Hydraulic and Mechanical Properties Affecting Ground-Water Flow and Aquifer-System Compaction, San Joaquin Valley, California

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ABSTRACT

This report summarizes hydraulic and mechanical properties affecting ground-water flow and aquifer-system compaction in the San Joaquin Valley, a broad alluviated intermontane structural trough that constitutes the southern two-thirds of the Central Valley of California. These values will be used to constrain a coupled ground-water flow and aquifer-system compaction model of the western San Joaquin Valley called WESTSIM. A main objective of the WESTSIM model is to evaluate potential future land subsidence that might occur under conditions in which deliveries of imported surface water for agricultural use are reduced and ground-water pumping is increased. Storage values generally are components of the total aquifer-system storage and include inelastic and elastic skeletal storage values of the aquifers and the aquitards that primarily govern the potential amount of land subsidence. Vertical hydraulic conductivity values generally are for discrete thicknesses of sediments, usually aquitards, that primarily govern the rate of land subsidence. The data were compiled from published sources and include results of aquifer tests, stress-strain analyses of borehole extensometer observations, laboratory consolidation tests, and calibrated models of aquifer-system compaction.

INTRODUCTION

The San Joaquin Valley (fig.1), a broad alluviated intermontane structural trough, constitutes the southern two-thirds of the Central Valley of California (Poland and others, 1975; Lofgren, 1976; Ireland, 1986). The Central Valley and pertinent features in the area of focus—the San Joaquin Valley—are shown on figure 1.

Land subsidence owing to ground-water withdrawal began in the San Joaquin Valley during the mid-1920s. By 1970, the maximum subsidence exceeded 28 ft (Poland and others, 1975) and reached 29.7 ft in 1981. More than 5,200 mi^2 of irrigable land, nearly one-half of the entire valley, has subsided at least 1 ft (Ireland, 1986). The subsidence occurred so slowly and uniformly over such a broad area throughout most of the affected area that its effects have been largely unnoticed by most observers. Locally, however, the differential subsidence has appeared abrupt and nonuniform, resulting in severe problems in the design and maintenance of canals and waterways, the expenditure of millions of dollars in repair and replacement of deep irrigation wells, and changes in irrigation and other farming practices (Lofgren, 1976).

The importation of surface water to subsiding areas by way of canals, such as the Friant–Kern and Delta–Mendota canals beginning in the 1950s, and the California Aqueduct beginning in 1968, reduced the pumping of ground water in these areas and reversed the rapid decline of hydraulic head (measured as water levels in wells) starting in the late 1960s and early 1970s. In 1983, ground-water levels in most actively subsiding areas of the San Joaquin Valley had returned

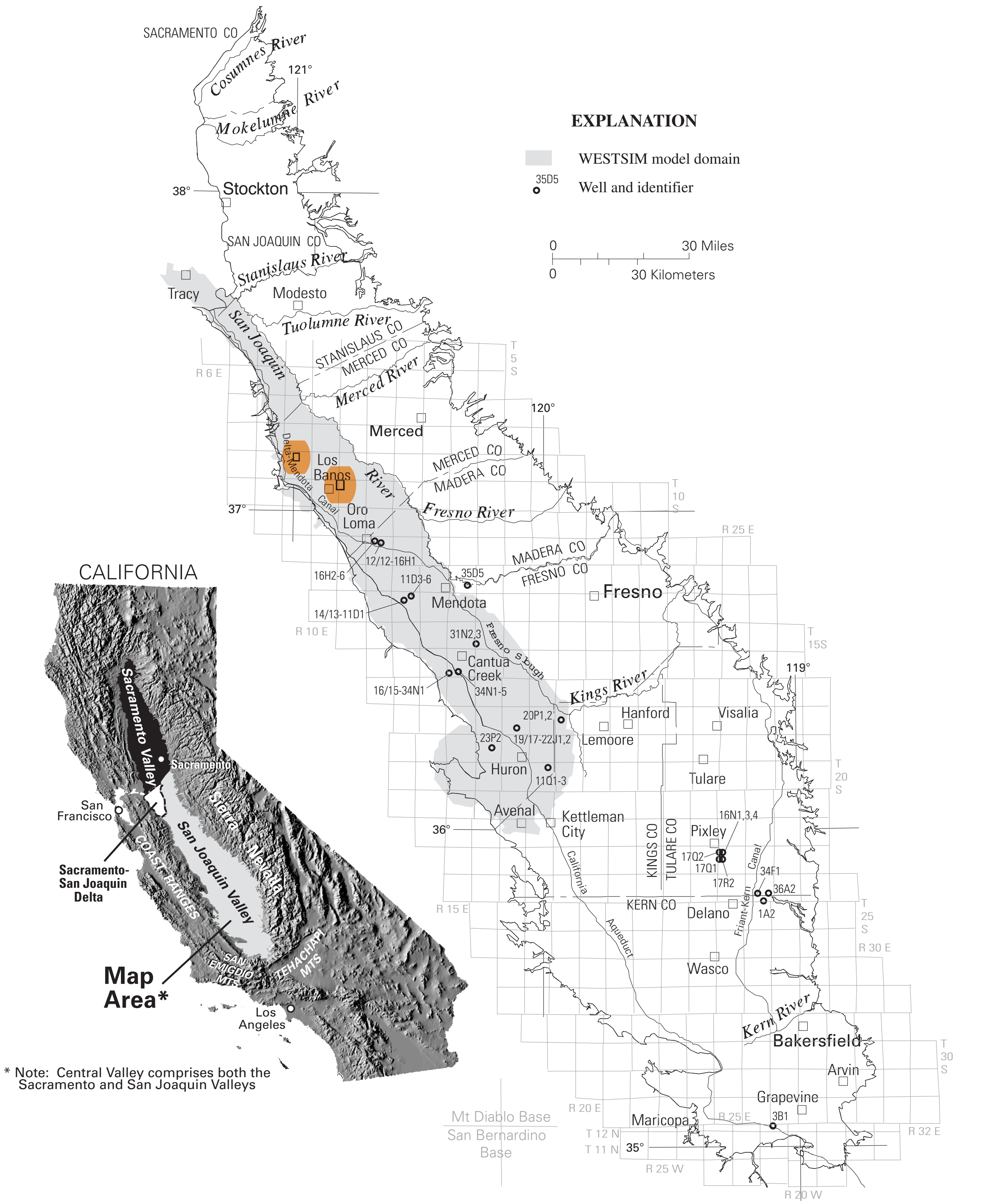

Figure 1. Location of selected features in the Central Valley, California.

to, or recovered above, their 1940–1950 levels, and the subsidence had slowed considerably or ceased (Ireland, 1986).

A detailed ground- and surface-water flow model of the western San Joaquin Valley called WESTSIM is being developed by the U.S. Bureau of Reclamation (USBR) to evaluate potential future land subsidence that might occur under conditions in which deliveries of imported surface water for agricultural use are reduced, resulting in increased ground-water pumping. A realistic model of land subsidence requires realistic values of model parameters that govern the magnitude and timing of aquifer-system compaction and the resulting land subsidence. These values include the skeletal specific storage, thickness, and vertical hydraulic conductivity of the aquitards. This report principally focusses on the skeletal specific storage values; vertical hydraulic conductivity of the aquitards is a secondary focus, and thicknesses of aquitards are minimally discussed.

Purpose and Scope

This report summarizes hydraulic and mechanical properties for the aquifer system in the San Joaquin Valley. The data were compiled from published sources and include results of aquifer tests, stress-strain analyses of borehole extensometer observations, laboratory consolidation tests, and calibrated models of aquifer-system compaction. These data will be used by the USBR to model ground-water flow and aquifer-system compaction (land subsidence) in a coupled ground-water flow and land subsidence model of the western San Joaquin Valley (WESTSIM).

Location of Study Area

The San Joaquin Valley includes roughly the southern two-thirds of the Central Valley of California (fig. 1). It is a broad structural trough surrounded on three sides by mountains—the Sierra Nevada on the east, the Coast Ranges on the west, and the Tehachapi and San Emigdio mountains on the south. The San Joaquin Valley is separated from the Sacramento Valley on the north by the combined deltas of the Sacramento and San Joaquin rivers. The valley extends 250 mi southward from north of Stockton to Grapevine at the foot of the Tehachapi Mountains. The width of the valley floor ranges from 25 mi near Bakersfield to 55 mi near Visalia and averages about 35 mi. The area of the valley floor is 10,000 mi^2, excluding the rolling foothills that skirt the mountains (Davis and others, 1959; Poland and others, 1975; Lofgren, 1976; Ireland, 1986).

The geographic focus of this report, coincident with the WESTSIM model domain, is the western part of the San Joaquin Valley, which includes lands from Tracy on the north to Avenal on the south, and from the valley-side of the Coast Ranges on the west to the San Joaquin River and Fresno Slough on the east (fig. 1). Surrounding areas were included in this report, however, especially east of the WESTSIM model domain, because the estimates of hydraulic and mechanical properties in that area may be useful for comparable areas within the WESTSIM model domain.

Hydrogeologic Setting

The San Joaquin Valley is a major structural trough whose main axis trends northwest-southeast. Throughout Late Cretaceous (Mesozoic Era) and Tertiary (Cenozoic Era) Periods of geologic time, thousands of feet of shallow-water marine sediments were deposited in this down-warping geosyncline. Overlying these marine deposits are continental deposits of late Cenozoic age. In aggregate, these marine and continental deposits form an immense wedge that thickens from east to west and from north to south. At the extreme southern end of the valley, the thickness of sediments exceeds 28,000 ft (Lofgren, 1976).

The valley was formed chiefly by tectonic movement during late Cenozoic (late Tertiary Period and Quaternary Period) time that included major westward tilting of the Sierra Nevada block. Quaternary deformation has been principally along the southern and western borders of the valley, where the marine and continental rocks are tightly faulted and folded and the stream terraces are conspicuously elevated (Lofgren, 1976). A detailed discussion of the geology of the entire Central Valley is given by Page (1986).

Ground water in the San Joaquin Valley occurs under confined and unconfined conditions. Three distinct ground-water bodies exist in much of the western, central, and southeastern parts of the valley. In downward succession, these include (1) a body of unconfined and semiconfined fresh water in alluvial deposits overlying a widespread lacustrine confining bed—the

Corcoran Clay Member of the Tulare Formation (hereinafter called the Corcoran Clay), (2) an extensive reservoir of fresh water confined beneath the Corcoran Clay in alluvial and lacustrine deposits, and (3) a body of saline water contained in marine sediments that underlies the fresh water body throughout the area. In much of the eastern part of the valley, especially in the areas of major streams, the Corcoran Clay is not present and ground water occurs as one fresh water body to considerable depth (Lofgren, 1976).

AQUIFER-SYSTEM STORAGE

The concepts relating the compressibility of the aquifer system and its storage properties are briefly reviewed in the following sections. Various storage terms are used to define and delineate the components of the aquifer system that contribute to the total aquifer-system storage. The term "aquifer system" refers to a complex set of variably extensive, faulted, and interbedded aquifers (coarse-grained sediments) and aquitards (fine-grained sediments) that function regionally as a water-yielding unit (Poland and others, 1972). Correct application of the storage values in this report requires an understanding of these terms.

Elastic and Inelastic Compressibility (Specific Storage)

Under saturated confined conditions, the skeletal component of compressibility of an aquifer system governs the inverse change in volume and direct change in density of the material in response to a change in the intergranular stress. The law of effective stress (Terzaghi, 1925) states that when total stress on the aquifer system does not vary, the change in intergranular (effective) stress, σ_e, is related to the change in pore-fluid pressure, p, by

$$\Delta\sigma_e = -\Delta p$$

Fluid pressure variations cause equal but oppositely sensed changes in intergranular stress. Expressed in terms of hydraulic head, h:

$$h = p/\rho g$$

where ρ is the density of the pore water and g is the acceleration resulting from gravity. The changes in intergranular stress can be determined by measuring or simulating hydraulic-head variations

$$\Delta\sigma_e = -\Delta h \rho g$$

assuming ρ is constant.

For the purposes of this report, the skeletal specific storage of an aquifer system, S^*_{sk}, is expressed in terms of the skeletal compressibility, α^*_k, where the subscript k refers to the skeletal component of specific storage or compressibility and the superscript * refers to an aquifer-system property. Specific storage represents the volume of fluid taken into, or released from, a unit volume of aquifer-system sediment for a unit change in head (Lohman, 1972). The water being exchanged is derived from two processes—expansion or compression of the sediment that results from a change in effective stress, and expansion or compression of the fluid caused by a change in pore-fluid pressure.

The skeletal component of specific storage addresses the first of these processes, which for most unconsolidated alluvial aquifer systems is the dominant component. Skeletal compressibilities of fine-grained aquitards and coarser-grained aquifers typically differ by several orders of magnitude; therefore, it is useful to define them separately. Skeletal specific storages of the aquitards, S'_{sk}, are defined for two ranges of stress, elastic and inelastic.

$$S'_{sk} = \left| \begin{array}{ll} S'_{ske} = \alpha'_{ke}\rho g, & \sigma_e < \sigma_{e(max)} \\ S'_{skv} = \alpha'_{kv}\rho g, & \sigma_e > \sigma_{e(max)} \end{array} \right. \quad (1)$$

The primes (′) signify aquitard properties, and the subscripts e and v refer to elastic and inelastic properties, respectively. For a change in effective stress, the aquitard deforms elastically when the effective stress remains less than the previous maximum effective stress, $\sigma_{e(max)}$; when the effective stress exceeds $\sigma_{e(max)}$, the aquitard deforms inelastically. For coarse-grained sediments typically found in aquifers, inelastic skeletal compressibility is negligible; therefore, skeletal specific storage of the aquifer, S_{sk}, is adequately represented by the fully recoverable, elastic component of skeletal specific storage, S_{ske}: