GROUND MOVEMENT STUDY

LIVERMORE VALLEY, CALIFORNIA

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PROJECT NO.: 150370

Prepared for
Zone 7 Water Agency

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1. Introduction

1.1 Genesis of This Study

Ground surface movement within valleys and sedimentary basins is a complex geologic phenomenon that results from various earth processes. Movement can manifest at many scales of magnitude, at differing rates, and over variable periods of time.

Zone 7 and much of California have been faced with unprecedented drought in recent years, which has focused attention on ground surface movement that may or may not in some way be associated with the current climatic environment. Zone 7 wishes to synthesize existing information regarding various ground surface movements, including expansive soil movement and ground surface deformation accompanying groundwater elevation changes that may accompany climate swings.

1.2 Project Goals and Objectives

This study is intended to compile and synthesize available information regarding soils, geology, tectonics, groundwater elevation variability and monitoring, and ground surface elevation monitoring to understand the framework for ground surface changes that may be observed within the Livermore Valley particularly during drought (and recovery) periods. The objective of the study is to understand regional and local ground movement mechanisms in the Livermore Valley, the causes of the movements, how they are expressed at the ground surface, and their potential impacts on public infrastructure and private property.

1.3 Scope of Work

The scope of work completed for this study included:

1. Literature research and review regarding mechanisms of expansive soil response to changes in soil moisture.
2. Literature research and review regarding mechanisms of ground deformation as related to changes in groundwater levels.
3. Compilation of published and unpublished soils mapping and regional geologic mapping.
4. Consultation with area municipal public works staff regarding areas of historically identified problematic expansive soils.
5. Research and review of available published historic evapotranspiration data for the Livermore area.

6. Assembly of published and unpublished information regarding the hydrogeology of the Livermore Valley, including Zone 7's Groundwater Management Plan.
7. Compilation of Zone 7 data, operational information, and data/interpretive reports relating to monitoring of groundwater levels and ground surface elevation monitoring in the Livermore Groundwater Basin, including the Agency's *Annual Report for the Groundwater Management Program* (*2013 and 2014 Water Years*).
8. Consultation with Zone 7 staff and consultants regarding existing well logs and subsurface information, and modeling of basin hydrogeology.
9. Consultation with Zone 7 staff.

2. Understanding the Ground Movement Mechanisms

2.1 Potential Sources of Ground Movement

Numerous mechanisms can affect movement of the earth's surface. However, this study is focused on three ground movement mechanisms that can be expected to occur within the project study area considering the current geologic regime. From shallow to deep, the mechanisms which are considered as potential sources of ground surface movement are volumetric changes in expansive, near-surface soils due to soil moisture content, changes in the volume of sedimentary deposits due to variation in groundwater elevation, and tectonic-related deformation. Other mechanisms, such as mass-wasting processes and seismically-induced soil volume changes, are not addressed herein.

2.2 Expansive Soils

The soil that mantles the ground surface is a product of many factors: climate; organisms living in the soil; relief/topography; parent material; and time (Jenny, 1946). The "climate" factor includes temperature and moisture. "Parent material" means the gravel, sand, silt and clay particles that compose the soil; these may be derived from the weathered rock immediately underlying a given site, or may be transported from elsewhere and deposited at the site.

Expansive soil is a term generally used to describe a soil material that has the potential for swelling or shrinking with changes in soil moisture content. The mechanisms of swelling and shrinkage are complex and are controlled by several factors. The primary factors influencing the potential for and occurrence of swelling and shrinking are the soil properties as summarized in Table 1, and environmental conditions as summarized in Table 2 (Nelson and Miller, 1992).

The soil aspects that are most important for this study are the percentage of expansive clay, how expansive the clay mineral grains are, and the soil moisture content. There are many different clay minerals, some of which shrink and swell according to changes in moisture content and pore water chemistry. When moisture is added to a soil containing significant fractions of expansive clay, the soil expands. The proportionate volume of expansion is related to the amount of moisture uptake due to clay mineralogy, percent clay, pore water chemistry, and consolidation (loading) history within the soil. When moisture is lost from such a soil, it undergoes volume loss or shrinkage. As is the case with swelling of these soils, the proportionate volume change is related to the same set of factors.

Table 1. Soil properties that influence shrink-swell potential

Factor	Description
1. Clay mineralogy	Clay minerals which typically cause soil volume changes are montmorillonites, vermiculites, and some mixed layer minerals. Illites and Kaolinites are infrequently expansive, but can cause volume changes when particle sizes are extremely fine (less than a few tenths of a micron).
2. Soil water chemistry	Swelling is repressed by increased cation concentration and increased cation valence. For example, Mg^{2+} cations in the soil water would result in less swelling than Na^{+} cations.
3. Soil suction	Soil suction is an independent effective stress variable, represented by the negative pore pressure in unsaturated soils. Soil suction is related to saturation, gravity, pore size and shape, surface tension, and electrical and chemical characteristics of the soil particles and water.
4. Plasticity	In general, soils that exhibit plastic behavior over wide ranges of moisture content and that have high liquid limits have greater potential for swelling and shrinking. Plasticity is an indicator of swell potential.
5. Soil structure and fabric	Flocculated clays tend to be more expansive than dispersed clays. Cemented particles reduce swell. Fabric and structure are altered by compaction at higher water content or remolding. Kneading compaction has been shown to create dispersed structures with lower swell potential than soils statically compacted at lower water contents.
6. Dry density	Higher densities usually indicate closer particle spacings, which may mean greater repulsive forces between particles and larger swelling potential.

After Table 2.1 in Nelson and Miller (1992).

Table 2. Environmental conditions that influence shrink-swell potential

Factor	Description
1. Initial moisture condition	A desiccated expansive soil will have a higher affinity for water, or higher suction, than the same soil at higher water content, lower suction. Conversely, a wet soil profile will lose water more readily on exposure to drying influences, and shrink more than a relatively dry initial profile. The initial soil suction must be considered in conjunction with the expected range of final suction conditions.
2. Moisture variations	Changes in moisture in the active zone near the upper part of the profile primarily define heave. It is in those layers that the widest variation in moisture and volume change will occur.
2.1 Climate	Amount and variation of precipitation and evapotranspiration greatly influence the moisture availability and depth of seasonal moisture fluctuation. Greatest seasonal heave occurs in semiarid climates that have pronounced, short wet periods.
2.2 Groundwater	Shallow water tables provide a source of moisture and fluctuating water tables contribute to moisture.
2.3 Drainage and manmade sources	Surface drainage features, such as ponding around a poorly graded house foundation, provide sources of water at the surface; leaky plumbing can give the soil access to water at greater depth.
2.4 Vegetation	Trees, shrubs, and grasses deplete moisture from the soil through transpiration, and cause the soil to be differentially wetted in areas of varying vegetation.
2.5 Permeability	Soils with higher permeabilities, particularly due to fissures and cracks in the field soil mass, allow faster migration of water and promote faster rates of swell.
2.6 Temperature	Increasing temperatures cause moisture to diffuse to cooler areas beneath pavements and buildings.
3. Stress conditions	
3.1 Stress history	An overconsolidated soil is more expansive than the same soil at the same void ratio, but normally consolidated. Swell pressures can increase on aging of compacted clays, but amount of swell under light loading has been shown to be unaffected by aging. Repeated wetting and drying tend to reduce swell in laboratory samples, but after a certain number of wetting-drying cycles, swell is unaffected.
3.2 In situ conditions	The initial stress state in a soil must be estimated in order to evaluate the probable consequences of loading the soil mass and/or altering the moisture environment therein. The initial effective stresses can be roughly determined through sampling and testing in a laboratory, or by making in situ measurements and observations.
3.3 Loading	Magnitude of surcharge load determines the amount of volume change that will occur for a given moisture content and density. An externally applied load acts to balance interparticle repulsive forces and reduces swell.
3.4 Soil profile	The thickness and location of potentially expansive layers in the profile considerably influence potential movement. Greatest movement will occur in profiles that have expansive clays extending from the surface to depths below the active zone. Less movement will occur if expansive soil is overlain by nonexpansive material.

After Table 2.2 in Nelson and Miller (1992).

Ground surface deformation resulting from soil moisture changes in expansive soils is a near-surface phenomenon that generally occurs within the upper 20 feet of the soil profile (see Fig. 1). The main interface across which soil loses moisture is the air/soil interface – the ground surface. The depth of significant soil moisture variation is generally referred to as either the *zone of seasonal fluctuation* or the *active zone*. For a given soil deposit, the deeper the active zone, the more total swelling and shrinking will occur.

The depth of the active zone at a given site can be a function of both natural and man-made climatic conditions. The natural climatic conditions which can affect the depth of the active zone are typically quantified by C_w, *climatic rating* or by the TMI, *Thornwaite Moisture Index* (Nelson and Miller, 1992). The lower the C_w or TMI, the greater the potential for large and sustained variations in climate (temperature changes, relative humidity, wind, seasonal changes in evapotranspiration rates, etc.) that lead to a deeper active zone and corresponding large, naturally occurring variations in near surface soil moisture content. Both the C_w and TMI for the Livermore Valley are near the lowest end of the scale (Greenfield and Shen, 1992) indicating the prevalence of conditions conducive for development of a naturally occurring deep active zone.

The manmade conditions that can affect the depth of the active zone include irrigation, ground surface cover, and vegetation. When ground is regularly and uniformly irrigated the potential for variations in soil moisture content is reduced and the active zone is kept to a relatively shallow depth. Relatively impermeable ground surface cover such as pavements, slabs, or membranes also tend to reduce the depth of the active zone as the soil moisture is trapped by the covering. The impact of vegetation is complex and variable. For example, the use of significant regular, uniformly distributed irrigation to support vegetation will tend to result in a shallower active zone. The uptake of soil moisture by plant roots in areas where there is no irrigation or where loss of moisture from plants to the atmosphere (evapotranspiration) outstrips the input from irrigation will tend to cause an increase in the depth of the active zone.

If soil moisture is lost uniformly from a homogeneous soil, as its volume lessens, the ground surface drops uniformly; the reverse occurs upon wetting. However, soils are typically non-homogeneous and the moisture loss or gain is never truly uniform. It is the non-uniformity and variability of soil deposits and soil moisture conditions which are problematic for shallow-founded structures and other ground level improvements. The result of the non-uniformity is differential volume change, differential shrinkage/swelling, and differential settlement/uplift that create problems (see Fig. 2). For natural soils, the extent of non-homogeneity is a primarily a function of the depositional environment. For manmade soil deposits, the variation depends on the source of the materials and means by which the materials are placed. The non-uniformity of soil moisture results from environmental factors other than climate, such as the influence of vegetation and surface exposure/aspect. Different types of vegetative cover are more effective at extracting moisture from the soil. These differences have been quantified mainly for agricultural applications, but are applicable to urban landscape settings (for example, see Crop Coefficient Leaflets 21427 and 21428 published by University of California Cooperative Extension). The presence of slopes, and the direction in which they face (i.e. toward the sun), are additional factors in soil moisture distribution patterns (see Fig. 3).

2.3 Groundwater Level Changes

Ground deformation accompanies both the rise and fall of groundwater levels. The key to understanding this process is to understand how different sedimentary deposits – those which serve as aquifers and those which serve as aquitards – respond to changing groundwater levels.

The first key concept is that groundwater occupies the voids between the individual sedimentary grains in the ground. In nature, these grains are not a random collection of differently sized grains -- rather, they are sorted as they are deposited. For example, sediments deposited by a fast-moving stream tend to consist of coarser clasts (cobbles, gravels, and sands) with little or no fines (silt and clay). In contrast, sediments deposited in a lakebed or floodplain setting are much richer in fines, with little or no sand, and no cobbles or boulders.

"Aquifer" refers to an underground body of sediment (or fractured rock) that contains extractable groundwater. Since water flows most easily through coarse-grained sediments (they have higher "transmissivity"), the intake screens of wells are usually placed in these coarser intervals.

"Aquitard" refers to typically finer-grained intervals of sediment composed of mainly clay and silt. Water passes much more slowly through these intervals (of lower transmissivity).

Although it seems counterintuitive at first, it is useful to think of water moving *through* an aquifer, while the real water *storage* occurs in the aquitards. The reason for this has to do with compressibility of sediment.

Groundwater extraction is essentially the removal of water from between mineral grains. Groundwater recharge is the opposite: refilling of the voids between mineral grains. As groundwater is extracted, the water levels in the aquifer system drop; as recharge occurs, the water levels in the system rise again.

When groundwater is extracted, there is an accompanying drop in ground surface elevation as grains compress together; when recharge occurs, there is an accompanying rise in ground surface elevation. This ground surface deformation can be completely reversible ("elastic"), or largely permanent ("inelastic"). The magnitude of the elastic subsidence and rebound are small. An example scenario outlined in Borchers and others (2014) using typical observed values would result in 0.25 feet of elastic subsidence from hydraulic head decline of 100 feet in a 500-foot-thick aquifer of average elastic compressibility. The elastic compressibility of fine-grained (aquitard) intervals is much greater than that for coarse-grained sediments (Borchers and others, 2014). The extent to which water levels drop, and the type of sediment, are the controls on whether the deformation is elastic or inelastic; the mechanism for this is described below. In a sediment-water system, it is only the sedimentary particles that compress; water is essentially incompressible.

In sediment (either aquifer or aquitard) that is below the groundwater level (the piezometric surface), the voids are full of water, and the pressure of each grain on the next is partially offset by the buoyant force of water. As water is pumped or drained from that sedimentary sequence, the water level (hydraulic head, or piezometric surface) drops as the voids between sedimentary grains begin to drain (water still clings to the margins of the grains), and the buoyant force of water is reduced. As a result, the grains exert ever more pressure on each other (the “effective stress” is higher).

In a coarse-grained sedimentary sequence like sand or gravel, the increase in effective stress that goes with water level drop has a negligible effect on the sediment, and a negligible effect on the amount of void space that could be refilled by water if the aquifer is recharged. Coarse-grained sediments largely behave elastically, and there is no permanent change in water storage ability.

However, in fine-grained sediments, the more the water level drops, the more the buoyant force is reduced (effective stress increases). The more the effective stress increases, the more it tends to cause the individual grains to rearrange themselves into a more compact mass. If this rearrangement occurs, there is a net loss of void space that is not recoverable – there is a permanent inelastic) loss in water storage ability.

Permanent (inelastic) compaction only happens when the effective stress between sediment grains rises higher than it ever has before (in soil mechanics terminology, this is akin the pre-consolidation pressure being exceeded and virgin consolidation). Stated another way, inelastic compaction only occurs when water levels drop below their previous historic low.

The magnitude of inelastic compressibility is typically 20 to >100 times as great as the elastic compressibility of an aquitard (Borchers and others, 2014). This means that the volume of water released through inelastic consolidation (sometimes referred to as the “waters of compaction”) is on the order of 20 to 100 times the specific yield achieved through elastic consolidation (Riley, 1998; cited in Sneed, 2001). Using typical inelastic compressibility values for clay-rich sediments, a 100-foot drop in hydraulic head below the historic low (the preconsolidation stress) would result in 20 feet of subsidence (Borchers and others, 2014) in an aquifer system containing 500 feet of aquitard sediments (as compared to 0.25 feet of elastic subsidence).

