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CALIFORNIA DEPARTMENT OF WATER RESOURCES

Assessment of the Vegetation Area on the Face of the Oroville Dam

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INTRODUCTION

This report documents the history and impact of vegetation occasionally visible on the face of Oroville Dam. The report summarizes information collected during original construction and design of the dam, as well as ongoing performance monitoring information regarding seepage collected over five decades since construction.

1.1 BACKGROUND

Oroville Dam is an earthfill embankment dam built from clay, rock and other natural materials that sits on the Feather River in Butte County in Northern California.

Oroville Dam is the tallest dam in the United States, rising 770 feet tall and stretching approximately 5,600 feet across. In comparison, Oroville Dam is 44 feet taller than Hoover Dam in Nevada and slightly longer than 19 football fields. It was designed and constructed by the California Department of Water Resources (DWR) in the 1960s and is owned, operated and maintained by DWR.

Oroville Dam is the largest water storage facility in the State Water Project. The operation, maintenance, and safety of Oroville Dam is overseen and regulated by the California Division of Safety of Dams (DSOD) and the Federal Energy Regulatory Commission (FERC).

Lake Oroville was created by the impoundment of the North, Middle, West and South Forks of the Feather River by Oroville Dam. With 3.5 million acre-feet of water of storage capacity, Lake Oroville is the second largest reservoir in California behind Lake Shasta. Aside from the benefits of flood control, water storage, releases from the reservoir help with downstream water quality for fish and salinity control in the Delta. Lake Oroville is also one of the State's premier recreation areas for boating, camping and fishing, and is an important wildlife preservation area.

The majority of water releases from Lake Oroville are controlled through a separate concrete spillway called the Lake Oroville Flood Control Outlet Spillway, or "main spillway." The main spillway is separate from the face of Oroville Dam. This is different from many familiar dams like Hoover Dam or Folsom Dam that have their main spillways over the crests of the dams.

Adjacent to the main spillway is the emergency spillway, which releases water if reservoir levels top 901 feet. Unlike the main spillway, which is controlled by radial gates that open and close, the emergency spillway is a curved wall that water flows over – like the edge of a bathtub.

FIGURE 1. *Aerial Photograph of Oroville Dam*

1.2 VISIBLE VEGETATION ON THE FACE OF OROVILLE DAM

Since the mid-1960s, before original construction was complete, a band of vegetation has grown along the face of Oroville Dam during wet seasons. This band is approximately 100 to 150 feet wide, and generally located between elevation 570 and 670 feet, on the upper midpoint of the dam slope (see Figure 2). The area runs across the entire width of the dam, but is more concentrated on the right, looking upstream toward the reservoir. The vegetation area dries out during the hot summer months, turning yellow or brown during the dry season and becomes less visible. The cycle begins again during the next wet season.

FIGURE 2. *View of vegetation on the downstream face of Oroville Dam. (Photograph taken on March 9, 2011, near the end of the rain season)*

1.3 DAM CONSTRUCTION

Oroville Dam is an earthfill embankment dam built from clay, rock and other natural materials. The dam is comprised of different zones of tightly compacted material, which increases the density of the structure, making it more impervious to seepage.

Zone 1 is located in the very center of the dam. This central clayey core is approximately 27-feet-wide at the top of the dam and almost 300-feet-wide at the bottom of the core and was constructed in 10-inch layers compacted to a high density. Based on nearly 2,000 tests completed during original dam construction, DWR found that the average density in Zone 1 was 100 percent of DWR's Standard Maximum Density, meaning the core is very dense and almost completely impervious to seepage or leaking. Another 70 tests showed that the average permeability of the constructed clayey core was 10 times more impervious than what engineers originally considered during the Oroville Dam design phase.

DWR calculates seepage using the following parameter: $k = 0.0002$ feet/day, with "k" representing the mean permeability rate measured for samples obtained during construction. Using this value, the measured permeability of the clayey core is approximately 2 million times more impervious than the bulk of the dam, including the downstream face of the dam where vegetation is located.

For comparison, the average permeability of the clayey core is 10 times more impervious than the material placed in 3-foot-wide slurry cutoff walls constructed through levees in Yuba, Sutter, and Butte counties.

Using the average permeability value of the clayey core material, the seepage through the entire dam embankment at maximum reservoir level was calculated to be about five gallons per minute. This is considered to be a very close match to the 8 – 10 gallons per minute that has historically been measured at the seepage weir during the dry season (see Section 2.2).

Oroville Dam has a unique and comprehensive seepage collection system, discussed in greater detail in Section 2. A nearly vertical drain downstream of the central clayey core was constructed to intercept and collect seepage. The vertical drain then conveys the seepage to a monitored drainage pool at the base of the dam.

