Technical Memorandum

ARUP

77 Water St.
Arup
New York, NY 10005
www.arup.com

Project title	California WaterFix (Delta Habitat Conservation and Conveyance Program)	Job number	237477
cc		File reference	
Prepared by	Foteini Vasilikou; Michael Chendorain, PE	Date	March 17, 2017
Subject	Assessment of Potential Water Leakage Rates from California WaterFix Tunnel		

1 Introduction

The California WaterFix program has been developed to stabilize water deliveries from the Sacramento – San Joaquin River Delta (Delta) area. The program utilizes a twin tunnel concept. A tunnel leakage study was performed in 2012, but since that time the design concept for the project has been changed, with the pumps being moved from the intakes to the terminus of the project, which significantly changes the water pressure in the tunnels and consequently the potential leakage rate. Metropolitan Water District (MWD) has requested that Arup North America, Ltd. (Arup) evaluate the impact of design updates to the tunnel alignment, elevation and internal pressure on water seepage rates from the tunnel to the surrounding ground. MWD has authorized this evaluation in Task Order Number 5, signed on October 13th, 2016, as part of Agreement Number 143949. The scope of work includes the following:

- Review and compilation of estimated relevant external pressures (along tunnel alignment);
- Review and compilation of estimated internal tunnel pressures;
- Estimation of micro-cracking in the segmental lining and resulting permeability of the lining;
- Review of Jacobs Associates report dated July 10th 2012; and
- Estimate of water seepage rates from the tunnel to the surrounding ground.

The following information has formed the basis for this review:

- Geotechnical Data Report (GDR): California Department of Water Resources (DWR), 2013. 2009 Through 2012 Geotechnical Data Report, Pipeline/Tunnel Option. Delta Habitat Conservation and Conveyance Program, Standard Agreement 4600008104, TO WGI 14. Revision 0. April 2013.
- Tunnel Alignment Drawings: California Department of Water Resources (DWR), 2015. Conceptual Engineering Report, Volumes 1 (Report) and 2 (Drawings) – Final Draft (CER). Delta Habitat Conservation and Conveyance Program, Dual Conveyance Facility, Modified Pipeline/Tunnel Option – Clifton Court Forebay Pumping Plant. Project Number 240010. July 1, 2015.
- Agreement 82817 TO 14 - Tunnel Lining Feasibility Study, Project Memorandum No. 6, Rev 1, Conceptual Engineering Evaluations for 40-ft Inside Diameter Gravity Flow Tunnel, July 10, 2012.

Technical Memorandum

237477 March 17, 2017

2 Project Background

As part of the California WaterFix program, new twin tunnels and intakes will be constructed to stabilize water deliveries from the Delta area. The invert of the twin tunnels will be up to 175 feet below ground level (ft bgl) with a length of around 30.15 miles per tunnel and will be excavated using Tunnel Boring Machines (TBMs). The North Tunnels will transport water from the intakes to the intermediate forebay, and total 13.5 miles in length. Water will then be transported from the intermediate forebay via the Main Tunnels to Clifton Court Forebay. The tunnel construction will also be supported by the construction of fifteen shafts and a number of safe haven work areas (i.e. subsurface evacuation areas)[1].

The tunnel alignment consists of:

- The North Tunnels, which include three separate tunnel lengths:
  - North Tunnel, Reach 1 – 1.99 miles of single 28-foot-ID tunnel between Intake No.2 and Intake No.3 (Stations[2] 3350-3450)
  - North Tunnel, Reach 2 – 6.74 miles of single 40-foot-ID tunnel between Intake No.3 and the Intermediate Forebay (Stations 3000-3350).
  - North Tunnel, Reach 3 – 4.77 miles of single 28-foot-ID tunnel between Intake No.5 and the Intermediate Forebay (Stations 5000-5250)
- The Main Tunnels - 30.2 miles of twin 40-foot-ID tunnels between the Intermediate Forebay (Reach 4, Station 0) and Clifton Court Forebay Pumping Plant (Reach 7, Station 1592).

In 2012, Jacobs Associates produced estimates of tunnel leakage rates. At the time the Jacobs Associates report was produced, the program configuration consisted of pumping plants located at each of the three river intakes, which lifted water from the Sacramento River into the tunnel system. Tunnel diameters were sized based on this arrangement. This concept was subsequently revised such that water will now flow by gravity from the Sacramento River through the tunnel system to a pumping facility located near the project terminus at Clifton Court.

The revised design is analyzed in this memorandum which provides updated estimates of leakage relevant to the current design, which is shown in Figure 1. Figure 2 illustrates the differences between the previous and current designs. The key changes from 2012 to the current design with respect to the potential for leakage are the revised locations of the pumping facilities and the resulting lower internal pressure, the shallower tunnel depth and the change in the assumed elevation of groundwater from five feet below ground level to elevation 0ft. As a result, for the current design, there are significant lengths where the groundwater pressure is now higher than the internal tunnel pressure, and inflow rates have been estimated at these locations.