Pumping from a well produces a pressure gradient; the flow of groundwater toward the well intake is acting to restore the system to pressure equilibrium in the aquifer system (Le Chatelier's Principle). As a result, the effects of groundwater level declines tend naturally to be distributed throughout a groundwater basin, across a broad geographic area. There is a lag in this pressure equilibration process imposed by the transmissivity (or permeability) of the sediment holding the water. As a result of this lag in pressure equilibration, in a layered or heterogeneous aquifer system, it is possible for localized inelastic compaction to occur in aquitard materials if groundwater withdrawal reduces the fluid pressure below that associated with historic lows, even if overall groundwater levels have not dropped below historic lows (S. Ingebritsen, pers. communication, 2015).

2.4 Tectonic Deformation

Tectonic deformation affects virtually the entire Earth's surface, albeit at different rates. The mechanism of plate tectonics involves the formation, relative movement, and destruction of crustal plates. Major zones of deformation and faulting are concentrated at the boundaries between plates, with less extensive deformation and faulting occurring within individual plates.

Tectonic plates move relative to one another in three basic ways: apart from one another (at spreading centers such as the Mid-Atlantic Ridge); toward one another, with one ultimately diving beneath the other (at subduction zones such as the Alaskan Trench); or horizontally past each other (at strike-slip faults such as the San Andreas fault).

Internally within tectonic plates, stresses may be accommodated or expressed by faulting, folding, uplift and subsidence. Depending on locality, the terrain affected by one or more of these processes may be uplifting, subsiding, tilting, or otherwise deforming at rates that typically vary from tenths of a millimeter per year, to tens of millimeters per year.

The tectonic setting of the Livermore Valley, and the associated deformation, is described in a later section.

3. Geologic Setting

3.1 Physical Setting

The Livermore Valley lies within the Coast Ranges geomorphic province of California. This province is characterized by northwest-southeast trending mountain ranges and intervening valleys. These ranges in a broad sense are a reflection of major faults in the area.

The Livermore Valley is bordered on the west by the East Bay Hills, with the Calaveras fault marking the western boundary of the basin (see Fig. 4). The basin is bordered on the east by the Altamont Hills, with the Greenville fault marking the eastern boundary of the basin.

To the north of the valley is the Mt. Diablo uplift, and to the south of the basin, the Diablo Range.

The Livermore Valley is drained by Arroyo de la Laguna, which flows southward out of the valley near its southwestern corner. Arroyo de la Laguna is renamed Alameda Creek at Sunol, as it continues its westward flow toward San Francisco Bay.

The overall flow pattern in the valley is from east to west, which is a reflection of the valley floor's tectonic subsidence and the basin's overall drainage exit route via Alameda Creek.

The general elevation of the valley floor ranges from approximately 580 feet above mean sea level (msl) in eastern Livermore/Altamont, to approximately 330 feet msl near the 680/580 interchange, to approximately 285 feet msl near the intersection of I-680 with Sunol Boulevard, where the Arroyo de la Laguna (headwaters of Alameda Creek) leave the main valley floor.

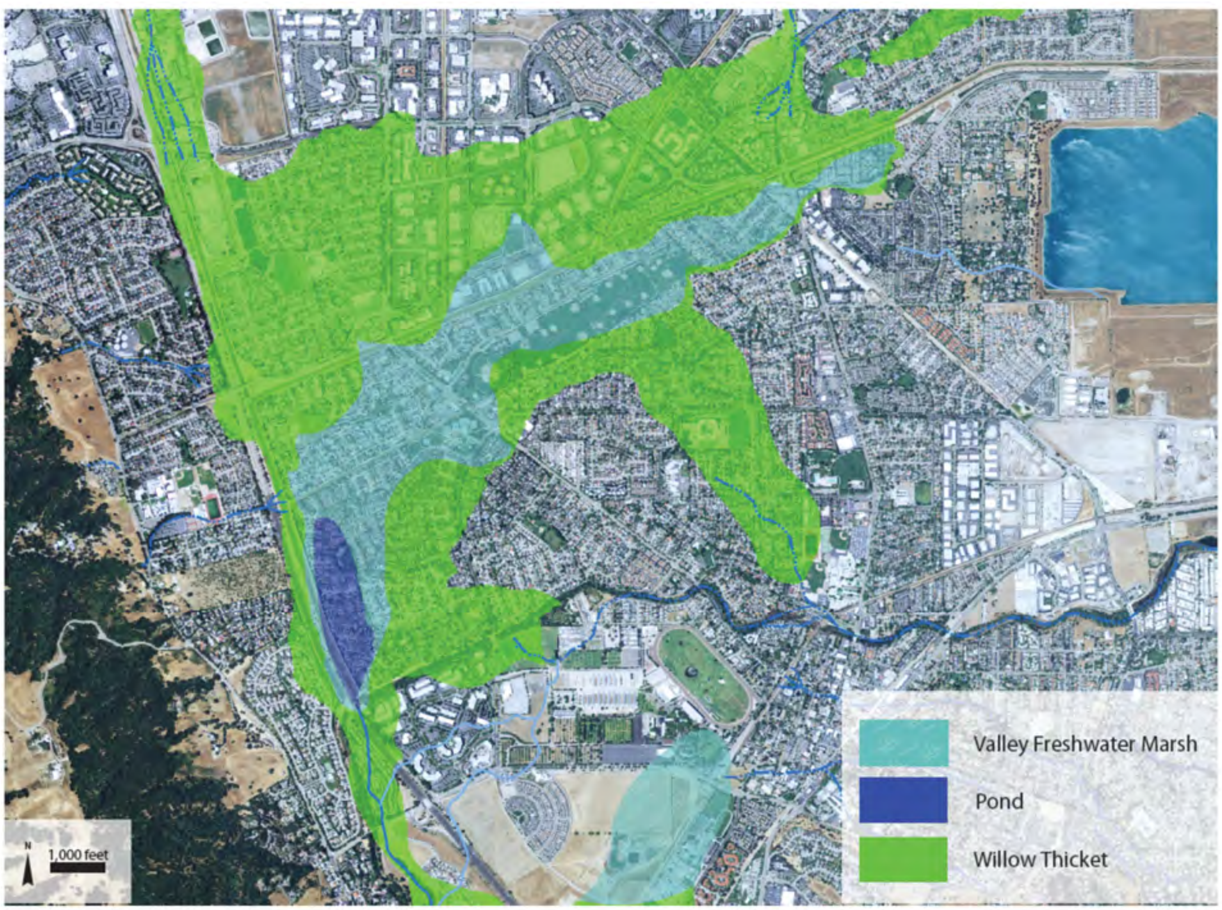
The elevations of the mountainous areas bounding the basis vary widely. Mt. Diablo's summit is 3849 feet msl. The divide along the East Bay Hills is on the order of 1100 to 1600 feet msl. The Altamont Hills rise to elevations on the order of 700 to 1500 feet msl. The Diablo Range south of the site rises to elevations on the order of 1400 feet msl.

3.2 Livermore Valley Surficial Deposits and Soils

For the soils in the hilly areas surrounding the Livermore Valley, the weathered bedrock is the parent material for the soils.

For the soils on the valley floor, in contrast, the parent material is the sediment deposited by creeks that drain the surrounding hilly areas. These creeks erode the upland areas, and transport sediment through the basin, eventually leaving the southwest corner of the valley via Alameda Creek. The Livermore Valley is a tectonically active basin that has experienced subsidence, with the result that some of the sediment is trapped within the basin (see Fig. 5), resulting in the thick accumulation over time that forms the groundwater basin. Fast-moving streams can transport relatively coarse sediment (cobbles, gravel and sand). The more slowly a creek moves, the finer the sediment that is deposited. The alluvium containing the most clay within the Livermore Groundwater Basin is material that is deposited by streams in poorly drained valley floor areas.

Even in historic times, areas of marshland were known. The City of Pleasanton, occupies the site of a former 2,600-acre marsh complex (SFEI, 2013). The marshland was cleared for agriculture beginning in the mid-1800's, and was complete by the early 1900's (SFEI, 2013). The Valley Trails area of Pleasanton is perhaps the most recent remnant of the wetland complex (SFEI, 2013). The natural soil profile in these areas reflects the fine-grained sediment (the basin deposits described above) deposited in such a setting. A second wetland complex (the "Springtown Sink") was present east of modern Livermore.



Map showing historic extent of the Pleasanton marsh complex (Figure 4.19 from SFEI, 2013).

In general, the northern side of the Livermore Valley was characterized by clay-rich, fine-grained soils that flooded each year. The southern side of the valley had coarser-grained, better-drained soils that reflected the stream transport northward out of the Diablo Range.

The surficial soils in the study area have been mapped by the USDA National Resource Conservation Service (USDA/NRCS). Many soil types have been identified in the vicinity of the site, with a great variety in properties. Individual soil types reflect the soil forming factors noted above, with many subclasses according to the slope of ground in a given area. Figure 6, although its main purpose is to illustrate certain soil properties described more extensively below, portrays the extent of individual soil series with thin gray lines. Soils mapping by the USDA/NRCS (both current, and archived) has been made available over the web at http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

From the standpoint of surface ground movements associated with soil type, the most important characteristics are: the proportion of expansive clays contained in the upper few feet of the soil; and the type of clay minerals present.

Using data gathered as part of mapping and characterizing the individual soil series, the USDA/NRCS has classified soils according to shrink/swell potential and other attributes, and has classified various soils as to limitations they place on various uses, such as “Dwellings Without Basements” (essentially, single-family homes most likely to reflect expansive soil movement), and “local roads and streets.” While informative, maps developed by the USDA/NRCS (accessible at the website referenced above) include “slope” and “depth to hard bedrock” as factors in determining limitations, and do not single out the expansion potential of soils, which is of interest here.

One of the tests used by the USDA/NRCS to quantify the potential for shrink/swell movement measures “linear extensibility.” Linear extensibility is a measure of the volume change a soil goes through as it loses moisture. As used by the USDA/NRCS (see USDA/NRCS, 2015, National Soil Survey Handbook, Section 618.41), it is defined as “the linear expression of the volume difference of natural soil fabric at 1/3 bar or 1/10-bar water content and oven dryness.” We used laboratory test data from the USDA/NRCS to develop a map (Figure 6) that classifies the linear extensibility of soils mapped at any point on the ground into four classes: low, medium, high, and very high. That map is presented in this report as Figure 6 with the outline of the Livermore Valley groundwater basin shown. These four classes describe the percent volume change of soil as it dries, so the soils with the highest linear extensibility values have the highest shrink-swell potential (USDA/NRCS, 2015, National Soil Survey Handbook, Section 618.41).

Several features are apparent from Figure 6, all of which reflect the local geology and soil parent materials:

The most expansive soils (soils with the highest linear extensibility) are associated with the western part of Pleasanton, with parts of the San Ramon Valley, and with certain narrow valley floor areas in the uplands northeast of Pleasanton and San Ramon – the flanks of Mt. Diablo.

Expansive soil is very common in the hillside areas, as well as in valley floor areas. These expansive soils reflect the weathering product of the local bedrock, and indicate that the bedrock parent material is expansive as well as the soils derived from them.

In valley floor areas, those areas with less expansive soils (lower linear extensibility) are underlain by coarser alluvium that is relatively low in clay content (compare Figure 5 and Figure 6). Those valley floor areas with more expansive soils (higher linear extensibility) are concentrated near the western and northwestern perimeter of the valley, in areas of fine-grained sediments deposited in and around a marshy setting.

The distribution of expansive soils as measured by linear extensibility (see Fig. 6) correlates strongly with the historic limits of the Pleasanton marsh complex (see Fig. 5 and the excerpted marsh complex map presented above).

The City of Pleasanton Department of Public Works (verbal communication, 2015) reports that the westernmost portion of the city, especially areas near channels and floodplains, has historically experienced common expansive soil distress to improvements. The City of Dublin does not report such areas of common expansive soil distress (verbal communication, 2015).

3.3 Livermore Valley Geology

The Livermore Valley lies in a geologically complex area with ongoing tectonic activity.

The geology and tectonic setting of the Livermore Valley is reviewed in Norfleet (2004), and is summarized herein; the reader is referred to that report for additional detail. Additional information regarding geologically recent (Quaternary) deposits is drawn from Knudsen and others (2000), and SFEI (2013). The major elements of the geologic setting are shown on Figure 4. Geologically recent (Quaternary age) deposits are shown on Figure 5.

3.3.1 Bedrock

The Diablo Range, south of the Livermore Valley, consists primarily of Franciscan Complex rocks that formed in a subduction zone setting, and which were subsequently metamorphosed (Graymer and Brabb, 1996; Dibblee, 1980). As a result of tectonic activity, multiple thrust slices have been stacked vertically, with uplift beginning probably in Pliocene time.

Mt. Diablo and associated rocks are also largely subduction related and ocean floor (Great Valley Sequence) rocks that underwent metamorphism well before beginning to be uplifted probably in late Pliocene (roughly 6 million years ago) to early Pleistocene time.

The East Bay Hills consist of primarily low-grade metamorphic and sedimentary rocks that have juxtaposed against the western end of the Livermore Basin by strike-slip activity along the Calaveras fault.

The Altamont Hills consist primarily of low-grade metamorphic and sedimentary rocks that have been elevated since at least the Pliocene. Salts leached from these marine rocks have contributed to alkali and saline soils in the eastern part of the Livermore Valley (SFEI, 2013).

3.3.2 Valley Fill

The Livermore Valley formed as a result of fault activity, which led to the relative downdrop of the valley and relative uplift of adjacent uplift areas. The valley (and associated groundwater basin) began to form about 6 million years ago in the Pliocene, with parts of it having been overridden by the southward-vergent thrusts that accommodate uplift of Mt. Diablo (Fig. 4). As a result, sediments within this basin (see Fig. 5) may extend northward under the southern fringe areas of bedrock exposed at the modern ground surface. A total thickness of as much as 8 km of sediment has filled this basin since its inception (Isaacson, 1990.

During early stages of the basin's evolution, large volumes of coarse sediment were carried out of the Diablo range, depositing the "Livermore Gravels," which reach up to 4,000 feet in thickness (Barlock, 1988 and 1989; SFEI, 2013). The overall transport direction of waters transporting and depositing these gravels was at times northward into and through the San Ramon Valley, and at times southward (as today) through the Sunol Valley and through Niles Canyon (Helley, 1997). Depending on the presence or lack of blockage in either drainage path, the base level for the Livermore Valley changed, leading to deposition of thick, fine-grained sedimentary intervals interlayered with coarser deposits (see Fig. 7).

