delta [*California Department of Water Resources*, 2009].

[14] Detailed information on the hydrogeology, geochemistry and groundwater management issues of the area can be found in work by *Poland et al.* [1956, 1959], *California Department of Water Resources* [1961], *Reichard et al.* [2003], *Land et al.* [2004], and *Reichard and Johnson*

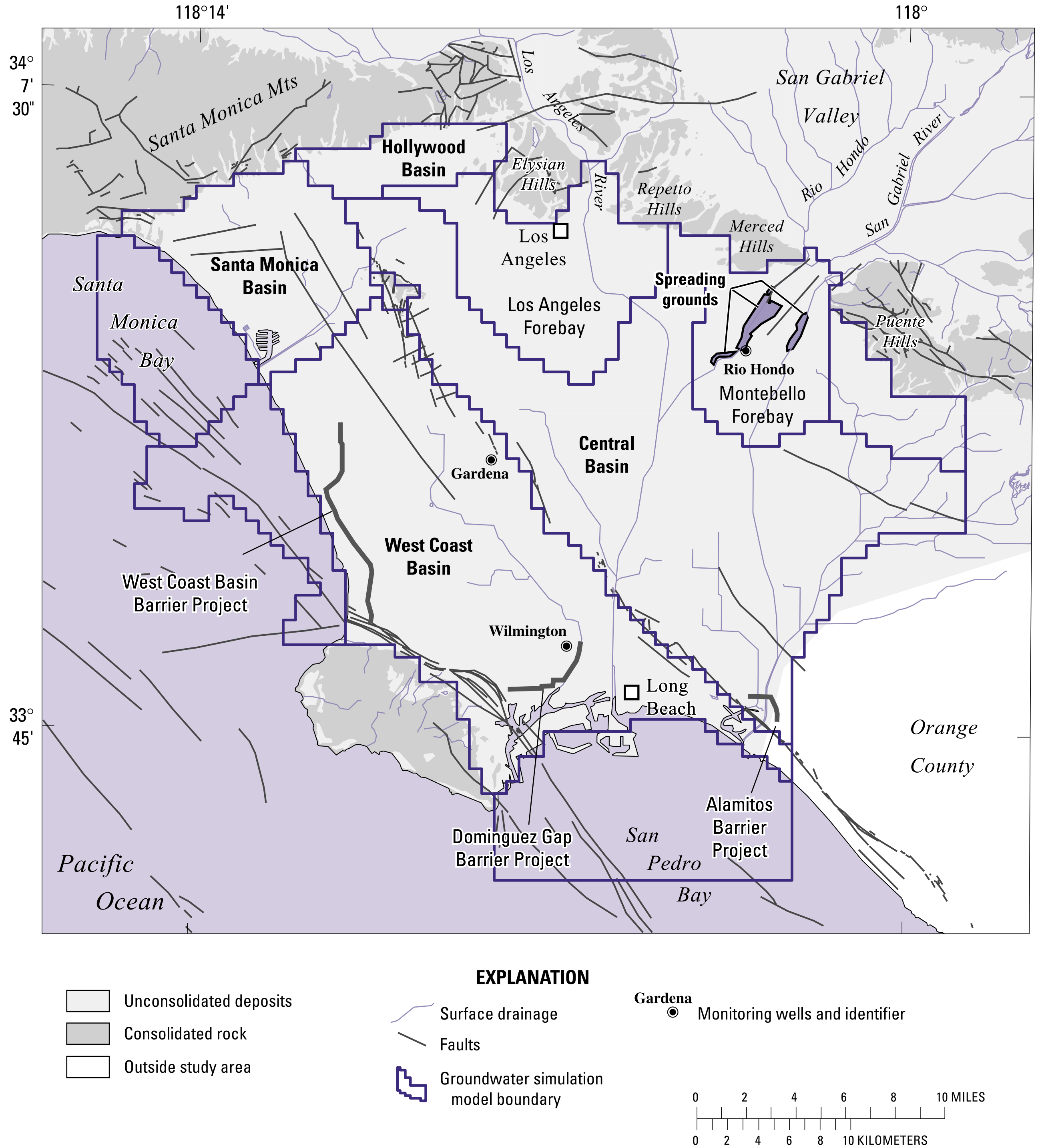

Figure 2. Study area: Central and West Coast Groundwater Basins, Los Angeles County, California.

[2005]. A MODFLOW model [*Harbaugh et al.*, 2000; *Harbaugh and McDonald*, 1996] has been developed for the study area [*Reichard et al.*, 2003]. The four-layer model contains 4,480 cells, each with a horizontal dimension of 0.805 km (0.5 mi) along rows and columns. The four layers represent the major aquifer systems: Recent, Lakewood, Upper San Pedro, and Lower San Pedro. Approximately 80 percent of the groundwater pumpage is from the Upper San Pedro Aquifer system, which is represented by model layer 3. The analyses presented below focus on water levels in this aquifer system.

4. Simulation of Hydraulic Impacts of Water-Supply Emergency Scenarios

[15] The assumed characteristics of the water-supply emergencies are the following. The overall planning period (T) is 25 years. The duration of the disruption, *dur,* is either

6 months or 2 years. It is assumed that a disruption in the delivery of imported surface water occurs at time t^* (assumed to be the middle of year 11 for the 6-month duration case and the beginning of year 11 for the 2-year duration case). A percentage of imported-water delivery, p, is made up by groundwater. Initially we simulate a discrete set of scenarios with different values of *dur* and p, and different management actions. We then use the results from those simulations to generate response functions. Finally, we incorporate those response functions into a Monte Carlo analysis, which considers the uncertainty in p, in order to assess incremental costs of using groundwater as a backup supply and the emergency benefits of groundwater management.

[16] There are several important assumptions in this formulation. We only consider uncertainty regarding two components of the analyses: the percentage of imported-water delivery, p, made up by groundwater, and the duration of the disruption, *dur*. As is described below, uncertainty in p is rigorously addressed by incorporating continuous response functions and probability distributions into Monte Carlo analyses. Uncertainty in *dur* is only represented by considering two alternative values, 6 months and 2 years, which are assumed to bracket the possible range of disruption durations. The 6-month disruption is considered the most likely disruption that water managers would feel a need to plan for, and a 2-year disruption is considered an extreme case [see, e.g., *California Department of Water Resources*, 2009]. Separate Monte Carlo analyses are conducted for the two *dur* values. The methodology could be extended to consider a continuous range of possible values of *dur*. A major simplification in the analyses is that we assume that we know with certainty that, if a disruption occurs (i.e., $p > 0$), it will occur at time t^*. The methodology also could be extended to consider a range of possible values of t^*. Incorporation of uncertainty in t^* could be accomplished with the framework presented in this paper; it would involve generation of multivariate response functions, rather than the univariate response functions presented below. While not all uncertainty components are explicitly incorporated in this the analyses presented here, the methodology can provide useful results in spite of its simplifications, and serve as a systematic framework to build on.

[17] For the scenarios considered below, it is assumed that entities with their own groundwater wells will make up a portion of their lost imported water by pumping additional water from these wells. Water users who do not have their own wells are assumed to utilize wells from adjacent entities. As stated initially, it is assumed that the local distribution system is largely intact, and that there is sufficient surplus well capacity to pump additional groundwater. In the scenarios considered below, it also is assumed that when there is any reduction in delivery of imported surface water, no imported water is used for either spreading or injection.

[18] The groundwater simulation model discretizes the 25-year planning period, into 6-month stress periods. The set of simulated scenarios, which are used to generate the response functions, consider four discrete values of p, (0, 30, 75, and 100%), two different disruption durations, *dur*, (6 months and 2 years), and three alternative groundwater management strategies (status quo, additional spreading (M1), and additional spreading and injection (M2)), a total of 21 scenarios (Table 1). Note that the four discrete values of p used for simulated scenarios were chosen to span the range of possible values. Alternative or additional values could be simulated and incorporated into the derivation of response functions described below.

[19] The assumed status quo values for spreading and injection are 148 million m^3/yr (120,000 af/yr) and 47 million m^3/yr (38,000 af/yr). The additional spreading in strategies M1 and M2 consists of an incremental 37 million m^3/yr (30,000 af/yr) of recharge in years 1–10 in spreading grounds located in the northeastern part of the study area (Figure 2). This represents a 25 percent increase from the status quo spreading. The additional injection in strategy M2 consists of a combined incremental injection of 12 million m^3/yr (10,000 af/yr) in years 1–10 in the West Coast and Dominguez Gap barrier projects along the coast (Figure 2). This represents a 26 percent increase from the status quo injection.

[20] Base case pumpage is taken as 316 million m^3/yr (256,000 af/yr). Current average imported water delivery is 382 million m^3/yr (310,000 af/yr). Therefore, a p value of 30%, for example, implies pumping 115 million m^3/yr (93,000 af/yr) of additional groundwater to replace disrupted imported water deliveries.

[21] The hydraulic responses assessed with the model are: 1) the summed products of pumping lifts and pumpage (*qlift*) at all pumping locations, computed at representative times during the planning period; 2) the additional area potentially affected by subsidence (*sub*); and 3) the additional area potentially affected by seawater intrusion (*Int*). The responses for all 21 simulated scenarios are tabulated in Table 1. Before describing how the simulation results listed in Table 1 are used to develop response functions, it is helpful to look at some features of example results from four of the simulated scenarios: the base case, and scenarios 3, 3_M1 and 3_M2. As listed in Table 1, the base case is status quo (no additional management activities) and has no disruption in imported-water deliveries. This is equivalent to ABC in Figure 1. In scenarios 3, 3_M1, and 3_M2, imported-water deliveries are disrupted for 2 years, and 75 percent of the imported water is made up by groundwater. Scenario 3, which involves no additional management activities, could be represented by a curve equivalent to ABDE in Figure 1. Scenarios 3_M1, which involves additional spreading; and scenario 3_M2, which involves additional spreading and injection could be represented by curves equivalent to AFGIJ in Figure 1b.

4.1. Water Levels and Pumping Lifts

[22] Figure 3 shows the simulated difference from base-case water levels at year 12 (the end of the disruption period) and year 25 (the end of the planning period) for scenario 3 (imported-water deliveries are disrupted for 2 years, and 75 percent of the imported water is made up by groundwater; see Table 1). As can be seen from Figure 3a, water levels at the end of the disruption (year 12) are as much as 61 m (200 ft) below base case levels. Figure 3b shows that, even at the end of the 25-year planning period, simulated water levels are still below base case values throughout the area.

