## Executive Summary

### Table ES1. Review of Pebble Limited Partnership's (PLP's) Environmental Baseline Document (EBD): Hydrologic characterization

| | |
|---|---|
| Basic issue | Does PLP have sufficient hydrologic data and an adequate process-based understanding of the Pebble site hydrology to evaluate the potential impacts of mining on downstream waters? |
| Approach, data quality, and intended uses | Hydrologic data collection for the Pebble baseline studies followed accepted approaches, and the data are generally of high quality. The hydrologic modeling work presented in the EBD uses a modeling package that is not well-suited to modeling the extensive interactions between surface water and groundwater that have been observed at Pebble. The modeling is also overly parameterized and the parameters used are not always true to observed data. Thus while the calibrations demonstrate a reasonable agreement with observations, it is not clear that the model represents the physical system adequately for impact analysis. |
| Primary data gaps | There are limited data available on winter flows in all of the streams, and the precipitation gages appear to be "missing" between 25% and 40% of all rain and snowfall. These are both important components of the site water balance, and represent data gaps that should be filled. Extreme events are also not well-characterized, since the period of record reported in the EBD is less than four years long. |
| Principal findings and recommendations | The baseline hydrologic information reported in the EBD represents the foundation on which all future modeling and impact analysis will be undertaken. Based on the information presented in the EBD, the water balance model is insufficient; the period of monitoring is too short to characterize hydrologic extremes; there are numerous instances where model parameters conflict with field-measured values; and the modeling frameworks currently being used are inadequate for describing the system. These shortcomings indicate that PLP's current understanding of the baseline hydrology is inadequate to evaluate the short-term or long-term impacts of large-scale mining on the hydrology of this ecologically sensitive area. Substantial additional work is required to fill existing gaps in the baseline hydrologic data, and to develop an integrated groundwater-surface water model that is capable of simulating both baseline and future conditions. |

## Introduction

Any open pit or underground mine design for extracting the Pebble ore would require large-scale dewatering and discharge operations that would redistribute flows both spatially and temporally. In addition, surface impoundments required to store tailings and waste rock will necessarily limit infiltration to groundwater over their footprint. Quantifying the impacts of these changes to the hydrologic system on streamflow and salmonid spawning and rearing will be an essential part of mine development. PLP must therefore demonstrate that their understanding of baseline site hydrology (including spatial and temporal variability) is robust enough to reliably predict deviations from baseline conditions caused by mining.

This review summarizes and critiques the information presented in Chapters 7 and 8 of the EBD released by PLP in 2011 (PLP, 2011a, 2011b). Chapter 7 summarizes the surface water hydrology of the Bristol Bay watersheds. My review of Chapter 7 focused primarily on the main text, Appendix 7.2A (Hydrologic Analysis), Appendix 7.2B (Low Flow Analysis), and Appendix 7.2C (Peak Flow Analysis). Chapter 8 of the EBD summarizes the groundwater hydrology of the site, and my review of Chapter 8 focused primarily on the main text, Appendix 8.1I (Water Balance Model), and Appendix 8.1J (Groundwater Model). The other appendices in these chapters contain supporting information such as hydraulic testing results, borehole logs, interpretive cross-sections, and groundwater elevation and gradient data.

The review contained herein is necessarily limited in its scope: collectively, Chapters 7–8 and their 21 appendices constitute nearly 3,500 pages of information. As a result, the review focuses on data, model inputs and outputs, and interpretations in the EBD that raise the most significant issues for the development of a baseline site conceptual model. In particular, these issues are:

- The water balance is insufficient: inputs and outputs to the hydrologic system are not balanced based on measured data.
- The estimation of hydrologic extremes is based on a period of monitoring that is too short to characterize natural variability.
- The numerical groundwater model is over-parameterized, and there are numerous instances where model parameters conflict with field-measured values.
- The modeling software used for the numerical groundwater model is inadequate for describing the interconnected groundwater-surface water system.