As interpreted by Norfleet (2004), the Livermore Gravels volumetrically make up the largest identifiable component of the Livermore Basin's aquifers. In the central portion of Livermore Valley, these gravels are relatively clean (low fines content), and have high transmissivity; Norfleet's analysis refers to these as "clean gravels" in their hydrostratigraphic analysis. Surrounding the central basin area where the clean gravels are found are sediments that contain more fines; Norfleet's analysis terms these "sandy gravels," and notes that the transmissivity is significantly lower. Pumping rates and associated water levels differ significantly between such areas. The sandy gravels were derived from various upland areas around the valley, not just the Diablo Range.

In addition to these coarser intervals, there are fine-grained intervals of sediment that probably reflect past lacustrine (lake) and floodplain sequences. These finer-grained intervals constitute the main aquitards.

The main sedimentary units making up the basin fill (see Fig. 7), and their hydrogeologic roles, as identified by Norfleet (2004) in their analysis of Zone 7 well log data are: lacustrine clays and silts (aquitard); overbank and floodplain clays and silts (aquitard); fluvial gravels and sands of braided streams (aquifer); and deltaic gravels and sands (aquifer).

The subsurface geometry of these complexly shaped bodies of sands, gravels, silts and clays means that pumping rates, groundwater levels and potential for recharge can vary over distances as short as hundreds of feet (Norfleet, 2004). While some of these differences were at first interpreted as evidence of faults in the subsurface, more recent analysis has found them to be a result of original deposition.

The modern valley floor ground surface of course represents the most recent episode of basin fill. Detailed geologic mapping by Knudsen and others (2000) differentiates the major sedimentary deposit types present at the ground surface (see Fig. 2). Much of the valley floor is mapped as Holocene alluvial fan deposits, with fine-grained alluvial fan deposits along the northern side of the valley floor. Holocene basin deposits (typically silt and clay, deposited in a marshy setting) are mapped at the western end of the valley floor, and are also fringed to the north and northeast by fine-grained alluvial fan deposits. Generalizing, areas of relatively coarse sediment and thin surficial soils tend to be more common in the eastern portion of the Livermore Valley, and along the southern margin. Areas with a greater amount of fine sediment, and thicker surficial soils, tend to be concentrated in the western part of the basin. Before settlers modified the local drainages, the valley floor streams were commonly braided or spreading streams that were not necessarily continuous.

3.3.3 Livermore Valley Groundwater

This section reviews the overall groundwater system for the Livermore Valley, and draws extensively from: Norfleet (2004); Zone 7 Water Agency's Well Master Plan (CH2MHill, 2003); Zone 7 Water Agency's Groundwater Management Plan (Jones & Stokes, 2005); and San Francisco Estuary Institute (2013).

Hydrostratigraphy and History of Usage

Local streams such as Arroyo Mocho and Arroyo las Positas in their natural state tended to be discontinuous, which facilitated recharge of the unconfined upper aquifer. Flood control projects, together with efforts to drain the Pleasanton marsh, channelized these streams and reduced their recharge impact. These streams recharged the uppermost (unconfined) aquifer, which farther to the west (down-valley) is confined by the relatively thick clay capping soils that were deposited in the Pleasanton marsh complex. As a result, artesian conditions existed in the western portion of the Livermore Valley in pre-settler days (SFEI, 2013).

Irrigation using spring water became widespread after about 1850 (SFEI, 2013). Artesian wells were dug in part to drain the marshland in the Pleasanton area. By about 1912, attention was already being paid to the potential for groundwater recharge through coarse gravels. By about 1916, the lowering of the water table was noticeable, and the dry year of 1913 led to localized drops in water levels west of Livermore of up to 50 feet, according to well records (SFEI, 2013).

Pumping began to be controlled and reduced beginning in the late 1940's, when large-scale pumping by SFPUC ended in the Pleasanton area (SFEI, 2013).

The groundwater hydrogeology of the Livermore Groundwater Basin is reviewed in more detail in Norfleet (2004) and Jones & Stokes (2005), and is more generally summarized herein.

Investigation of the Livermore Valley's groundwater began in earnest in the 1940s, when the California Department of Water Resources (DWR) began studying the valley. Based on work done by DWR from the 1940s into the 1960s, the valley was thought to consist vertically of three aquifer zones, separated by gently dipping clayey aquitards. Local differences in water levels and pumping rates were interpreted as reflecting local faults.

Norfleet (2004) performed a thorough reanalysis of the basin's hydrostratigraphy, analyzing the sedimentary sequences apparent in well logs. The role of tectonism and uplift was recognized, which have resulted in complex interrelationships between depositional sequences. These variously linked, cross-cutting, and stacked (coarse-grained) channels are locally separated by fine-grained materials. Four main sediment types and settings in which they accumulated ("lithofacies") were distinguished (see Fig. 7): lacustrine (lake) clays and silts; overbank and floodplain clays and silts; fluvial (stream-laid) gravels deposits by braided streams; and deltaic (stream mouth) gravels and sands deposited at the mouths of streams where they entered a lake. No evidence for significant fault offset within the aquifer system stratigraphic section was observed. None of these sediment types occurs as a laterally continuous blanket, although overall patterns permit them to be treated as such for some groundwater modeling purposes (see Fig. 7).

Hydrologic Basins

The net result of these aquitards is to divide the overall Livermore Valley Groundwater Basin into several groundwater subbasins, the limits of which are shown on Figure 2 (names are not shown for legibility). The *"Main Basin"* occupies the floor of the Livermore Valley, and is divided into the (from east to west) the *Mocho II, Amador, Bernal,* and *Castle* subbasins. The Main Basin is flanked on the northwest by the *Bishop, Dublin, and Camp* fringe subbasins; on the west by the *Dublin Uplands,* and *Sinbad Uplands*; on the south by the *Livermore Uplands*; and on the east and northeast by the *Cayetano, May, Vasco, Spring, Altamont, and Mocho 1* subbasins. We refer the reader to the Zone 7 Groundwater Management Plan (Jones & Stokes, 2005) and Zone 7 Annual Report to the Groundwater Management Plan (Zone 7, 2014) for additional background and detail regarding the subbasins.

The Main Basin is connected hydrologically to these adjacent fringe basins via relatively young, shallow alluvium. There is only minor subsurface groundwater flow from the fringe basins into the Main Basin (Zone 7, 2014 – Annual Report for GMP 2013YW). Virtually all municipal and industrial groundwater supply wells (including municipal and industrial retailers' wells, and Zone 7 production wells) are located within the Main Basin (see Fig. 8).

Aquifer Zones

Multiple lenses, layers, and elongate bodies of coarse-grained (sandy, gravelly) materials are present in the Main Basin, which are most usefully divided into two main aquifer zones, separated by a central aquitard zone of variable thickness (tens of feet thick) composed of silty clay (see Fig. 9. A schematic east-west geohydrologic cross-section is shown on Figure 7, distinguishing aquifer and aquitard earth materials, and illustrating their complex interlayering.

The *"Upper Aquifer Zone"* consists of mainly sandy gravel and sandy, clayey gravels. This aquifer is considered confined only in its western portion, where it is capped by a surficial clay layer. In the eastern part of the Main Basin, the Upper Aquifer Zone is exposed at the ground surface, and is therefore unconfined. In the western part of the Main Basin, the upper surface of this aquifer ranges from 5 to 70 feet below ground surface (bgs), while its base is about 80 to 150 feet bgs.

The Upper Aquifer Zone overlies a clayey aquitard that is considered leaky – recharge from the Upper Aquifer Zone passes through this leaky central aquitard into the "Lower Aquifer Zone" below. The thickness of this central aquitard is quite variable, based on Zone 7's analysis of well log data (Zone 7 staff, personal communication, 2015). As shown on Figure 9, this aquitard where present is typically on the order of 20 to 30 feet thick, ranging up to more than 80 feet in thickness.

The "*Lower Aquifer Zone*" is an inclusive term that aggregates an interbedded sequence of "semi-confined to confined, coarse-grained, water-bearing units interbedded with relatively low permeability, fine-grained units" (Zone 7, 2014 – Annual Report for the Groundwater Management Program). The Lower Aquifer Zone is considered to be semi-confined to confined. As noted, it appears to be recharged by downward flow from the Upper Aquifer Zone through the aquitard separating the Upper and Lower Aquifer Zones.

3.4 Livermore Valley Tectonics

The Zone 7 service area lies within the tectonically active Coast Ranges, which is cut by multiple active faults associated with the San Andreas Fault Zone (see Fig. 4). These faults accommodate the relative movement between the Pacific Plate (west of the plate boundary) and the North American Plate (east of the plate boundary).

The interaction between the numerous tectonic blocks between these multiple faults results in some areas undergoing uplift relative to others along dip-slip (up-and-down) faults. Other areas experience horizontal relative movement (strike-slip offset). Many faults exhibit a component of both dip-slip and strike-slip offset, with strike-slip motion dominating.

Overall the plate boundary is experiencing offset at a rate of about 38 mm/yr [Burgman and others, 2006]. A portion of that offset is accommodated by the rocks and faults in the general vicinity of the Livermore Valley. Major pertinent faults include the Calaveras fault (near the western end of the basin), and the Greenville fault (near the eastern end of the basin).

This tectonic activity is ongoing; for example, the larger faults east and west of the Livermore Valley – the Calaveras and Greenville faults – are both creeping, and Mt. Diablo continues to rise (and move south toward the Livermore Valley) at a slightly faster pace than erosion can lower it. The upland areas of the Diablo Range, south of the study area, are moving northward toward the basin.

Broad deformation from this activity is fast enough to be detectable, and significant earthquakes can be marked by relative offsets on the order of feet. The Livermore earthquake sequence of 1980 on the Greenville fault resulted in surface rupture. The southern flank of Mt. Diablo is being uplifted at $\geq$ 1 mm/yr, based on InSAR and GPS data (Burgman and others, 2006], and parts of the East Bay Hills (west of the Calaveras fault) are being uplifted at 0 – 1.5 mm/yr (Burgman and others, 2006). The creep rate on the Greenville fault is estimated to be 2 mm/yr (Sawyer and Unruh, 2012), and 3.0 to 3.5 mm/yr on the Concord fault (Galehouse, 1998). The Calaveras fault (central segment) north of Calaveras Reservoir is creeping at between 2 and 4 mm/yr (Galehouse and Lienkaemper, 2003).

The net effect of this tectonic activity is that the basin is tending to drop relative to the upland areas.

The Livermore Valley currently drains southward along Arroyo de la Laguna, which becomes Alameda Creek. This creek system exploits the weak rocks along the Calaveras fault, ultimately escaping westward through the East Bay Hills to San Francisco Bay.

Tectonic deformation and fault movement therefore are a major control on the elevation of Alameda Creek, and the elevation of the floor of the Livermore Valley floor. These in turn control whether sediment tends to accumulate there or be transported on through the system.

As one might expect, survey benchmarks located within a tectonically deforming region by nature are affected by deformation.

4. Comparative Expression of Ground Movement Processes at Ground Surface

The various processes of ground deformation described above will have broadly characteristic expression at the ground surface. Whether these are even detectable depends on frame, or scale of reference. For example, deformation detectable at the scale of thousands of feet may not be resolvable at a scale of tens of feet.

In the sections below, we try to consider the effects of the mechanisms above through the lens of scale.

It is useful to think of how these processes can be described at the earth's surface. Two measures of this are *angular distortion*, and *radius of curvature*.

Angular distortion – A measure of deflection of a linear or planar element from an originally straight or planar condition. An example is the angle by which an originally straight wire is bent, or an originally planar sheet of cardboard is creased or folded. If the straight/planar segments are very long/extensive, a very small angular distortion can result in a significant offset at the far end of the line or plane.

Radius of curvature – This refers to how tightly a line or plane curves as it passes from one straight/planar segment to another. If stress (i.e. a "bend") is allowed to be distributed through a curve with a large radius of curvature, there may be no permanent effect. If stress is concentrated along a curve with a tight radius, there may be permanent effect. An example would be bending a piece of tubing to bend through a large-radius arc like a hula hoop, versus forcing it to bend tightly and causing a kink.

4.1 Expansive Soil Shrink/Swell

The effects of this process are detectable over distances of few feet to tens/hundred(s) of feet (CalGeo, 2013). The process and its effects are localized to areas with significantly expansive soils or bedrock, and are therefore not detectable in nonexpansive soil or bedrock.

Various aspects of the interaction of structures, slopes, pavement coverings and soil moisture variations are illustrated on Figures 2 and 3.

Impervious surfaces impede the loss of moisture to atmosphere, and impede local infiltration/recharge (Noe and others, 2007). Bare soil surfaces lose moisture more rapidly than mulched or otherwise covered surfaces (see Fig. 3).

Vegetation and evapotranspiration increase the transfer of moisture from soil to atmosphere, and root mats serve to extend the reach of vegetation (Perpich and others, 1965). With unusually warm drought conditions, there is an increased moisture gradient that exacerbates this process.

Irrigated areas such as golf courses, parks, and corporate landscaping tend to counteract local drying effects, although some landscaped areas are engineered to drain quickly and do not encourage infiltration.

Different types of vegetative cover are more effective at extracting moisture from the soil (Perpich and others, 1965; Hidalgo and others, 2005). These differences have been quantified mainly for agricultural applications, but are applicable to urban landscape settings (for example, see Crop Coefficient Leaflets 21427 and 21428 published by University of California Cooperative Extension).

There have been attempts to determine whether there are long-term trends in evapotranspiration rates over the scale of decades, but results are scattered, with no clear historical trends (M. Dettinger, personal communication, 2015).

Associations/Settings

The shrink/swell cycling of expansive soil places stress on even nonrigid structures, and on root systems of plants. There are a number of characteristic settings or associations where expansive soil movement and related distress are observed (Noe and others, 2007; CalGeo, 2013).

<u>Impervious/exposed soil transitions</u> - The interface between impervious (paved) and exposed (unpaved) area are more likely to experience distress, during both drying and rewetting, due to the differential change in soil volume. Examples:

- Perimeter of (even large) buildings, at the interface between soil that is covered by a (particularly slab-on-grade) foundation and bare soil in adjacent areas (see Fig. 2).

- Perimeter of paved parking lot, at interface with bare soil or minimally planted area (see Fig. 3).

- Perimeters of in-ground swimming pools, at interface between pool shell and adjacent slab-on-grade pool deck.

- Perimeters of swimming pool decks, at interface with grassy areas or bare ground. Linear cracks, and localized voids under the slab edge (if not turned down) are common where the soil has shrunk away from the rigid overlying material.

- Homes with shallow foundations and raised floors, where perimeter soils will experience greater drying than interior foundations. A common effect is for the structure to be arched over a relatively high area of slightly moister soil, with the perimeter depressed. Common results include cracks at the corners of door and window openings, binding and misaligned doors, and misaligned window frames (see Fig. 2).