[23] Figure 4 shows hydrographs of water levels for the base case, and scenarios 3, 3_M1, and 3_M2 (Table 1), at three locations in the area: Rio Hondo, located in the Central Basin in the northeastern part of the basin near the spreading

Table 1. Model Simulation Results for Emergency Scenarios

Disruption Scenario	Management Scenario	Disruption Duration (years)	Imported Water Replaced by Groundwater (%)	Subsidence Area (square miles)		Intrusion Area (square miles)	Qlift, Pre-disruption (million acre-ft/year*ft)	Qlift, Disruption (million acre-ft/year*ft)	Qlift, Post-disruption (million acre-ft/year*ft)
				15 m Threshold	30 m Threshold				
Base case	Status Quo	0	0	2.5	0	3.75	25.56	25.63	25.65
Base_M1	Additional spreading	0	0	2	0	2.25	22.65	23.06	23.74
Base_M2	Additional injection and spreading			1.5	0	1.25	21.8	22.52	23.31
1	Status Quo	2	100	215.5	96	14.75	25.56	108.04	31.26
1_M1	Additional spreading	2	100	194	81.5	14.25	22.65	104.38	29.32
1_M2	Additional injection and spreading	2	100	189.5	72.75	11.75	21.8	103.35	28.92
2	Status Quo	0.5	100	154.5	18.75	6.5	25.56	94.68	27.06
2_M1	Additional spreading	0.5	100	139.75	16.75	5.75	22.65	90.81	25.09
2_M2	Additional injection and spreading	0.5	100	133.75	13.75	3.75	21.8	89.85	24.67
3	Status Quo	2	75	180.75	32	12.75	25.56	82.53	30.05
3_M1	Additional spreading	2	75	161	29.25	11.75	22.65	79.1	28.09
3_M2	Additional injection and spreading	2	75	152.75	23	9.75	21.8	78.15	27.68
4	Status Quo	0.5	75	127.25	7.75	5.5	25.56	73.69	26.73
4_M1	Additional spreading	0.5	75	114.5	7.25	4	22.65	70.06	24.78
4_M2	Additional injection and spreading	0.5	75	106.25	5.75	2.75	21.8	69.07	24.35
5	Status Quo	2	30	41	1.25	7.75	25.56	45.1	27.94
5_M1	Additional spreading	2	30	24.25	1	6.75	22.65	42.16	25.96
5_M2	Additional injection and spreading	2	30	19.25	1	4.5	21.8	41.42	25.53
6	Status Quo	0.5	30	23	0.5	3.75	25.56	41.89	26.19
6_M1	Additional spreading	0.5	30	12.25	0.25	2.75	22.65	38.75	24.24
6_M2	Additional injection and spreading	0.5	30	10	0.25	1.75	21.8	37.95	23.82

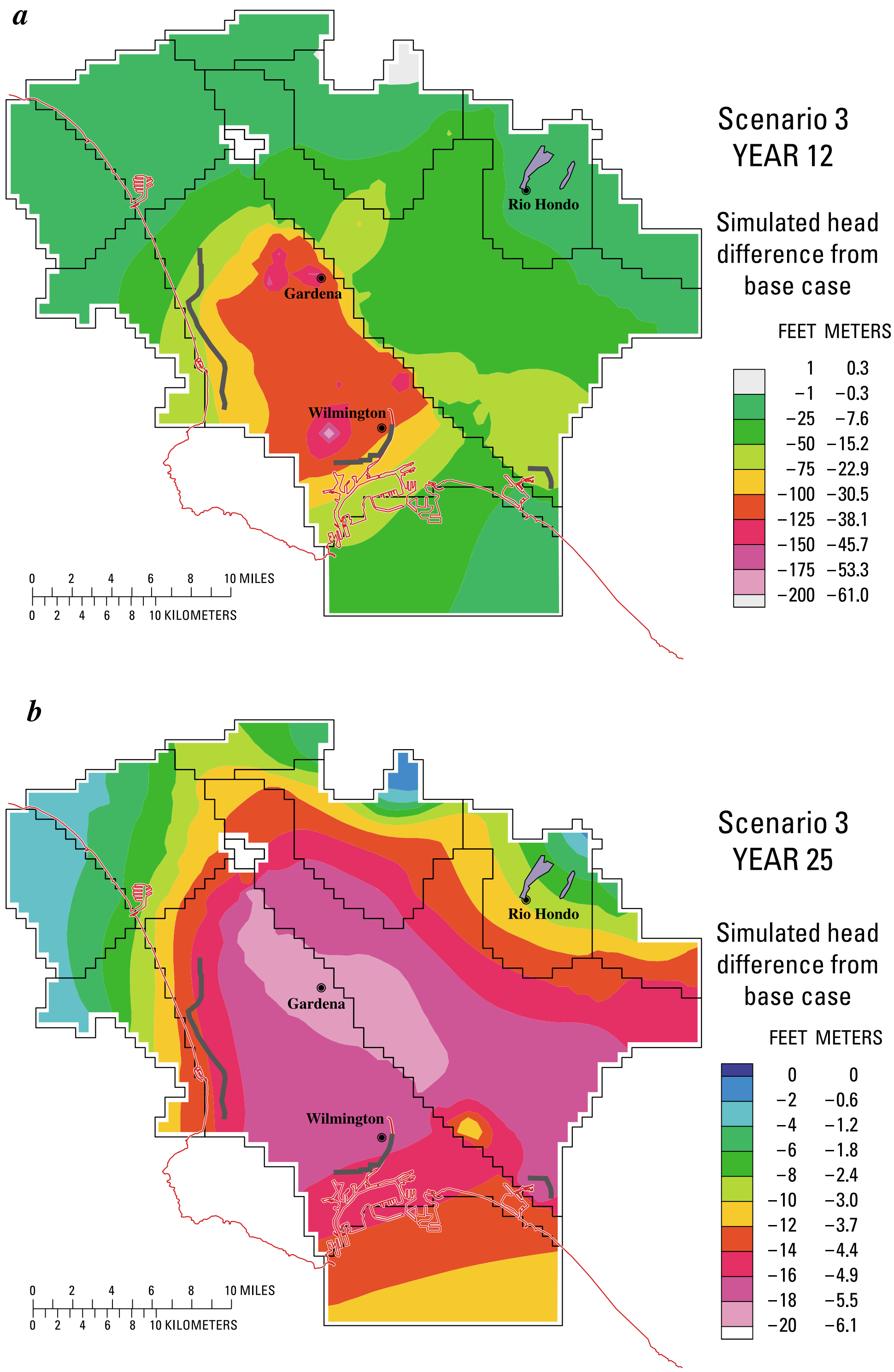

Figure 3. Difference in simulated water levels from base case for Scenario 3: (a) year 12 and (b) year 25. (Note that different contour ranges are used for Figures 3a and 3b. The largest head difference range shown for year 12 is −53.3 to −61 m; the largest head difference range shown for year 25 is −5.5 to − 6.1 m).

facilities, Wilmington, located near one of the barrier injection projects in the West Coast Basin, and Gardena, located within a pumping center farther from the injection projects in the West Coast Basin (see Figure 2). The Rio Hondo site is located in an area of unconfined-to-semi-confined conditions, whereas the Wilmington and Gardena sites are located in an area of confined conditions. Figure 4 illustrates the steep drawdowns that occur at Wilmington and Gardena during the disruption period, and the long time required for water-level recovery. At Rio Hondo, strategies M1 (additional spreading) and M2 (additional spreading and injection) have similar impacts on water levels; the additional

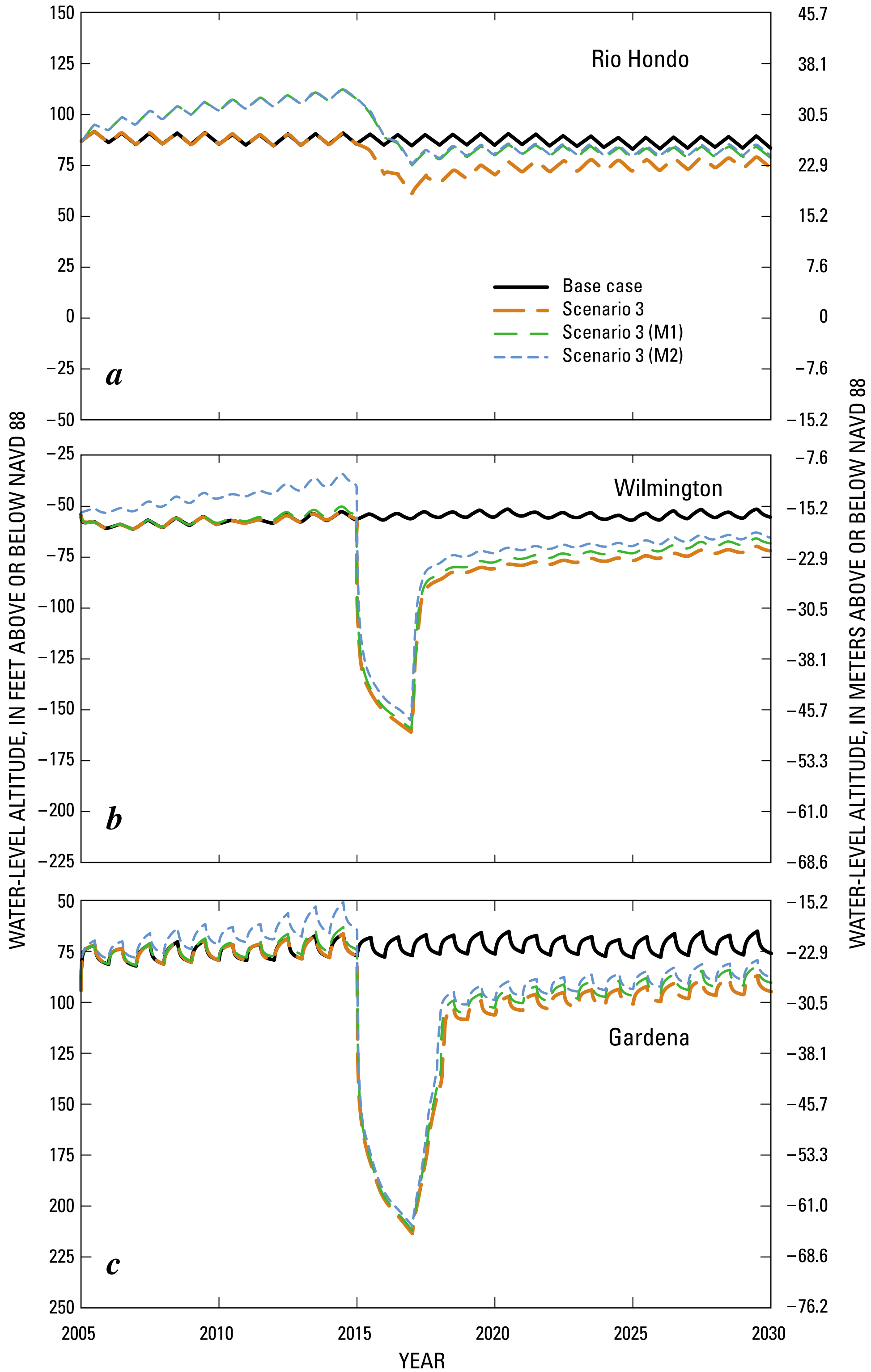

Figure 4. Time series of simulated water levels for base case, scenario 3, scenario 3_M1, and scenario 3_M2 at (a) Rio Hondo, (b) Wilmington, and (c) Gardena.

injection near the coast has minimal effect on water levels at this location. At Wilmington, located near injection wells, management strategy M2 (additional spreading and injection) has the greatest impact, although strategy M1 (just additional spreading) does have a very small effect on post-disruption water-level recovery. At Gardena, neither strategy has significant effects on water levels during the disruption, but both have some impact on post-disruption recovery.