Tests completed during construction indicate that the material placed in the vertical drain was constructed to be approximately 20 million times more pervious than the central clayey core material. The vertical drain has ample capacity to intercept and collect any seepage through the core.

Construction records indicate that the outside embankment material (Zone 3 gravels) in the elevation range where the vegetation area is observed ended up having more sand and fine soil than most of the other Zone 3 gravel material placed above and below it. This localized area of finer material is more likely to retain perched, or trapped, rainwater for a longer time than surrounding areas and therefore support vegetation growth.

1.4 SEEPAGE MONITORING REVIEWS

In addition to annual inspections conducted by the Division of Safety of Dams, federal and state regulations require Oroville Dam to be formally inspected, and its operational performance reviewed, by an independent outside consultant every five years. (California Code of Regulations 332). Vegetation on the face of the dam was noted in the majority of these inspections, and was never identified as a dam safety concern.

Two recent FERC five-year inspections include recommendations by for an improved seepage monitoring program that DWR has taken steps to address. A summary of actions is noted below.

- Eighth FERC Part 12D Independent Inspection (2010) recommended development of a long-term monitoring plan of the phreatic surface, or seepage level, through Oroville Dam.
- DWR submitted the requested seepage monitoring plan, "Long-Term Plan for Monitoring of the Phreatic Surface of Oroville Dam, State Dam No. 1-048, Butte County," to FERC and DSOD on Dec. 20, 2012. The plan relied upon design and construction information and results of monitoring information from prior instrumentation systems; it did not call for installation of additional seepage monitoring instruments. DWR determined that its seepage monitoring system at the downstream toe, coupled with piezometric monitoring data collected in the 1960s through 2000, established seepage patterns within the dam. Ongoing measurements at the toe seepage weir provides ongoing

and long-term seepage measurements through the dam, and serves as a means to monitor the phreatic surface in the downstream portion of the dam.

- Ninth FERC Part 12D Independent Inspection (2014) recommended a comprehensive review and evaluation of seepage conditions in the dam, including an evaluation of the vegetation area on the face of the dam. This comprehensive review and evaluation is to include reviews of design and construction information, materials placed in the dam, monitoring information, evaluations of the effects of precipitation, and new seepage and slope stability analyses. The evaluation is slated to be completed before the next FERC Part 12D Independent Inspection, scheduled for 2019.

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OROVILLE DAM SEEPAGE COLLECTION

2.1 DESIGN FEATURES

As stated in Section 1.3, Oroville Dam was designed to minimize seepage. The dam's seepage control is based on widely accepted dam safety designs that employ a central impervious core, continuous along the entire dam axis, to reduce seepage.

As shown in Figure 3, the top surface of the seepage level in the downstream portion of a dam (phreatic surface) is very low if the permeability (k) in the central core is at least 1,000 times less than that in the outer portion or shell of the dam.

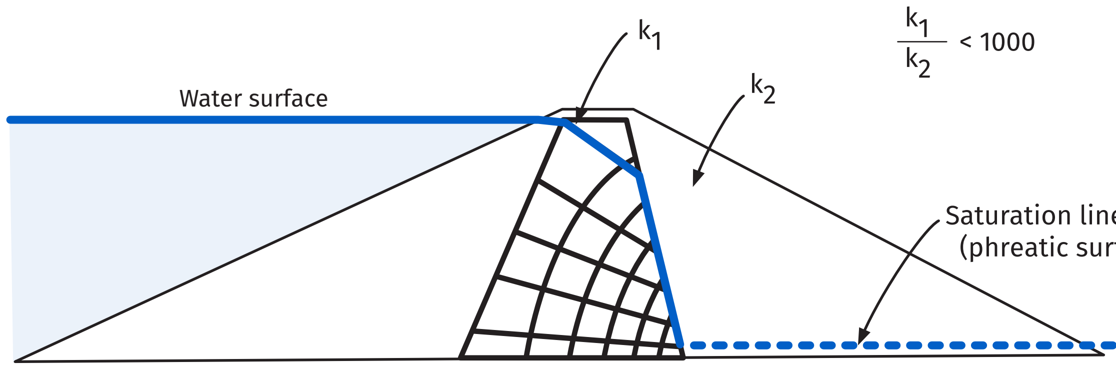

FIGURE 3. *Low Saturation/Seepage Line Resulting when an Embankment Dam has a Central Core that is 1,000 times or more Less Pervious than Outer Shell Material (adapted from Cedergren, 1997).*

As shown in Figure 4, the design for seepage control in Oroville Dam follows this general principle and incorporates a central clayey core (Zone 1) that is about 2 million times more impervious than the outer shell zone (Zone 3) – a far higher ratio than the ratio of 1,000 needed to assure a very low phreatic surface and dry slope.