- Linear bare or vegetated areas between impervious surfaces, such as parking strips between paved roadway and soil areas, median strips, fill prisms at the outboard road edge of pavement, canal or creek banks next to strip parks. Linear cracks parallel to the top-of-slope and/or slab edge, commonly with hexagonal pattern offshoots at 120-degree angles, are common in such a setting (see Fig. 3).

- Impervious surfaces of limited extent, such as driveways or walkways, especially where near irrigated areas and areas of episodic ponding during wet weather (e.g. parking strips ground surface depressed below adjacent slab/pavement grade). The outer edges, especially corners, of slabs are commonly more subject to settlement or differential heaving due to more rapid drying. The presence of large shrubs and trees next to slabs can result in significant localized soil shrinkage due to extraction of moisture from the soil by root systems (see Fig. 3).

- V-ditches, curbs and other concrete structures with limited footprint that are constructed on shallow foundations, and surrounded by exposed ground. Shrinkage of soils beneath structures such as these commonly results in soil/concrete gaps, cracked and irregularly tipped/settled concrete sections.

Foundation type transitions – As a generality, the shallower soil layers respond more quickly to soil moisture changes, and tend to experience more fluctuations in volume. As expected, structures with foundations that derive support from shallower soil intervals likewise respond more quickly, than structures that derive support from deeper intervals. Vulnerable structures can include:

- Bridge abutments. The approaches to bridges are commonly constructed of engineered fill, while the bridge structure itself is supported by abutments founded many feet below grade. Differential behavior between the two can result in pavement distress at the transition. This can have various contributing factors in addition to possible contribution by expansive materials (e.g. inadequate fill compaction; inadequate subgrade preparation; compaction due to fill surcharge).

- Houses with perimeter structures such as decks and walkways. The foundation of a typical residence, for example, commonly derives its support from deeper in the soil profile than adjacent non-structural improvements such as decks. These two structures commonly will experience differential movement as they respond independently to soil moisture changes.

- Raised decks with isolated footings. The soil underneath decks, although largely removed from direct sunlight, is commonly not vegetated. The footings may be affected by soil creep, while the adjacent structure (e.g. the house) is less so, or is differently affected.

- Houses with attached slab-on-grade garages. There may be at least two foundation types/depths involved in such a setting. Differential movement is common between the house and garage structure, between the garage and/or house and the floor slab, and between the garage and the exterior driveway slab.

- Concrete front steps and slab-on-grade perimeter walkways, particularly where these structures are on sloping ground and there may be a cut/fill transition.

<u>Slope Behavior</u> - Where expansive soil is located on a slope, repeated shrinking/swelling cycles have the tendency to promote accelerated downhill creep of the surficial soils (see Fig. 3). This is due to the fact that when a soil expands, it tends to expand directly toward the nearest “free face.” Since this is roughly perpendicular to the slope face, it involves a small component of movement in the downhill direction. The following shrinkage cycle, however, merely allows the soil to drop straight down under the influence of gravity, instead of “pulling” it back upslope. For this reason, highly expansive soils tend to perform less well in fill slopes. Areas or associations where this process is commonly exhibited include:

- Tops of fill slopes, such as the outer edge of a landscaped field or yard where it transitions to a fill slope below.

- Tops of fill slopes at the outboard edge of paved roadways, walkways, or sidewalks (see Fig. 3).

- Fences, fence posts, and non-engineered landscaping bulkheads. These tend to tilt in a downslope direction over time, in part due to the loss of support on the downslope side, and accumulation of soil and debris on the upslope side.

Structures that are supported on shallow foundations are thus vulnerable to the creep of shallow soils, which tend to transport the foundations along with them.

A common thread in these types of settings where distress from expansive soil movement is observed is that the angular distortion associated with the movement occurs over a short radius of curvature. If this radius of curvature is tighter than the structure can tolerate, features such as cracks or unacceptable bending/deflection are observed.

4.2 Elastic Ground Deformation Associated With Groundwater Rise/Fall

This process is typically detectable over distances measured in thousands of feet (Galloway and others, 1999).

The process of urbanization itself has significant effects on patterns of runoff and potential recharge areas (Hibbs, 2012). Examples include the channelization of streams into storm sewer systems, and extensive impervious soil covers (e.g. buildings, pavements).

Groundwater basin response to yearly cycles of water level rise and fall is a widely known phenomenon. High-accuracy surveys, and satellite-based measurement systems are commonly designed so as to avoid placing key benchmarks in sedimentary basins.

The effect at the ground surface is most pronounced wherever the decline in groundwater levels is greatest, and the greatest thickness of aquitard materials compress elastically. Assuming the decline in groundwater levels is gradual, the ground surface response is muted and distributed across a broad area. The effect decreases to zero at the sedimentary basin margin.

The elastic response of the (mainly aquitard) layers in the basin is due to the cyclic gain and loss of water from between compressible grains, as described above.

The angular distortion associated with elastic ground surface deformation is very low, since elevation differences of fractions of a foot occur over horizontal distances of typically hundreds to thousands of feet.

Another way to express this is to say that the radius of curvature of elastic ground surface deformation is very large (the curve is very gradual), with the radius on the same order of magnitude as the basin's width – on the order of thousands of feet, or miles.

4.3 Inelastic Ground Deformation During Groundwater Rise/Fall

Inelastic ground deformation associated with groundwater level declines is generally similar in lateral extent to inelastic deformation. The chief difference is that it is due to decline in groundwater level below historic lows, and the net deformation (subsidence) over time is not reversible.

As with elastic ground deformation, the effect at the ground surface is most pronounced where the decline in groundwater levels is greatest, and where the greatest thickness of aquitard materials are subjected to water table drawdowns that are lower than historic lows.

Inelastic ground surface deformation is most typically detectable over distance of hundreds to thousands of feet. The subsidence effects are observed within the area of unconsolidated (basin fill) sediments, lessening to zero at the basin margin. The effect is not detectable in bedrock areas.

Inelastic subsidence due to groundwater withdrawal was first noted in the Santa Clara Valley, California. Total subsidence ranged from 2 to 8 feet (Ingebritsen and Jones [1999], in Galloway and others [1999]). Once an ongoing system of groundwater basin management was instituted, inelastic subsidence was essentially halted by 1969.

More recently, inelastic subsidence has also been documented in the northern San Joaquin Valley, reaching 8.5 meters (28 feet) to date (Sneed and others, 2013). An effective groundwater management program has yet to be put into place, and inelastic subsidence is continuing, with measured rates as high as 3/16" to ½" per month reported (B. Martin, GRA webcast, May, 2015). As much as 42 percent of the groundwater pumped from some parts of the San Joaquin Valley is inferred to have originated through inelastic compaction (Prudic and Williamson, 1986; cited in Sneed (2001)). The effect of even such rapid and profound inelastic subsidence is commonly evident only on features that span great distances, and which are sensitive to elevation changes. Cracking of the Delta-Mendota Canal concrete lining is described as "rare," with the major effects related more to elevation and gradient (B. Martin, GRA webcast, May, 2015). For a canal, loss of gradient can result in slower flow velocities, and in sediment buildup. The Delta-Mendota Canal, for instance, has experienced reduction in flow capacity due to loss of gradient (Sneed and others, 2013). Changes in gradient can result in inadequate levee crest elevation, loss of freeboard above desired/modelled water level, and loss of flood protection. Erosion of levees can occur if water levels rise above the design elevation, such as above an interval of protective riprap. These effects involve low angular distortion, over a very large radius of curvature. As noted, cracking of the concrete canal lining is described as rare, and no damage to structures such as pump stations has been reported.

Well casings that experience downdrag from subsidence of surrounding sediments can be damaged. As reviewed by Burbey (2002), buckled pipelines and twisted railroad tracks resulted from horizontal displacement spawned by differential compaction.

There are instances where groundwater levels have been drawn down rapidly enough that fissures have formed (Holzer and Pampeyan, 1981). Heavy groundwater pumping near Las Vegas, for example, appears to have resulted in subsidence rates reaching 2.5 cm/yr, and localized ground fissures formed (Bell and others, 2002). The occurrence of fissures generally appears to be associated with compressible deposits spanning a vertical fault or other feature resulting in rapid lateral changes in thickness of compressible deposits (Burbey, 2002). Such an occurrence appears to indicate angular distortion occurring over a relatively short distance (tight radius of curvature). Various scenarios under which fissures have been observed are reviewed in Borchers and others (2014).

4.4 Tectonic Warping/Uplift/Subsidence

Tectonic warping, uplift and subsidence are processes that are typically at work over distances of thousands of feet. They are typically only detectable over distances of thousands of feet.

Tectonic uplift and subsidence rates are measured in mm/yr. These processes affect large areas of the earth’s surface, and unless this offset is somehow forced to be accommodated over a very short distance, such as within tens of feet across an earthquake fault, it is often difficult to detect without specialized instrumentation and monitoring.

4.5 Fault Creep and Fault Offset

Fault creep and offset may be ongoing, or may occur only during earthquake. The offset or distortion is localized to the span of the fault zone, and not present/detectable elsewhere.

Fault creep rates are typically on the order of mm/yr. Not all faults experience creep; some move only during earthquake events.

Fault creep is commonly seen in the field where the cumulative offset of a linear element over time has been enough to be recognizable. For example, the seismic literature has famous photographs of warped street curbs, deflected fences, and warped railroad tracks.

The angular distortion accompanying fault creep is usually low, although it builds over time and may require repair. The University of California Berkeley Memorial Stadium is built across the creeping Hayward fault. For many decades, the offset was more an object of curiosity. A recent reconstruction project specifically incorporated a means to accommodate this creep without damage to the structure.

5. Ongoing Monitoring Programs and Data Resources

Various tools can be used to monitor ground movement, depending on the application.

5.1 Expansive Soil Movement, Evapotranspiration Rates

Due to the generally localized effects of expansive soil movement, monitoring most often takes the form of repeat measurements across cracks; or installed measurement devices that permit repeated measurements across interfaces such as where concrete slabs meet each other, or a wall meets a slab-on-grade. Evaluation of structures that are experiencing distress that may be attributable to expansive soil movement will sometimes use floor level surveys (manometer surveys) to characterize differences in floor level. These surveys can be conducted during different seasons to observe the fluctuations in floor level occurring as a result of variation in the soil moisture such as from climatic seasonal changes, and changes in irrigation. Up to a few inches of elevation difference can be observed in floor slabs supported on highly expansive soils with large variations in the soil moisture content.

The California Irrigation Management Information System (CIMIS) measures evapotranspiration rates at various weather stations throughout California, and makes that data available online (accessible at http://www.cimis.water.ca.gov/). The closest station (Station #191) to the study area is located in Pleasanton.

5.2 Zone 7 Monitoring in Livermore Valley

Zone 7 is relatively fortunate among water agencies in having fairly early recognized the need for groundwater management and monitoring; as noted above, major pumping by an out-of-basin user (SFPUC) was halted in the 1940's due to drawdown in groundwater levels.

Zone 7 has a Well Master Plan (WMP) that was finalized in 2003 (CH2MHill, 2003). The WMP identified preferred areas for wells, and developed specifics regarding well spacing, sustainable pumping/production rates, well construction, and water quality impacts. It also looked at sustainable yield under drought conditions.

Zone 7's Groundwater Management Plan (GMP) was finalized in 2005, although elements of it had been in place before that date. In accordance with the California Groundwater Management Planning Act, the GMP brought together the cities of Livermore, Pleasanton and Dublin, and four large water retailers, to prepare an integrated plan for management of the Livermore Valley Groundwater Basin. The GMP itself does not put forth new policy. Topics addressed by the GMP include various monitoring programs; mitigation of overdraft conditions; protocols relating to regulation/mitigation of contaminated groundwater, water recycling, wellhead and well integrity against contamination; and control of salt water intrusion. Monitoring programs include groundwater level monitoring; ground surface elevation monitoring; recharge monitoring; groundwater quality monitoring; surface water flow/quality monitoring; and meteorological/climatological monitoring. Two of these monitoring programs (groundwater elevation, and ground surface elevation) are described further below.

5.3 Groundwater Elevation Monitoring

Zone 7's groundwater elevation monitoring program tracks groundwater levels in the various subbasins, identifies trends, and permits proactive changes in policy regarding groundwater management (i.e. pumping, recharge). There are 236 wells in Zone 7's groundwater monitoring program, which undergo sampling/monitoring at various intervals depending on specific needs (see Fig. 8). The results of this monitoring and associated analysis are presented in an annual report to the Groundwater Management Program (see www.zone7water.com/publications-reports/reports-planning-documents).

5.4 Ground Survey Monitoring

Ground surface elevations have been monitored by Zone 7 since 2002 as a component of the Agency's Groundwater Management Plan. A network of approximately 60+ elevation benchmarks has been established that spans the Bernal and Amador subbasins within the Main Basin, with reference benchmark (datum) points located outside the sedimentary basin (see Fig. 10). All of Zone 7's production wellfields are encompassed by the survey monitoring network. Data from twice-yearly high precision leveling surveys are analyzed annually, and results presented in Zone 7's Annual Report to the Groundwater Management Plan (accessible online at the URL cited above).In the Livermore Groundwater Basin, ground surface monitoring points appear to rise and fall on the order of 0.025 to 0.050 feet, on an annual basis. These elevation changes are detectable within the area of unconsolidated (basin fill) sediments, with the effect lessening toward basin margin. They are not detectable or are insignificant in bedrock areas. As discussed below under Section 6.4.6 (Benchmark Points and Survey Points), some of the apparent movement may be associated with whether survey points are fixed to ground surface features as opposed to deriving support from deeper in the ground. Currently, groundwater levels are being managed so as to remain above historic lows, in order to assure that the aquifer's response is elastic.

5.5 Comparative and Historical Analysis of Groundwater and Ground Elevation Monitoring

These parallel monitoring programs (groundwater levels, ground surface elevation) are cross-compared and analyzed in order to avoid the possibility of inelastic deformation in the aquifer system by keeping the groundwater levels well above historic lows.

The monitoring programs are operated in tandem with hydrogeologic modelling of the basin hydrogeology by Zone 7, using a well log database of over 3,000 wells and boreholes, and a GIS that builds on data extracted from selected well logs and other data layers.

5.6 Tectonic Monitoring

Fault creep along the Calaveras fault has been monitored for over 30 years. Creep rates from a 20-year period were summarized by Galehouse and Lienkaemper (2003). The northern Calaveras fault, which passes through the Zone 7 service area, is creeping at 3 – 4 mm/yr.

Uplift on the southern flanks of Mt. Diablo is also monitored, with measured uplift rates of approximately 1 mm/yr (Burgmann and others, 2006).

Fault creep on the Greenville fault is monitored, with the creep rate measured at 1.1 mm/yr (McFarland and others, 2009).

6. Conclusions

In the sections below, we compare and contrast the water-related ground movement processes: processes of groundwater rising/falling (with either elastic or inelastic ground surface response), and expansive soil moisture changes. For completeness, we also review the effects of tectonic deformation, although it is not water-related.

We then review the nature of anticipated future ground movements likely to be observed in the Livermore Valley.

6.1 Separate Processes, Related by Water

Both expansive soil movement and land subsidence associated with groundwater level decline are related to water, however they are distinctly separate processes. Tectonic deformation is an entirely separate phenomenon.

6.1.1 Expansive Soil Movement

Expansive soil movement is most apparent near a wetting/drying front, with the atmosphere the biggest front. This means it is by nature a shallow process, with potential for relatively localized expression.

Expansive soil movement is strongly governed by soil clay content, and the soil's geologic inheritance (mineralogy) and variations in the soil moisture content. Variations in the soil moisture content can be due to climatic/seasonal variations (e.g. dry summer versus rainy winter) or man-induced (e.g. the introduction or removal of landscaping and irrigation systems).

6.1.2 Inelastic and Elastic Ground Surface Movement

Groundwater level decline affects the aquifer system at depth; elastic and inelastic response to those declines/rises is occurring at depth and reflected at the ground surface. As a deep process that is controlled by regional water level/pressure, these effects are distributed over a broad area. Localized distress or damage can result, but it is relatively infrequent and distress is more usually associated with warping of improvements that span very significant distances.

Both the deep behavior of the aquifer system, and the shallow behavior of the surficial soils, are strongly controlled by their geologic past. The sediments deposited in the Livermore-Amador Groundwater Basin over time, and the most recent deposits that make up the modern soil, are not randomly distributed, but rather were determined by the geologic processes acting in any one area – e.g. coarse gravels transported and deposited by streams in some areas, and clayey, organic material deposited in a marsh setting in other areas (see Fig. 5). The behavior of these deposits can be broadly anticipated based on their geologic history and makeup.

6.1.3 Tectonic Deformation

Tectonic deformation is localized near active tectonic features; examples of these in the study area would include the Calaveras and Greenville faults, and the uplift of Mt. Diablo (see Fig. 4). Unless there is actual fault offset either through earthquake or ongoing creep, the effects are distributed over a broad area. Tectonic deformation is not water-related. The depth of groundwater extraction is not sufficient for there to be any link between pumping and earthquakes.

6.2 Nature of Recovery

Expansive soil as it goes through multiple shrink/swell cycles will change in character between a hard, overconsolidated clay-rich soil with shrinkage (desiccation) cracks when dry, and a soft, mucky, sticky clay when wet. The ground surface elevation differential of a thick profile of highly expansive soil can be on the order of a few inches between its fully dry state (shrinkage limit) and its completely saturated state. Highly expansive soil, when subjected to additional loads (such as construction of a building atop it), may not fully recover its initial volume in subsequent shrink/swell cycles, as it adjusts to the new loads.

Groundwater level cycles, so long as they remain within the elastic realm (above historic low levels), will not result in irreversible consolidation. Recharge is a slower process than extraction, so response to wet periods is likely to be slower than response to extraction. There is a time lag in response by the aquifer system (aquitards in particular), since it takes time for groundwater pressure to equilibrate.

Tectonic deformation is not cyclic, and is nonrecoverable.

6.3 Anticipated Phenomena in Livermore Groundwater Basin

This section outlines in a general fashion the types of ground movement features that we would anticipate observing in the Livermore-Amador Valley Groundwater Basin, with particular reference to drought conditions.

6.4 Climatic Trends and Cycles

Climatic cycles will affect the Livermore-Amador Groundwater Basin in the years to come, and these cycles will affect the geologic and hydrologic processes at work in the basin. There will be times of drought, and times of wetter than normal winters.

Weather records appear to indicate that climatic swings may be becoming more extreme, in which case droughts may be more severe than experienced in historic time, and wet periods likewise may be more extreme. The effect of these on groundwater levels, and on soil moisture cycles, is not yet clear.

Weather records also indicate that overall average temperatures are on a rising trend, which if continued, would tend to facilitate soil moisture loss.

6.4.1 Expansive Soil Response to Drought

If the current drought intensifies, and soils become drier to a greater depth than experienced in historic time, the shrinkage effect will be more pronounced than experienced to date.

There will be greater total shrinkage of the near-surface expansive soil profile resulting from this more extreme drying, and greater depth of drying. This will be manifested at the ground surface as hard, overconsolidated, desiccated clays with ground shrinkage cracks, and a decrease in the ground surface elevation relative to when the soil was wet.

Areas of mapped highly expansive soils are the most likely to experience future distress during future drying cycles. In our judgment, it is highly likely that future distress will be especially common in areas within or near mapped highly expansive soils (see Fig. 6, which corresponds to the extent of the historic Pleasanton marsh complex (SFEI, 2013; and Fig. 5).

The drying effect of drought conditions in developed areas is typically compounded by cutbacks in irrigation rates, in that there is reduced input of soil moisture at the same time there is increased rate of moisture loss.

Based on our review of the literature, our experience, and on our knowledge of the general geology and soils of the Livermore Valley, we think there is a high likelihood of distress concentrations:

- Along the canal alignments, which roughly follow the pre-development drainage axes.
- Along paved roadways, particularly near the edges of pavements where there is adjacent bare ground.
- Near the edges of large relatively impervious surfaces, where juxtaposed against bare or vegetated ground, such as near corporate developments, boulevards, parking lots, and playgrounds.

Commonly, engineered structures on expansive soils will have deeper foundations that are intended to derive their support from soils below the interval of soil that experiences significant variation in soil moisture content. If drying of the soil profile extends to greater depths than previously experienced and designed for, structures may experience the effects of shrinkage.

More extreme drying of the soil profile may result in distress to buildings that previously experienced only minor expansive soil movement due to non-structural (non-foundation) elements that reduced shrink/swell cycling. These include irrigation patterns, soil-covering slabs or decking, and surface and subsurface drainage systems.

6.4.2 Expansive Soil Response to Wet Periods

Expansive soils will swell and soften during future wet periods.

Areas of mapped highly expansive soils are the most likely to experience future distress during future wetting cycles.

Wetting cycles (with accompanying swelling) will cause distress to many of the same features that suffer under drying cycles: shallow foundations, pavements, slabs-on-grade, and slopes in expansive materials.

6.4.3 Ground Surface Response to Groundwater Level Decline

We anticipate that ground surface elevation changes will be substantially the same in character as the apparently elastic responses observed in the data gathered since 2002, and reported annually by Zone 7 as part of the Groundwater Management Plan, so long as groundwater levels do not drop below historic lows.

If groundwater levels decline below historic lows, there may be renewed inelastic subsidence. As documented in the literature (Borchers and others, 2014; Sneed and others, 2013), renewed inelastic subsidence can progress more rapidly than inelastic subsidence does at its initial onset. If this were to occur, the inelastic compaction would affect primarily the aquitard intervals within the groundwater basin (see Fig. 7). The inelastic subsidence may not be uniform, depending on total thickness of aquitard sediments present in any one area and whether they become subjected to groundwater level declines below historic lows. As one example of this, the thickness of the central aquitard between the Upper Aquifer Zone and Lower Aquifer Zone alone varies over several tens of feet (see Fig. 9); inelastic subsidence of this interval could be expected to vary accordingly.

Residual compaction refers to the delayed response of aquitard sediments to the effective pressure experienced at the time of historic groundwater lows. Based on the data we reviewed, we cannot eliminate the possibility that although those historic lows are now many years past, the residual response of aquitard sediments could still be ongoing, though slowed considerably.

6.4.4 Ground Surface Response to Water Level Rise

We anticipate that ground surface elevation changes will be substantially the same in character as the elastic responses observed in wet year(s). The elastic response will have limits, however – continued recharge will not "inflate" the valley floor (Galloway and others, 1999).

6.4.5 Tectonic Deformation

Creep and limited deformation will be ongoing near the Calaveras and Greenville faults, as will the uplift of Mt. Diablo.

Zone 7 may wish to evaluate the location of reference survey benchmarks used for ground survey monitoring, in relation to benchmarks used for tracking tectonic creep. It may be advisable to employ multiple datum points. For example, the Zone 7 semi-annual ground surface monitoring program revealed that one benchmark thought to be located on bedrock was actually experiencing some elastic response.

6.4.6 Survey Benchmarks and Survey Points

A cursory review of the survey points used to track ground surface elevations (see Zone & Annual Report to the Groundwater Management Plan [Zone 7, 2014]) suggests that benchmark sites within the basin experience little or no movement compared to other survey points that utilize chisel marks on surface structures, or spikes or brass disks in roadways. It appears that the movement on survey points within the basin *other* than the more deeply-founded benchmark sites may be generally 3 to 10 times greater than for the benchmark points.

Benchmark points employing features that make for more repeatable measurements will be more reliable data points in future surveys, and will allow better discrimination between expansive soil movements, and groundwater-related effects. Examples of these features include use of bars or pipes embedded several feet into the ground to be less susceptible to ground surface movements caused by soil moisture content variation. The tops of well casing may also provide good survey points as the casing extends deep into the ground, below the soil active zone.

7. Limitations

The conclusions and recommendations of this report are based upon information provided to us, our geologic reconnaissance and research, subsurface conditions described on the boring logs, the results of monitoring summarized in reference reports, interpretation and analysis of the collected data, and professional judgment.

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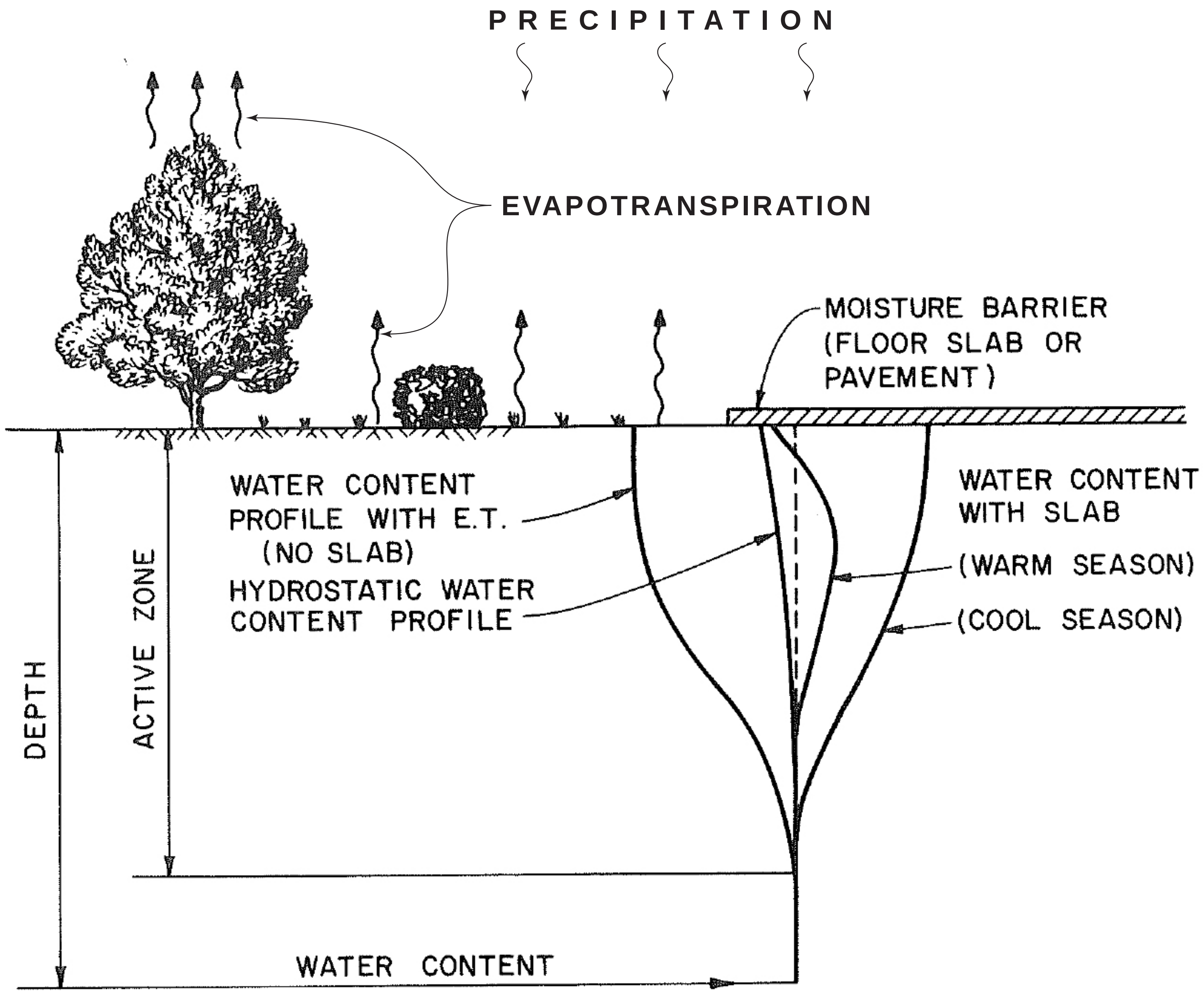

Figure adapted from Figure 2.2 in Nelson and Miller (1992)

Schematic illustration of the active zone - the surface layer of soil in which moisture content is influenced by climate

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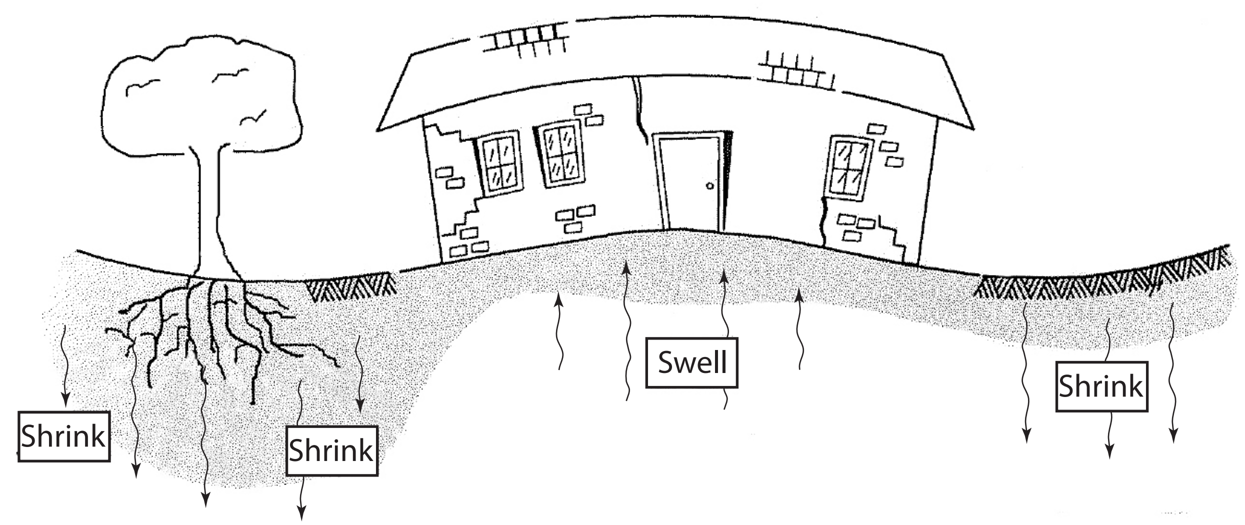
ACTIVE ZONE OF SOIL PROFILE
LIVERMORE VALLEY GROUND MOVEMENT STUDY