[24] Differences in water levels for the example simulated scenarios illustrated in Figures 3 and 4 imply differences in pumping lifts, and hence differences in pumping costs. To quantify this, the product of pumping rates and pumping

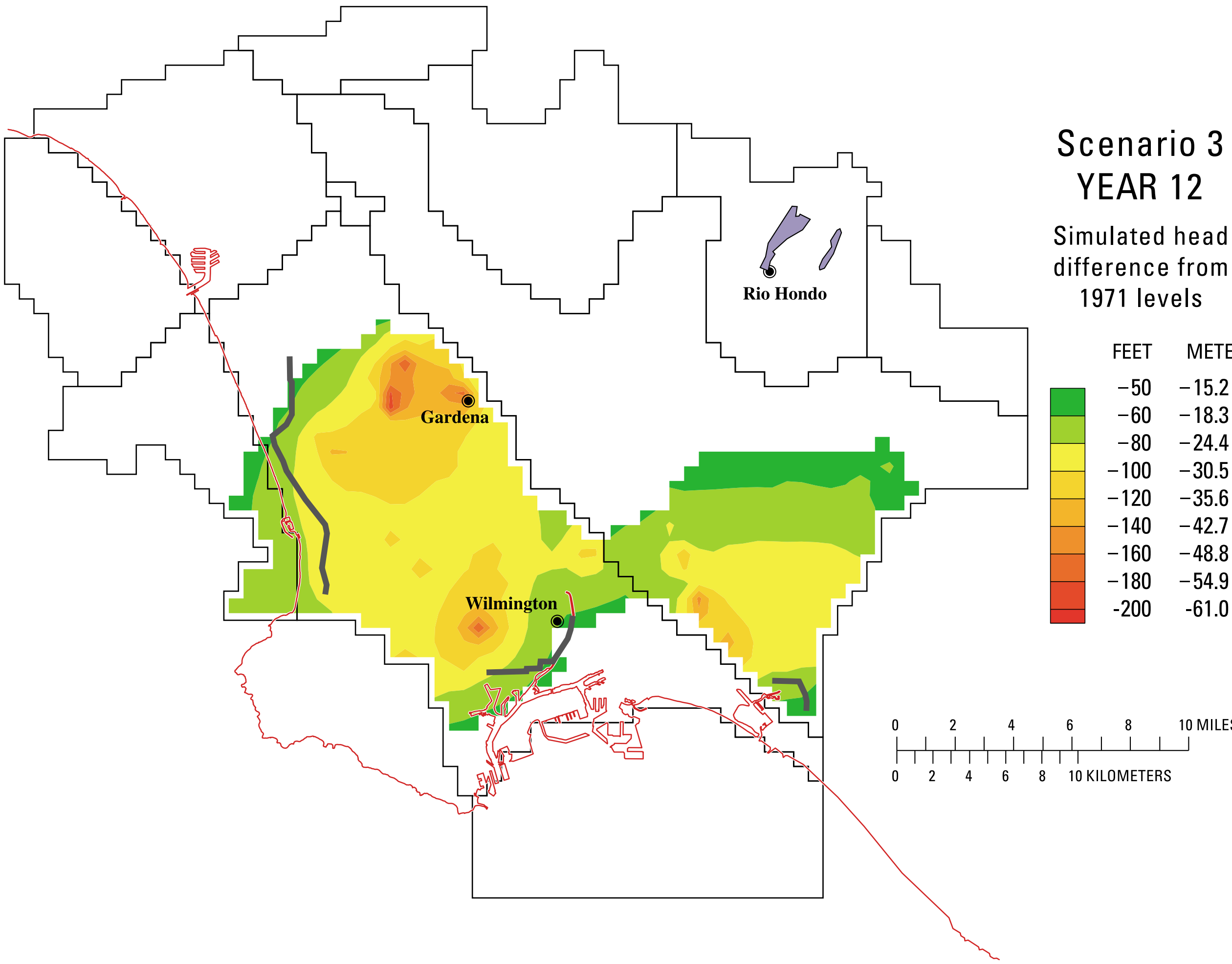

Figure 5. Simulated drawdown from 1971 water levels for scenario 3 at end of year 12.

lifts are computed for each well in the study area and summed over all wells during representative years in the analysis period. For each scenario, Table 1 lists this summed product, *qlift*, at three representative times: pre-disruption (t = 10 years), at the end of the disruption (the end of year 11 or year 12, depending on whether the disruption is assumed to be for 6 months or 2 years), and post-disruption (t = 18 years, in the middle of the post-disruption recovery). As note that, the disruption is assumed to begin in middle of year 11 for the 6-month duration case the start of year 11 of the 2-year disruption case.

4.2. Land Subsidence

[25] The groundwater flow model does not explicitly simulate subsidence. As a simple surrogate, the model was used to delineate areas where water levels decline to elevations that are likely to be near or below historic low values. Such historic low water levels are referred to as preconsolidation heads, and represent the previous maximum effective stress. When water levels fall below the preconsolidation head, inelastic compaction of sediments can occur [*Hoffmann et al.*, 2003; *Galloway et al.*, 1999]. The simulation model was originally developed to simulate water levels beginning in 1971, at which time water levels were considered to be in a quasi-steady state condition. Based on water-level data for long-term monitoring wells, historic low water levels in the area occurred approximately 10 years earlier [*Water Replenishment District of Southern California*, 2006, Figures 3.7–3.10], Historic low water levels were estimated to range from 0 to 24 m (80 ft) below 1971 levels in many parts of the study area. For the computations here, we consider two example drawdown thresholds for subsidence: 15 m (50 ft) and 30 m (100 ft) below 1971 water levels.

[26] The model was used to determine the areas where drawdowns exceed these specified thresholds. This serves as a useful indicator of areas potentially subject to subsidence. However, we emphasize that this is a very simplified representation of subsidence susceptibility. It does not consider how the physical properties of the materials affect subsidence. Because the simulation model does not account for the water released from storage during inelastic compaction, it likely overestimates drawdowns, and hence the area affected by subsidence. Any overestimate of drawdowns would also affect the estimates of pumping lifts and the hydraulic gradients that impact seawater intrusion.

[27] Figure 5 shows model cells at which water levels at the end of the disruption period for scenario 3 (imported-

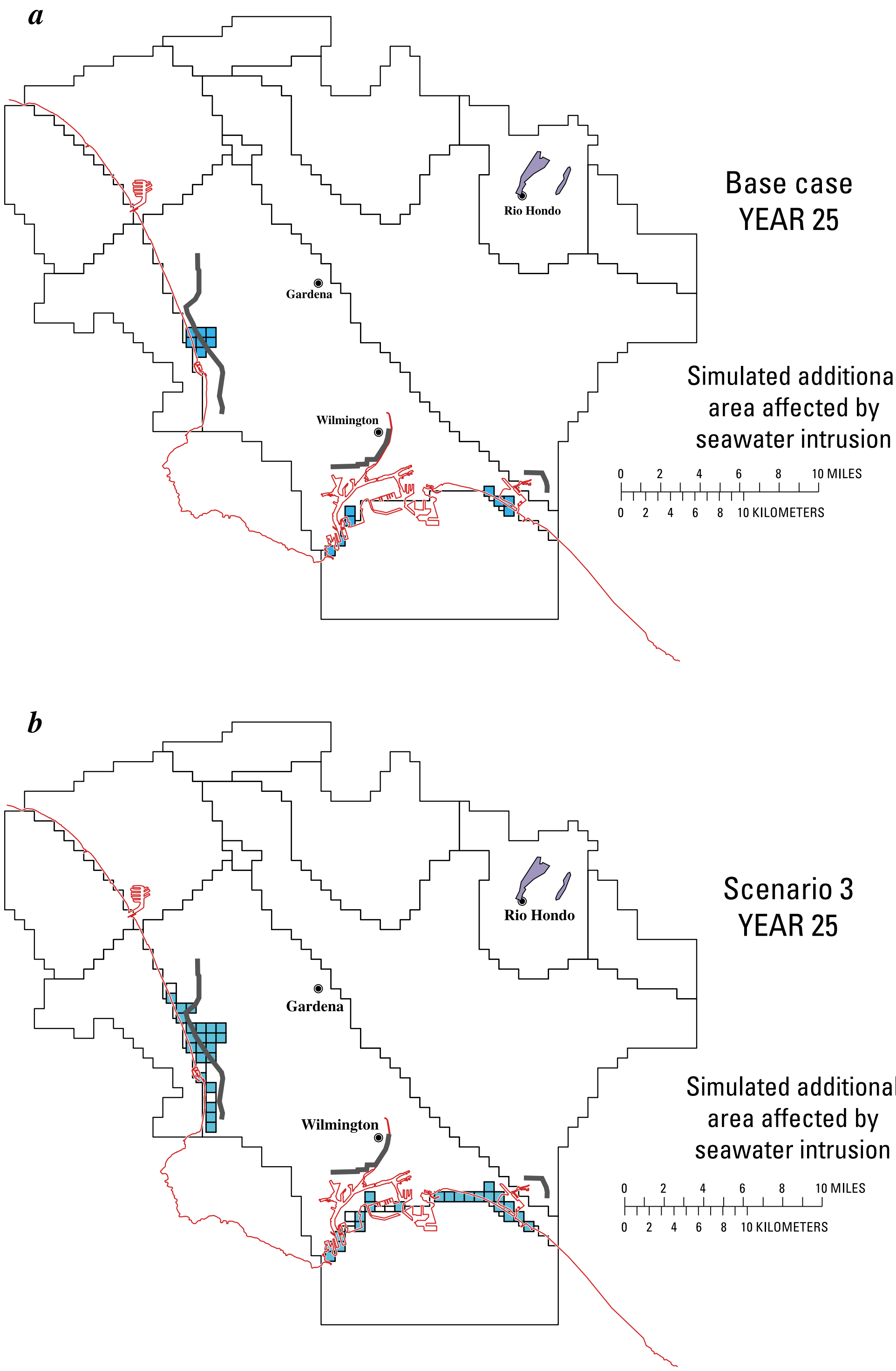

Figure 6. Simulated additional area affected by seawater intrusion in year 25: (a) base case and (b) Scenario 3.

water deliveries are disrupted for 2 years, and 75 percent of the imported water is made up by groundwater) were at least 15 m (50 ft) below 1971 values, indicating potential susceptibility to subsidence. The total area, *Su*, in which water levels are 15 m (50 ft) or more below 1971 levels, is 469 km^2 (181 mi^2). The total area, *Su*, in which water levels are 30 m (100 ft) or more below 1971 levels, is 83 km^2 (32 mi^2). Table 1 lists *Su* for all 21 scenarios, for both 15 m (50 ft) and 30 m (100 ft) drawdown thresholds.