The seepage collection and monitoring system in Oroville Dam provides an unusually effective way of monitoring seepage through a zoned dam. The design incorporates elements to reduce seepage, intercept seepage passing through the dam, and convey the seepage to a place where it can be easily monitored.

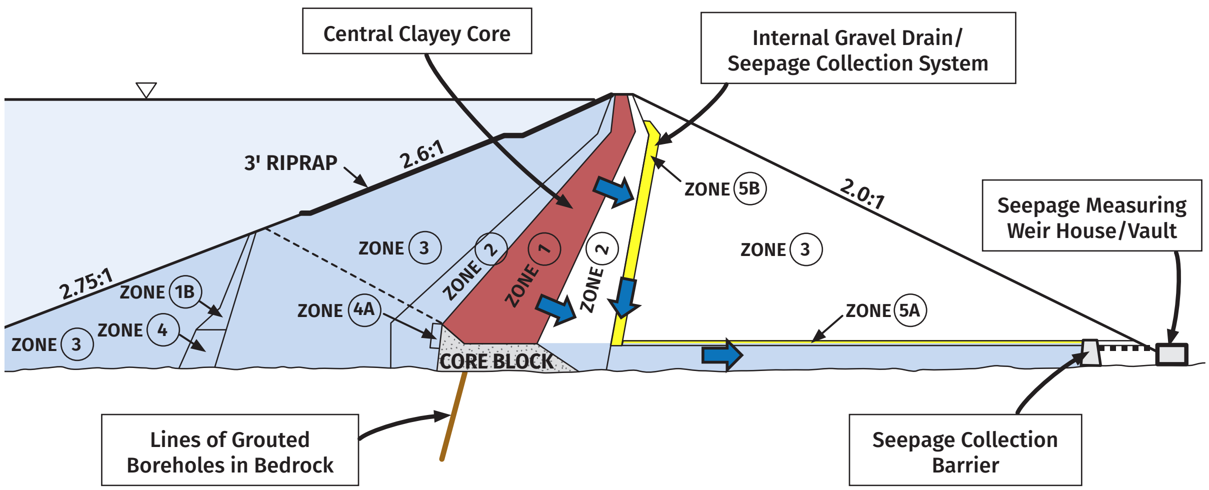

FIGURE 4. *Cross Section of Oroville Dam illustrating Designed Seepage Barriers and Seepage Collection System.*

As shown in Figure 4, the key barrier for seepage through the dam is the central clayey core within the dam (Zone 1). The key barrier for seepage through the foundation is grout injected into a line of boreholes in the bedrock beneath the core (red line below concrete core block). The clayey core is founded on a concrete block (core block) in the central section of the dam to prevent differential settlement of the core.

Figure 4 shows a near vertical gravel drain (Zone 5B) constructed downstream of the core (yellow zone) to collect seepage passing through the dam. Any seepage coming through the central clayey core is intercepted by this drain and then drops down to a low internal pool (blue-shaded zone in lower portion of embankment downstream of the core and core block).

By design, the low internal pool was created by a low seepage collection barrier constructed near the base of the dam. This allows for seepage to be measured. The top surface of this low internal pool is only about 12 feet above the normal water surface of the Feather River below the dam.

Also shown in Figure 4, embankment seepage flows through a pipe from the low internal pool (dashed line) and out into a seepage measuring house (or vault) where it is measured by a weir as it discharges into the Feather River.

DWR has measured the quantity and quality of the seepage exiting through the weir and water levels within the low internal seepage pool since 1966, prior to the dam's completion and initial filling of the reservoir. The rates have remained consistently low.

During the dry season, the seepage flow measured at the weir is only about 10 gallons per minute, an extremely low amount of seepage for a dam this size. Even wet season seepage flow measurements, commonly up to 100 gallons per minute, represent consistent seepage flows since construction was completed. By contrast, large zoned embankment dams with smaller heights commonly seep several hundred gallons per minute.

FIGURE 5. *View of Seepage Measuring Vault which contains a Measuring Weir, and Interior Low Water Pool Level within Oroville Dam. (Photograph taken on April 22, 2017, when seepage flow was approximately 53 gallons per minute, a relatively low seepage amount.)*

2.2 PERFORMANCE MONITORING INSTRUMENTATION

In accordance with industry standards, several types of performance monitoring instruments were installed during Oroville Dam construction to monitor internal stresses, displacements, and seepage.