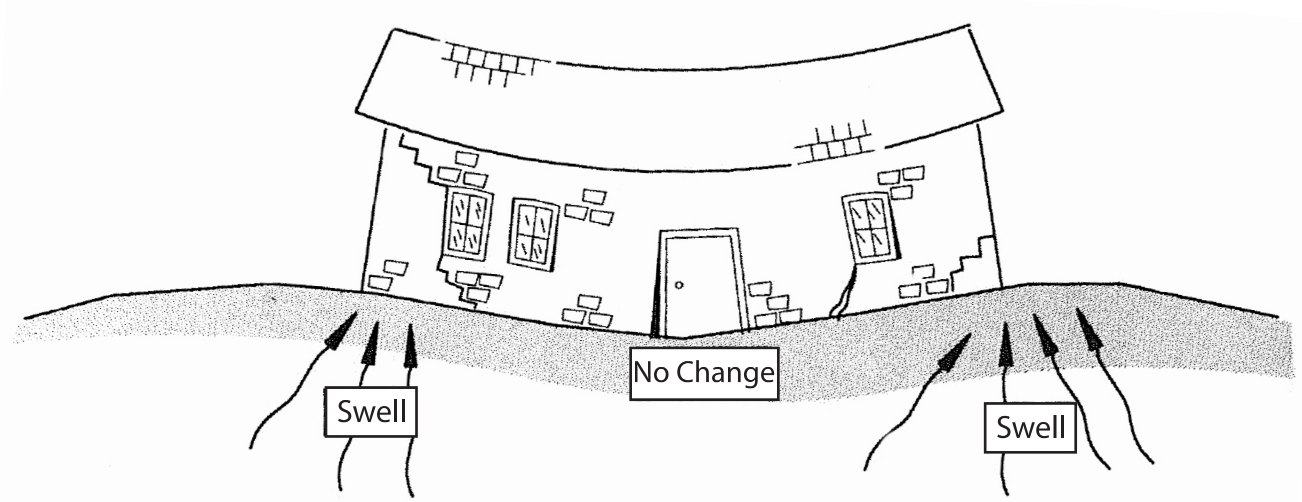
ALAMEDA & CONTRA COSTA COUNTY, CALIFORNIA

150370	JUNE 2015	FIGURE 1



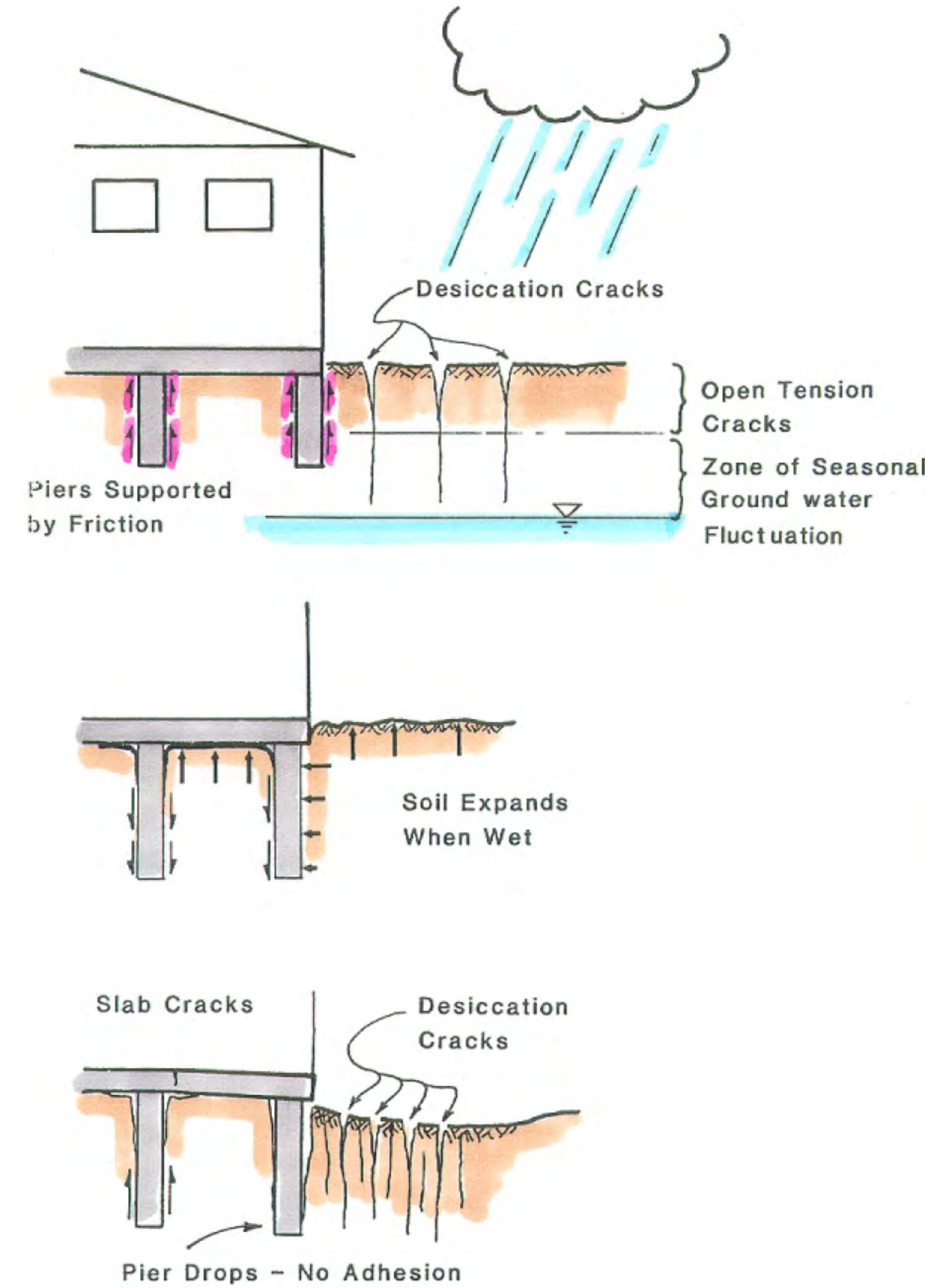
Schematic illustration of how a structure can be distorted by shrinkage of soils around its perimeter, swelling of soils beneath the interior, or both. Note that trees can extract moisture from soils.

Figure adapted from Wray (1995)



Schematic illustration of how a structure can be distorted by swelling of soils around its perimeter.

Figure adapted from Wray (1995)



Example of how soil moisture changes can affect a structure on shallow piers.

Figure adapted from Rogers (2015)

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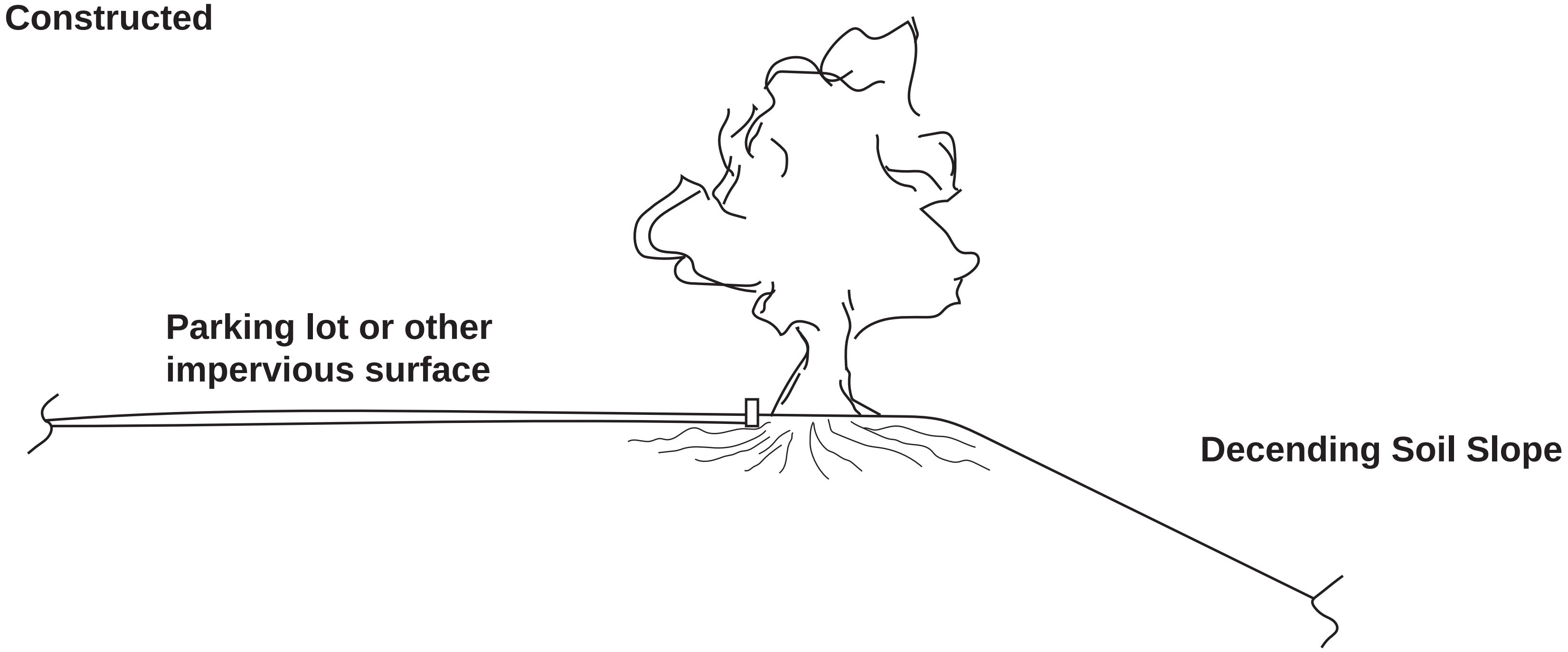
INTERACTION OF STRUCTURES AND SOIL MOISTURE VARIATIONS
LIVERMORE VALLEY GROUND MOVEMENT STUDY

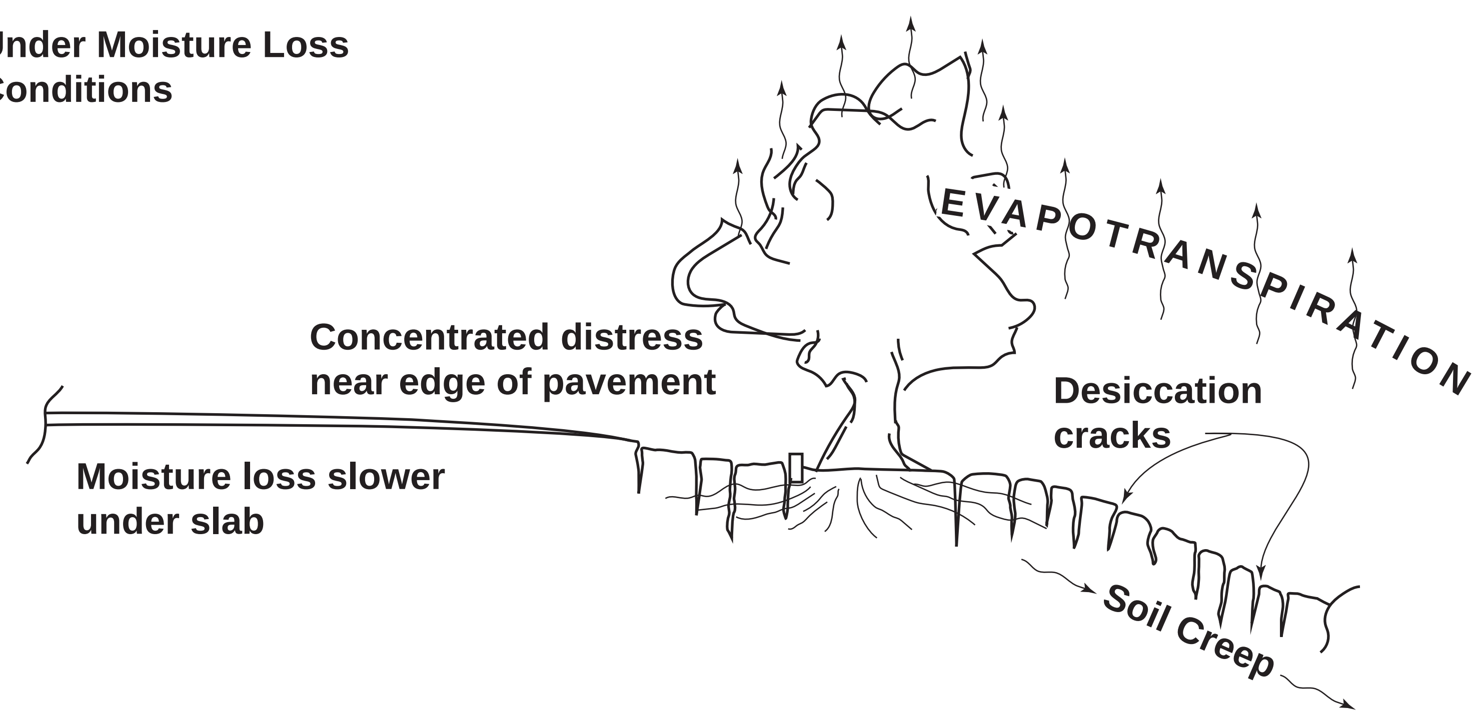
ALAMEDA & CONTRA COSTA COUNTY, CALIFORNIA

150370	JUNE 2015	FIGURE 2

I - As Constructed



II - Under Moisture Loss
Conditions



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INTERACTION OF SLOPES, TREES AND
SOIL MOISTURE VARIATIONS
LIVERMORE VALLEY GROUND MOVEMENT STUDY