[1] Number of shafts is based on design progress as of July 1 2015.
[2] Stationing along the alignment is provided in hundreds of feet, i.e. Station 1600 is 160,000 ft along the alignment

Technical Memorandum

237477 March 17, 2017

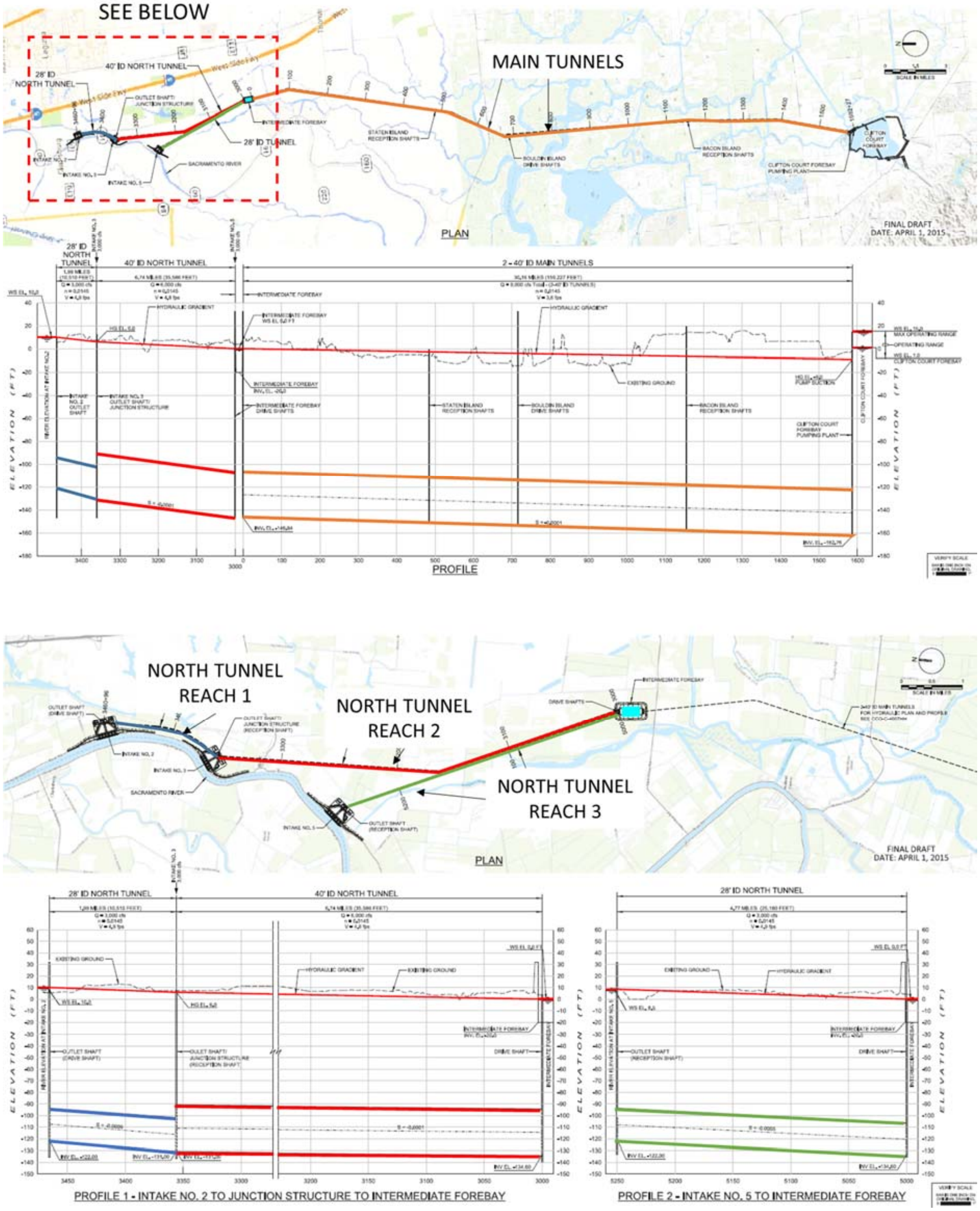

Figure 1. Overall Hydraulic Plan and Profile Along the Alignment.

Technical Memorandum

237477 March 17, 2017

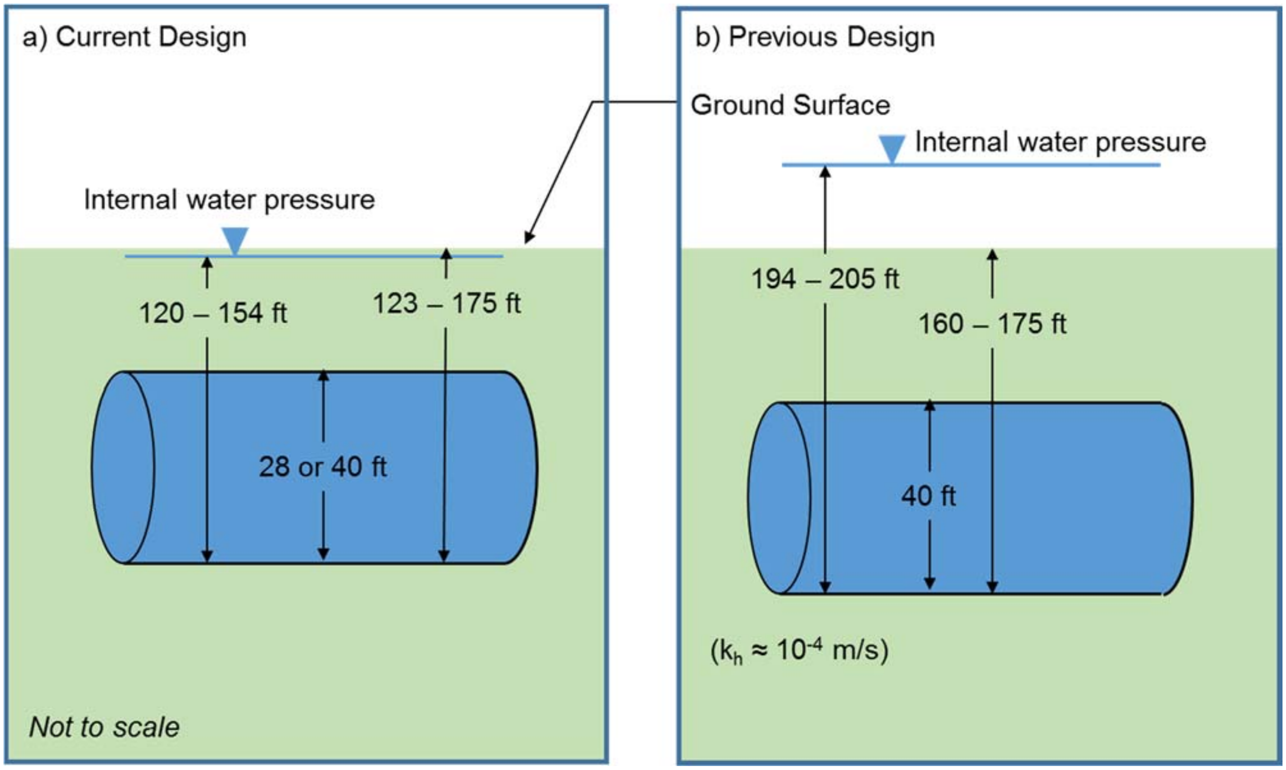

Figure 2. Sketches of a) Current Design, and b) Previous 2012 Design (Not to scale).

3 Hydrogeological Setting

The tunnel alignment lies within an agricultural area where groundwater is generally managed in order to maintain the groundwater level below crop root zones. For the purposes of this analysis, groundwater has been taken at an elevation of 0 ft, to be consistent with the CER[3].

Based on the current proposed tunnel alignment, the depth of the tunnels is between about 123 and 175 ft bgl. Soils widely range through the alignment and include both low permeability clays as well as sands and gravels (which are likely to have much higher permeability). Geotechnical boreholes and Cone Penetrometer Testing (CPT) boreholes provide limited information on the types of materials to be encountered in the tunnel. Based on a review of the available data from the GDR and comparison with the current tunnel alignment drawings the following is noted:

- The current alignment closely follows the alignment which was considered in the GDR for the southern two-thirds of the Main Tunnels (Reaches 5, 6 and 7, between stations 600 and 1400) and thus existing geotechnical data is representative of subsurface conditions which will be encountered during tunneling.
- Between stations 0 and 600 (Reach 4) and between station 1400 (Reach 7) and the southern end of the Main Tunnels alignment (at around station 1592), the existing geotechnical data is offset significantly. Across these lengths the representativeness of the existing geotechnical data from the GDR is unclear.
- Geotechnical data associated with North Tunnels (north of the Intermediate Forebay) is focused on intake areas rather than the tunnel alignment.

In general, the current proposed tunnel alignment (where data is representative) will encounter mostly low permeability materials (clays and silts). However there will be lenses of sands and gravels encountered across the alignment. It is unclear from the available information how many of the sands and gravels have aquifer potential and how many are discontinuous lenses with no significance for water supply. However given the alluvial nature of the local geology, it may be expected that there will be some sands and gravels which act as aquifers through which groundwater flows.

[3] "For the net internal pressure design of the liner during conceptual phase, the external ground water pressure is assumed to be at elevation 0.0 (MSL) along the majority of the alignment. Occasionally, lower ground water elevation may occur due to local conditions". CER Volume 1, 11.2.6.

4 Estimation of Tunnel Inflow and Leakage Rates

Inflow and Leakage rates along the tunnel alignment are estimated as shown in Figure 3 through Figure 5 and Figure 6 (in Section 5). These estimates are based on the following assumptions:

- Ground surface along the alignment has been derived from the tunnel alignment drawings. Groundwater is assumed to be at elevation 0.0 ft (MSL) along the alignment to be consistent with the CER. In some cases, ground surface is below elevation 0.0ft, so this assumption may result in a minor underestimate of leakage rates, and a minor overestimate of inflow rates.
- The tunnel invert varies between about 123 and 175 ft bgl (down to -163ft elevation) for the Main Tunnels, The proposed tunnel profile range is shown on Sheet Nos. CCO-C-1035TN to 1038TN (CER). Variation of the tunnel profile within this range has no noticeable impact on the calculated leakage rates.
- The internal pressure head in the tunnel in the updated design is lower than the previous design and varies from 120 ft to 154 ft relative to the tunnel invert. Internal tunnel pressures are reported along the alignment based on Sheet Nos. CCO-C-4005HH to 4007HH of CER.
- The maximum differential water pressure[4] is expected to range from a minimum of -9 ft (where the external water pressure is greater than internal) to a maximum of +9 ft (where the internal water pressure greater than external). The range of pressures along the alignment is evenly spread between these two values.
- The estimated inflow and leakage rates documented in this memorandum are the long term steady-state flow rates during operation of the entire tunnel system (both twin tunnels filled), and not irregular, transient, or periodic peak leakage rates.
- Leakage rates are estimated according to the framework proposed by Fernandez (1994). Nomogram 1 in the Fernandez paper is used to estimate leakage and pore pressure outside pressurized tunnel liners. A base case liner permeability of 10^{-6} cm/s (10^{-8} m/s) was adopted in accordance with the assessment by Fernandez. This liner permeability was selected since liner strains (ε_θ^L), along the alignment are less than 1.5 x 10^{-4} at all locations and thus micro cracking is not likely to take place.
- To account for the potential variability of liner permeability due to leakage through the gaskets, a sensitivity analysis was undertaken to envelope a lower and upper range of leakage rates; where the upper estimate is assumed to be the base value. The liner permeability ranged between 10^{-7} cm/s, an order of magnitude lower than the base value and up to the base value. It should be noted, that with a precast concrete segmental lining manufactured in factory conditions, the concrete permeability is likely to be at the lower end of this sensitivity range, but leakage through the gaskets could make the overall permeability closer to the base value assumed. A review of typical inflow specifications for completed tunnels indicates that a permeability equivalent to 10^{-7} cm/s is the industry standard; even better performance can be achieved with careful attention to segment specification and erection.

[4] Differential water pressures given in feet of water. Negative differential water pressures indicate inflow to the tunnel would be expected to occur, while positive differential water pressures indicate leakage from the tunnel is expected.

Technical Memorandum

237477 March 17, 2017

- It is expected that segments under compression will exhibit slightly lower permeability than segments under a net tensile load where micro-cracking might occur. However, in the current design, the lining is expected to be under compression, and as noted above, micro-cracking is not anticipated.
- In addition, ground permeability was varied by an order of magnitude (both for higher and lower permeabilities) to capture ground uncertainties.
- Inflow rates have been estimated based on the method given by Goodman (1980) and endorsed by Fernandez (1994). Inflow potentially occurs at locations where the external water head exceeds the internal water pressure in the tunnel (i.e. negative differential water pressure within the tunnel).
- The modulus of elasticity of liner is calculated using ACI 318 'Building Code for Structural Concrete' with an assumed concrete compressive strength of 7,000 psi.

The input parameters assumed in the calculations are presented in Table 1. The results of the sensitivity analysis are presented in Table 2 (in Section 5).

Table 1. Input Parameters

Parameter	Description	Value	Unit	Comment
k_m	Ground Permeability (Assumed to be as sand)	9.8×10^{-5} (2.8×10^{-5})	ft/sec (m/s)	Sensitivity analysis included an order of magnitude lower and greater than the assumed ground permeability.
k_L	Liner Permeability	3.3×10^{-8} (1.0×10^{-8})	ft/sec (m/s)	Based on $\varepsilon_\theta^L < 1.5 \times 10^{-4}$ (Fernandez, 1994)
r_T^O	Tunnel outside radius	15.3, 21.7	ft	For internal diameters (ID) of 28 and 40', respectively.
r_T^i	Tunnel inside radius	14, 20	ft	For ID of 28 and 40', respectively.
th	Tunnel liner thickness	1.3, 1.7	ft	For ID of 28 and 40', respectively.
α	Radius to liner center	14.7, 20.8	ft	For ID of 28 and 40', respectively.
E_m	Modulus of Elasticity of Ground	4.5 (6.48×10^5)	ksi (lbf/ft^2)	
E_L	Modulus of Elasticity of Liner	4,770 (6.9×10^8)	ksi (lbf/ft^2)	
ν_m	Poisson Ratio of Ground	0.30	unitless	
ν_L	Poisson Ratio of Liner	0.20	unitless	
ν_w	Specific Weight of Water	62.4	lbf/ft^3	

During construction, or if the tunnel is unwatered for future maintenance, the gaskets between the segmental lining will avoid the flow of any small particles into the tunnel. This situation is similar to a typical transportation tunnel, and there is a long track record of large diameter tunnels in similar ground conditions that do not see a loss of ground. A typical specification is to require no visible water inflow above springline, and damp patches only (no flowing water) below springline.

Technical Memorandum

237477 March 17, 2017

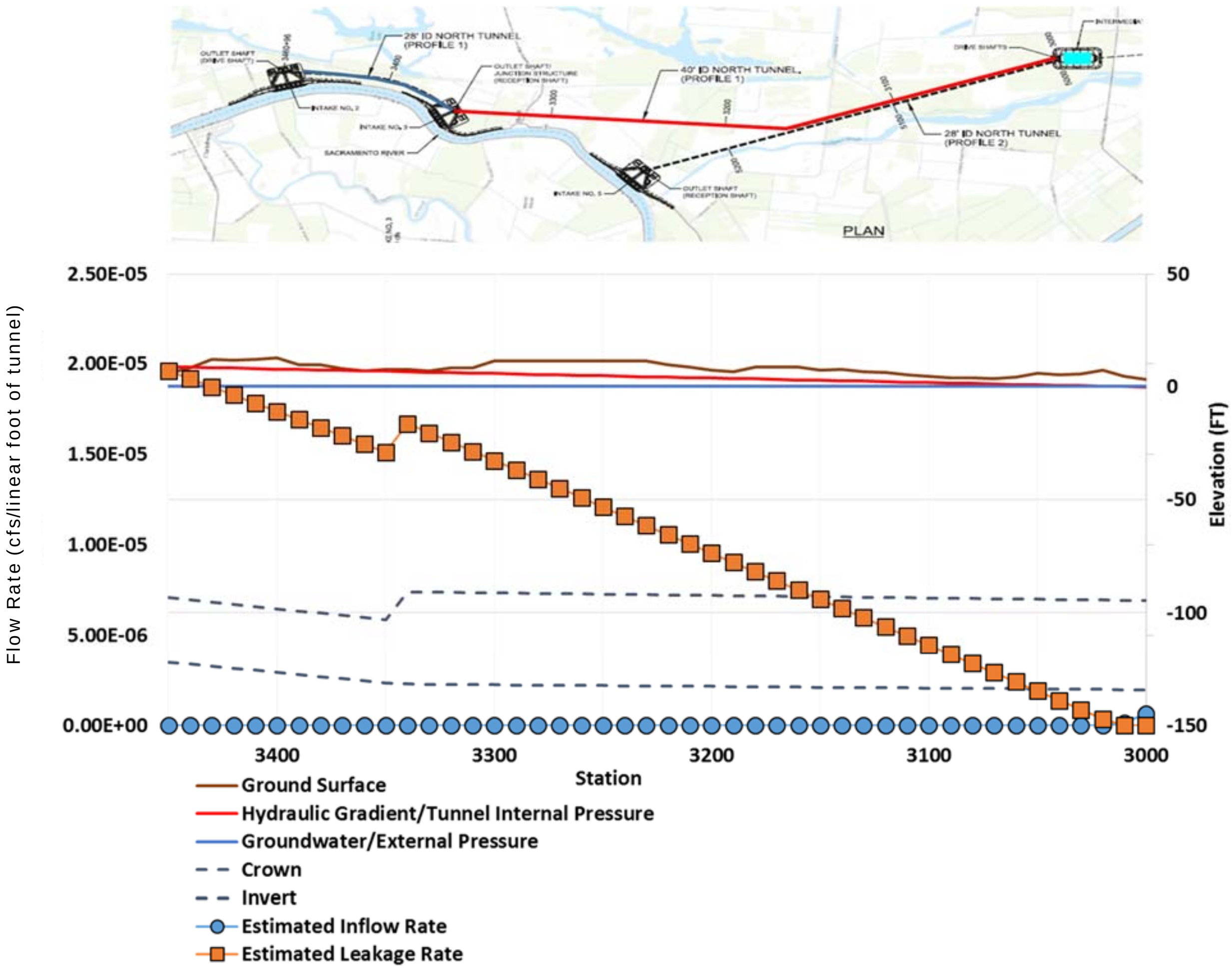

Figure 3. Estimated Tunnel Inflow and Leakage Rates – North Tunnel Reach 1 and Reach 2.

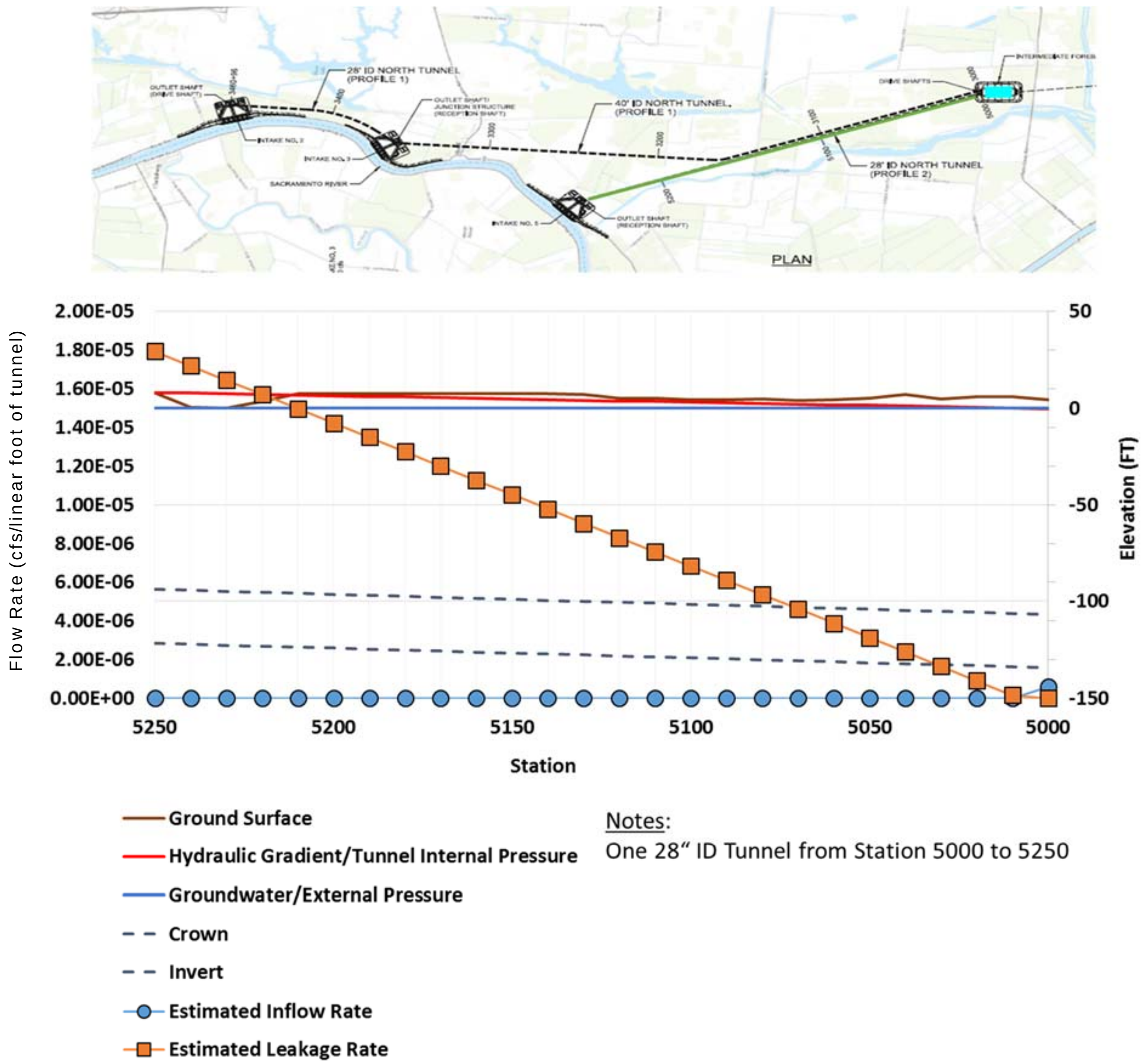

Figure 4. Estimated Tunnel Inflow and Leakage Rates – North Tunnel Reach 3.

Technical Memorandum

237477 March 17, 2017

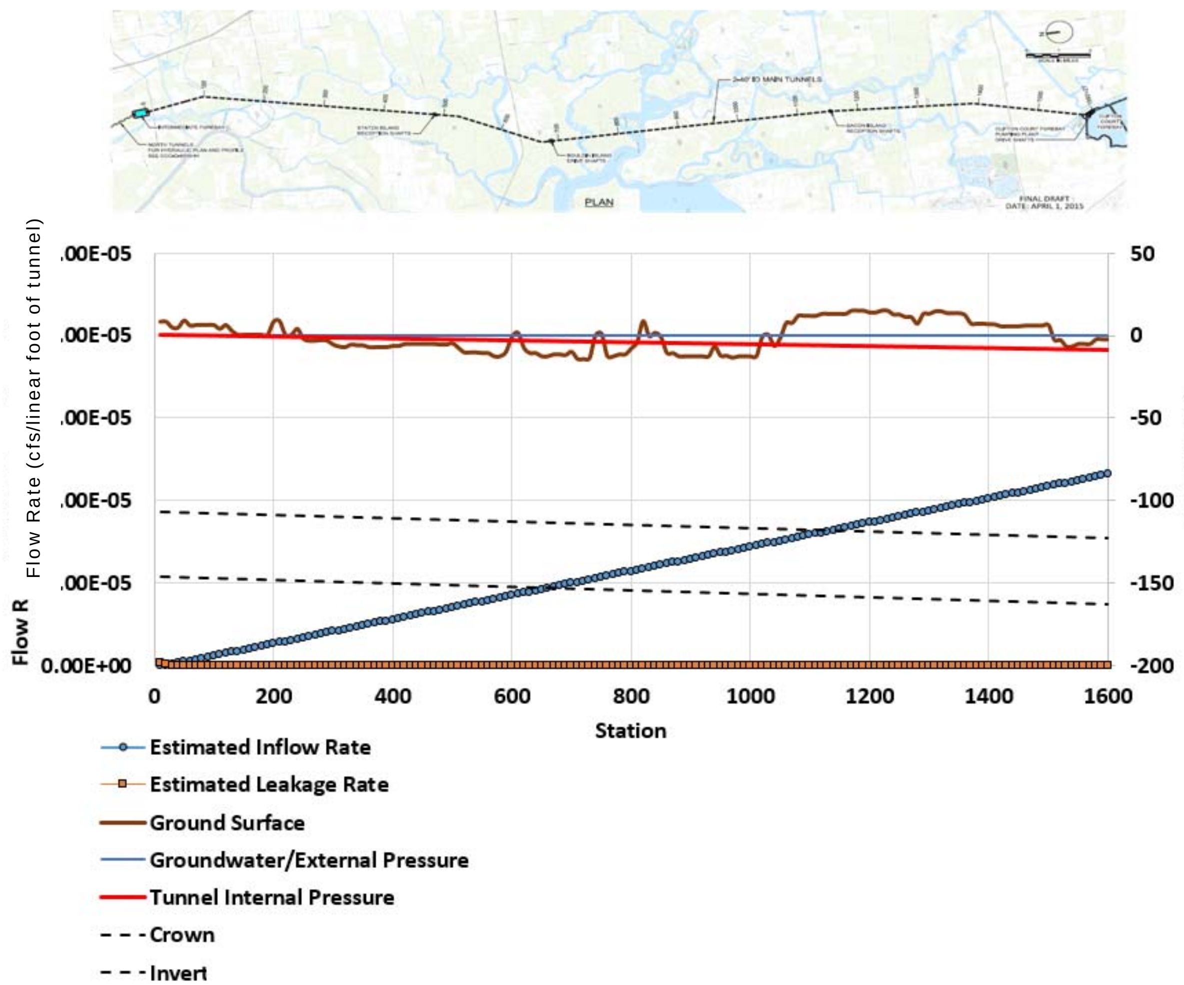

Figure 5. Estimates of Tunnel Inflow and Leakage Rates – Main Tunnels (Reaches 4, 5, 6, 7) per Tunnel.

Table 2. Estimated Total Inflow (-) and Leakage Rates (+) for Current Design

Tunnel Length (feet)	Tunnel Configuration	Estimated Inflow (cfs)	Estimated Leakage (cfs)	Net Estimated Leakage Whole Tunnel (cfs)	Estimated Leakage Sensitivity Analysis** Whole Tunnel (cfs)	2012 Design Alternative A1 (cfs)* (for comparison)
46,100	28' & 40' ID North Tunnel Reaches 1 & 2	0.00	+0.5	+0.5	+0.1 to +0.5	Not assessed
25,200	28' ID North Tunnel Reach 3	0.00	+0.2	+0.2	0.0 to +0.2	Not assessed
2 x 159,200	Two 40' ID Main Tunnels Reaches 4 to 7	-3.7	0.00	-3.7	-0.4 to -3.7	2827
Total		-3.7	0.7	-3.0	-0.30 to -3.0	

Notes:

The lengths of tunnel where the internal water pressure is lower than the external groundwater pressure will have inflow, and where the internal water pressure is higher than the external pressure the tunnel will leak. So overall, for all the tunnels taken together (reaches 1 to 7), the sections subject to inflow will have a total inflow of -3.7cfs, and the sections subject to leakage will have a total leakage of 0.7 cfs; overall the entire system has an inflow of 3cfs.

*Alternative A1 refers to one-pass precast concrete segmental lining with tension reinforcement. The leakage rates have been calculated by taking an average of the estimated leakage rates from both the concrete liner and the gaskets, and applying over a 60.3 miles length for twin tunnels.

** The sensitivity analysis looked at concrete permeabilities in the range of 10^{-5} cm/s to 10^{-6} cm/s and ground permeabilities one order of magnitude above and below the base assumption.

5 Comparison with 2012 Leakage Estimates

A comparison between the assumptions and estimation of the leakage rates for the 2012 design study and the current analysis is presented in Table 3 and the resultant leakage rates are presented as a function of differential head in Figure 6.

Table 3. Comparison of assumptions between current and previous designs

	2012 Estimate	Current Estimate
Ground Characterization	Sand	Sand
Tunnel Diameter	40 ft	40 ft and 28 ft
Tunnel Invert Depth Range below Ground Surface	160 ft to 175 ft	123 ft to 175 ft
Groundwater	5 ft bgs	0 ft bgs
Internal Design Pressure Head in the Tunnel	194 ft to 205 ft	120 ft to 154 ft
Maximum differential water pressure	50 ft	9 ft
Radial (Longitudinal) Cracking of the Lining	Liner strains (ε_θ^L) >$1.5\text{x}10^{-4}$, so increased liner permeability was assumed, based on Fernandez (1994)	Liner strains (ε_θ^L) <$1.5\text{x}10^{-4}$. Sensitivity analysis performed with regards to liner permeability to account for leakage through the gaskets and to capture various lining designs
Lining Permeability	$5.3\text{x}10^{-5}$ to $7.3\text{x}10^{-5}$ ft/sec	$3.28\text{x}10^{-8}$ ft/sec
Head Loss Across Lining	4 to 5.5 %	~1 %
Comparison of Leakage Rates	Lower leakage rates are now estimated, as would be expected due to the lower internal tunnel head pressures.	

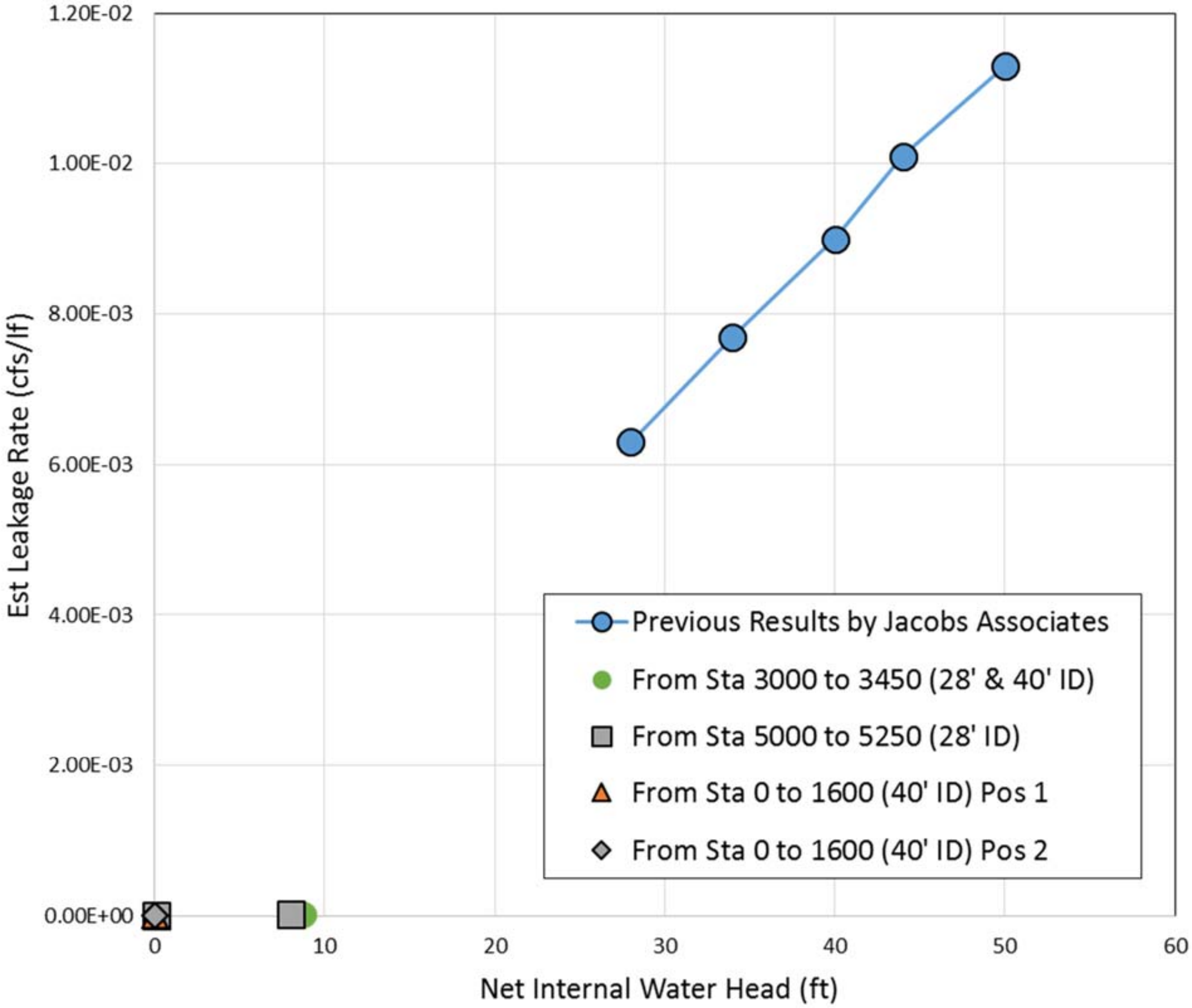

Figure 6. Comparison between estimated leakage rates for current design and 2012 design

6 Conclusions

Leakage rates between the ground and the tunnel are sensitive to the differential pressure between the external groundwater system and the internal water pressure. Where the groundwater head is above the pressure head in the tunnel, inflow to the tunnel may occur. This is mainly in sections of the alignment which run beneath areas of relatively higher ground. Where the pressure head in the tunnel exceeds the external head (such as in in valley locations and more low lying topography) leakage may occur.

The permeability of the liner has a significant effect on the calculated leakage rates. Leakage rates are noticeably more sensitive to liner permeability than ground permeability. The elevation of the tunnel makes almost no difference to the leakage rates.

Under the low differential pressures which will occur with the current alignment and design water pressures, radial cracking is not expected, and the liner permeability will be a function of the concrete, as well as the circumferential and radial joints.

The net load on the segmental lining is anticipated to be external, with the confining pressure of the soil and external groundwater providing a higher load than the internal water pressure. This will maintain the segmental lining in compression (avoiding higher permeability due to micro-cracking) and also keep the gaskets sealed.

The leakage rates estimated based on current design conditions are lower to those estimated for the previous 2012 design. The main differences between the two analyses is the current design internal pressure is less than the previous design (by between 65 to 126 ft. of water). With the current tunnel alignment, hydraulic grade line and an assumed water table elevation of 0.0 ft (MSL), the internal and external water pressures are essentially balanced, which results in no overall leakage and a negligible overall inflow. The tunnel leakage rate should be further evaluated in the preliminary and final design stages upon availability of site-specific geotechnical and hydrogeological data.

During construction, or if the tunnel is unwatered for future maintenance, the gaskets between the segmental lining will avoid the flow of any small particles into the tunnel. This situation is similar to a typical transportation tunnel, and there is a long track record of large diameter tunnels in similar ground conditions that do not see a loss of ground. A typical specification is to require no visible water inflow above springline, and damp patches only (no flowing water) below springline.

7 Recommendations

These estimates have been made for average conditions, and are based on generalized values of hydrogeological parameters. The effect of transient or short term fluctuations or spatial variations in both internal and external water pressures should be considered, particularly in relation to the potential for cracking of the lining and also scour of sediment outside the tunnel.

To minimize leakage, there are a number of steps that can be taken, that correlate with good practices taken to limit inflows in segmentally lined tunnels:

- Specification of a high quality concrete, with low permeability. This will also meet the goal of having a concrete with high durability. Measures to achieve this would include use of pozzolans such as fly ash, specification of well graded aggregate, and a low water cement ratio. The permeability can be made a specific contract requirement and be tested for during segment production. This assessment has used 10^{-7} cm/s, which is typical but there are examples of projects where with special attention to the concrete 10^{-9} cm/s or even 10^{-10} cm/s have been specified. This is normally for durability reasons but the impact on leaks will be a reduction, although not as significant as the order in magnitude changes would suggest since most leakage will occur at the joints.
- Careful detailing of inserts, such as the plastic sockets used for grout holes. Leakage around these inserts is a common cause of water flow through a segmental lining. An example of good detailing would be the addition of hydrophilic seals around the outside of the inserts. This is normally

considered in design and specification, but not to the extent of testing the components. For tunnels of this length this may be justified and would add assurance that leakage would be minimized.

- Specification (and enforcement) of tight build tolerances for the segmental lining. A well-built lining will have better alignment at gaskets and will avoid concrete damage, which will reduce leakage potential. This varies a lot between projects and contractors, and is likely to have the biggest impact on leakage. Careful attention to build could reduce the leakage by an order of magnitude compared with this prediction.
- Specific quality control measures that can be taken in the field to ensure good segment build include dimensional checks on each ring assembled, to ensure that the tunnel diameter is within tolerance and that steps and lips between adjacent segments are minimized; and careful development and monitoring of the grout mix, pump pressure and injection volume to ensure complete filling of the annular void with a grout that provide stability to the lining and minimize displacement after erection.
- The gasket details and the segment connections will need to be designed to ensure the gaskets remain adequately compressed when the internal water pressure is applied. The gaskets rely on being compressed together to give a good seal, and a lining such as this with a net low loading will have to rely on a combination of a gasket that requires a low load to maintain closure, and connections that hold the segmental rings together over the life of the project. Adequate annular void grouting will also be essential to provide external restraint. While this is standard practice, this recommendation has been included because this is a fairly unique situation where the filling of the tunnel reduces the gasket compression

8 References

California Department of Water Resources (DWR), 2013. 2009 Through 2012 Geotechnical Data Report, Pipeline/Tunnel Option. Delta Habitat Conservation and Conveyance Program, Standard Agreement 4600008104, Task Order WGI 14. Revision 0. Dated April 2013.

California Department of Water Resources (DWR), 2015. Conceptual Engineering Report, Volume 2, Concept Drawings – Final Draft. Delta Habitat Conservation and Conveyance Program, Dual Conveyance Facility, Modified Pipeline/Tunnel Option – Clifton Court Forebay Pumping Plant. Project Number 240010. Dated 1 July, 2015.

Fernandez, G., 1994. Behaviour of Pressure Tunnels and Guidelines for Liner Design. Journal of Geotechnical Engineering. 120 (10): 1768 – 1791.

Goodman, R.E., 1980. Introduction to Rock Mechanics. John Wiley and Sons, New York, NY.

Jacobs Associates, 2012. Tunnel Lining Feasibility Study Project Memorandum No.6. MWD Agreement 82817, Task Order 14. Dated July.

Technical Memorandum

237477 March 17, 2017

DOCUMENT CHECKING

	Prepared by	Checked by	Approved by
Name	Foteini Vasilikou; Michael Chendorain, PE	Michael Chendorain	Jon Hurt
Signature			