The predominant purpose of this instrumentation was to confirm that the dam was behaving within acceptable limits during construction and initial filling of the reservoir. All the instrumentation related to seepage through the dam confirmed that the amount of seepage passing through the dam was very small, that the dam materials downstream of the central core were not saturated, except within the low internal seepage collection pool as designed, and that the seepage conditions within the dam were as expected by the designers:

2.2.1. A commonly used instrument during construction was a piezometer, which measures the pressure of water within soil or rock. Instrumentation during construction confirmed that the amount of seepage passing through the dam was very small, that the dam materials downstream of the central core were not saturated (except within the low internal seepage collection pool as designed), and that the seepage conditions within the dam were as expected by designers.

DWR engineers installed 16 piezometers to measure internal water levels downstream of the clayey core, 12 of which were placed above the low internal pool. Between initial filling of the reservoir in 1968 and the mid-1980s, the 12 downstream piezometers above the low seepage pool all showed dry conditions (see Figure 6).

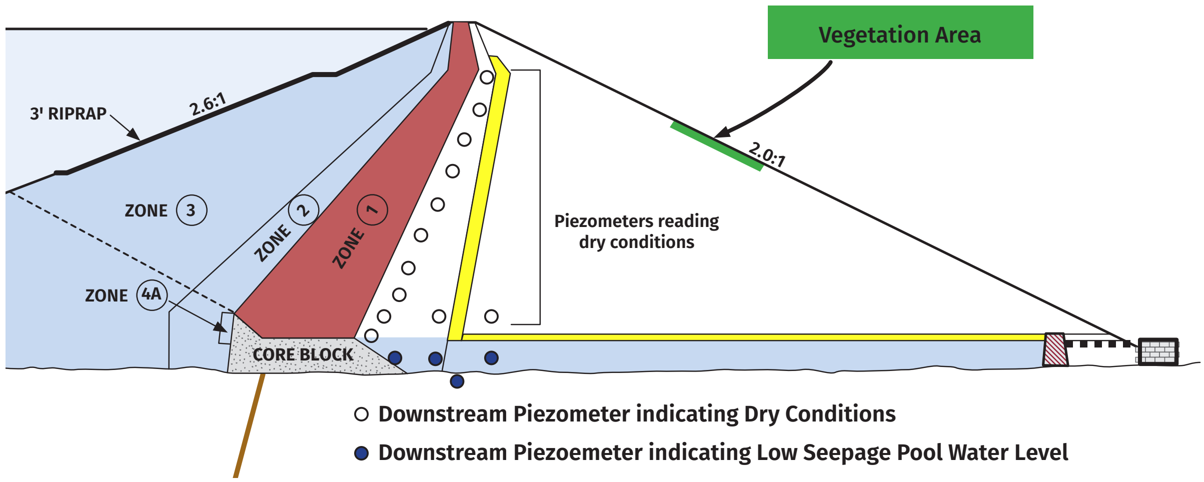

FIGURE 6. *Cross Section of Oroville Dam illustrating Water Levels Indicated by Downstream Piezometers between 1968 and mid-1980s.*

Four downstream piezometers placed within the low seepage pool indicated water levels comparable to the top of the seepage pool (about elevation 240-245 feet, about 330 feet below the bottom of the vegetation area).

While these instruments were abandoned in 2000 due to expected loss of functionality, all the piezometers still functioning continued to read dry if they were located above the low internal pool or to read the level of the top of low internal pool if they were located within the pool.

2.2.2. Two cross-arm settlement devices (Cross-arm "A" and Cross-arm "C") were installed in the downstream slope of the dam. These instruments were installed to measure internal settlements of the downstream portion of the embankment. Water levels could also be measured inside the telescoping casings of these two instruments. Water levels measured in the 1960s and 1970s indicated water levels comparable to the top of the low internal pool (see Figure 7).