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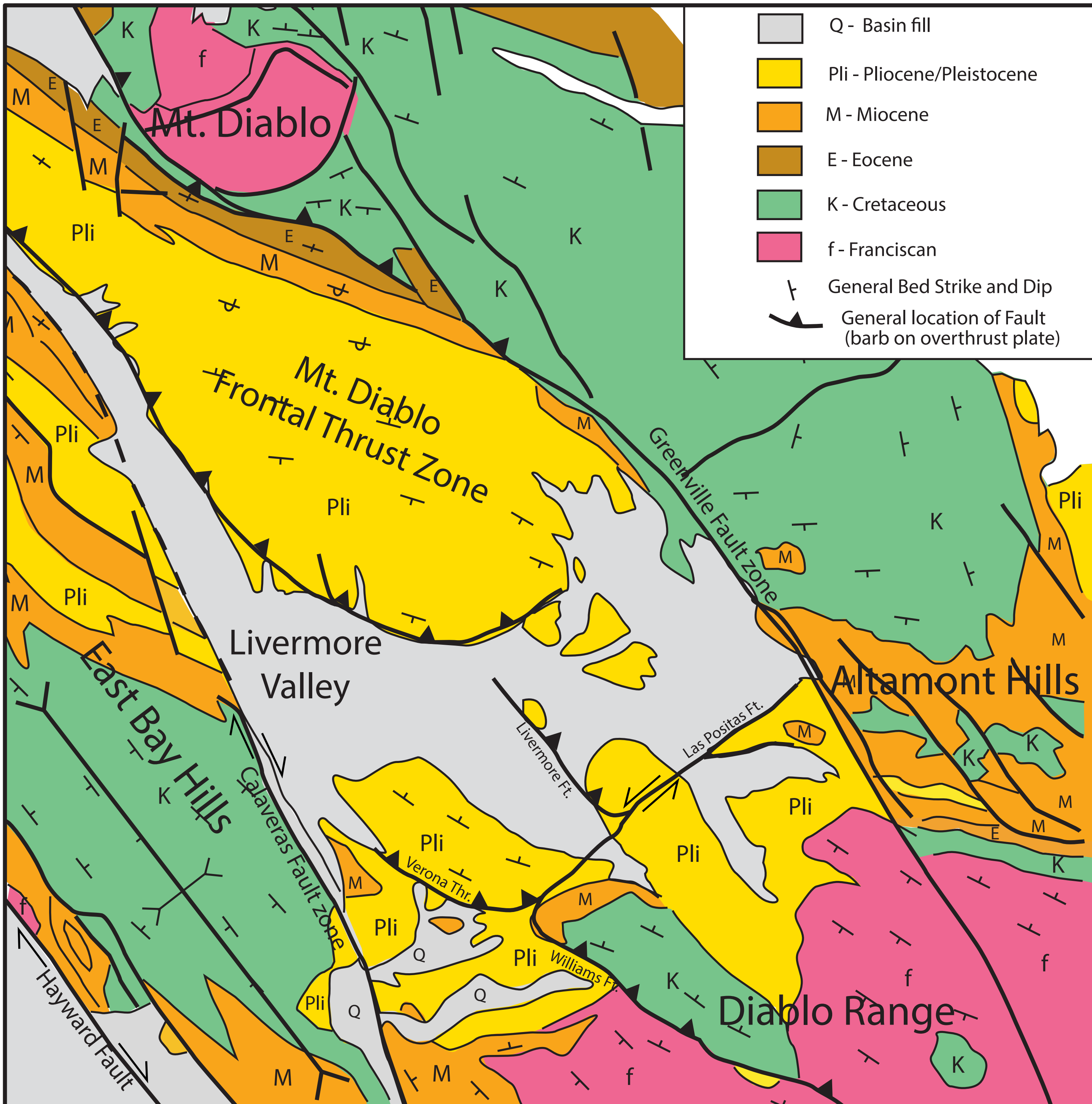
150370	JUNE 2015	FIGURE 3



Not to Scale

N

Generalized geologic/tectonic map of the Livermore Valley vicinity. The major bedrock upland areas bounding the Livermore Valley are labelled, as are the major fault boundaries. The extent of "basin fill" (shown in gray) corresponds to the extent of the Livermore Valley groundwater basin. Figure adapted from Norfleet (2004).

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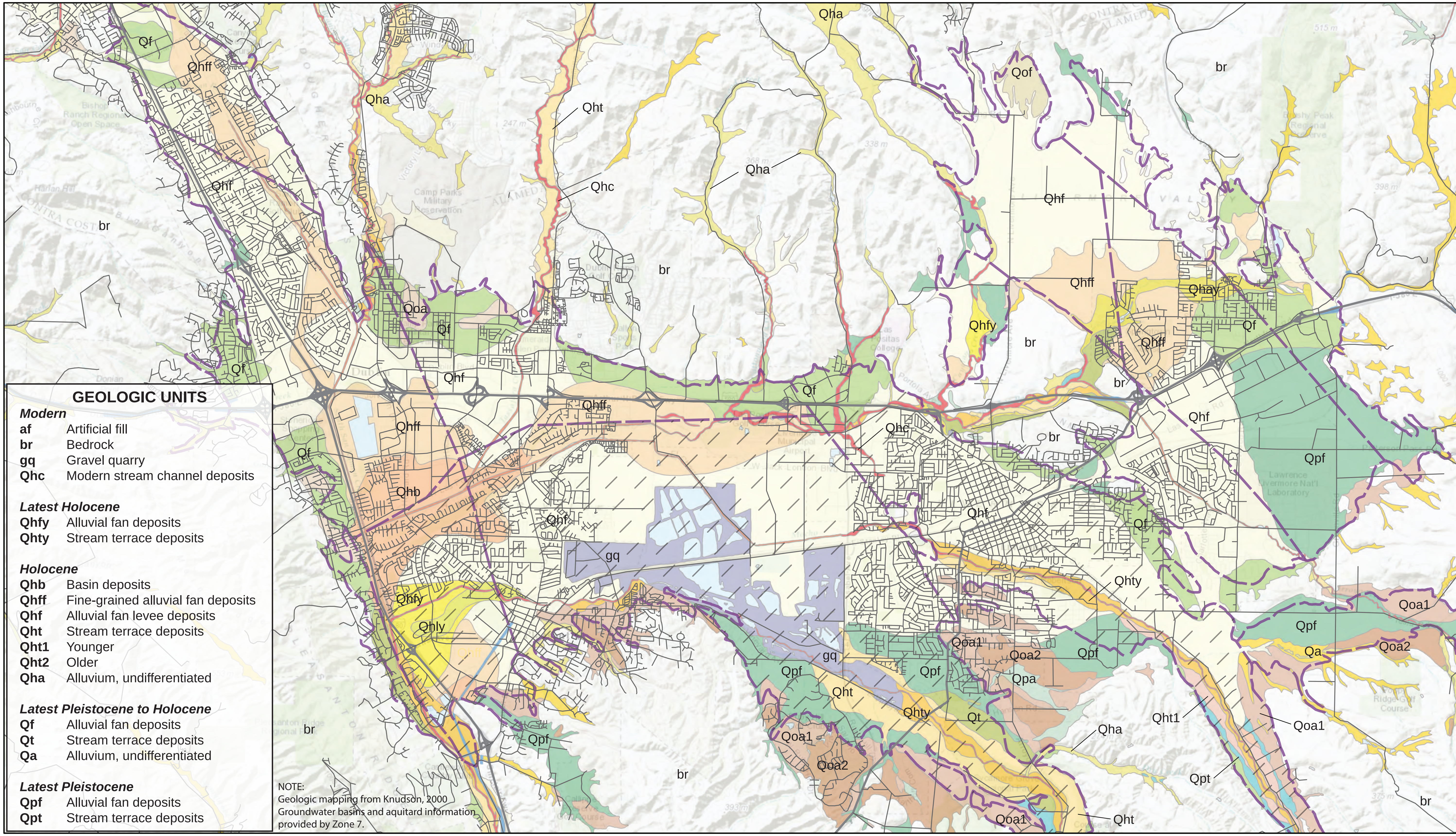
GENERALIZED GEOLOGIC/TECTONIC MAP
LIVERMORE VALLEY GROUND MOVEMENT STUDY

ALAMEDA COUNTY, CALIFORNIA

150370	MAY 2015	FIGURE 4



EXPLANATION

Main groundwater basin

Groundwater subbasin boundaries

0 6,000 12,000

Feet

N

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REGIONAL QUATERNARY GEOLOGIC MAP
LIVERMORE VALLEY GROUND MOVEMENT STUDY

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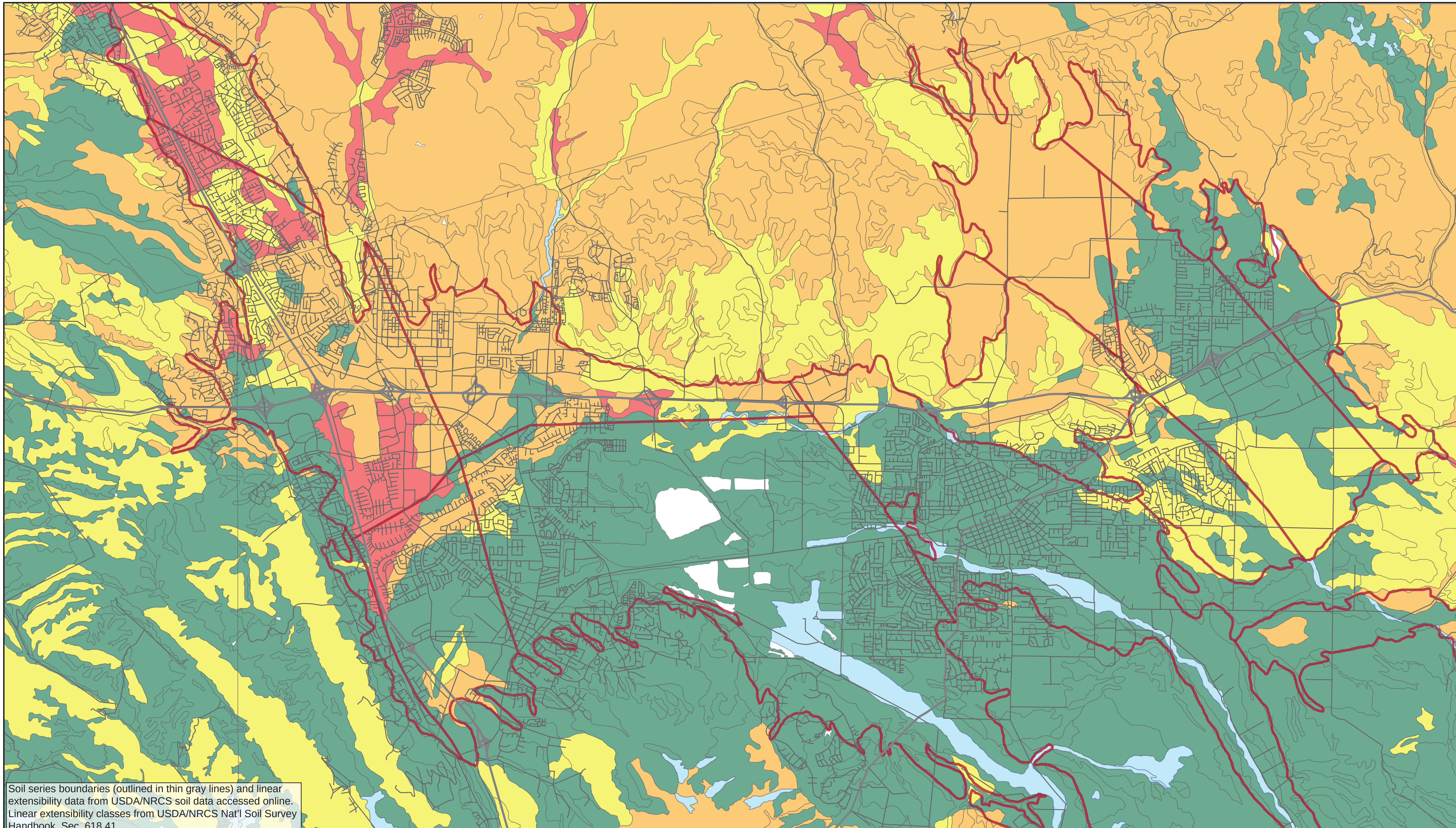
150370	JUNE 2015	FIGURE 5



Linear Extensibility (Percent)

Low	Med	High	V. High
<3%	3.0-5.9%	6.0-8.9%	≥9.0%

Subbasin Boundaries

0 6,000 12,000
Feet

N

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REGIONAL SOIL SHRINK-SWELL POTENTIAL MAP
LIVERMORE VALLEY GROUND MOVEMENT STUDY

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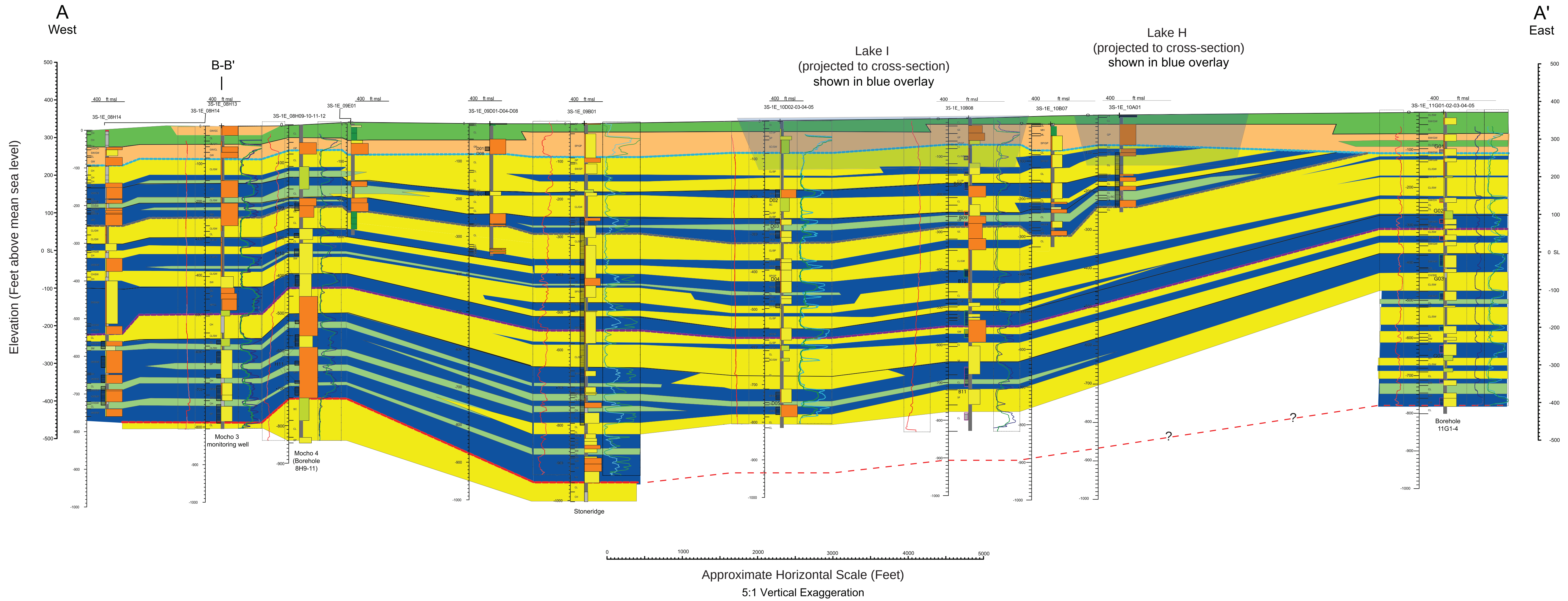
150370	JUNE 2015	FIGURE 6



Major Alluvium Types

- (Aquitard) - Overbank and lakebed clay and silt
- (Aquifer) - Fluvial gravel
- (Aquifer) - Fluvial overbank and floodplain clay and silt. May include lakebed deposits
- (Aquifer) - Fluvial and deltaic(?) sand and gravel
- (Aquitard) - Lakebed clay and silt (discontinuous). May include floodplain and overbank deposits.

This cross-section extends approximately east-west across part of the Livermore Valley. It is intended to portray the complex interlayering of major alluvium types within the basin, some of which act as aquifers, some of which act as aquitards. See Figure 4 for location of section.

The cross-section was developed on the basis of data from well logs (see vertical lines or profiles representing various types of data). This section was simplified greatly from Plate 3 of Norfleet (2004); refer to that figure for detail regarding well log data types.

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SCHEMATIC CROSS-SECTION, PORTION OF VALLEY
LIVERMORE VALLEY GROUND MOVEMENT STUDY

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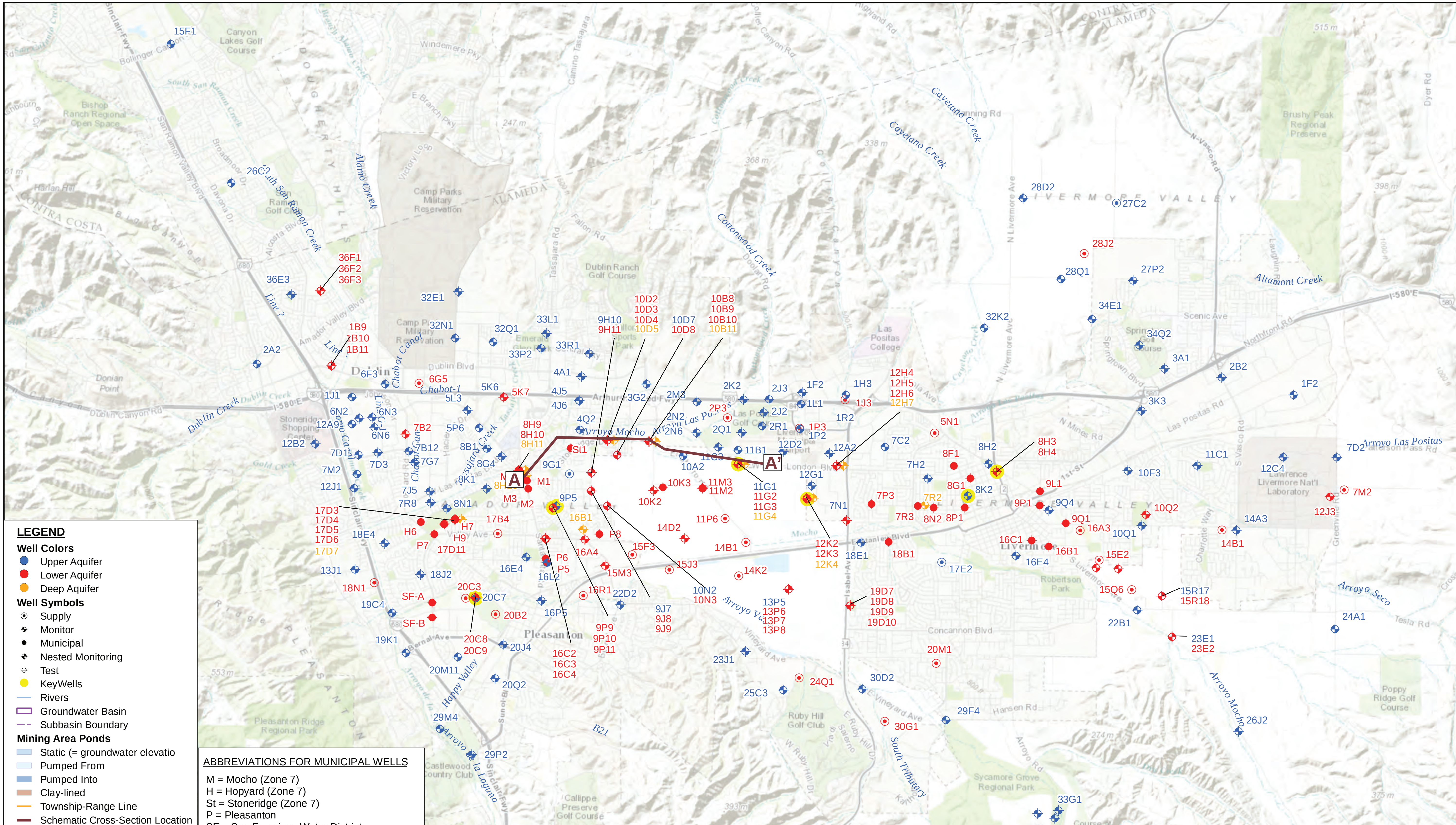
150370	JUNE 2015	FIGURE 7



Groundwater levels are measured >2 times/year (monthly or continuously in some) in the 236 wells shown. For details and findings of monitoring program, see Zone 7's Annual Report for the Groundwater Management Program for the 2013 Water Year (accessed at http://www.-zone7water.com/images/pdf_docs/groundwater/2013-6_gwmp_2.4_gw-mntrng.pdf). This figure slightly modified from Fig. 2.4-1 of that report.

0 6,000 12,000
Feet

N

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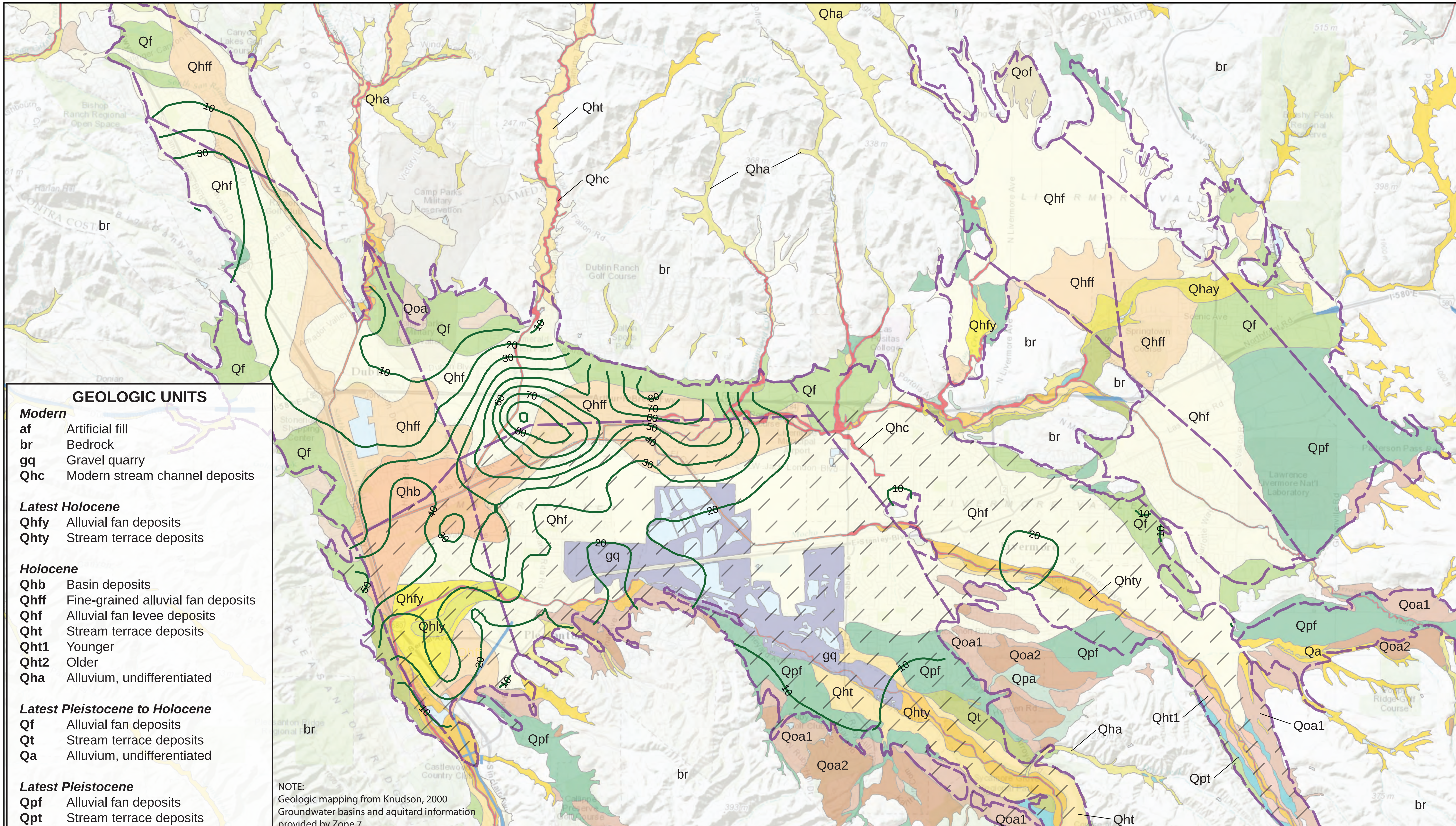
GROUNDWATER ELEVATION MONITORING POINTS
LIVERMORE VALLEY GROUND MOVEMENT STUDY

ALAMEDA & CONTRA COSTA COUNTY, CALIFORNIA

150370	JUNE 2015	FIGURE 8



GEOLOGIC UNITS

Modern

af	Artificial fill
br	Bedrock
gq	Gravel quarry
Qhc	Modern stream channel deposits

Latest Holocene

Qhfy	Alluvial fan deposits
Qhty	Stream terrace deposits

Holocene

Qhb	Basin deposits
Qhff	Fine-grained alluvial fan deposits
Qhf	Alluvial fan levee deposits
Qht	Stream terrace deposits
Qht1	Younger
Qht2	Older
Qha	Alluvium, undifferentiated

Latest Pleistocene to Holocene

Qf	Alluvial fan deposits
Qt	Stream terrace deposits
Qa	Alluvium, undifferentiated

Latest Pleistocene

Qpf	Alluvial fan deposits
Qpt	Stream terrace deposits

EXPLANATION

Main groundwater basin

Groundwater subbasin boundaries

80 Aquitard thickness (feet) separating Upper and Lower Aquifer Zones

0 6,000 12,000
Feet

N

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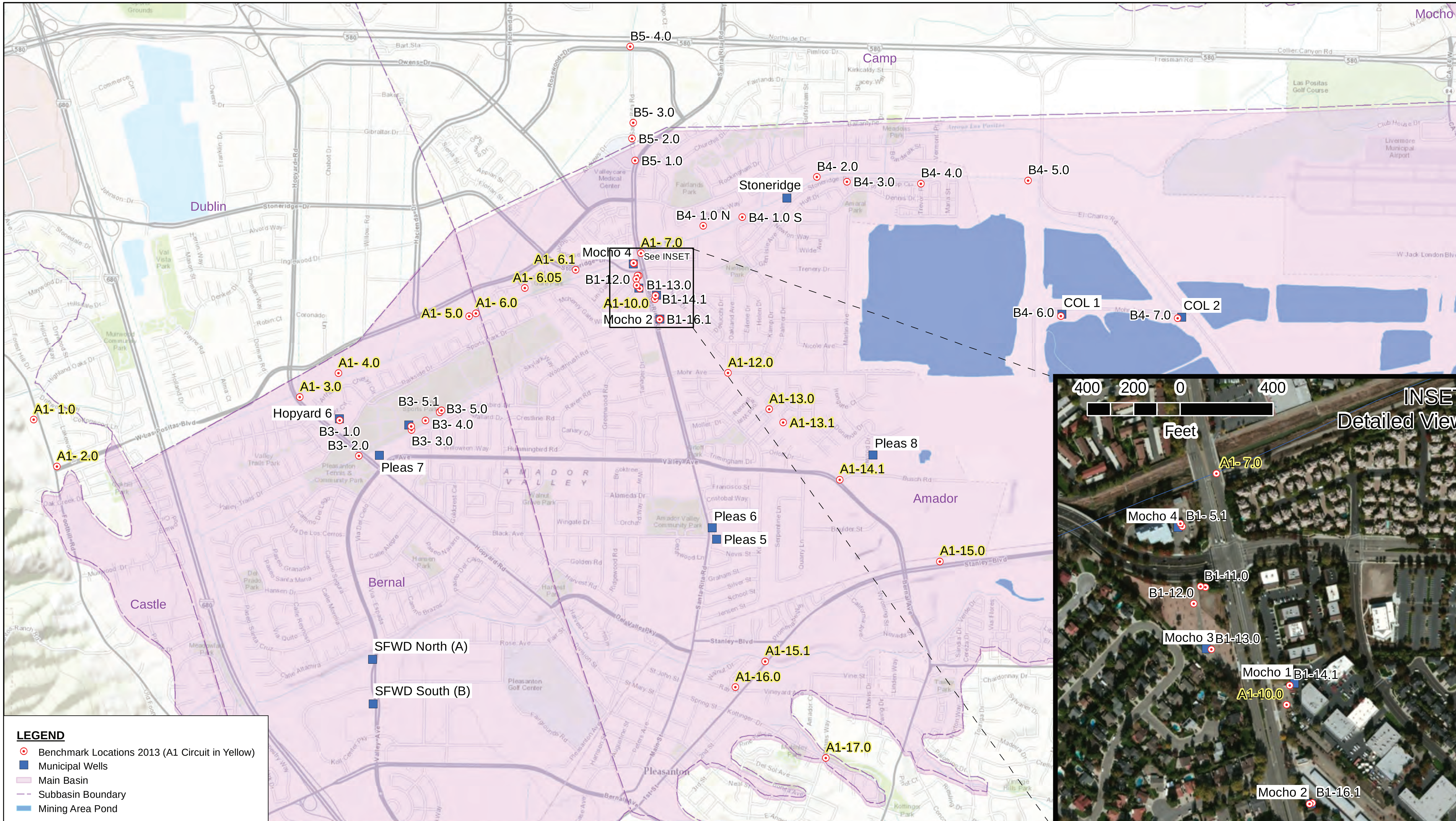
REGIONAL QUATERNARY GEOLOGIC MAP
LIVERMORE VALLEY GROUND MOVEMENT STUDY

ALAMEDA & CONTRA COSTA COUNTY, CALIFORNIA

150370	JUNE 2015	FIGURE 9



Ground elevations are resurveyed >2 times/year at the survey benchmarks shown. For details and findings of monitoring program, see Zone 7's Annual Report for the Groundwater Management Program for the 2013 Water Year (accessed at www.zone7water.com/images/pdf_docs/groundwater/2013-7_gwmp_2.5_subsidence-mntrng.pdf). This figure slightly modified from Fig. 2.5-1 of that report.

0 2,000 4,000
Feet

N

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GROUND SURVEY MONITORING POINTS
LIVERMORE VALLEY GROUND MOVEMENT STUDY

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150370	JUNE 2015	FIGURE 10