## Criteria for Evaluation

The criteria for evaluation of the EBD included three major components. First, I evaluated the degree to which the methods used for data collection and analysis followed standard practices. For example, I evaluated whether PLP used the proper instrumentation to collect their hydrologic data, and whether they used acceptable modeling tools and techniques to process these data. Second, I evaluated the completeness of the data. The analysis of data completeness focused on both the frequency and duration of monitoring and on the methods employed to fill any data gaps. Third, I evaluated the degree to which PLP's interpretations of the hydrologic data, where applicable, are consistent with the reported data.

## Evaluation and Implications

### *Acceptability of Methodologies*

Based on the level of review I was able to conduct, it appears that PLP used standard and acceptable methods to collect their hydrologic data. River stage was measured continuously at 26 stations using autonomous pressure transducers, and the data were converted to discharge using standard rating curve methods (e.g., Rantz, 1982). Groundwater depths were monitored monthly at over 200 locations and converted to elevations based on surveyed well casing elevations. Meteorological data were collected using autonomous weather stations, including NOAH II precipitation gages for measurement of rain and snowfall. All these data collection methods appear to be consistent with accepted methodologies (U.S. EPA, 2003).

The groundwater modeling described in the EBD was conducted using MODFLOW-SURFACT™. This model was calibrated to surface water and atmospheric inputs through a spreadsheet-based water balance model. MODFLOW-SURFACT™ is a widely accepted software package for simulating groundwater flow; however, there are two problems with the groundwater modeling in this instance. First, because the water balance outputs are the main calibration targets for the numerical groundwater model, the MODFLOW-SURFACT™ model is only as good as the water balance. As described below, the water balance has some important issues that must be addressed, which calls into question the numerical groundwater modeling interpretations in the EBD. And second, as noted multiple times throughout the EBD, groundwater and surface water are closely coupled at Pebble; water moves freely between surface and groundwater reservoirs in this area. Due to these extensive interactions, a code that more explicitly simulates groundwater-surface water interactions such as MODHMS® or MIKE-SHE® would have been more appropriate for this task. In fact, the developers of MODFLOW-SURFACT™ recommend a more integrated code for systems like Pebble that have extensive surface-groundwater interactions (HGL Software, 2012).[1]

1. The frequently asked question (FAQ) page for MODFLOW-SURFACT™ states: "MODFLOW-SURFACT™ / MODHMS® does incorporate interaction between the unsaturated zone and rivers and lakes; however, for a rigorous treatment of surface water-groundwater interactions the integrated surface water-groundwater code MODHMS® is recommended." Other codes, such as Mike-SHE®, also treat groundwater-surface water interactions more explicitly.

***Data Completeness***

From 2004 to the present, PLP has collected a large amount of hydrologic baseline data for the proposed Pebble project. These data include meteorological records, stream gaging records, boring log and water level data, hydraulic conductivity estimates using pumping and response tests, and seep flow data. The majority of these data were collected either continuously (e.g., meteorological and stream gaging records) or with sufficient frequency to capture inter- and intra-annual variability in hydrologic conditions (e.g., approximately monthly measurements of groundwater elevations and seep flows). Although the hydrologic data are generally complete, there are some important exceptions that limit PLP's ability to characterize baseline conditions in the Pebble watersheds. Three notable exceptions are described below.

First, although the hydrologic data have been collected from 2004 through at least 2011, the EBD only reports the data collected through 2007. This limits PLP's ability to characterize peak flows and low flows, since the uncertainty associated with estimating the magnitude of extreme hydrologic events decreases as the duration of monitoring increases. As an example, using a 10-year flood record rather than a 5-year record will cut the uncertainty on the 100-year peak flood estimation roughly in half (Dunne and Leopold, 1978). With only three complete years of monitoring reported in the EBD, the interpretations of the hydrologic system are correspondingly limited, and PLP's analyses of peak flows and low flows presented in Chapter 7 (Appendix 7.2C–D) have extremely large uncertainties. Any mine water management infrastructure must be designed to withstand extreme events, and the design criteria must rely on an adequate description of what these events might look like in the future. Mischaracterizing these extremes could therefore result in flooding of infrastructure, impoundment overflows, or unanticipated erosion. Reducing uncertainties in these estimates should have been a goal of the EBD, and including the hydrologic data collected since 2007 would have reduced these uncertainties.