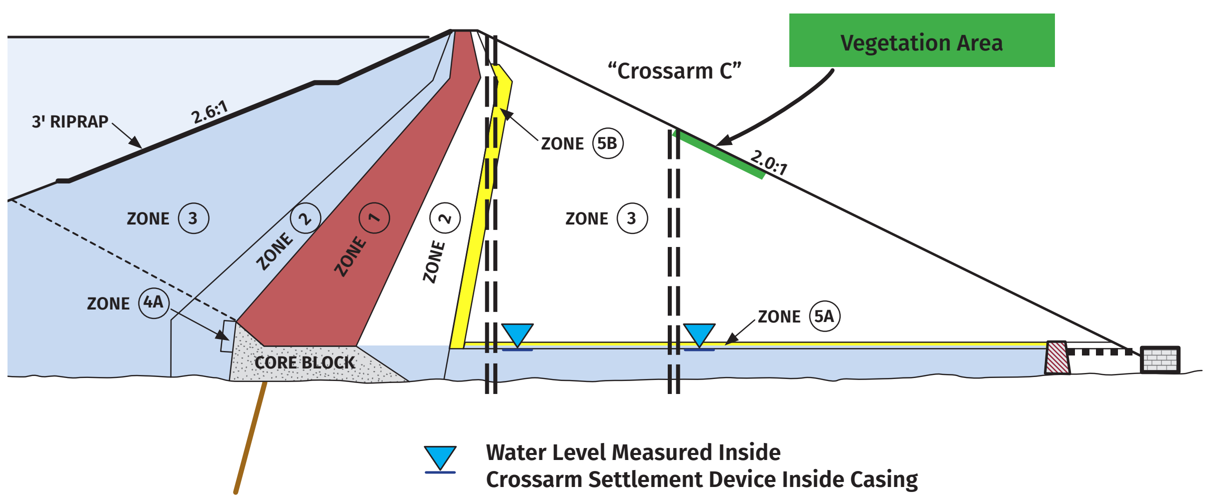

FIGURE 7. *Cross Section of Oroville Dam illustrating Water Levels Indicated by Downstream Cross-Arm Settlement Devices in 1960s and 1970s.*

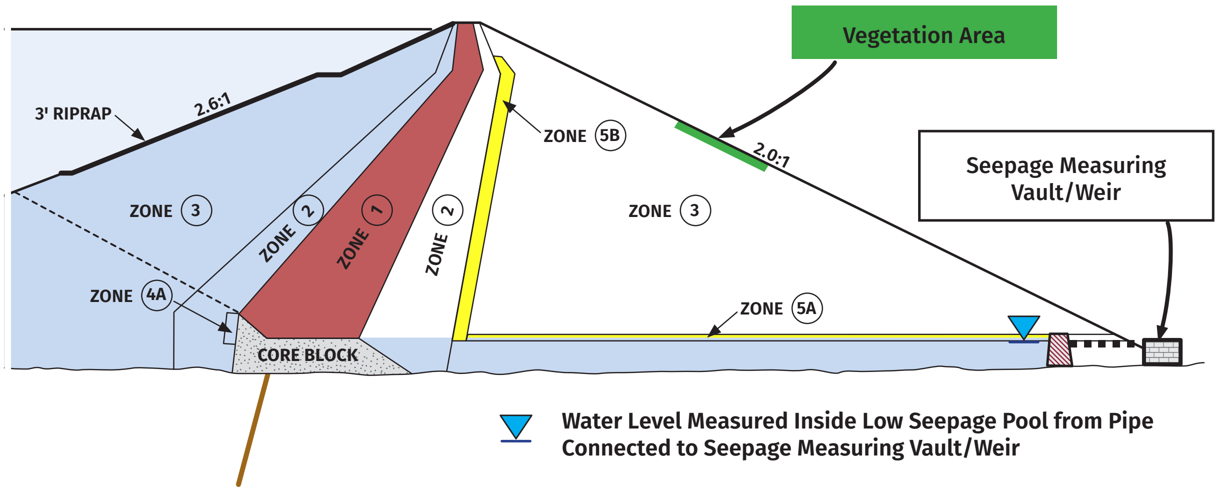

FIGURE 8. *Cross Section of Oroville Dam illustrating Water Level Indicated by Downstream Toe Seepage Weir – 1960s to Present.*

2.2.3. The pipe connected to the downstream seepage measuring vault/weir measures the water level within the low internal pool in the dam. This level has fluctuated between elevation 237 and 239.5 feet since initial reservoir filling in 1968 (see Figure 8). It continues to function and register a water level in the dam that is approximately 330 feet below the bottom elevation of the vegetation on the face of the dam.

2.2.4. During the wet seasons of 1966 and 1967, rainwater infiltration was measured at the seepage weir at the base of the Oroville Dam into the downstream slope of the dam. This occurred during dam construction, and before the reservoir was initially filled in 1968.

Seepage has been monitored once a week since construction, and DWR maintains an alarm on the seepage level in the event seepage should ever exceed the action level set by the department.

In recent years, DWR has implemented higher frequency automated data collection of the seepage rate. The measured seepage flows continue to be significantly affected by rainfall, but during the dry season weir measurements indicate flows commonly about 10 gallons per minute, and as low as eight gallons per minute (see Figure 9). As stated previously, this is an extremely low level of seepage considering the height of Oroville Dam, but compares very well with the five gallons per minute calculated using the average permeability measured in the clayey core during construction.