4.3. Seawater Intrusion

[28] The groundwater flow model also can be used to generate estimates of the area potentially affected by seawater intrusion. As described by *Reichard et al.* [2003], the model was not calibrated as a solute transport model. Detailed transport simulation would require finer vertical discretization, and extensive calibration to measured chloride data. However, by applying the groundwater transport

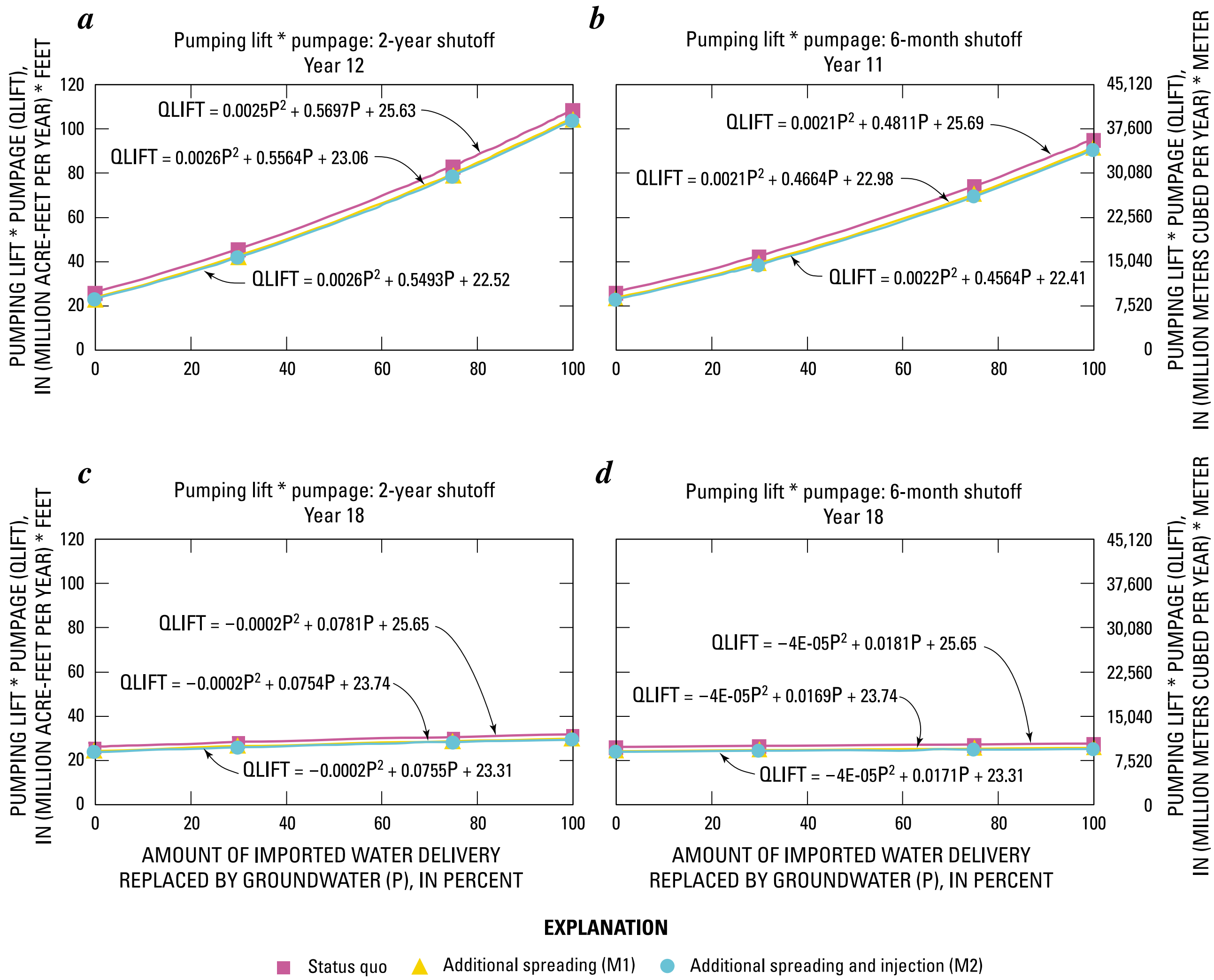

Figure 7. Response functions for qlift (pumping lift * pumpage) as a function of percent imported water replaced by groundwater (p): (a) 2-year shutoff, end of year 12; (b) 6-month shutoff, end of year 11; (c) 2-year shutoff, end of year 18; and (d) 6-month shutoff, end of year 18.

(GWT) process of MODFLOW [*Konikow et al.*, 1996; *Harbaugh et al.*, 2000], we use the model to provide estimates of the differences in area likely to be affected by seawater intrusion. This is done by simulating the advective landward transport of water from the offshore portions of the aquifers. This analysis does not consider high chloride water that is already present onshore. It also does not consider dispersion or density effects.

[29] Taking all of these assumptions and simplifications into account, the model can still provide useful information regarding expected differences in areas potentially affected by seawater intrusion. Figure 6 shows inland cells at which the model simulates seawater to have reached at the end of the 25-year study period for both the base case (Figure 6a) and scenario 3 (imported-water deliveries are disrupted for 2 years, and 75 percent of the imported water is made up by groundwater) (Figure 6b). Note for the purposes of this simplified simulation, offshore portions of the aquifers were assigned a concentration of 1; initial concentrations of 0 were assigned to all onshore cells Seawater was considered to have reached an onshore cell if the simulated concentration of the cell was 0.02 or larger. Based on Figures 6a and 6b, the additional area affected by seawater intrusion, *Int*, for the base case is 9.7 km^2 (3.75 mi^2); the additional area affected by seawater intrusion, *Int*, for scenario 3, is 33.0 km^2 (12.75 mi^2) Figure 6 shows that, although the disruption is only for a limited period, its effect on a long-term process, such as seawater intrusion, is significant. The increased landward gradient continues long after the end of the disruption, thereby causing long-term increased rates of seawater intrusion. Table 1 lists the additional area affected by seawater intrusion, *Int*, for all scenarios.

5. Generation of Response Functions From Simulation Results

[30] The results tabulated in Table 1 show the simulated hydraulic impacts of using groundwater as a backup supply for disrupted imported water for a set of discrete scenarios. These simulation results can be generalized by formulating response functions that express hydraulic impacts as a function of *p*, the percentage of imported-water deliveries

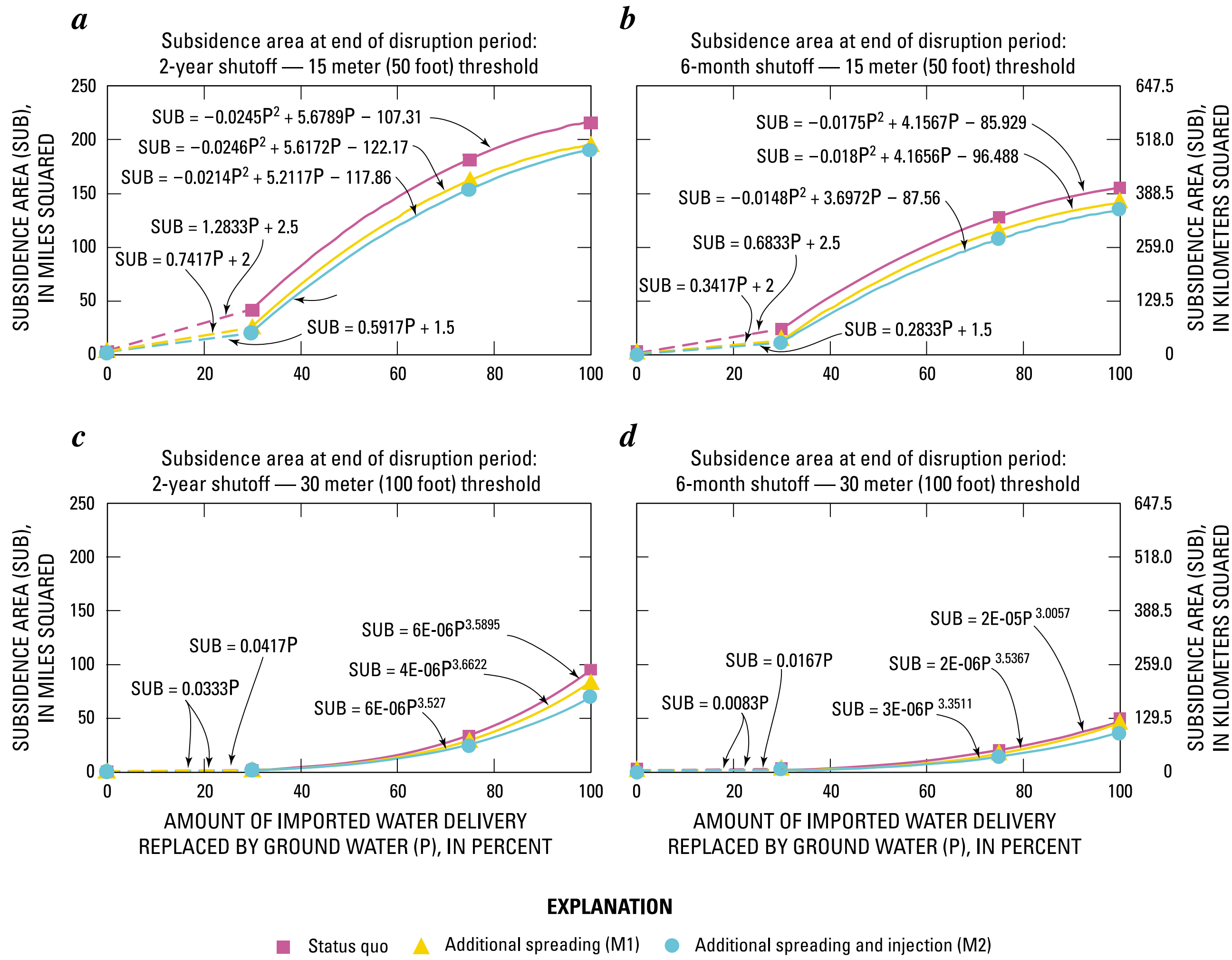

Figure 8. Response functions for subsidence area (sub) at end of disruption period, as a function of percent imported water replaced by groundwater (p): (a) 2-year shutoff, 15 m (50-ft) drawdown threshold for subsidence; (b) 6-month shutoff, 15 m (50-ft) drawdown threshold for subsidence; (c) 2-year shutoff, 30 m (100-ft) drawdown threshold for subsidence; and (d) 6-month shutoff, 30 m (100-ft) drawdown threshold for subsidence.

replaced by groundwater. Figures 7, 8, and 9 show hydraulic impacts, *qlift*, *Su*, and *Int*, plotted against *p*. Figures 7–9 illustrate several expected features. First, all of the impacts increase with higher values of *p*. Second, the impacts from a 6-month disruption are less than those of a 2-year disruption. Finally, the implementation of groundwater management strategies reduces the impacts. Management strategy M2, which incorporates additional spreading and injection, has a greater impact than strategy M1, which only incorporates spreading.

[31] The results shown in Figures 7–9 can be fitted by simple response functions. Any form of response function can be incorporated into the analyses. In the examples presented here, relationships are expressed as linear, quadratic, and power functions. Response functions for *qlift* (Figure 7) are quadratic, except for *qlift* in year 10 (not shown in Figure 7), which is simply a constant value, since it is unaffected by the magnitude of the disruption (9,610, 8,520, 8,200 million (m^3/yr)* m pumping lift for status quo, M1 and M2, respectively). Response functions for *sub* are piecewise expressions (linear for *p* less than 30%, and quadratic or power expressions for *p* of 30% or greater) (Figure 8). Response functions for *int* are quadratic (Figure 9). With the response functions presented in Figures 7–9, for a given management strategy (status quo, M1, or M2), and assumed duration of disruption, *dur*, (6 months or 2 years) one can compute a value for all the hydraulic impacts for any assumed value of *p*.

6. Computation of Costs of Hydraulic Impacts

[32] By combining the response functions for hydraulic impacts presented in Figures 7–9, with inputs from decision makers regarding cost coefficients for pumping lift (*cp*), land subsidence (*cs*) and seawater intrusion (*cint*); discount rate (*r*); and expectations regarding the likely percentage of imported-water deliveries replaced by groundwater (*p*), it is possible to compare the differences in hydraulic costs for different scenarios. The total future costs of pumping, subsidence, and seawater intrusion for a given management

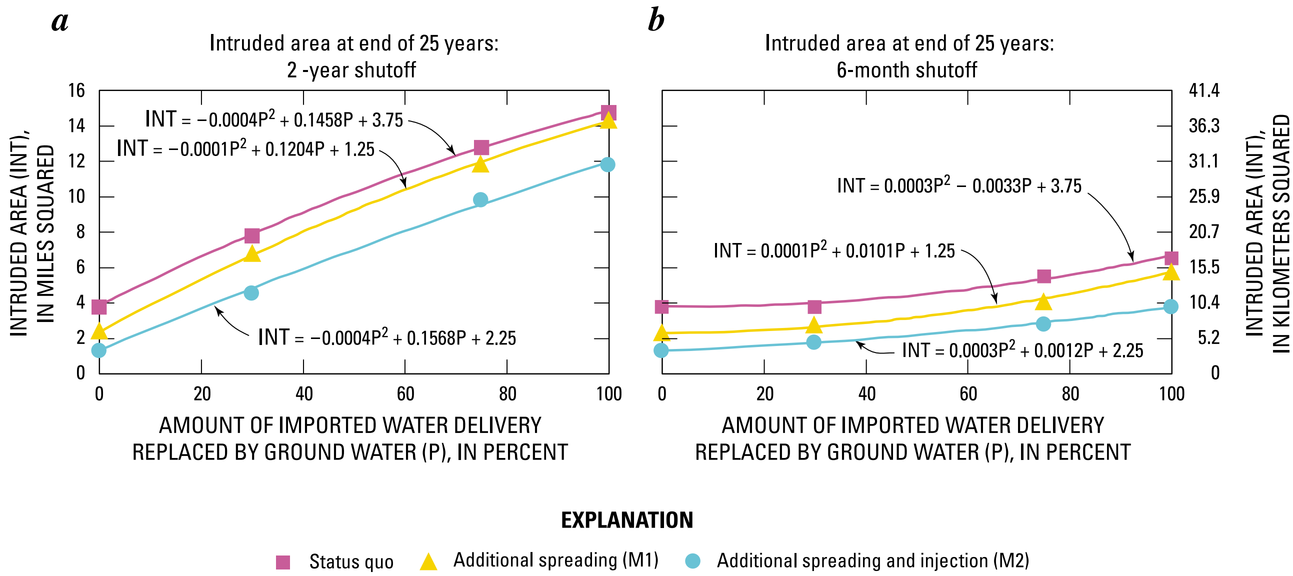

Figure 9. Response functions for intruded area (int) at end of 25 years, as a function of percent imported water replaced by groundwater (p): (a) 2-year shutoff and (b) 6-month shutoff.

strategy, *i*, and percentage of imported-water deliveries made up by groundwater, *p*, and disruption duration, *dur*, can be expressed as

$$Tot\_cost_{i,p,dur} = Pump\_cost_{i,p,dur} + Sub\_cost_{i,p,dur} + Int\_cost_{i,p,dur} \quad (1)$$

where $Tot\_cost_{i,p,dur}$ = total hydraulic costs of groundwater use under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* ($); $Pump\_cost_{i,p,dur}$ = total costs of pumping under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* ($); $Sub\_cost_{i,p,dur}$ = total costs of subsidence under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* ($); $Int\_cost_{i,p,dur}$ = total costs of seawater intrusion under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* ($); *p* = percentage of imported water replace by groundwater; *i* = management strategy (status quo, M1, or M2); *dur* = duration of disruption (6 months or 2 years).

Pumping costs

$$Pump\_cost_{i,p,dur} = cp \sum_{t=1}^{T} qlift_{i,p,dur,t}/(1+r)^t \quad (2a)$$

$$qlift_{i,p,dur,t} = \sum_{k=1}^{K} q_{i,p,k,dur,t} * lift_{i,p,k,dur,t} \quad (2b)$$

where $q_{i,p,k,dur,t}$ = pumping rate at well k, for management strategy i, percentage of imported water made up by groundwater *p*, disruption duration *dur*, in time period t (L^3/T; $lift_{i,p,dur,t}$ = pumping lift at well k, for management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur*, in time period t (L); $qlift_{i,p,dur,t}$ = sum of products of pumping x pumping lift at all K wells, for management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur*, in time period t ($[L^3/T]*L$); *cp* = unit pumping cost ($0.66 /[(1000 m^3/yr)* m pumping lift]) ($0.25/[(acre-ft/yr) * ft of pumping lift]) ($/[($L^3$/T)*L]); *r* = discount rate (assumed to be 3%) *t* = year of planning period *T* = length of planning period (25 years) *K* = total number of pumping wells

Subsidence costs

$$Sub\_cost_{i,p,dur} = csu^* Su_{i,p,dur}/(1+r)^{12} \quad (3)$$

where $Su_{i,p,dur}$ = area potentially affected by subsidence under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* (L^2); *csu* = unit subsidence cost ($0.77 million / km^2 [$2 million/mi^2] area potentially affected by land subsidence) ($/$L^2$).

Intrusion costs

$$Intru\_cost_{i,p,dur} = c\ \mathrm{int}^* Int_{i,p,dur}(1+r)^{12} \quad (4)$$

where $Int_{i,p,dur}$ = area potentially affected by seawater intrusion under management strategy i, percentage of imported water made up by groundwater, *p*, disruption duration, *dur* (L^2); *cint* = unit intrusion cost ($0.77 million/$km^2$ [$2 million/$mi^2$] area potentially affected by seawater intrusion) ($/$L^2$);

[33] Total hydraulic costs of groundwater use (equation (1)) are the sum of pumping costs (equation (2)), subsidence costs (equation (3)), and seawater intrusion costs (equation 4). Note that pumping costs are summed and discounted annually (equation (2)). The costs of subsidence (equation (3)) and seawater intrusion (equation (4)) are taken as one-time costs that are discounted from the year 12. The rationale for this discounting strategy is to take the maximum impact for subsidence and seawater intrusion, apply a cost coefficient, and apply a discount factor approximating the middle of the planning period (year 12). Alternate discounting approaches

could be applied, including a more detailed analysis which incorporated different costs for every time period. The unit cost coefficients for subsidence and intrusion are presented strictly as example values. The costs of subsidence would include the engineering damage to buildings and infrastructure, as well as indirect impacts such as flooding. The costs of intrusion would include the additional costs of required treatment or the costs of acquiring alternative sources of water. It should be emphasized that the values used for the unit cost coefficients are and the discount rate can be easily varied in the analysis. As described above, the response functions for pumping lift times pumpage ($qlift$), subsidence area (Su), and intruded area (Int) are all nonlinear (Figures 7–9); therefore the cost functions associated with these are nonlinear as well.

[34] For a given management strategy, i, and a disruption duration, dur, the difference in total hydraulic costs of groundwater use from those computed for the case of no disruption, p*, represents the incremental cost of using groundwater as a backup supply:

$$Inc\_Cost_{\mathrm{i,p,dur}} = Tot\_cost_{\mathrm{i,p,dur}} - Tot\_cost_{\mathrm{i,p*,dur}} \qquad (5)$$

p* = 0 (no disruption)

[35] In Figure 1b, this is equivalent to the area between curves ABDE and ABC, or the difference between curves AFGIJ and AFGH. It can be compared with the costs of other alternative backup supplies.

[36] For a specified duration, dur, and percentage of imported water made up by groundwater, p, the expected hydraulic benefits of groundwater management action, i, are computed as the reduction in total costs of groundwater use from those for the status quo, i*, (no additional management actions):

$$Ben_{\mathrm{i,p,dur}} = Tot\_cost_{\mathrm{i^*,p,dur}} - Tot\_cost_{\mathrm{i,p,dur}} \qquad (6)$$

[37] In Figure 1b, this is equivalent to the area between curves ABC and AFGH, or between curves ABDE and AFGIJ.

[38] For a particular groundwater management action, i, the difference in benefits from those computed for the case of no disruption, p*, represents the emergency benefits:

$$Emerg\_Ben_{\mathrm{i,p,dur}} = Ben_{\mathrm{i,p,dur}} - Ben_{\mathrm{i,p*,dur}} \qquad (7)$$

p* = 0 = no disruption. This is equivalent to the difference between the hachured and gray areas in Figure 1b.

7. Use of Monte Carlo Analysis to Estimate the Incremental Costs of Using Groundwater as Backup Supply and the Emergency Benefits of Groundwater Management Actions

[39] Uncertainty can be incorporated by means of Monte Carlo analysis. The percentage of imported water made up by groundwater, p, can be expressed as a random probability distribution. Such probability distributions could be elicited from water managers, reflecting their expectations as to the likely severity of an imported-water disruption and the associated increase in groundwater use to make up for a portion of the disrupted imported-water deliveries. Three example probability distributions are considered: triangular (0, 20, 50), which implies a minimum percentage of 0, a maximum percentage of 50, and a most likely percentage of 20; triangular (0, 35, 60), which implies a minimum percentage of 0, a maximum percentage of 60, and a most likely percentage of 35; and uniform (0,100), which implies that percentages from 0 to 100 are equally likely. These three probability distributions assume progressively greater likelihood of significant percentages of imported-water deliveries made up by groundwater.

[40] The Monte Carlo analyses were conducted using the software RiskAMP (Monte Carlo add-in for EXCEL, RiskAMP, www.riskamp.com, 2007). For each analysis, 1500 Monte Carlo realizations were generated. For each realization of p, hydraulic cost components are computed (equations (2)–(4)). Figure 10 shows example histograms of total hydraulic costs (equation (1)) for selected Monte Carlo analyses. Tables 2a and 2b show the median and standard deviation of total hydraulic costs for the different probability distributions for percentage of imported water made up by groundwater, p, for both 6-month and 2-year durations (dur) of the disruption, and for the two different thresholds for subsidence.

7.1. Incremental Costs of Using Groundwater as a Backup Supply

[41] The incremental costs of using groundwater as a backup supply can be computed by applying equation (5) to the costs listed in Tables 2a and 2b (i.e., subtracting median total hydraulic costs from those computed for the case of no disruption, $p = 0$). The results are presented in Table 3. Looking at the status quo case, no additional groundwater management, the total incremental costs of using groundwater a backup supply range from $25 to $184 million, when a 15 m (50 ft) drawdown threshold for subsidence is assumed, and from $4 to $38 million when a 30 m (100 ft) drawdown threshold is assumed (Table 3).

7.2. Emergency Benefits of Groundwater Management

[42] The costs of extracting groundwater are reduced when groundwater management strategies M1 (additional spreading) or M2 (additional spreading and injection) are considered. The reduced costs reflect the hydraulic benefits of these strategies. The benefits for each management action can be computed by applying equation (6) to the costs listed in Tables 2a and 2b (i.e., computing the difference between the median total hydraulic costs of groundwater use with and without the management action). These results are shown in Table 4. When it is assumed that there is no incremental groundwater use to replace imported-water (i.e., $p = 0$), the benefits of management strategy M1 are about $13 million, whereas the benefits of strategy M2 are about $17–18 million.

[43] Emergency benefits, which are shown in Figure 11, can be computed by applying equation (7). As would be expected, the additional emergency benefits associated with the management plans are larger when it is assumed that there is greater likelihood of increased use of groundwater. Specifically, the emergency benefits are highest when the probability distribution expressing the likely percentage of imported water made up by groundwater, p, is uniform (0,100); emergency benefits are lowest for triangular (0, 20, 50) probability distribution.

[44] When it is assumed that the threshold for potential subsidence is a drawdown of 15 m (50 ft) below 1971 levels,

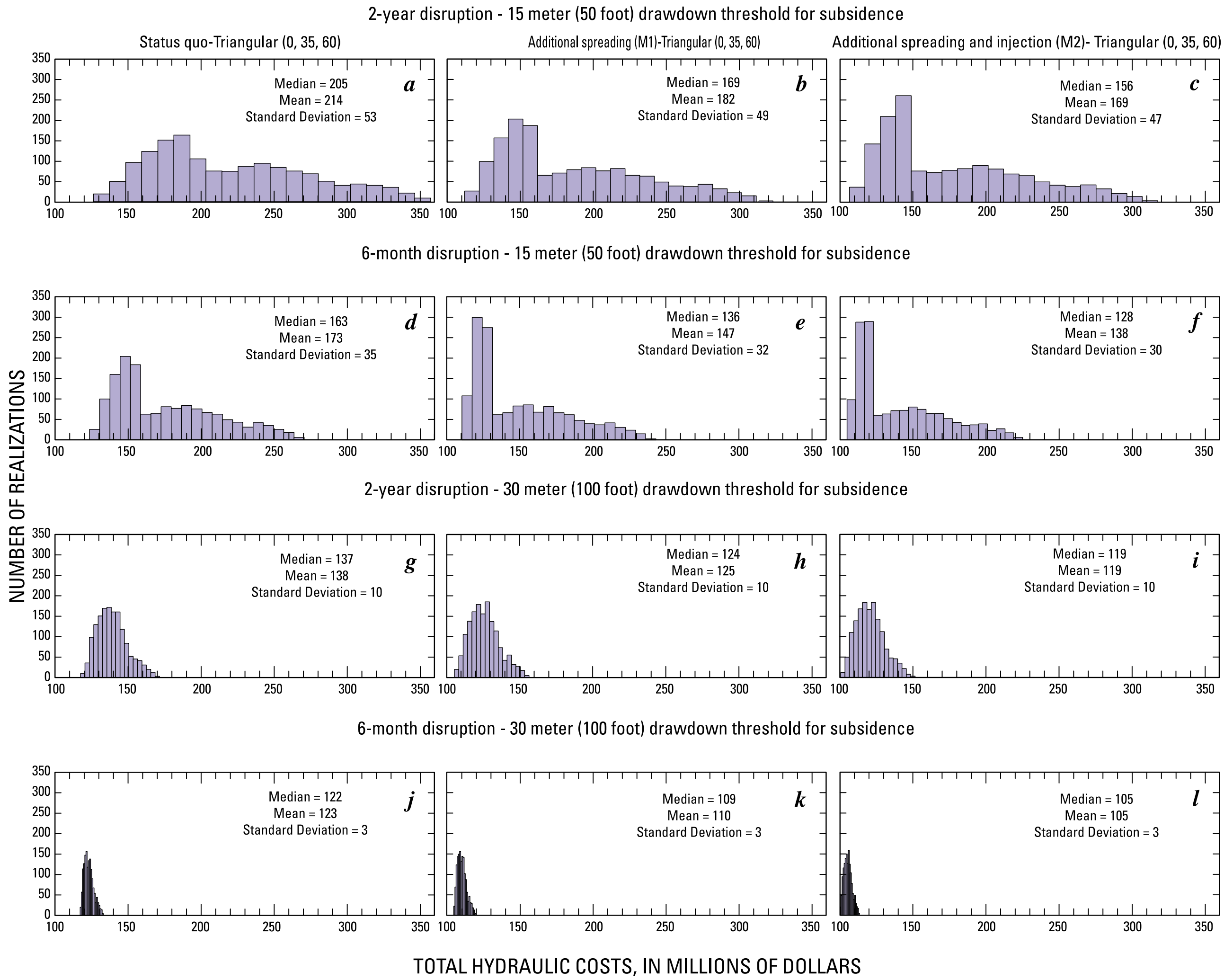

Figure 10. Example histograms from Monte Carlo results. Each row represents a particular disruption and subsidence threshold, from most severe at the top to least severe at the bottom. Each column represents a different management strategy, from status quo on the left to spreading and injection on the right.

the emergency benefits from management strategy M1 (additional spreading) range from \$11 (*dur* = 0.5 years; *p* = triangular (0,20,50)) to \$24 (*dur* = 2 years; *p* = uniform (0,100)) million (Figures 11a and 11b). The emergency benefits from M2 (additional spreading and injection) range from \$12 to \$36 million (Figures 11c and 11d). Most of the emergency benefits are due to the reduced costs of subsidence. Subsidence is a hydraulic impact that has a threshold. Note that *Tsur and Zemel* [2004] addressed the unique influence that threshold impacts have on the optimal groundwater extraction. If water levels are above a certain level, inelastic subsidence is unlikely to occur; if water levels are below that level, subsidence may occur. The management strategies involve artificially recharging more water in the ground, thereby reducing the portion of the groundwater system where water levels will fall below the threshold level during periods of additional pumpage.

[45] When it is assumed that the threshold for potential subsidence is 30 m (100 ft) drawdown below 1971 levels, the threat of additional subsidence is much lower. In this case, the emergency benefits from management strategy M1 (additional spreading) are less than \$1.0 million (Figures 11e and 11f). The emergency benefits from M2 (additional spreading and injection) range from \$0.02 (*dur* = 0.5 years; *p* = triangular (0, 20, 50)) to \$2.5 (*dur* = 2 years; *p* = uniform (0,100)) million (Figures 11g and 11h). The emergency benefits associated with reduced subsidence for the 30 m (100 ft) drawdown threshold are much less than the 15 m (50 ft) threshold case.

[46] In this example problem, the costs associated with pumping and seawater intrusion have less impact on emergency benefits than subsidence. The results shown in Figure 11 show that there are positive emergency benefits associated with pumping costs for management strategy M1 (additional spreading) for all cases, and for M2 (additional spreading and injection) for the 6-month disruption case. For seawater intrusion, there are only positive emergency benefits of management associated with the M2 management strategy for a 2-year disruption. For the other cases, computed emergency benefits associated with pumping and seawater intrusion are very small negative values (Figure 11). These negative values are considered to effectively be zero;

Table 2a. Medians and Standard Deviations of Discounted Costs of Pumping, Subsidence, and Seawater Intrusion for 15 m Drawdown Threshold for Subsidence[a]

Duration of Disruption (years)	Imported Water Replaced by Groundwater (%)	Status Quo				Scenario M1, Additional Spreading				Scenario M2, Additional Spreading and Injection			
		Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost
2	0	111.45	3.51	5.26	120.22	100.78	2.81	3.16	106.74	97.98	2.1	1.75	101.84
2	triangular (0,20,50)	119.55 (3.91)	44.00 (31.20)	9.58 (1.86)	173.13 (36.75)	108.67 (3.83)	26.21 (26.19)	7.82 (2.02)	142.70 (31.58)	106.02 (4.00)	20.78 (24.09)	5.48 (1.70)	132.27 (29.31)
2	triangular (0,35,60)	123.23 (4.78)	70.71 (46.77)	11.27 (2.14)	205.22 (53.51)	112.28 (4.69)	46.93 (42.39)	9.67 (2.34)	168.87 (49.09)	109.80 (4.95)	39.29 (39.90)	7.06 (2.02)	156.15 (46.54)
2	uniform (0,100)	129.99 (11.74)	159.89 (102.87)	14.02 (4.39)	303.90 (118.86)	118.92 (11.56)	134.41 (95.81)	12.68 (4.84)	266.01 (112.02)	116.93 (12.59)	123.29 (93.42)	9.78 (4.55)	250.00 (110.38)
0.5	0	111.45	3.51	5.26	120.22	100.78	2.81	3.16	106.74	97.98	2.1	1.75	101.84
0.5	triangular (0,20,50)	114.44 (1.49)	25.07 (20.78)	5.37 (0.17)	144.88 (22.35)	103.74 (1.44)	13.59 (17.95)	3.41 (0.24)	120.74 (19.45)	100.94 (1.43)	11.04 (16.25)	2.14 (0.22)	114.12 (17.71)
0.5	triangular (0,35,60)	115.86 (1.85)	42.03 (32.85)	5.55 (0.28)	163.44 (34.92)	105.11 (1.79)	26.89 (30.37)	3.65 (0.35)	135.65 (32.41)	102.29 (1.78)	22.89 (27.81)	2.36 (0.29)	127.54 (29.77)
0.5	uniform (0,100)	118.54 (4.75)	108.17 (74.69)	6.06 (1.13)	232.77 (80.48)	107.70 (4.60)	92.25 (70.26)	4.27 (1.31)	204.22 (76.07)	104.88 (4.60)	83.24 (66.62)	2.80 (0.83)	190.91 (71.99)

[a]Costs are given million $. Standard deviation is shown in parentheses.

Table 2b. Medians and Standard Deviations of Discounted Costs of Pumping, Subsidence, and Seawater Intrusion for 30 m Drawdown Threshold for Subsidence[a]

Duration of Disruption (years)	Imported Water Replaced by Groundwater (%)	Status Quo				Scenario M1, Additional Spreading				Scenario M2, Additional Spreading and Injection			
		Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost
2	0	111.45	0.00	5.26	116.71	100.78	0.00	3.16	103.93	97.98	0	1.75	99.74
2	triangular (0,20,50)	119.55 (3.91)	1.32 (1.60)	9.58 (1.86)	130.45 (7.20)	108.67 (3.83)	1.05 (1.43)	7.82 (2.02)	117.54 (7.11)	106.02 (4.00)	1.05 (1.27)	5.48 (1.70)	112.55 (6.83)
2	triangular (0,35,60)	123.23 (4.78)	2.19 (3.63)	11.27 (2.14)	136.70 (10.22)	112.28 (4.69)	1.88 (3.26)	9.67 (2.34)	123.83 (9.97)	109.80 (4.95)	1.76 (2.83)	7.06 (2.02)	118.62 (9.54)
2	uniform (0,100)	129.99 (11.74)	10.23 (34.88)	14.02 (4.39)	154.25 (49.66)	118.92 (11.56)	9.06 (32.39)	12.68 (4.84)	140.66 (47.42)	116.93 (12.59)	8.02 (26.25)	9.78 (4.55)	134.73 (42.33)
0.5	0	111.45	0.00	5.26	116.71	100.78	0.00	3.16	103.93	97.98	0	1.75	99.74
0.5	triangular (0,20,50)	114.44 (1.49)	0.53 (0.59)	5.37 (0.17)	120.34 (2.22)	103.74 (1.44)	0.26 (0.46)	3.41 (0.24)	107.41 (2.09)	100.94 (1.43)	0.26 (0.33)	2.14 (0.22)	103.34 (1.95)
0.5	triangular (0,35,60)	115.86 (1.85)	0.96 (1.18)	5.55 (0.28)	122.37 (3.25)	105.11 (1.79)	0.61 (1.01)	3.65 (0.35)	109.36 (3.08)	102.29 (1.78)	0.48 (0.71)	2.36 (0.29)	105.13 (2.72)
0.5	uniform (0,100)	118.54 (4.75)	3.49 (8.17)	6.06 (1.13)	128.09 (13.85)	107.70 (4.60)	2.78 (9.16)	4.27 (1.31)	114.75 (14.79)	104.88 (4.60)	2.02 (5.90)	2.80 (0.83)	109.70 (11.11)

[a]Costs are given million $. Standard deviation is shown in parentheses.

Table 3. Incremental Costs of Using Groundwater as Backup Supply During Water Supply Emergency

Duration of Disruption (years)	Imported Water Replaced by Groundwater (%)	Status Quo				Scenario M1, Additional Spreading				Scenario M2, Additional Spreading and Injection			
		Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost	Pumping Costs	Subsidence Costs	Intrusion Costs	Total Cost
						15 m Drawdown Threshold for Subsidence							
2	triangular (0,20,50)	8.10	40.50	4.32	52.91	7.90	23.40	4.66	35.97	8.03	18.67	3.73	30.43
2	triangular (0,35,60)	11.78	67.20	6.01	85.00	11.50	44.12	6.51	62.13	11.81	37.19	5.30	54.30
2	uniform (0,100)	18.54	156.38	8.76	183.68	18.14	131.60	9.52	159.27	18.94	121.19	8.03	148.16
0.5	triangular (0,20,50)	2.99	21.56	0.11	24.66	2.97	10.78	0.25	14.00	2.95	8.94	0.39	12.28
0.5	triangular (0,35,60)	4.40	38.52	0.29	43.22	4.33	24.09	0.49	28.91	4.31	20.79	0.60	25.70
0.5	uniform (0,100)	7.08	104.66	0.80	112.55	6.92	89.45	1.12	97.48	6.89	81.13	1.05	89.07
						30 m Drawdown Threshold for Subsidence							
2	triangular (0,20,50)	8.10	1.32	4.32	13.73	7.90	1.05	4.66	13.61	8.03	1.05	3.73	12.81
2	triangular (0,35,60)	11.78	2.19	6.01	19.98	11.50	1.88	6.51	19.89	11.81	1.76	5.30	18.88
2	uniform (0,100)	18.54	10.23	8.76	37.53	18.14	9.06	9.52	36.73	18.94	8.02	8.03	34.99
0.5	triangular (0,20,50)	2.99	0.53	0.11	3.63	2.97	0.26	0.25	3.48	2.95	0.26	0.39	3.60
0.5	triangular (0,35,60)	4.40	0.96	0.29	5.65	4.33	0.61	0.49	5.43	4.31	0.48	0.60	5.39
0.5	uniform (0,100)	7.08	3.49	0.80	11.38	6.92	2.78	1.12	10.81	6.89	2.02	1.05	9.96

they are a numerical artifact of computing differences between response functions, which were generated by curve fitting to discrete simulation results. However, it is important to note that nonlinearities in a groundwater system could cause there to be negative emergency benefits from a particular management action (i.e., the hachured area in Figure 1b could be smaller than the gray area).

[47] The emergency benefits associated with 2-year and 6-month disruptions can be compared. With a 15 m (50 ft) drawdown threshold for subsidence, the emergency benefits for groundwater management for an assumed 2-year imported water disruption are considerably higher than for a 6-month disruption (Figures 11a–11d). For the case of a 30 m (100 ft) subsidence threshold, the total emergency benefits are very small, and the differences in benefits between a 2-year and a 6-month imported water disruption are not consistent (Figures 11e–11h).

[48] The emergency benefits resulting from management strategies M1 and M2 also can be compared. As shown in Figure 11, the emergency benefits of management strategy M2 are greater than those of M1 for all but one case.

[49] In general, the magnitude of emergency benefits of a specific strategy will depend on the relative shape of its response functions (such as those presented in Figure 7) relative to the response functions for status quo. A management strategy will have emergency benefits if it brings about a greater reduction in hydraulic impacts, relative to status quo, when there is a disruption in imported-water delivery.

7.3. Role of Cost Coefficients

[50] As noted above, the cost coefficients used in the foregoing analyses were only presented as example values. A constant cost per unit affected area is applied for subsidence and intrusion. The location of the impacted area, the land use, and the magnitude of subsidence or chloride concentrations are not considered. A logical extension of

Table 4. Benefits of Groundwater Management Strategies: Difference in Costs From Status Quo[a]

Duration of Disruption (years)	Imported Water Replaced by Groundwater (%)	M1 Additional Spreading Benefits				M2 Additional Spreading and Injection Benefits			
		Pumping	Subsidence	Intrusion	Total	Pumping	Subsidence	Intrusion	Total
				15 m Drawdown Threshold for Subsidence					
2	0	10.68	0.70	2.10	13.48	13.47	1.40	3.51	18.38
2	triangular (0,20,50)	10.88	17.79	1.76	30.43	13.53	23.23	4.10	40.86
2	triangular (0,35,60)	10.95	23.78	1.61	36.34	13.43	31.42	4.22	49.07
2	uniform (0,100)	11.07	25.48	1.34	37.89	13.07	36.60	4.24	53.90
0.5	0	10.68	0.70	2.10	13.48	13.47	1.40	3.51	18.38
0.5	triangular (0,20,50)	10.70	11.48	1.96	24.14	13.51	14.03	3.23	30.76
0.5	triangular (0,35,60)	10.75	15.14	1.90	27.79	13.57	19.14	3.19	35.90
0.5	uniform (0,100)	10.84	15.92	1.79	28.55	13.66	24.93	3.26	41.85
				30 m Drawdown Threshold for Subsidence					
2	0	10.68	0.00	2.10	12.78	13.47	0.00	3.51	16.98
2	triangular (0,20,50)	10.88	0.27	1.76	12.90	13.53	0.27	4.10	17.90
2	triangular (0,35,60)	10.95	0.31	1.61	12.87	13.43	0.43	4.22	18.08
2	uniform (0,100)	11.07	1.17	1.34	13.59	13.07	2.22	4.24	19.52
0.5	0	10.68	0.00	2.10	12.78	13.47	0.00	3.51	16.98
0.5	triangular (0,20,50)	10.70	0.27	1.96	12.93	13.51	0.27	3.23	17.00
0.5	triangular (0,35,60)	10.75	0.35	1.90	13.00	13.57	0.48	3.19	17.24
0.5	uniform (0,100)	10.84	0.72	1.79	13.35	13.66	1.47	3.26	18.40

[a]Given in million $.

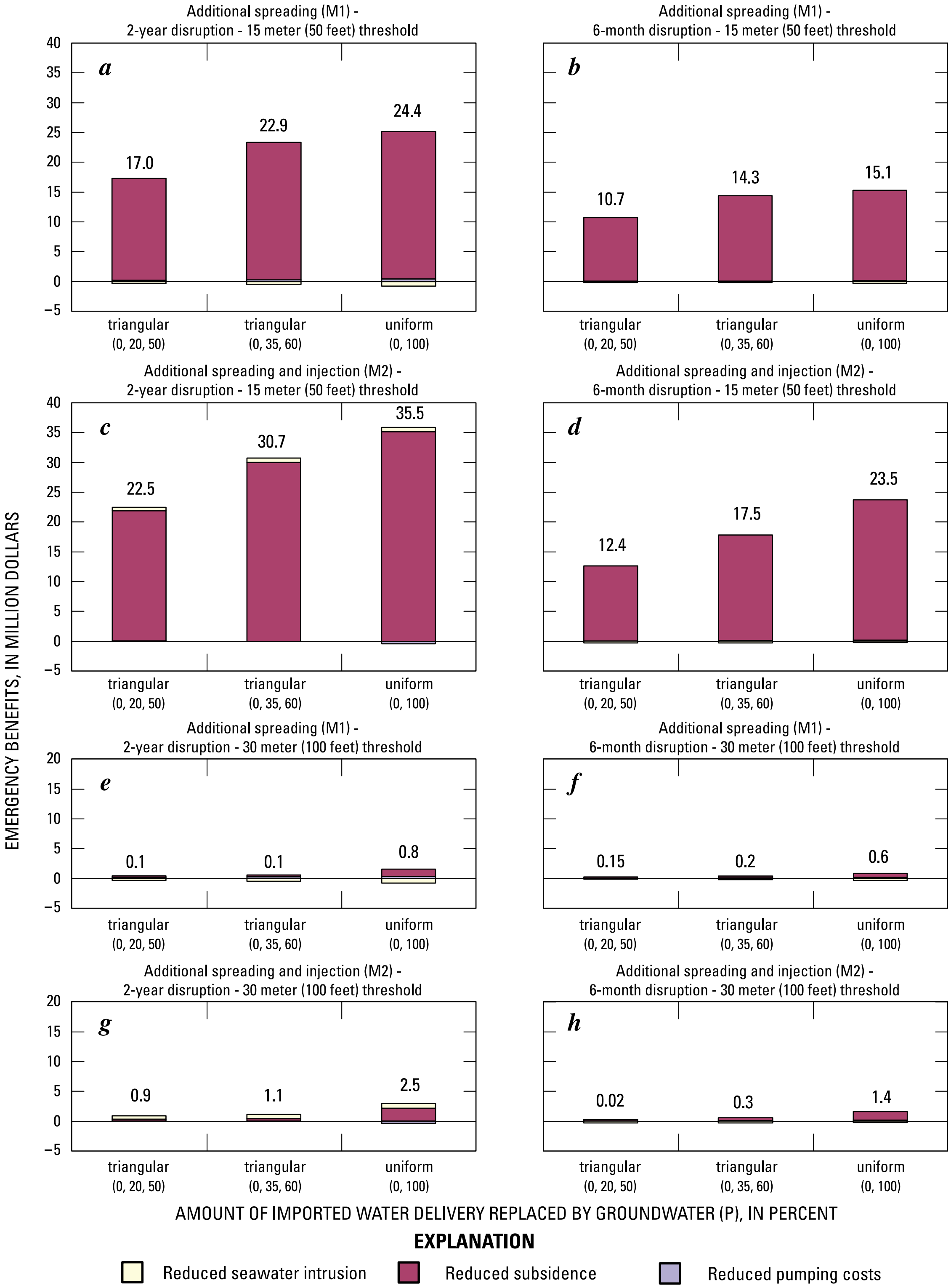

Figure 11. Emergency benefits of management strategies: (a) management strategy M1, 2-year disruption, 15 m (50 ft) drawdown threshold for subsidence; (b) management strategy M1, 6-monthdisruption, 15 m (50 ft) drawdown threshold for subsidence; (c) management strategy M2, 2-year disruption, 15 m (50 ft) drawdown threshold for subsidence; (d) management strategy M2, 6-month disruption, 15 m (50 ft) drawdown threshold for subsidence; (e) management strategy M1, 2-year disruption, 30 m (100 ft) drawdown threshold for subsidence; (f) management strategy M1, 6-month disruption, 30 m (100 ft) drawdown threshold for subsidence; (g) management strategy M2, 2-year disruption, 30 m (100 ft) drawdown threshold for subsidence; and (h) management strategy M2, 6-month disruption, 30 m (100 ft) drawdown threshold for subsidence.

this work would be to incorporate spatially varying cost coefficients. For example, the costs per area of subsidence for different land uses could vary by many orders of magnitude. *Galloway et al.* [1999] review estimates of the costs of subsidence in the Santa Clara and San Joaquin Valleys in California, and the Houston-Galveston area in Texas. They note that quantifying the economic costs of subsidence is difficult, but conclude that the combination of direct and indirect costs has been extremely large in these highly affected areas.

[51] Applying different cost coefficients, *cp*, *csu*, *cint*, would affect the relative economic importance of the different hydraulic impacts. In particular, applying a higher value of *csu*, the unit cost per area potentially affected by subsidence, would increase the overall emergency benefits of all strategies, especially those in which it is assumed that the threshold drawdown for potential subsidence is 15 m (50 ft).

7.4. Variability of Results

[52] As illustrated by the histograms of results shown in Figure 10, and the statistics shown in Tables 2a and 2b, there is a relatively wide range of possible outcomes, given the example probability distributions assumed for the likely percentage of imported water made up with groundwater, *p*. While the focus of most of the discussion is on the median value, the histograms in Figure 10 show that there is a possibility of much more severe consequences. As indicated in Tables 2a and 2b, subsidence is the cause of most of the variance in this example. The ratio of the standard deviation to the median of subsidence costs is high for all cases. Relatively small changes in the magnitude of likely additional groundwater pumpage, *p*, can result in large differences in the area potentially susceptible to subsidence. Therefore, the uncertainty regarding *p* leads to considerable uncertainty in the likely costs of subsidence.

8. Discussion

[53] For areas that overlie productive aquifers, groundwater can play an important role in water-supply emergency planning. Since the costs of disruption in water deliveries resulting from an event like an earthquake may be extremely high [*Brozović et al.*, 2007; *Jones et al.*, 2008], there are benefits to preparing to utilize groundwater to mitigate these costs. The focus of this analysis has been on implementation of groundwater management projects (artificial recharge) to store more water in the ground, for use during imported-water disruptions. It has been assumed that sufficient well capacity exists.

[54] We have introduced a framework for using a regional simulation model to estimate the basin-wide hydraulic impacts of different scenarios of disruptions and utilization of groundwater during emergencies. Basin-wide response functions are derived from model simulations. Coupling the response functions with cost coefficients, a discount rate, and a probabilistic representation of the likely percentage of imported water supplies replaced by groundwater, enables quantification of the incremental hydraulic costs of utilizing groundwater as a backup supply, and estimation of the emergency benefits of different groundwater management strategies. Three components of hydraulic benefits of groundwater management have been considered: reduced pumping lifts, reduced potential for subsidence, and reduced seawater intrusion. The primary results of the analyses are summarized below.

[55] 1. Groundwater can provide an important backup supply in the event of water emergencies. Simulation models can be used to assess the hydraulic impacts of different scenarios.

[56] 2. Incremental hydraulic costs of utilizing groundwater as a backup supply can be quantified and compared with the costs of any alternative water sources.

[57] 3. For the example problem considered, the expected emergency benefits of the groundwater management strategies considered – artificial recharge using spreading and injection- are dominated by reduction of potential subsidence costs. Inelastic compaction is an impact involving a threshold for initiation. In areas in which such threshold impacts may result from modest water-level drawdowns, there may be significant emergency benefits to management strategies that raise water levels.

[58] 4. The analyses presented here have considered potential new artificial recharge programs. The same approach could be applied to quantify the emergency benefits of continuing existing programs that augment the supply of groundwater and protect its quality.

[59] 5. Probability distributions reflecting an assumed larger quantity of groundwater usage during the imported-water disruption lead to higher estimated emergency benefits of management strategies.

[60] 6. For longer expected durations of imported-water disruption, there are greater emergency benefits derived from groundwater management actions. For the example analyses, the difference is significant for the case where the assumed drawdown threshold for subsidence is 15 m (50 ft).

[61] 7. The Monte Carlo analyses allow consideration of the variability of results. Much of the variability is due to potential subsidence. Relatively small changes in the amount of additional pumpage during emergencies can lead to large increases in area potentially affected by subsidence. While much of the discussion in this paper has focused on the median values of results, water managers may well be more risk averse, and incorporate the possibility of more extreme outcomes into their decision making.

[62] 8. The analyses presented here assumed that the time at which the imported water delivery may be disrupted, t*, is known with certainty. The impact of t* on the emergency benefits of groundwater management will depend on multiple factors. For example, if the disruption occurs earlier, there will have been less cumulative hydraulic impact from artificial recharge, which implies smaller undiscounted benefits. However, the benefits occur sooner, and therefore are discounted less.

[63] While there are multiple simplifications and assumptions in the foregoing analyses, the framework presented in this paper may provide a useful approach for water emergency planning in a range of settings. The framework can be extended to include more detailed representation of uncertainty in duration of the disruption, consider additional components of uncertainty (e.g., timing of disruption, cost coefficients, and the level of functioning of the local distribution system), quantify the benefits of investing in additional well capacity, calculate the costs of implementing alternative groundwater management strategies, and estimate the regional costs of unmet water demand.

[64] **Acknowledgments.** The authors express their great appreciation to the three journal reviewers and to Stanley Leake, Richard Bernknopf, Theodore Johnson, and Larry Schneider. Support for this study was provided by the U.S. Geological Survey (USGS) Venture Capital Program, the USGS Cooperative Water Program, and the Water Replenishment District of Southern California. Mention of trade names or manufacturers does not imply endorsement by the U.S. Government.

References

Bredehoeft, J. D., and R. A. Young (1983), Conjunctive use of groundwater and surface water for irrigated agriculture: Risk aversion, *Water Resour. Res.*, *19*(50), 1111–1121.

Brozović, N. D., D. L. Sunding, and D. Zilberman (2007), Estimating business and residential water supply interruption losses from catastrophic events, *Water Resour. Res.*, *43*, W08423, doi:10.1029/2005WR004782.

California Department of Water Resources (1961), Planned utilization of the ground water basins of the coastal plain of Los Angeles County, Appendix A, Ground water geology, *Calif. Dep. Water Resour. Bull. 104*, 191 pp., Sacramento, Calif.

California Department of Water Resources (2009), Delta risk management strategy, phase 1 risk analysis report, technical memorandum, Sacramento, Calif. (Available at http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/phase1_information.cfm)

Cutter, W. B. (2007), Valuing groundwater recharge in an urban context, *Land Econ.*, *83*(2), 234–252.

Galloway, D., D. R. Jones, and S. E. Ingebritsen (Eds.) (1999), Land subsidence in the United States, *U.S. Geol. Surv. Circ.*, *1182*, 177 pp.

Gemma, M., and Y. Tsur (2007), The stabilization value of groundwater and conjunctive water management under uncertainty, *Rev. Agric. Econ.*, *29*(3), 540–548, doi:10.1111/j.1467-9353.2007.00366.x.

Harbaugh, A. W., and M. G. McDonald (1996), User's documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model, *U.S. Geol. Surv. Open File Rep., 96-485*, 56 pp.

Harbaugh, A. W., E. R. Banta, M. C. Hill, and M. G. McDonald (2000), MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process, *U.S. Geol. Surv. Open File Rep., 00-92*, 121 pp.

Hoffmann, J., S. A. Leake, D. L. Galloway, and A. M. Wilson (2003), MODFLOW-2000 Ground-water model—User guide to the subsidence and aquifer-system compaction (SUB) Package, *U.S. Geol. Surv. Open File Rep., 03-233*, 46 pp.

Jones, L. M., et al. (2008), The ShakeOut scenario, *U.S. Geol. Surv. Open File Rep., 2008-1150*. (Available at http://pubs.usgs.gov/of/2008/1150/)

Knapp, K. C., and L. J. Olson (1995), The economics of conjunctive groundwater management with stochastic surface supplies, *J. Environ. Econ. Manage.*, *28*, 340–356, doi:10.1006/jeem.1995.1022.

Konikow, L. F., D. J. Goode, and G. Z. Hornberger (1996), A three-dimensional method-of-characteristics solute-transport model (MOC3D), *U.S. Geol. Surv. Water Resour. Invest. Rep., 96-4267*, 87 pp.

Land, M., E. G. Reichard, S. M. Crawford, R. R. Everett, M. W. Newhouse, and C. F. Williams (2004), Ground-water quality of coastal aquifer systems in the West Coast Basin, Los Angeles County, California, 1999–2002, *U.S. Geol. Surv. Water Resour. Invest. Rep., 2004-5067*, 79 pp.

National Research Council (1997), *Valuing Groundwater, Economic Concepts and Approaches*, Natl. Acad. Press, Washington, D. C.

Poland, J. F., et al. (1956), Ground water geology of the coastal zone, Long Beach–Santa Ana area, California, *U.S. Geol. Surv. Water Supply Pap.*, *1109*, 162 pp.

Poland, J .F., A. A. Garrett, and A. Sinnot (1959), Geology, hydrology, and chemical character of ground waters in the Torrance-Santa Monica area, California, *U.S. Geol. Surv. Water Supply Pap.*, *1461*, 425 pp.

Reichard, E. G., and T. A. Johnson (2005), Assessment of regional management strategies for controlling seawater intrusion, *J. Water Resour. Plann. Manage.*, *131*(4), 280–291, doi:10.1061/(ASCE)0733-9496(2005)131:4(280).

Reichard, E. G., and R. S. Raucher (2003), Economics of conjunctive use of groundwater and surface water, in *Water: Science, Policy, and Management*, *Water Resour. Monogr.*, vol. 16, edited by R. Lawford et al., pp. 161–176, AGU, Washington, D. C.

Reichard, E. G., et al. (2003), Geohydrology, geochemistry, and ground-water simulation-optimization of the Central and West Coast Basins, Los Angeles, County, California, *U.S. Geol. Surv. Water Resour. Invest. Rep., 03-4065*, 184 pp.

Tsur, Y. (1990), The stabilization role of groundwater when surface water supplies are uncertain: The implications for groundwater development, *Water Resour. Res.*, *26*(5), 811–818.

Tsur, Y., and A. Zemel (2004), Endangered aquifers: Groundwater management under threats of catastrophic events, *Water Resour. Res.*, *40*, W06S20, doi:10.1029/2003WR002168.

Tsur, Y., and T. Graham-Tomasi (1991), The buffer value of groundwater with stochastic surface water supplies, *J. Environ. Econ. Manage.*, *21*, 201–224, doi:10.1016/0095-0696(91)90027-G.

Water Replenishment District of Southern California (2006), Regional groundwater monitoring report, water year 2004–2005, Lakewood, Calif.

C. Hermans, Advanced Science Research Center, Environmental Cross-Roads Initiative, CUNY, 925–926 Marshak Hall, 160 Convent Ave., New York, NY 10031, USA. (chermans@ccny.cuny.edu)

Z. Li and E. G. Reichard, U.S. Geological Survey, 4165 Spruance Rd., Ste. 200, San Diego, CA 92101, USA. (zhenli@usgs.gov; egreich@usgs.gov)