Second, none of the PLP stream gages collected measurements during the winter because the rating curves developed for stream gaging could not be used for flow beneath ice (Chapter 7, p. 14). Instead, the winter flows at the PLP gages are all calculated by scaling the U.S. Geological Survey gage measurements from lower in the catchments to the contributing drainage area at each gage. Using these simple scaled flows, the EBD suggests a complete understanding of winter flows that cannot be supported by the data:

> The lowest monthly flows, and the most prolonged periods of low flows, always occurred in the late winter (February through April) at all stations and in all years of the study period. (Chapter 7, p. 16)

While scaling discharge to drainage area is a generally acceptable method for estimating flows in ungaged headwater catchments, this methodology creates a substantial data gap in the coupled groundwater-surface water system at Pebble because flows in gaining and losing reaches along these streams cannot be estimated with these simple scaling relationships. Since the majority of the streams are ungaged during the winter, there is in fact significant uncertainty surrounding the magnitude of winter flows, and in particular where and when the headwater streams might become dry during the winter (if they go dry at all). This distinction could be critical for characterizing salmonid habitat under baseline conditions, and for understanding the impacts to this habitat under a mining scenario.

Third, although the meteorological data were collected continuously, the water balance model indicates that the measured precipitation may underestimate total precipitation by 25% to 40% (or alternatively, the stream gaging records overestimate discharge by a similar amount; see below). For example, the precipitation applied to the water balance for the SK119A catchment is nearly 40% higher than the highest precipitation observed at the Pebble 1 meteorological station (54.5 in. vs. 39 in.), even though these two locations are at nearly the same elevation and relatively close to one another. This correction occurs despite the use of a NOAH II precipitation gage, which is designed to minimize undercatch of frozen precipitation and appears to do a good job of measuring winter precipitation at the site, based on comparisons with snow course data (Appendix 7.2D, p. 28). The fact that the water balance requires an additional 40% correction factor to the measured precipitation demonstrates that there may be a significant problem with the completeness of the precipitation records and the accuracy of the water balance (U.S. EPA, 2003). A mine plan that relies on these measured precipitation records as a basis for a site water balance will either be incorrect or have a very high uncertainty. Again, this degree of uncertainty may be too high for designing mine water management infrastructure, with the potential for inadequate water management planning as a result.

### *Significant Findings*

Chapter 8 of the EBD presents the water balance and numerical hydrologic models that PLP has developed to simulate baseline conditions at Pebble. These hydrologic models are presented in a way that gives the impression of a well-characterized hydrologic system. Monthly flows are well approximated by the water balance model, and spatial and temporal patterns of flow are matched by the numerical groundwater model (Figure 1). However, when the components of these models are examined in detail, it is questionable whether PLP actually has an adequate understanding of the hydrologic system. Examples of these shortcomings are described below.