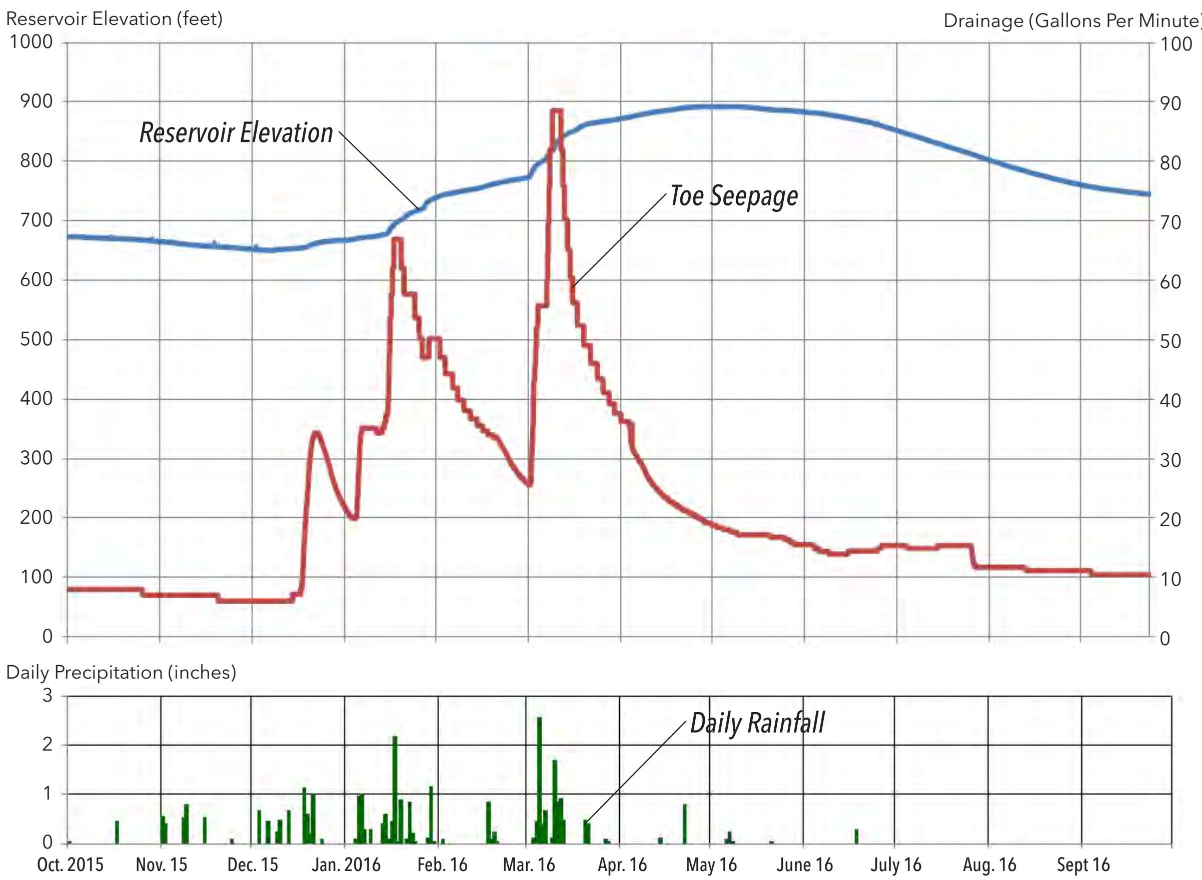

FIGURE 9. *Water Year 2015-2016 Rainfall and Seepage Measurements made at the Seepage Weir Located at the Base of Oroville Dam.*

2.3 RAINFALL EFFECTS ON SEEPAGE

2.3.1. Both the long-term seepage weir measurements and the piezometer readings obtained during construction show that seepage flows within the downstream portion of the dam are significantly affected by rainfall. Each year, seepage flows begin to increase after the first rain storms. The seepage flows induced by rainfall commonly increase up to 50 to 100 gallons per minute after rain events each year. These rainfall-driven seepage flows are much greater than those coming through the dam during the dry season, when flows are generally only about 10 gallons per minute.

2.3.2. The effects of rainfall on seepage do not immediately end after it stops raining. Both seepage measurements and construction piezometer data show that the effects of precipitation continue for months after rainfall has ended, with gradually reducing seepage and water levels persisting through the summer and fall months (see Figure 10).

The effects of winter and spring rainfall commonly last until October each year as rain water slowly drains out of the dam. The seepage levels then start rising when the rainy season begins. This cycle began in 1966 before the reservoir was filled.

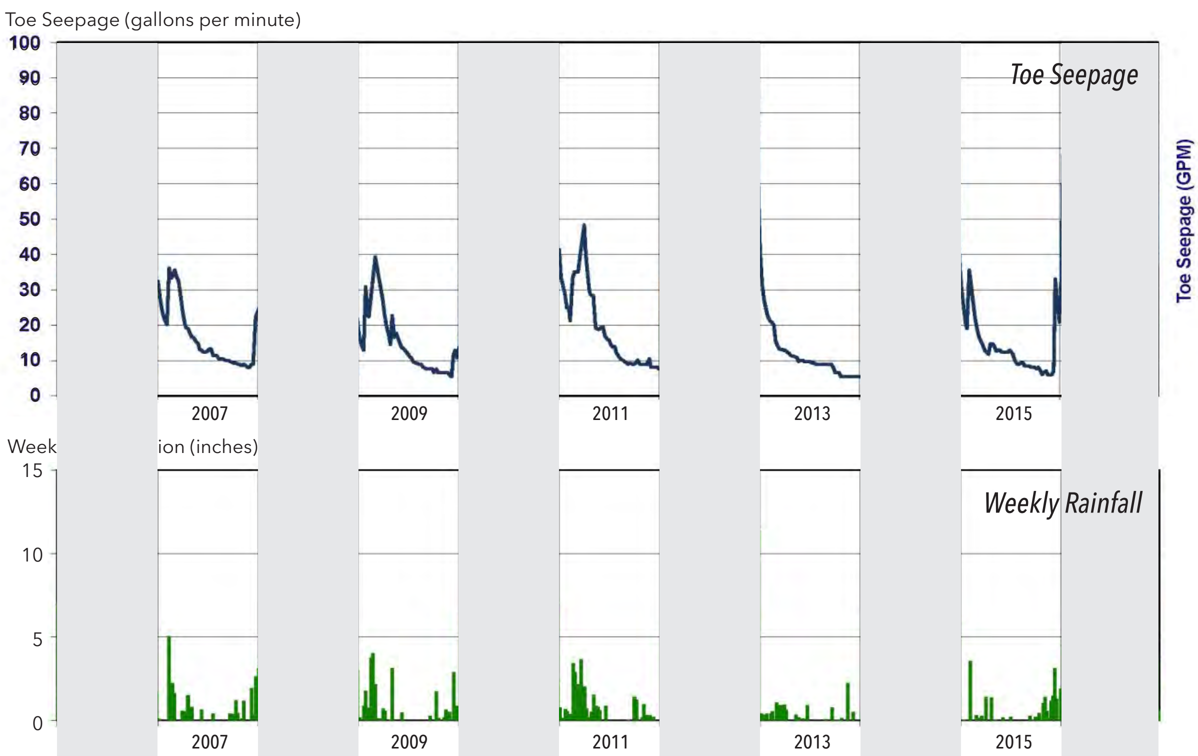

FIGURE 10. *2006-2016 Rainfall and Seepage Measurements made at the Seepage Weir Located at the Base of Oroville Dam.*

3

ASSESSMENT OF THE VEGETATION AREA

3.1 DESCRIPTION OF THE VEGETATION AREA

Lines of wet earth in the vegetation area were first observed during dam construction in 1966 and 1967, following rainfall and the formation of erosion rills on the dam surface (see Figures 11 and 12). It has been monitored and observed since that time.

3.1.1. Perched lines of wet areas shown in the construction photographs are from before the reservoir was first filled in 1968.

3.1.2. In addition to causing erosion rills or gullies in the downstream slope during construction, rainfall also resulted in the ponding of water on the surface of Zone 3 fill placement within the elevation range of the vegetation area (see Figure 13). Precipitation during construction periods tends to wash sandier and finer material into the ponds, creating layers of less pervious material with a tendency to trap water within the dam.

3.1.3. A DSOD inspection report dated February 1, 1967, observed ponded and perched water and seepage bands on the face of Oroville Dam as a result of rain water in the fill area described as the vegetation area in this report.

> *"There are several seepage bands showing up on the downstream face, particularly near the left abutment where gullying is also severe. In these gullies, tight bands force seepage to the surface and form steps within the gullies. At the road below the Palermo Canal about 15 to 20 gpm bleeds out of the fill and runs down the roadway. The laminations and tight layers in Zone 3 should not be a problem except for public relations and maintenance if Zone 5 is free draining."*

3.1.4. During the wet season of each year, the vegetation area turns green in the same general band across the dam face (see Figure 14).

3.1.5. The vegetation area dries out every year, turning yellow and brown during the dry season (see Figure 15).

3.1.6. As previously noted, the vegetation area occurs in an area of the dam that developed erosion rills and gullies due to rainfall during the construction of the dam. These erosion rills and gullies were repaired during original construction by filling them in with cobbles, not regular dam fill (see Figure 16). These highly pervious cobble fills encourage the percolation of rain water into the dam face in the region of the vegetation that grows on the face of the dam, rather than running down the slope.