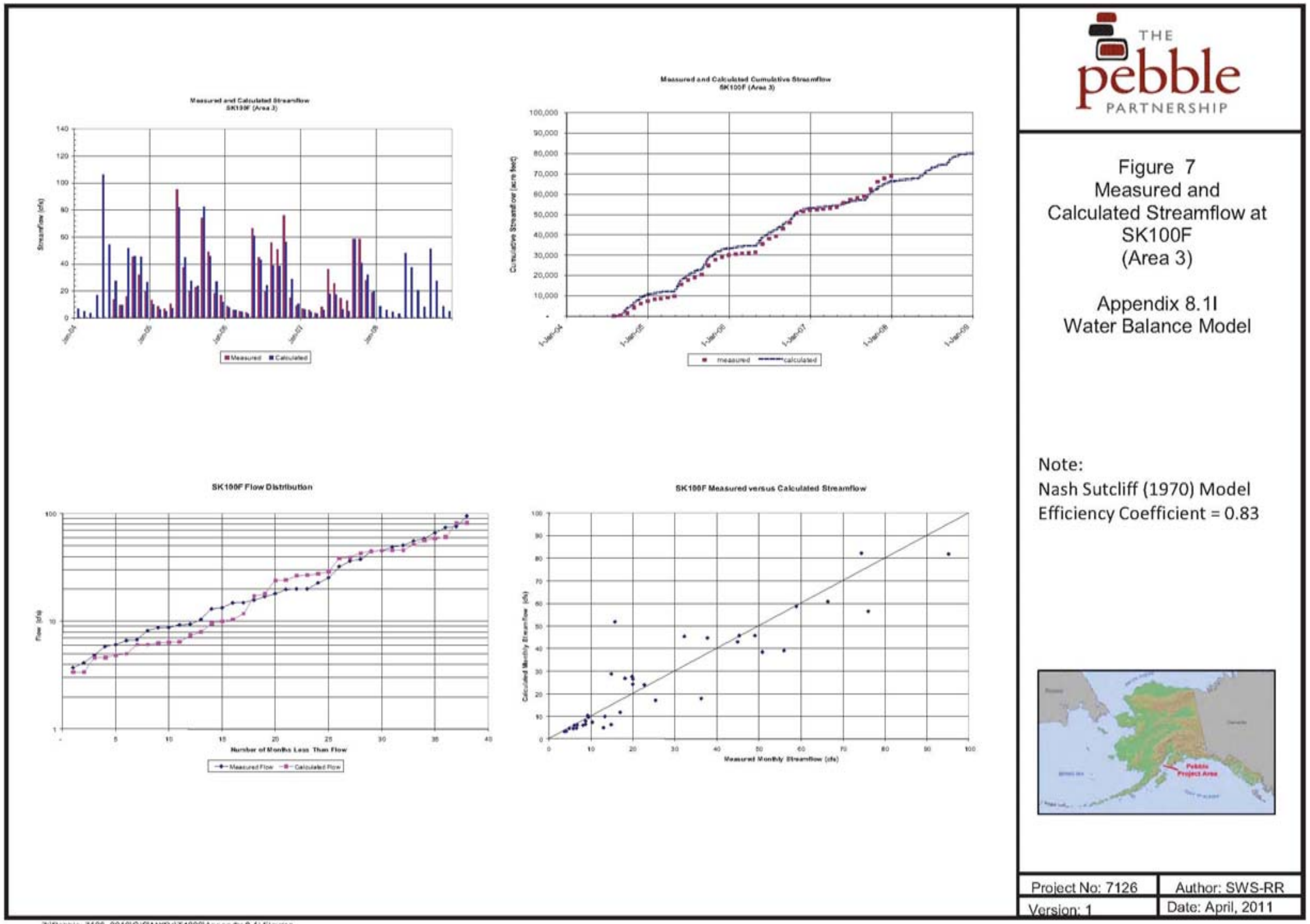


**Figure 1. Water balance results for SK100F.** Note that there is general correspondence between the water balance predicted and observed flows.

Source: PLP, 2011b.

## 1. Mismatch between measured precipitation and streamflow

Despite an extensive hydrologic data collection program, the only measured parameters used in the water balance are streamflow and groundwater elevations. All other variables are adjusted so that the remaining inputs and outputs to the hydrologic system match these parameters. From Chapter 8, page 26 of the EBD:

> The water balance was calibrated to the cumulative water volumes at selected stream gages by adjusting climate variables (precipitation and evapotranspiration). The estimated division of flow as immediate runoff, groundwater recharge, and groundwater discharge was then refined by adjusting the groundwater recharge and discharge rates to produce a match between estimated and measured monthly values of streamflows and groundwater levels.

Using this method, the modeled inputs and outputs to the hydrologic system are essentially guaranteed to balance, as presented in Appendix 8.1I. However, given the mismatch between *measured precipitation* and *measured streamflow* as described above, it is questionable whether this calibrated water balance paints a realistic picture of the hydrologic system. The water balance model requires between 40 and 55 in. per year of annual precipitation (an amount that varies by sub-catchment) in order to supply enough water to the system to match the measured streamflow. Yet the measured annual precipitation over the three years of monitoring is only 30–39 in. (EBD, Chapter 2). Thus, either the measured precipitation at the site is 25–40% too low or the measured streamflow at the site is 25–40% too high. It is nearly impossible to tell based on existing data which of these errors underlies the hydrologic imbalance at the site. However, given the magnitude of the discrepancy, it is clear that PLP must resolve this issue.

## 2. Calibration vs. validation

The second issue is that the calibration between the water balance and numerical groundwater models is circular. In other words, the two models are calibrated to one another, but there is no independent calibration to data, which means that it is possible that neither model is simulating the actual hydrologic system. This is evident from the first page of the numerical groundwater modeling appendix:

> The flow rates calculated by the calibrated Groundwater Model were then compared to the corresponding flow rates calculated with the Water Balance Model. The purpose of this phase of the calibration was to validate that the flows estimated by the Water Balance Model were hydrogeologically feasible, and to gain insights about potential refinements that may be appropriate for the Water Balance Model. (Appendix 8.1J, p. 1)

The remainder of Appendix 8.1J presents the results of the numerical groundwater model calibration, reporting statistics on goodness-of-fit, root-mean-square (RMS) errors, etc. However, these calibration statistics reflect the correspondence between the numerical groundwater model and a flawed water balance because *measured precipitation* is too low to explain *measured streamflow*, as described above. In addition, the numerical groundwater model is over-parameterized relative to the amount of data available. The model domain is broken into 644 hydraulic conductivity "zones," for which the hydraulic conductivity values used in the model have little to no relationship with field-measured conductivities. For example, Figure 2 is a plot of the hydraulic conductivity values used in the groundwater model vs. field-measured hydraulic conductivities. In general, the model values do not correspond at all to the field-measured values, indicating that the calibrated groundwater model ignores field-measured data.

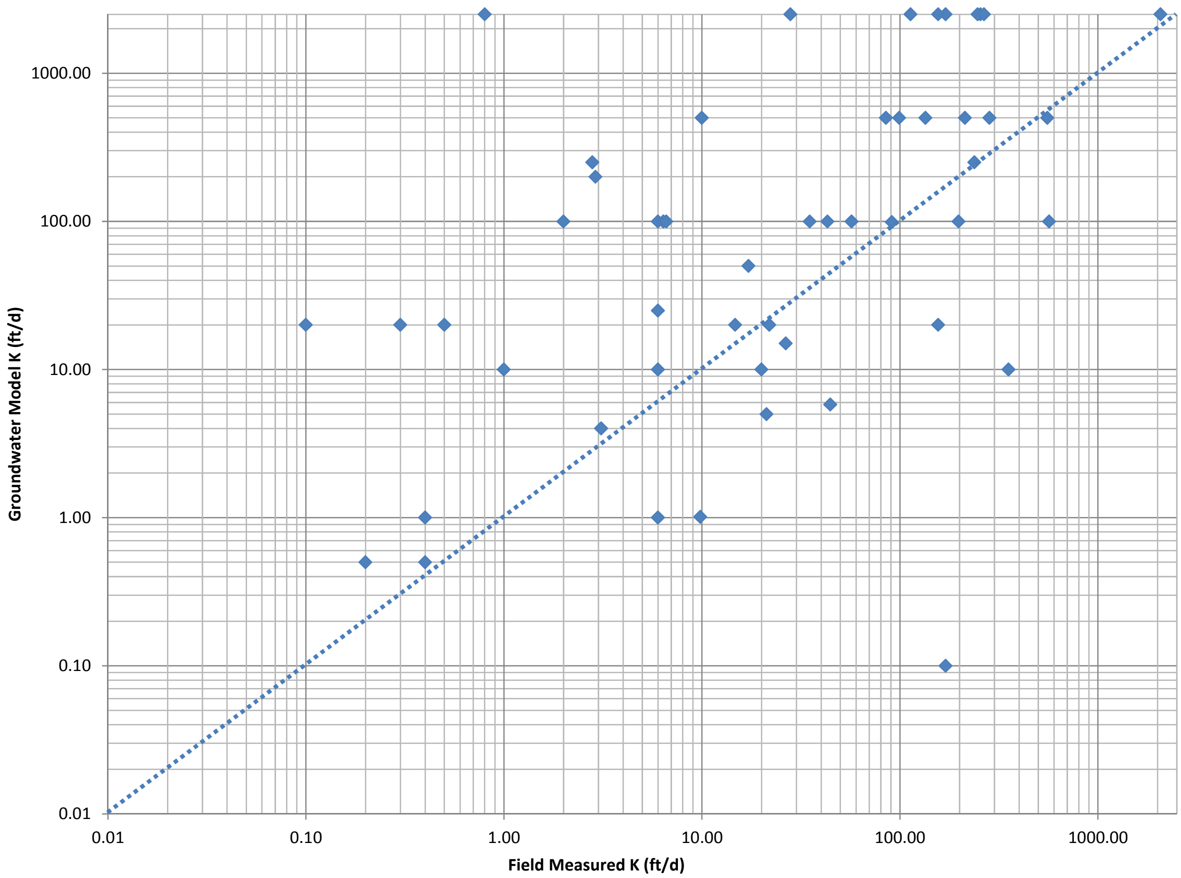


**Figure 2. Comparison of field-measured hydraulic conductivity values to values used in PLP's groundwater model.**

Data source: PLP, 2011b.

Thus, while the EBD presents a numerical model that appears to be well-calibrated, the number of parameters and the values required to achieve this calibration often have little relation to field-measured data. This could have significant implications when using this calibrated model to evaluate changes in hydrology related to mining. In particular, since the model inputs are not true to available site data, the model may have no predictive capability at all when used for impact analysis (U.S. EPA, 2003).

### 3. Influence of faults on groundwater flow

Third, the groundwater model does not incorporate the influence of faults on bedrock groundwater flow. The available data from tests in deep boreholes indicate that at least one of the major identified faults crossing the deposit area (the "ZE Fault") exerts a strong control on groundwater flow: hydraulic heads rise approximately 20 ft across this fault, which indicates that groundwater is under pressure beneath this fault zone (Figure 3). This fault and other deep bedrock faults that would be intersected by a pit are clearly influencing groundwater around the deposit area, and could be conduits for groundwater flow. This suggests that these faults could make it difficult to maintain a capture zone around the pit both during and after mining. As currently presented, the groundwater model makes no mention of faults at all, calling into question PLP's ability to predict the impacts of mining on groundwater. PLP must model the influence of major faults on groundwater flow, particularly near the pit where they could represent conduits for contamination to escape to downgradient surface water and groundwater resources.

### 4. Simulation of groundwater-surface water interactions

The hydrologic system at Pebble is not cleanly segmented into separate groundwater and surface water reservoirs, and should not be modeled as such. The software used by PLP (MODFLOW-SURFACT™) is a well-recognized program for simulating groundwater flow; but given the extensive interaction between groundwater and surface water at Pebble, a different modeling package would be more appropriate. For example, flow between surface water and groundwater in MODFLOW-SURFACT™ requires a "stream conductance" parameter, which controls the rate at which surface-groundwater exchange occurs across stream beds. In the PLP-calibrated MODFLOW-SURFACT™ model, the values of this stream conductance vary over approximately five orders of magnitude, but this parameter is completely unconstrained by field measurements. Other modeling packages that allow surface water-groundwater exchange to occur based on field-measured parameters could have been used, and this would make model results both better constrained by available data and more useful for predicting mining impacts.

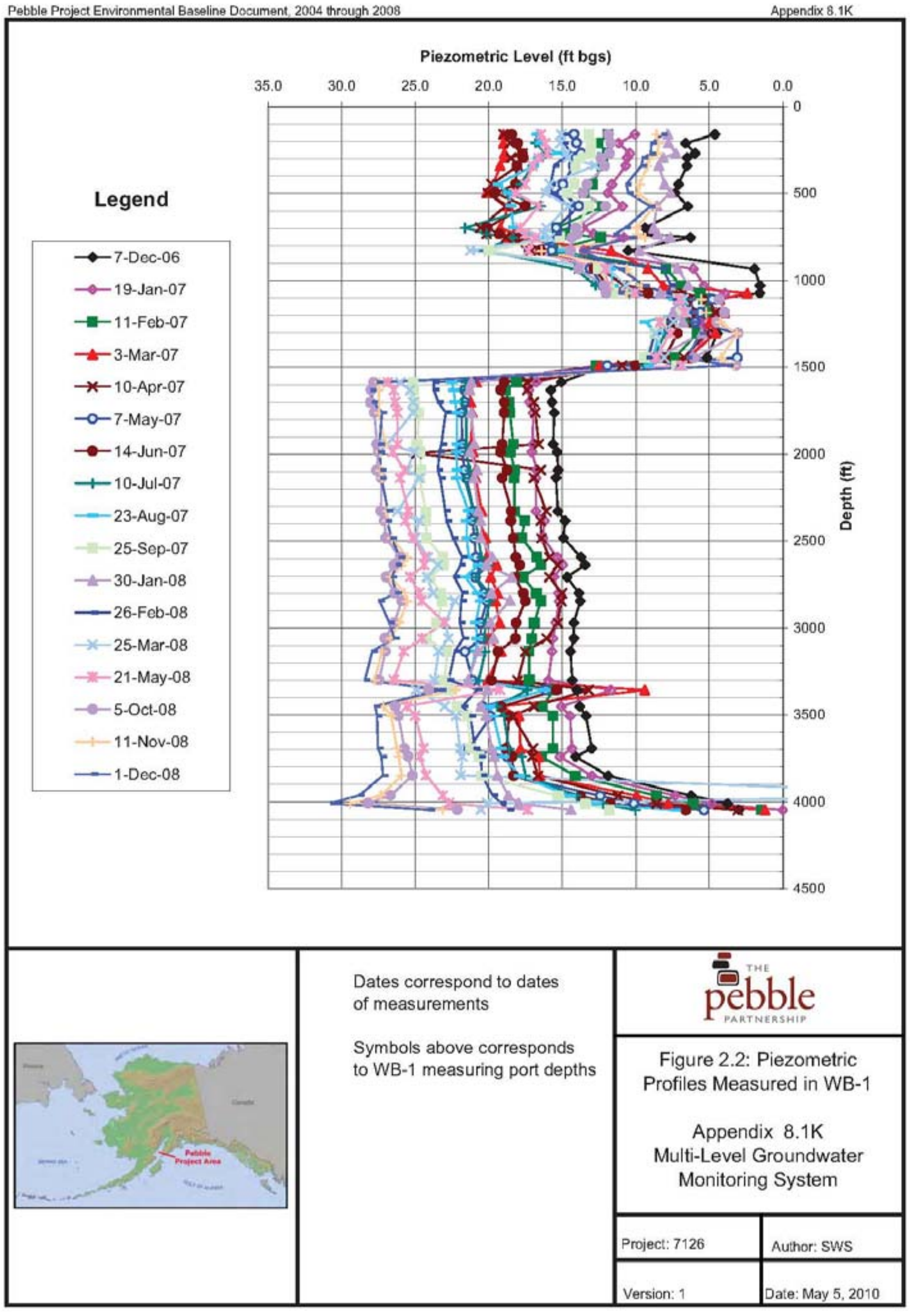


**Figure 3. Hydraulic heads (piezometric levels) measured across ZE fault.** Note significant change in head across the ZE fault (~ 1,500 ft), demonstrating the control of this fault on groundwater flow.

Source: PLP, 2011b.

## 5. Calibration period and hydrologic extremes

Even if the water balance and modeling issues described above were resolved, the hydrological modeling presented in the EBD is based on a calibration period of only three years, which is too short to characterize the range of extreme events that might be seen at Pebble over the mine lifetime. Even over this short model calibration period, the model begins to fall apart when stressed:

> Plots of residuals versus time (Appendix 8.1J) signify that the residuals at some wells start to increase during 2006 and 2007, which indicates that the model needs to be improved to simulate the conditions for these years in some areas (e.g., P05-07D, SRK-5M, and MW-3 in Upper SFK; MW-2D, GH04-30, and GH04-33 in Lower SFK; and MW-7 and MW-8 in NFK). (Chapter 8, p. 66/2500)

The years 2006 and 2007 were drier years than the earlier years of monitoring. The observation that head residuals increase with time indicates that while the numerical model may be adequately approximating the water balance during the early calibration period, it is not simulating conditions under hydrologically stressed conditions. This indicates that the modeling tools currently being used by PLP may also not be the right tools to simulate changes in hydrologic regimes under mining scenarios, or under a changing climate.

## Conclusions

As described in Chapters 7 and 8 of the EBD, the hydrologic system at Pebble is complex. It is characterized by spatially and seasonally variable interactions between surface water and groundwater, and by strong seasonal variability in precipitation and flows. Extraction of the Pebble ore body would require large-scale dewatering and discharge operations that would redistribute flows both spatially and temporally. Before PLP can evaluate the impacts of these mine-related dislocations on the hydrologic system, they will need an integrated set of data and models that adequately describes baseline conditions. Based on my review of the EBD, PLP does not yet have the tools to do this. While their baseline data are generally of high quality, there are a number of important data gaps that need to be filled. Equally important, the modeling results reported in the EBD suggest significant flaws in the conceptualization of the site water balance, groundwater-surface water interactions, and groundwater flow. All of these shortcomings must be corrected before PLP can model the potential impacts of the proposed Pebble mine operations on the hydrology of these watersheds and the fishery these waters sustain.

## References

Dunne, T. and L.B. Leopold. 1978. *Water in Environmental Planning*. W.H. Freeman and Company, San Francisco, CA.

HGL Software. 2012. Frequently Asked Questions about MODFLOW-SURFACT™ and MODHMS®. Available: http://www.hglsoftware.com/FAQ/MOD_FAQ.htm#Q11. Accessed 4/20/2012.

PLP. 2011a. Pebble Project Environmental Baseline Document 2004 through 2008. Chapter 7: Surface Water Hydrology, Bristol Bay Drainages. Pebble Limited Partnership.

PLP. 2011b. Pebble Project Environmental Baseline Document 2004 through 2008. Chapter 8: Groundwater Hydrology, Bristol Bay Drainages. Pebble Limited Partnership.

Rantz, S.E. 1982. Measurement and Computation of Streamflow. Vol. 1, Measurement of Stage and Discharge. Geological Survey Water-Supply Paper 2175.

U.S. EPA. 2003. EPA and Hardrock Mining: A Source Book for Industry in the Northwest and Alaska. Prepared by EPA Region 10 with the technical assistance of Science Applications International Corporation. January.