FIGURE 11. *Lines of wet areas, ponded water, and erosion rills prior to initial filling of the reservoir in future vegetation area. (Construction photograph taken on November 22, 1966)*

FIGURE 12. *Vegetation area showing lines of wet areas and erosion rills prior to initially filling the reservoir. (Construction photographs taken in January 1967)*

FIGURE 13. *Photographs of Ponded Water on the Construction Surface within the Vegetation Area Elevation Range.*

FIGURE 14. *Photographs of the vegetation area taken during the wet seasons over several decades.*

FIGURE 15. *Photographs of the vegetation area taken during summer months.*

FIGURE 16. *Eroded rills or gullies in the vegetation area that were filled with cobbles. This encourages rain water percolation into the fill instead of running down the slope. (Photographs taken January 20, 2017)*

4

SUMMARY ASSESSMENT OF THE VEGETATION AREA

4.1 EVALUATION OF POTENTIAL DAM SEEPAGE

The source of water for the wet area that foster vegetation growth on the face of the dam is not seepage from the reservoir through the dam. This is evidenced by the following:

- The same area on the face of the dam that fosters vegetation growth was observed to have lines of wet earth during original dam construction in the 1960s and two years before the reservoir was initially filled.
- The seepage control design for Oroville Dam includes a nearly impervious central clayey core to reduce seepage to a negligible value. Any seepage from the reservoir that does make its way through the core is intercepted by a vertical drain, preventing it from flowing to the downstream face of the dam. Seepage through the dam that is intercepted by the drain is conveyed to a low level internal pool at the bottom of the dam, and then to a seepage weir for observation and measurement.
- Materials testing performed during dam construction confirm the very high impervious nature of the central clayey core and the large drainage capacity of the vertical drain.
- Seepage measurements at the base of the dam show very low seepage flows during the dry season (only ~10 gallons per minute). These measured seepage flows are consistent with both the design intent and seepage calculations based on the soil permeabilities measured during construction.
- Performance monitoring instrumentation (piezometers, cross arms, and seepage weir) installed during construction show that the water level inside the dam downstream of the core is consistently low. The measured low water level is consistent with the top of the low internal pool designed for collection and measurement of seepage. This low water level is only about 12 feet above the typical water surface of the Feather River below the dam.

4.2 SOURCE OF WATER FOR THE VEGETATION AREA

The source of water for the vegetation area is concluded to be rainfall. This is evidenced by the following:

- Seepage measurements and construction piezometer readings showed that seepage in the dam has been greatly affected by rainfall percolating into the dam even before the reservoir was first filled. This response to rainfall has remained consistent every year since construction of the dam.

- Seepage measurements and construction piezometer readings show that seepage impacts from rainfall persist for months after the rainy season, indicating that the rainwater that has percolated into the dam drains slowly out of the dam.
- Construction operations during the 1966-67 rainy season resulted in ponding of water on the fill surface and the creation of stratified lenses or layers within the fill in the area where vegetation is now present. These stratified layers encourage the perching or trapping of water during rain events. Numerous inspection reports and aerial photographs taken during construction and prior to reservoir filling document the presence of wet areas seeping rain water that had percolated into the dam.
- Vegetation grows on an area of the dam that developed erosion rills and gullies due to rainfall during original dam construction. These erosion rills and gullies were repaired by filling them in with cobbles, not regular dam fill. These highly pervious cobble fills encourage the percolation of rain water into the dam face, rather than rainfall running down the slope.
- The vegetation area generally dries up and turns brown by the end of the summer, which would not happen if it had a constant water source.

4.3 EFFECTS OF THE VEGETATION AREA ON DAM SAFETY

As stated above, vegetation on the face of Oroville Dam is the result of rain water temporarily trapped within the dam's Zone 3 gravels. This vegetation area does not cause a dam safety concern. This is supported by the following:

- Rain water infiltrates the dam's gravelly shell each year and some of this water becomes temporarily perched on dirtier layers of gravel within the dam shell. This was observed during dam construction and is documented in DWR and DSOD construction and inspection reports and the cycle has occurred since before dam completion.
- The trapped height of water on these perched water levels is believed to be relatively low, and therefore requires several months to drain out. During this time, vegetation grows where the trapped water drains out onto the face of the dam. As the water drains out towards the end of summer, the vegetation dries out and turns brown. The cycle then begins again during the next wet season.
- Construction records show that the Zone 3 dam material placed within the elevation band associated with vegetation was densely compacted and has a high strength
- All portions of the dam's face, including the vegetation area, have performed well for over 50 years with no signs of distress, including after moderate earthquake shaking sustained during the 1975 Oroville Earthquake (M~6).

5

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March 27, 1967 photo of Oroville Dam before the dam was completed and the reservoir was first filled.

Oroville Dam, showing vegetation area, in Butte County, California. (Photo taken August 29, 2017)

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA