COMMENTS ON PEABODY WESTERN COAL COMPANY'S PERMIT RENEWAL FOR THE KAYENTA COAL MINE

Review of

2008 Cumulative Hydrologic Impact Assessment

2010 Probable Hydrologic Consequences

2011 Environmental Assessment

Peabody Groundwater Model

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October 2011

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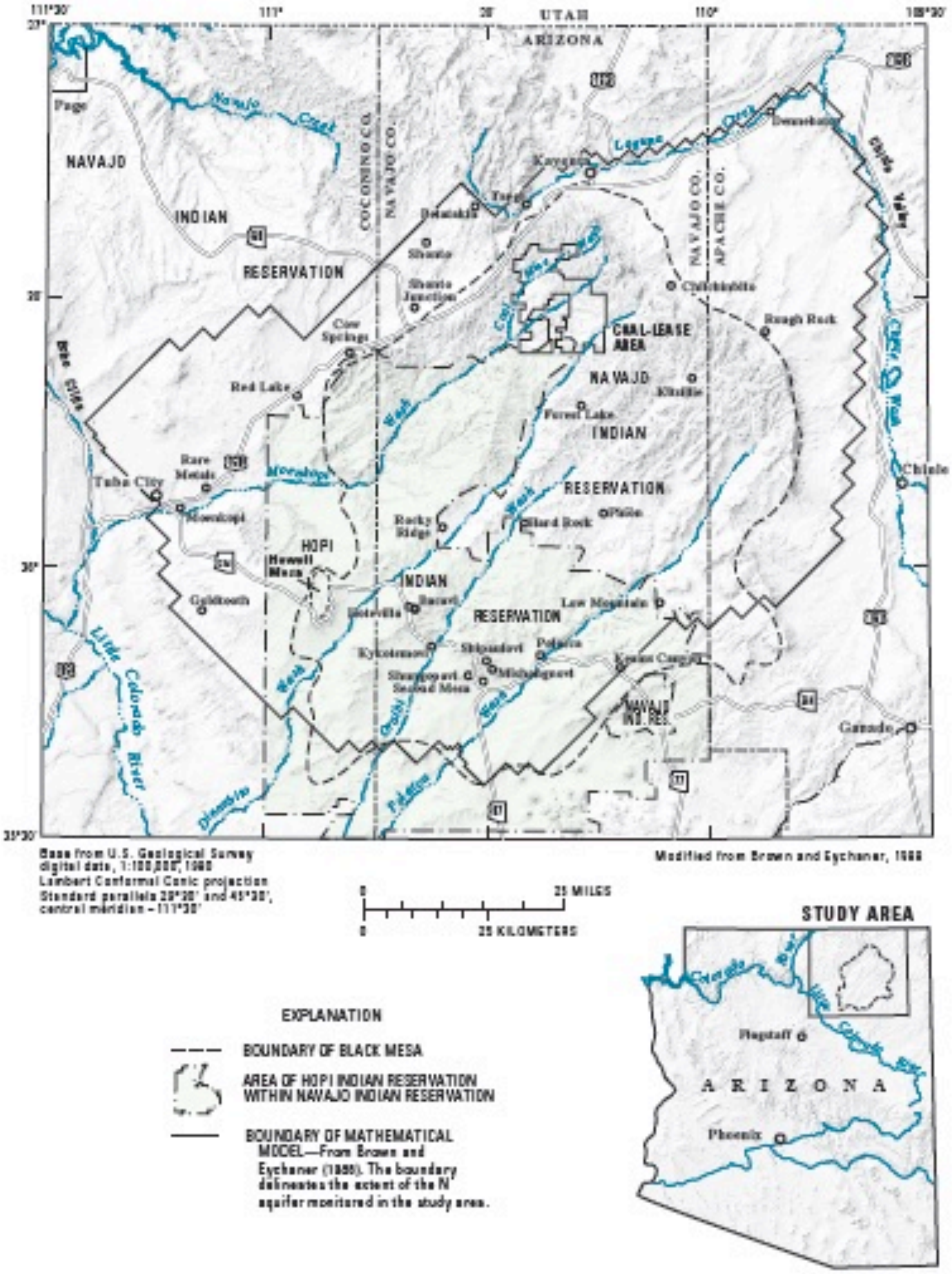
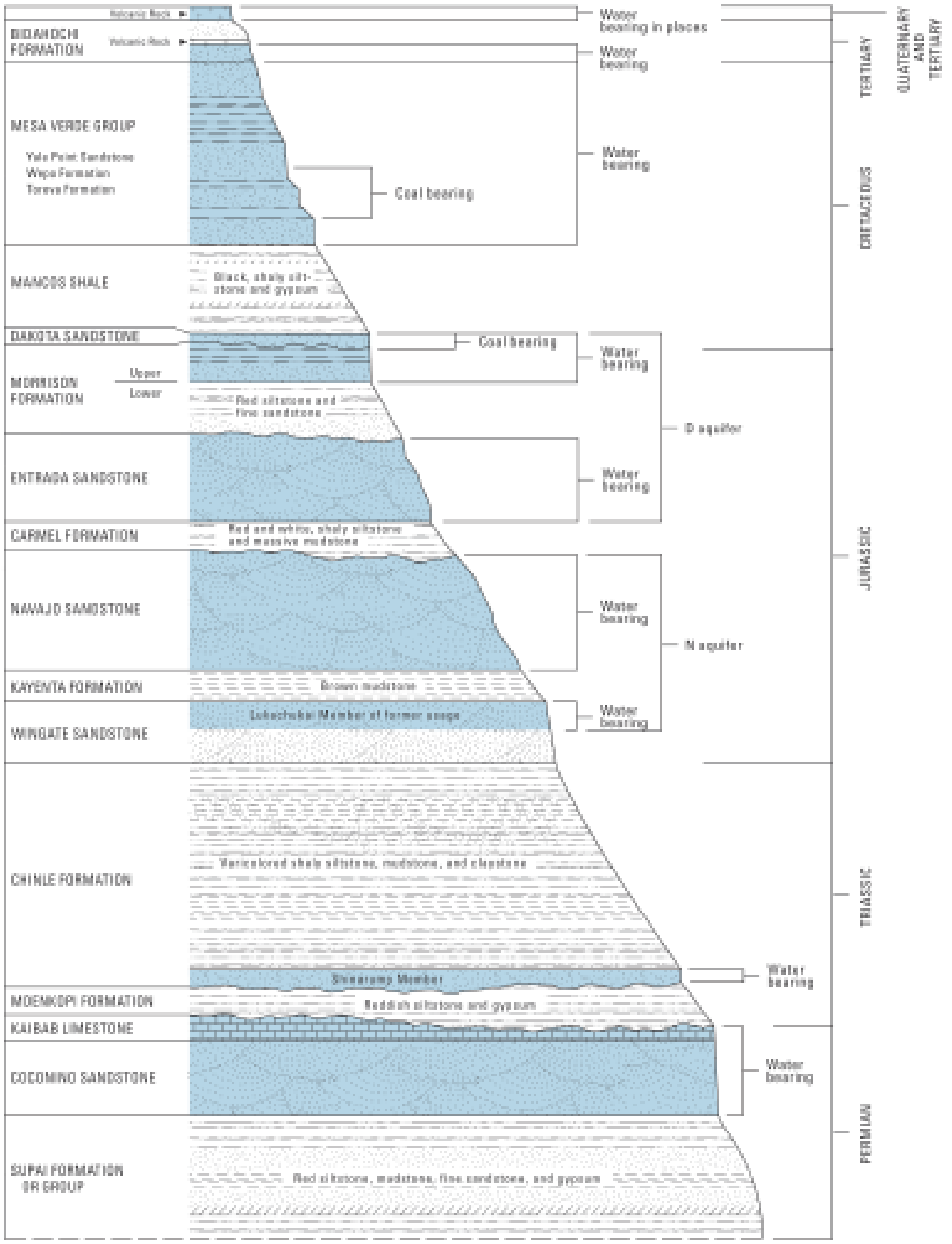
ACRONYMS & ABBREVIATIONS

CHIA	Cumulative Hydrologic Impact Assessment
EA	Environmental Assessment
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
OSM	Office of Surface Mining Reclamation and Enforcement
PAP	Permit Application Package
PHC	Probable Hydrologic Consequences
PWCC	Peabody Western Coal Company
USGS	United States Geological Survey



Map of Black Mesa (from Macy 2010).



Modified from Harshbarger and others, 1966

Rock formations and hydrogeologic units of the Black Mesa area (from Macy 2010).

INTRODUCTION

This report summarizes my evaluation of the policy-studies underlying Peabody Western Coal Company's permit-renewal process for its Kayenta Coal Mine at Black Mesa, Arizona. It includes Peabody's 2010 determination of *Probable Hydrologic Consequences* (PHC); Peabody's groundwater model of the N-aquifer; the Office of Surface Mining's (OSM) 2008 *Cumulative Hydrologic Impact Assessment* (CHIA); and OSM's 2011 *Environmental Assessment* (EA)[1].

Some of the analyses in this report were included in public comments that were submitted to OSM in July 2011. However, OSM did not acknowledge any of the findings in the prior report. Allen Klein, the Director of OSM's Western Region, responded on behalf of OSM's Director, Joseph Pizarchik, explaining:

> OSM has reviewed the report you provided and would like to offer the following clarifications. The documentation referenced for comment is several decades old, is based on predictions with limited data compared to the currently available data sets, and therefore is not appropriate for use given the availability of the current documentation. As new information develops, existing data sets are strengthened, and impact predictions are evaluated and modified as may be necessary. More specifically, the permit renewal application is supported by current hydrologic assessments associated with OSM's Cumulative Hydrologic Impact Assessment-CHIA (updated in 2008, with a 2011 update in process), PWCC's probable hydrologic consequences (PHC) document (updated/approved December 2010; a copy is enclosed for your information), the PWCC Groundwater Flow Model (completed in 1996, and validated in 2005 and again in 2011), and the above cited EA currently under development. (Klein 2011)

As the author of the report to which Mr. Klein is referring, I would like to respond to the rationale for dismissing its findings and concluding that it was "inappropriate for use" in OSM's decision-making responsibilities.

1) Asserting that the report was "based on [OSM's 1989 CHIA & 1990 EIS] predictions with limited data compared to the currently available data sets, and therefore is not appropriate for use given the availability of the current documentation" is tantamount to acknowledging that OSM's prior predictions were *not* accurate. Concurrently, it implies that OSM's new predictions in its 2008 CHIA and 2011 EA *are* accurate.

2) Following your rationale, if, over time, the *actual* groundwater conditions diverge from OSM's *predicted* conditions (provided in its 2008 CHIA and 2011 EA), then OSM

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[1] Prior to the release of the 2011 EA, OSM announced that its 2008 CHIA was being revised but would not be disseminated until after the EA's 30-day comment period. As such, OSM's 2011 CHIA revisions cannot be included in this study.

will, at that future time, also have an improved data set (e.g., "x" more years of monitoring data, refinements in the groundwater model, or improvements in the model's software platform), and may, as a consequence of this logic, dismiss the inaccuracy of its predictions and circumvent responsibility for impacts that result from its erroneous predictions.

3) Integrity is suspect when "experts" in science and technology implore the veracity of their methods and then, at a future point in time, ignore their errors when they are revealed (while imploring the veracity of their *new* methods). While the irrational circularity of such reasoning should be self-evident, it should be especially more so for decision-makers who are charged with protecting the *natural capital* of those who depend on local resources for their livelihoods and cultural continuity.

4) In order to accurately model and predict the future conditions of a large-scale aquifer, the modeler must have (1) accurate and complete field data (which are always incomplete), and accurate knowledge of future stressors (which will always be unobtainable; see Walker and Salt 2006; Oreskes 2003, 1998; Gunderson and Holling 2002; Westley et al. 2002; Oreskes et al. 1994).

5) The statement "As new information develops, existing data sets are strengthened, and impact predictions are evaluated and modified as may be necessary" expresses numerous contradictions. Throughout OSM's history of oversight at the Black Mesa-Kayenta complex, at no time has the agency acknowledged any insufficiency in data that limited the certainty of its predictions at the time the predictions were made. To the contrary, OSM has consistently argued for the comprehensiveness of its data sets and accuracy of its predictions. For example, in 1990, OSM stated:

> "Because the N-aquifer system is the main source of domestic, industrial, and agricultural water in the study area, OSM undertook extensive analysis to determine the potential impacts of mining on the N-aquifer system. This involved assembling a comprehensive inventory of wells and springs within and surrounding the study area (Chapter III, section C) and accounting for this water use in assessing hydrologic impacts. In addition, extensive input was received by the Hopi and Navajo Tribes and PCC regarding future mine and community use of water from the N-aquifer… To Consider the cumulative impacts of "all anticipated mining," past, present, and future conditions of the N-aquifer were simulated from 1965 steady-state conditions. The magnitude of impacts to the N-aquifer was determined by considering (1) the total drawdown of the proposed mining from 1985 through the life of the mine; (2) recovery time of the aquifer; and (3) the amount of drawdown that can be attributed to mine-related pumping versus community pumping. In addition to these considerations, OSM also applied the material damage criteria developed in consultation with both tribes, BIA, USGS, and PCC. These criteria are defined in section 5.2 of the CHIA" (OSM-EIS 1990: IV-24).

OSM's 1989 CHIA established four *material damage* criteria "as a means of keeping the big picture of hydrologic impacts before the regulatory authority at all times, so that if the accumulated impacts reach potentially damaging magnitudes, they can be dealt with in a timely manner" (OSM 1985), and in 1990, the Director of OSM explicitly stated that, "The conclusions in the EIS and in the CHIA regarding impacts on the N-aquifer are technically valid" (Snyder 1990). More recently, OSM's most recent annual report on the N-aquifer and its 2008 CHIA implore that *there have been and will be no mine-related impacts on the N-aquifer* (OSM 2006 and OSM-CHIA 2008).

And yet, in nearly 23 years since OSM's CHIA criteria were established, two of its material damage thresholds have been crossed (structural stability and discharge from springs), two have never been evaluated with the methodology OSM originally designed (water quality and discharge to streams), and the predictions in OSM's 1990 EIS have proven to be remarkably inaccurate[2].

Because the groundwater monitoring data have expressed declining trends over time (and are part of "the currently available data sets"), OSM's knowledge of N-aquifer dynamics should have been enhanced by this information (i.e. the "existing data sets are strengthened…") and OSM should have become increasingly aware of the potential errors in its conceptual model and of the mine's influence on the N-aquifer.

However, despite the declining trends in the monitoring data, and despite the evidence of mine-related impacts in prior public comments (July 2011), OSM maintains that all declining trends are the result of either tribal community withdrawals or recent drought conditions (see OSM-CHIA 1989; OSM-EIS 1990; OSM 1998, 2000, 2004, 2005, 2006; OSM-CHIA 2008; OSM-EA 2011). The agency has never modified its predictions ("as may be necessary") to increase its protection of the N-aquifer from potential mining-impacts. To the contrary, in 2008 OSM eliminated all of the material damage criteria for the specific mine-related impacts identified in the public comments.

6) The only "data set" that supports OSM's conclusions are the simulations of Peabody's groundwater model.

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[2] For example, one prediction in OSM's 1990 EIS stated that the closest that the potentiometric surface (i.e. head) would come to the top of the N-aquifer would be 366 feet at Keams Canyon in 2052 (OSM-EIS 1990, chapter IV). However, by 2005, a Kayenta well (BM3) was approximately 4 feet below the top of the N-aquifer, thus OSM's prediction was off by nearly fifty years, approximately 370 feet, and exceeded the material damage criterion for structural stability by nearly 104 feet. This report includes an empirical demonstration of the mine's influence at Kayenta which is so strong that it skews any evidence of local municipal withdrawals at that location.

The following sections in this report will summarize my assessment of the policy studies underlying Peabody Western Coal Company's application for a permit renewal for its Kayenta Coal Mine at Black Mesa, Arizona. The policy studies include:

i. 2008 Cumulative Hydrologic Impact Assessment (CHIA) performed by OSM (OSM-CHIA 2008)
ii. 2010 Probable Hydrologic Consequences (PHC) performed by Peabody (PWCC-PHC 2010)
iii. 2011 Environmental Assessment (EA) performed by OSM (OSM-EA 2011)

Because these documents derived all of their predictions from Peabody's groundwater model, and because this model has been updated with monitoring data and represents "the currently available data sets", this report will include an evaluation of the Peabody model's conceptualization of the N-aquifer, methodological approach, water-budget parameter values, data sources, assumptions, calibration and validation, and simulation results.

OSM'S ORIGINAL STANDARDS FOR MINING IMPACTS: THE 1989 CHIA

In 1985, Peabody Western Coal Company submitted an application to the Office of Surface Mining Reclamation and Enforcement (OSM) seeking a permit renewal for its Black Mesa-Kayenta Coal Mine at Black Mesa, Arizona (in operation since 1968). As required by federal statute, the application included Peabody's determination of *probable hydrologic consequences* (PHC) that would result from its proposed mining actions (PWCC-PHC 1985; OSM 1985). Subsequently, Peabody's PHC provided "the main source of input for the development of the *cumulative hydrologic impact assessment*" to be developed by OSM (OSM 2002). According to OSM, the CHIA is intended to keep "the big picture of hydrologic impacts before the regulatory authority at all times, so that if the accumulated impacts reach potentially damaging magnitudes, they can be dealt with in a timely manner" (OSM 1985).

Using OSM's CHIA standards for evaluating potential *material damage*, the agency can deny or delay permitting if the mine has, is, or may cause adverse impacts to the region's water resources; if impacts occur subsequent to permitting, mining activities can be temporarily or permanently ceased (OSM-CHIA 2008; OSM 2002, 1985).

In 1989, OSM produced the *Cumulative Hydrologic Impact Assessment of the Peabody Coal Company Black Mesa / Kayenta Mine* and concluded that the mine's impact on Black Mesa's water resources would be negligible:

> Impacts associated with the proposed operation and all anticipated mining were identified but none of the projected impacts exceed material damage criteria. Therefore, OSMRE makes the finding that there will be no material damage to the hydrologic balance associated with the proposed operation and all anticipated mining. (OSM-CHIA 1989: 1)

The rest of this section provides a brief summary of the key definitions, cumulative impact areas, and material damage criteria—as defined by OSM in its 1989 CHIA—that would provide the standards for OSM's regulatory oversight responsibilities in protecting Black Mesa's hydrologic resources from adverse impacts caused by mining actions.

1989 DEFINITIONS

- ***Material damage***[3]: "changes to the hydrologic balance caused by surface mining and reclamation operations to the extent that these changes would significantly affect

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[3] OSM highlights three caveats related to the material damage criteria: (1) a "measurable change" exceeding the threshold level does not necessarily indicate material damage; (2) a measurable change does not necessarily require any alteration of mining activities because the "total magnitude or persistence of the change must be considered in determining the significance of these impacts"; and (3) "…because simulated water levels before 1965 were on average of 28 ft different from observed water levels, the simulated water levels should not be expected to be closer than 50 ft to the actual water level at any location" (OSM-CHIA 1989: 6-20).

present and potential uses as designated by the regulatory authority" (OSM-CHIA 1989: 2).

- ***Hydrologic balance***: "the relationship between the quality and quantity of water inflow to, water outflow from, and water storage in a hydrologic unit such as a drainage basin, aquifer, soil zone, lake, or reservoir. It encompasses the dynamic relationships among precipitation, run-off, evaporation, and change in ground and surface water storage" (OSM-CHIA 1989, 5-1).
- ***Hydrologic impact:*** "a measurable change in hydrologic parameters" (OSM quoting the definition in OSM 1985: 2).
- ***Measurable change***: "Only parameter value changes that are larger than the measurement error can be considered as "true" or "measurable" changes, because changes that are smaller than the measurement error may be primarily due to measurement procedures rather than to an actual change in the discharge parameter[4]. It follows that a projected change in a parameter that is smaller than the measurement error is not a hydrologic impact. Therefore mining operations causing unmeasurable changes can be excluded from consideration as part of the CIA" (OSM-CHIA 1989).

1989 CUMULATIVE IMPACT AREA

- ***Groundwater CIA***: the entire 4,800 mi^2 of the Black Mesa and Blanding Hydrologic Basins.
- ***Surface-Water CIA***: 3,800 mi^2 draining Moenkopi & Dinnebito Washes (impounding 6,000 acre-ft. over 70 mi^2)

1989 MATERIAL DAMAGE CRITERIA

Section 5.2.2 of the 1989 CHIA outlines four criteria for determining if *material damage* to the N-aquifer has occurred as a result of mining activities. They were designed to limit adverse changes in groundwater quantity and quality that could (1) cause economic loss to existing or potential agricultural or livestock interests; (2) degrade domestic supply; (3) cause structural damage to the aquifer; and (4) degrade existing biological communities (OSM-CHIA 1989).

Thus, OSM designated that it would determine that material damage[5] to the N-aquifer had occurred if any of the following threshold-criteria were crossed:

- ***Structural Stability*** (water quantity)[6]: if the potentiometric surface falls below 100 feet above the confined N-aquifer;

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[4] Although this definition is for any "measurable change" within the material damage criteria, OSM explicitly discerns the "discharge parameter" in its definition. Coincidentally, future discharge measurements would become the subject of conflict between competing stakeholders on Black Mesa.

[5] If OSM concluded that any particular trend had been caused by a source unrelated to mining, then material damage *caused by mining* has not occurred (OSM-CHIA 1989).

- ***Water Quality***: if a value of leakage from the overlying D-aquifer into the N-aquifer exceeds 10%;
- ***Springs:*** if a reduction in N-aquifer spring discharge exceeds 10%;
- ***Streams***: if a reduction in N-aquifer discharge to the alluvium exceeds 10%.

STATISTICAL INDICATORS OF MINE-RELATED IMPACTS

This section summarizes two analyses that were included in the comments submitted to OSM in July 2011. They are included here (1) because OSM has not acknowledged them; (2) to demonstrate statistical indicators of the mine's impact on water-levels and spring discharge; (3) to review the current monitoring data; and (4) to examine the manner in which OSM has "evaluated and modified" its predictions and conclusions "as may be necessary" as new information has accumulated since 1985.

Keeping in mind OSM's original standards (from the prior section) and the following analyses in this section, the subsequent section (*THE 2008 CHIA*) will demonstrate that by changing its basic definitions, revising the cumulative impact area-boundaries, and implementing entirely new material damage criteria, OSM has eliminated the following impacts from its future evaluation of mine-related impacts.

KAYENTA: WATER LEVEL DECLINE

Recall that OSM's *material damage* threshold for structural stability of the N-aquifer is potentiometric surface (head) falling below 100 ft. above the top of the confined aquifer (OSM-CHIA 1989). In 1990, OSM concluded:

> "For there to be a reduction in well production or for structural damage to occur… the potentiometric surface would have to be drawn down to below the top of the confined portion of the aquifer… It can be seen that at no time does the potentiometric surface drop to this level anywhere within the affected area for any scenario. The closest the potentiometric surface gets to the top of the confined aquifer for [the proposed mining plan] is 366 feet at Keams Canyon in the year 2052." (OSM-EIS 1990: IV-28)

Recall also that by 2005, the water-level in Kayenta (well #BM3) was approximately 6 feet below the top of the aquifer (i.e. OSM's damage threshold has been exceeded by 106 ft). Thus, the N-aquifer is no longer saturated at this location and is, theoretically, vulnerable to compaction (see Figure 1; it is also notable that the predicted amount of

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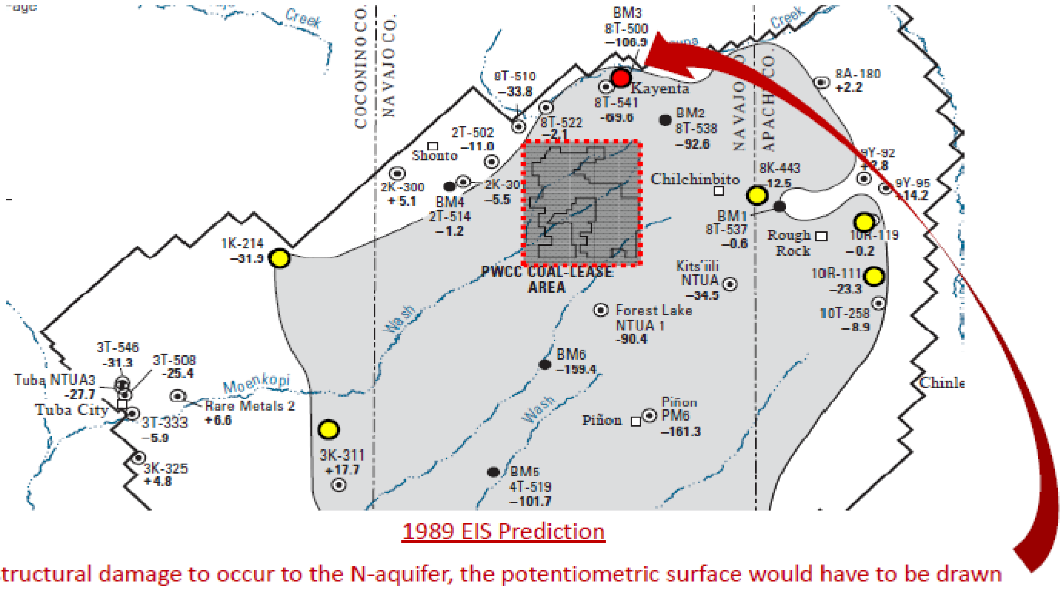
[6] At Any location where the N-aquifer is under confined conditions

water-level decline in OSM's 1990 EIS, quoted above, was inaccurate by approximately 370 feet and nearly fifty years).

However, in 1990 OSM had determined that the mine would cause 4% of the decline and municipal groundwater pumping (from the Kayenta well system) would cause 96% of the decline (see OSM-EIS 1990: IV-29).

In 1999, Peabody's hydrology consultants stated that Kayenta would cause 87% of the decline at Kayenta: "The effect of PWCC drawdown (as a percentage of total drawdown) at Kayenta is 13% in 2011… The drawdown at BM3 appears to be almost entirely related to local pumping at Kayenta and is similar in all scenarios" (HSIGeoTrans and WEHE 1999: 6-14, 6-16).

6 of 18 wells are below the 100 ft. OSM's "buffer" threshold,
1 of these 6 wells is <u>below</u> the top of the N-aquifer itself



<u>1989 EIS Prediction</u>

For structural damage to occur to the N-aquifer, the potentiometric surface would have to be drawn down to below the top of the confined portion of the aquifer… It can be seen that at no time does the potentiometric surface drop to this level anywhere within the affected area for any scenario.

(OSM-EIS 1990: IV-28)

Figure 1. Locations of the six wells exceeding OSM's 1989 threshold for material damage to structural stability. Wells below the 100-ft. buffer are in yellow; the well below the top of the N-aquifer at Kayenta (BM3) is in red (map and water-level data from Macy 2010, adapted by Higgins 2011; OSM's prediction data from OSM-CHIA 1989 and OSM-EIS 1990).

THE RELATIONSHIP KAYENTA'S WATER-LEVEL DECLINE & KAYENTA'S GROUNDWATER WITHDRAWALS

The public comments submitted to OSM in Jul y 2011 disproved the validity of OSM and Peabody's predictions by demonstrating that mine-related withdrawals had a far more significant influence on water-level decline at Kayenta than has been recognized or acknowledged (at least, OSM has not acknowledged them *publicly*).

The regression of the water levels in the Kayenta well BM3 and Kayenta's groundwater withdrawals expresses a weak linear relationship which is *not* statistically significant. However, this weak relationship is counterintuitive: as the rate of Kayenta's withdrawals increase, the water-level does not fall, it actually *rises* (Figure 2): r = 0.-44; $R^2 = 0.19$; $p = 0.05$.

It is hypothesized that the magnitude of Peabody's withdrawals simply skews any statistical indication of Kayenta's influence on well BM3 (see Figure 3). Or to clarify, it is hypothesized that Peabody's impact on the water-level at Kayenta is so strong that it hides any impact caused by Kayenta.

It is notable that the data point representing Kayenta's smallest volume of groundwater withdrawn in any single year (381 acre-feet in 2008; Figure 2, top chart, circled in blue) correlates with the BM3's largest water level decline (161.9 ft below land surface). Conversely, Kayenta's largest withdrawals (708 af in 1987 and 690 af in1988) correlate with the some of the well's highest water levels (131 and 135 ft. below land surface, respectively).

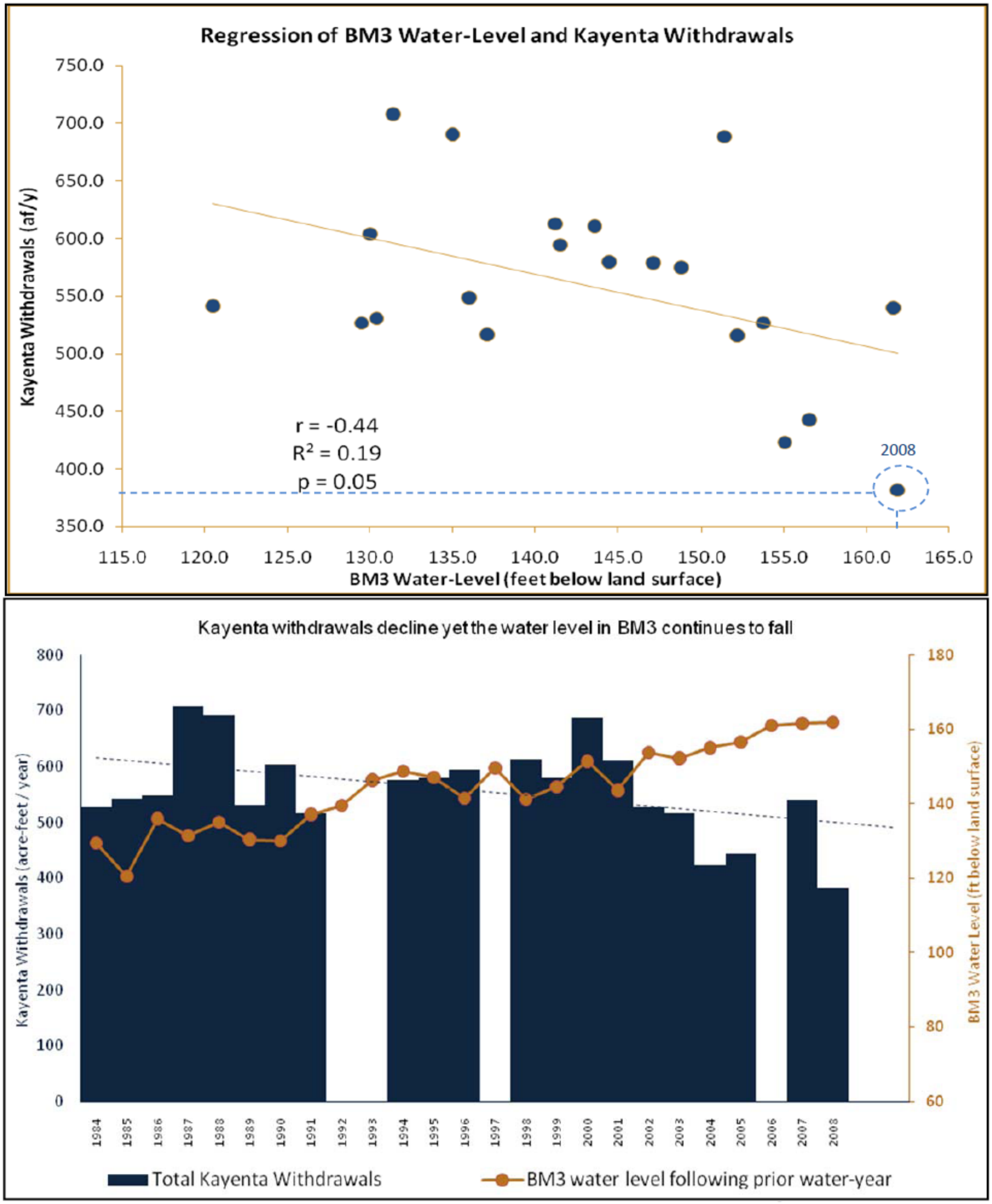


Figure 2: (Top graph) Regression of Kayenta's annual withdrawals and BM3's annual water-level, 1984-2008. (Bottom graph). Water levels (x-axis) are in *ft. below land surface*, so as the values increase, the water-level is falling. A temporal representation of the same withdrawal data for the same period. Withdrawal data are from the USGS monitoring reports (1984-2008), BM3 water-level data from BMMP (2011).

For the period of record (1984-2005), Peabody pumped approximately 7.2 times more groundwater each year than did Kayenta's municipal system (Figure 3; OSM-CHIA 2008, 1989; OSM-EIS 1990; the USGS monitoring reports provide data for withdrawals from the Kayenta well system beginning for water-year 1984; Peabody withdrawals were reduced by approximately 70% beginning in 2006 and are statistical outliers and thus are not included in this analysis; the statistical explanation of outliers is provided in *Appendix B*).

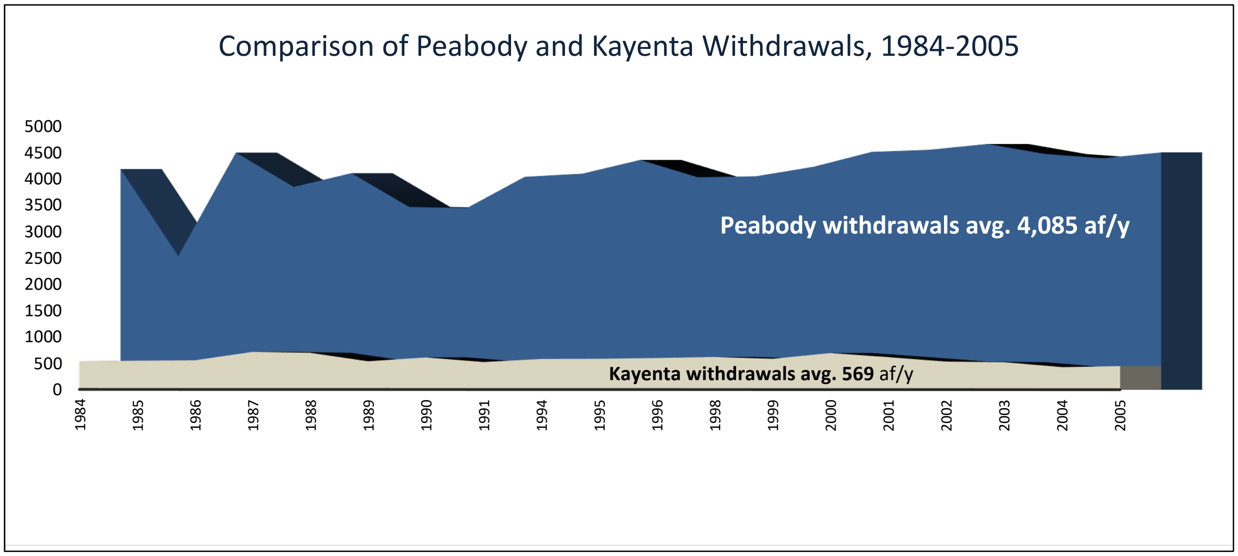


Figure 3. Comparison of Peabody's withdrawals from the N-aquifer to Kayenta's municipal withdrawals from the N-aquifer for the period 1984-2005. Withdrawal data are from Macy (2010).

RELATIONSHIP BETWEEN BM3 AND PEABODY WITHDRAWALS

Because the record for withdrawals from the Kayenta well system begins in 1984, the regression of BM3 water levels to Peabody withdrawals is performed for the same period (Figure 4, top graph). The regression conflicts with OSM's model-based conclusion: a relatively strong, statistically significant, linear relationship exists: as the volume of Peabody's withdrawals increase, the water-level in BM3 falls: $r = 0.75$; $R^2 = 0.56$; $p < 0.0001$.

Figure 4 (bottom graph) demonstrates this relationship temporally for the period (1984-2005).

Data for water-year 1985 (circled in red) is a strong indicator of the mine's influence on Kayenta's water level. Recall that, in 1985, Peabody ceased its groundwater withdrawals pipeline operations for six months due to maintenance at the Mohave Generating Station, withdrawing its smallest volume of in any single year (2,520 acre-feet). For the period that the Black Mesa-Kayenta Mine was fully operative (1972-2005), 1985 is a statistical outlier for Peabody withdrawals (see Figure 5, top box-plot).

For the period 1984-2005, 1985 expresses the *highest* water level in BM3 for any single year (120 ft. below land surface) correlating with Peabody's lowest volume of groundwater withdrawals.

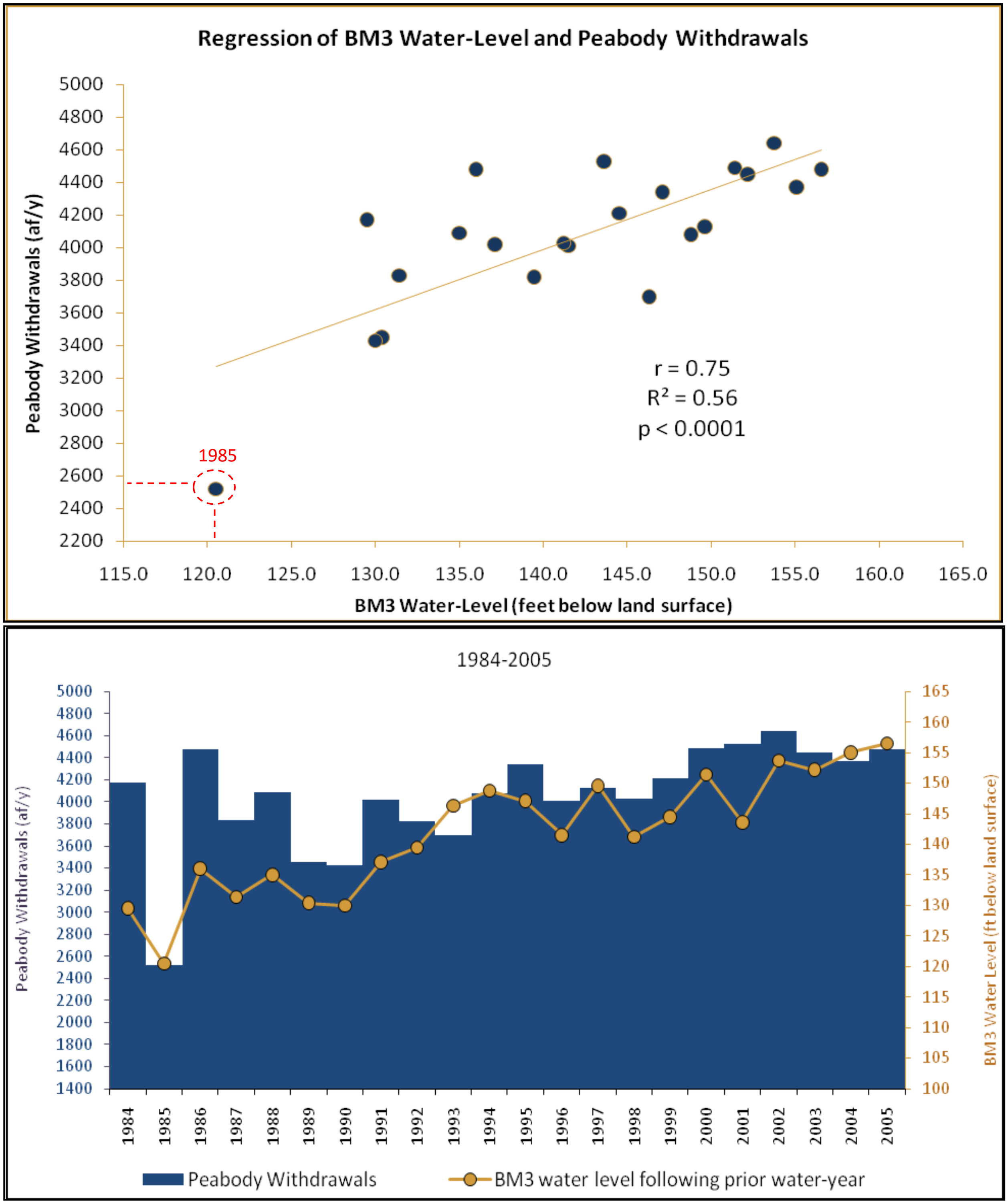


Figure 4. (Top graph) Regression of Peabody's annual withdrawals and BM3's annual water-level. (Bottom graph). Water levels (x-axis) are in *ft. below land surface*, so as the values increase, the water-level is falling. A temporal representation of the same withdrawal data for the period 1984-2005. Withdrawal data are from the USGS monitoring reports (1984-2005), BM3 water-level data from BMMP (2011).

INDICATORS USING BOX-PLOTS WITH OUTLIERS

The box-plot of Peabody withdrawals (Figure 5, top plot) demonstrates that water year 1985 (highlighted in red) is a statistical outlier for the period 1972-2005.

Concurrently, the box-plot of water levels in BM3 (middle plot) demonstrates that 1985 is the only year outside 2 standard deviations of the mean water level (1984-2008).

Finally, the box-plot for Kayenta's municipal withdrawals (bottom plot) shows that the community's withdrawals in 1985 is near the mean for withdrawals (1984-2008), and moreover, Kayenta withdrew only 381 acre-feet in 2008 (a statistical outlier for Kayenta's withdrawals) yet the water level in BM3 *fell* that year to its lowest level on record.

These relationships are inexplicable if Kayenta is causing 87% of the drawdown; rather, it seems plausible that mining withdrawals are responsible for this percentage of water-level decline at Kayenta.

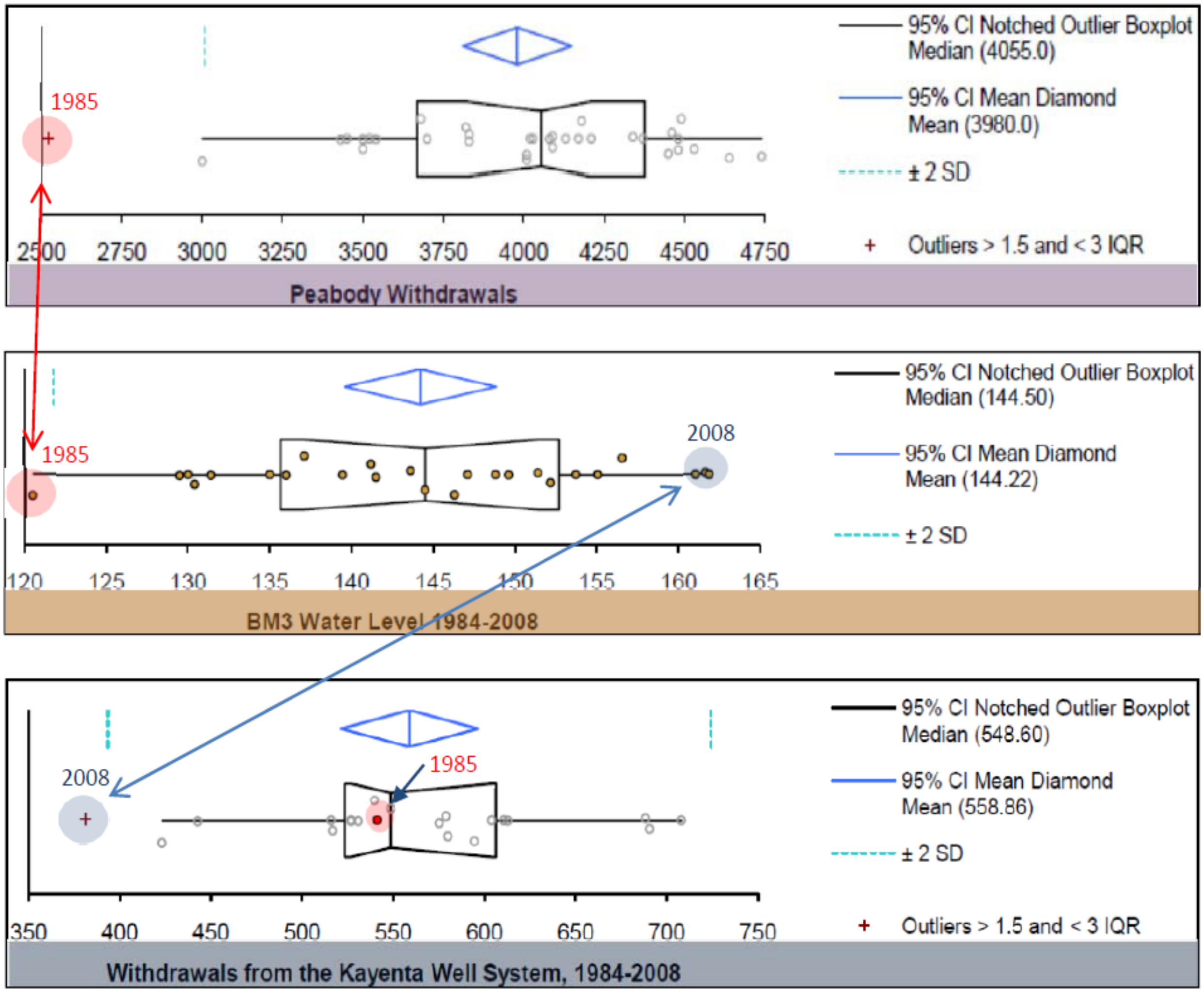


Figure 5. Boxplots for Peabody withdrawals, water-levels in Kayenta well BM3, and Kayenta withdrawals. Peabody withdrawal data from Macy (2010); BM3 water level data from BMMP (2010); Kayenta withdrawal data collected from the USGS monitoring reports for the period 1984-2010.

According to Peabody, the water-levels in wells influenced by *both* industrial and municipal withdrawals express greater annual variability (about 10-15 ft.) than wells influenced only by the mine (HIS GeoTrans & WEHE 1999: 4-14). This is can be seen when comparing the water-levels in two USGS observation wells in Figure 6 (below): well BM2 (hydrograph on the left) is southeast of Kayenta and is believed to be influenced by mining withdrawals only while well BM3 (hydrograph on the right) is in Kayenta and is believed to be influenced by both mining withdrawals and community withdrawals (the 10-15 ft. variability in BM3's water-level is apparent). Both wells are approximately the same distance from the center of the Peabody well field (Figure 7), and are approximately 7.5 miles apart from each other.

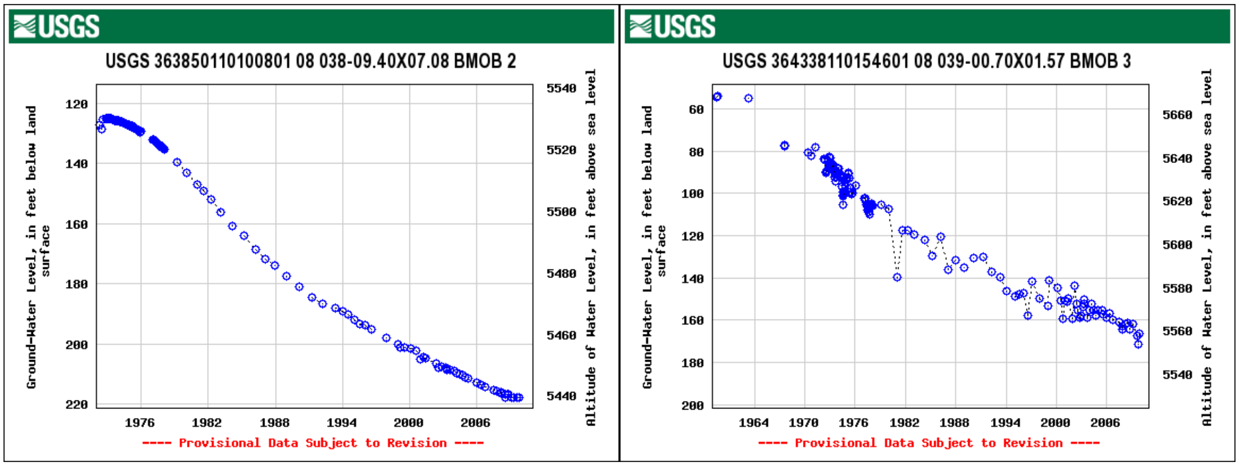


Figure 6. Groundwater-levels at BM2, left, and BM3, right (BMMP 2010).

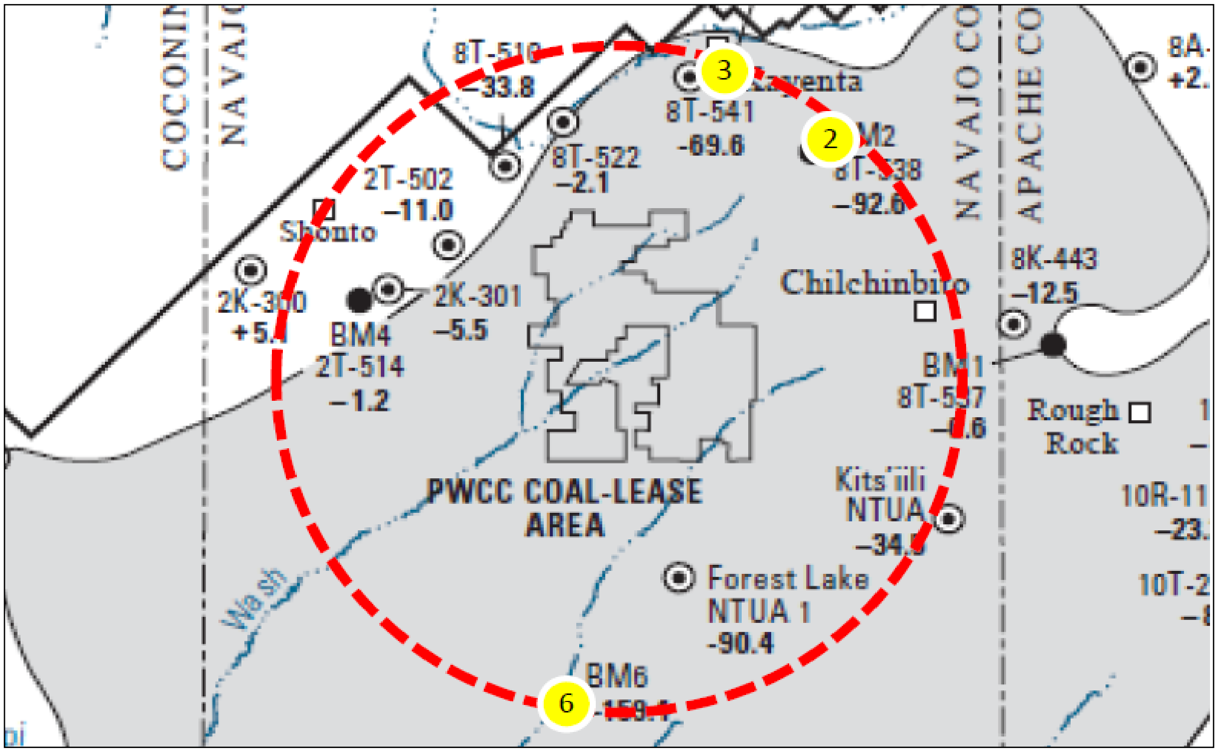


Figure 7. USGS observation well BM2 (#2) is southeast of Kayenta while BM3 (#3) is in Kayenta (map adapted from Macy 2010).

BM3 is located at Kayenta. To date, total decline in BM3 is 106.9 ft (Macy 2010).

BM2 is located southeast of Kayenta. To date, total decline is 92.6 ft (Macy 2010).

Thus, the water-level in BM3 is 14.3 ft. lower than the water level decline in BM2.

However, recall that the Peabody model determined that 87% of the water-level decline at BM3 is caused municipal withdrawals; the mine—which pumps 7.2 times more groundwater than Kayenta's municipal system and is approximately the same distance from both wells—causes only 13% of the decline (HSIGeoTrans & WEHE 1999; 6-14).

Yet, water level decline at BM3 is only 14.3 ft. greater than BM2.

Given the statistical demonstration of the mine's influence on BM3 (Figures 4 and 5: $r = 0.75$; $R^2 = 0.56$; $p < 0.0001$), and Kayenta's *lack* of influence on BM3 (Figure 2: r = 0.-44; $R^2 = 0.19$; $p = 0.05$), it is hypothesized that the 14 ft. difference in drawdown between BM2 and BM3 is simply the magnitude of the total impact from Kayenta's municipal withdrawals. If this is the case (OSM provides no empirical data that counter this hypothesis), then Kayenta's municipal withdrawals are accountable for 13.4% of the water-level decline in the area (14.3 ft. / 106.9 ft.) and the mine is accountable for 86.6% of the decline.

COMPARING DRAWDOWN IN WELLS BM3 & BM6

The Peabody model-report (1999) compares the water-levels of BM3 to BM6 (directly south of the Peabody well-field, Figure 7, above) for water year 1996:

> BM3 is nearly the same distance from the PWCC wells as BM6, yet has nearly 15 ft. greater drawdown. BM3's drawdown over time suggests a greater influence caused by local pumping, indicated by its greater annual fluctuation (i.e. 10-15 ft) than other BM wells, and by its already decreasing drawdown recorded prior to any PWCC pumping. (HSIGeoTrans and WEHE 1999: 4-14)

However, by 2005 (eleven years later) the water level in BM6 had fallen 161.7 ft, while BM3 (influenced by both industrial and municipal withdrawals) had fallen by only 103.6 ft. To clarify, the water-level in BM6—which is influenced ONLY by the mine's withdrawals—was 58.1 lower than BM3. Given Peabody's argument, the water-level decline in BM3 should far exceed that of BM6, while in actuality, BM6 far exceeds BM3.

OSM'S 2006 CONCLUSIONS

Since 1984, OSM, Peabody, and Peabody's hydrology consultants have consistently argued that "The drawdown at BM3 appears to be almost entirely related to local pumping at Kayenta" (HSIGeoTrans and WEHE 1999: 6-16). During this time, however, actual conditions diverged from this conclusion, yet in 2006 OSM remained steadfast that Kayenta was the primary source of drawdown in the area:

> "Approximately 423 acre-feet were withdrawn from the N-aquifer at this location by [the Kayenta well system] in 2004. The Kayenta municipal pumping currently accounts for 34% of all the non-industrial pumpage from the confined portion of the aquifer and approximately 15% of all municipal production from

> the N-aquifer (confined and unconfined). Therefore, lowering of potentiometric surface in the area near BM3 can be attributed to municipal use as well as PWCC pumping." (OSM 2006: 5)

While a significant stretch from its previous certainty, OSM seems to be implying that, in 2004, the magnitude of Kayenta's withdrawals (423 acre-feet) is profound because it accounts for 34% of the 1,240 acre-feet that comprised total tribal withdrawals. This implication lacks empirical logic (total municipal withdrawals are *distributed throughout the entire confined portion of the N-aquifer*) and, arguably, it lacks understanding of basic hydrogeological principles, for in 2004, Peabody withdrew 4,370 acre-feet from *one centralized location* in the confined N-aquifer – more than ten times the volume of Kayenta's 423 acre-feet.

To summarize, in 1985, Peabody's PHC concluded that 85% of the drawdown at Kayenta would be caused by municipal withdrawals (PCC-PHC 1985). In 1990, OSM concluded that 97% of this drawdown would be caused by municipal withdrawals (OSM-EIS 1990). In 1999, Peabody's consultants concluded that municipal withdrawals would cause 87% of this decline (HSIGeoTrans & WEHE 1999).

In 2006, OSM explained that the material damage criterion for structural stability "is subject to review and modification" in an upcoming report, but OSM it would continue to use this criterion for its evaluation of the N-aquifer's condition through 2005 (OSM 2006: 4). In 2005, the water-level in BM3 was *below the top of the N-aquifer* (Truini and Macy 2007), and OSM's material damage threshold for structural stability had been exceeded by more than 100 ft.

In 2006, OSM concluded that "material damage to the hydrologic balance of the N-aquifer, caused by mining, with respect to maintaining the potentiometric head above the top of the N-aquifer, has not occurred" (OSM 2006: 7).

OSM'S 2011 CONCLUSIONS

After this analysis was submitted to OSM in July 2011, OSM responded by explaining that because the analysis was an evaluation of a PHC, CHIA, and EIS that were performed between 1984 and 1990, its findings were not relevant given OSM's current, more comprehensive data set: "The documentation referenced for comment is several decades old, is based on predictions with limited data compared to the currently available data sets, and therefore is not appropriate for use given the availability of the current documentation. As new information develops, existing data sets are strengthened, and impact predictions are evaluated and modified as may be necessary." (Klein 2011)

However, for the subsequent period 1990 – 2011 (present), OSM has never departed from its conclusion that nearly 100% of the water-level decline at Kayenta is caused by Kayenta's municipal withdrawals. Rather, over time, OSM explicitly grows so certain of its conclusion that, in 2008, the agency eliminated structural stability from its material damage criteria (see OSM-CHIA 2008). To clarify, although there has never been good understanding of the hydrologic properties of the N-aquifer near Kayenta (USBR 1971), and despite the statistical strength of the previous analysis, and even though OSM reviewed this analysis in July-August 2011, OSM maintains that municipal withdrawals are the primary source of groundwater decline near Kayenta.

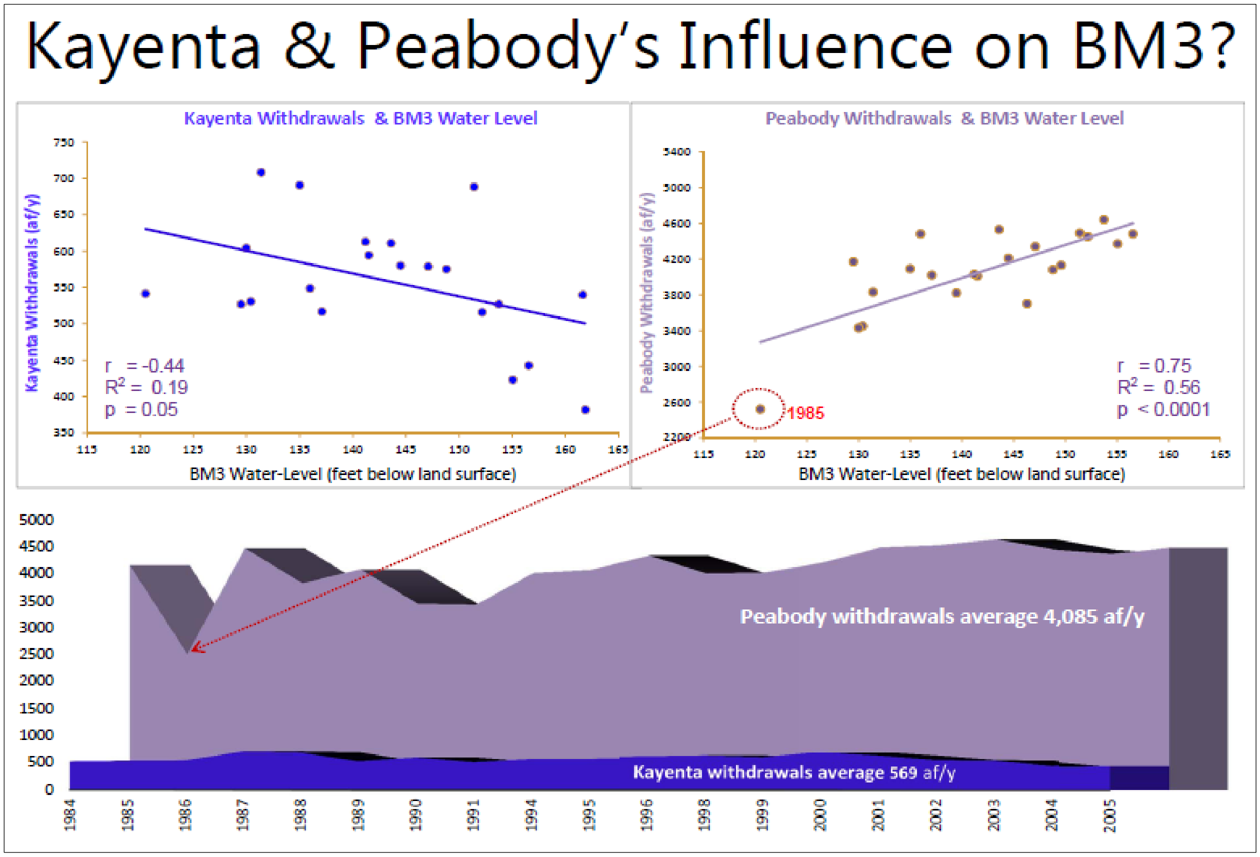


Figure 8. Summary illustration of Kayenta withdrawals (top left) and Peabody withdrawals (top right) and their influence on the water-level in Kayenta well BM3 for the period 1984-2005 (water-levels (*x-axes*) are in *feet below ground-surface* so as their values increase, the water-level in the well is falling). The bottom chart is a comparison of Kayenta and Peabody withdrawals for the period 1984-2005 (annual withdrawal data from collected from the USGS monitoring reports, 1984-2005; annual water-level data collected from the USGS Black Mesa Monitoring Program website (BMMP 2010).

OSM & Peabody on Kayenta's Water-Level Decline (1984 – 2011)

"As new information develops, existing data sets are strengthened,
and impact predictions are evaluated and modified as may be necessary" (Klein 2011)

Peabody's 1984 PHC:
"The significance of tribal community pumpage should not be understressed… At Kayenta, 85% of the total water level declines will be caused by community pumpage" (PWCC-PHC 1985: 46)

OSM's 1989 CHIA:
"None of the groundwater simulations indicate that the potentiometric surface will drop to less than 100 ft. from the top of the N-aquifer system at any point in areas where the aquifer is confined and, therefore, material damage to the hydrologic balance due to this criteria is projected to occur from mining related withdrawals." (OSM-CHIA 1989: 7-4)

OSM's 1990 EIS:
"For there to be a reduction in well production or for structural damage to occur… the potentiometric surface would have to be drawn down to below the top of the confined portion of the aquifer… It can be seen that at no time does the potentiometric surface drop to this level anywhere within the affected area for any scenario. The closest the potentiometric surface gets to the top of the confined aquifer for [the proposed mining plan] is 366 feet at Keams Canyon in the year 2052." (OSM-EIS 1990: IV-28)

"Simulated water-level changes… for the Kayenta area show heavy influence of community pumping on the aquifer. Water levels would decline a maximum of 99 feet below 1985 levels in 2052. Mine-related withdrawals would account for 4 feet [4%] of the drawdown and community pumping, 95 feet [96%]." (OSM-EIS 1990: IV-29; *emphasis added*)

Peabody's groundwater model:
"The effect of PWCC drawdown (as a percentage of total drawdown) at Kayenta is 13% in 2011… the drawdown at [Kayenta well] BM3 appears to be almost entirely related to local pumping at Kayenta and is similar in all scenarios" (HSIGeoTrans & WEHE 1999: 6-14)

OSM's 2006 Annual Report:
"material damage to the hydrologic balance of the N-aquifer, caused by mining, with respect to maintaining the potentiometric head above the top of the N-aquifer, has not occurred." (OSM 2006: 5-7. OSM also explained that the criterion for structural stability "is subject to review and modification in an update to the CHIA." (OSM 2006: 4)

OSM's 2008 EIS:
"All of the N-aquifer and D-aquifer wells that are predicted to experience water-level declines are located in the confined portion of the aquifer and are not predicted to have their water levels lowered to below the top of the aquifer. In other words, no reduction in saturated thickness is predicted for N- and D-aquifer wells." (OSM-CHIA 2008: 4-32).

OSM's 2008 CHIA:
"Because no material damage has occurred to date and the water levels are no rising, material damage has been prevented… Therefore, OSM will set no material damage criterion for the structural stability of N-aquifer." (OSM-CHIA 2008: 71)

"OSM has reviewed the relevant hydrologic information and hereby finds that the Peabody Western Coal Company's Black Mesa Complex has been designed to prevent material damage to the hydrologic balance outside its permit boundary." (OSM-CHIA 2008: 90)

Peabody's 2010 PHC:
"In summary, the data indicate that there is no risk to the structural integrity of the aquifer resulting from projected drawdown. Similarly, compaction has been and will be insignificant, and any compaction is expected to be insignificant." (PWCC-PHC 2010: 79)

OSM's 2011 EA:
"With the anticipated use of the N-aquifer, there are no significant predicted changes in the saturated thickness of the D and N-aquifer as a result of continued PWCC's [sic] pumping. Pumping has been primarily occurring within the confined part of the N-aquifer, and water levels are currently rising or are predicted to rise because of the reduction in PWCC's pumping [in 2006]. Near the boundary between the confined and unconfined areas of the aquifer, a small water-level drawdown in the unconfined aquifer is predicted north of the PWCC lease and Kayenta Mine permit areas near Kayenta and Shonto. The effects of mine-related pumping are minor compared to community pumping. Pumping by the communities in the unconfined parts of the aquifer would decrease the saturated thickness near those wells." (OSM-EA 2011: 107)

MOENKOPI: SPRING DISCHARGE

Four springs are monitored by the USGS monitoring program: (1) Moenkopi School Spring, (2) Burro Spring, (3) Pasture Canyon Spring, and (4) Unnamed Spring near Dennehotso (Figure 9). Peabody's 1985 PHC, and OSM's 1989 CHIA and 1990 EIS concluded that spring discharge in the area of Tuba City/Moenkopi may be reduced by 1-2% but would be caused *entirely* by municipal withdrawals from the Tuba City well system. The nearest measureable impact from Peabody's withdrawals (1 ft. of drawdown) comes no closer than fifteen miles from Moenkopi and occurs in 2052 (OSM-EIS 1990; OSM-CHIA 1989; PWCC-PHC 1985).

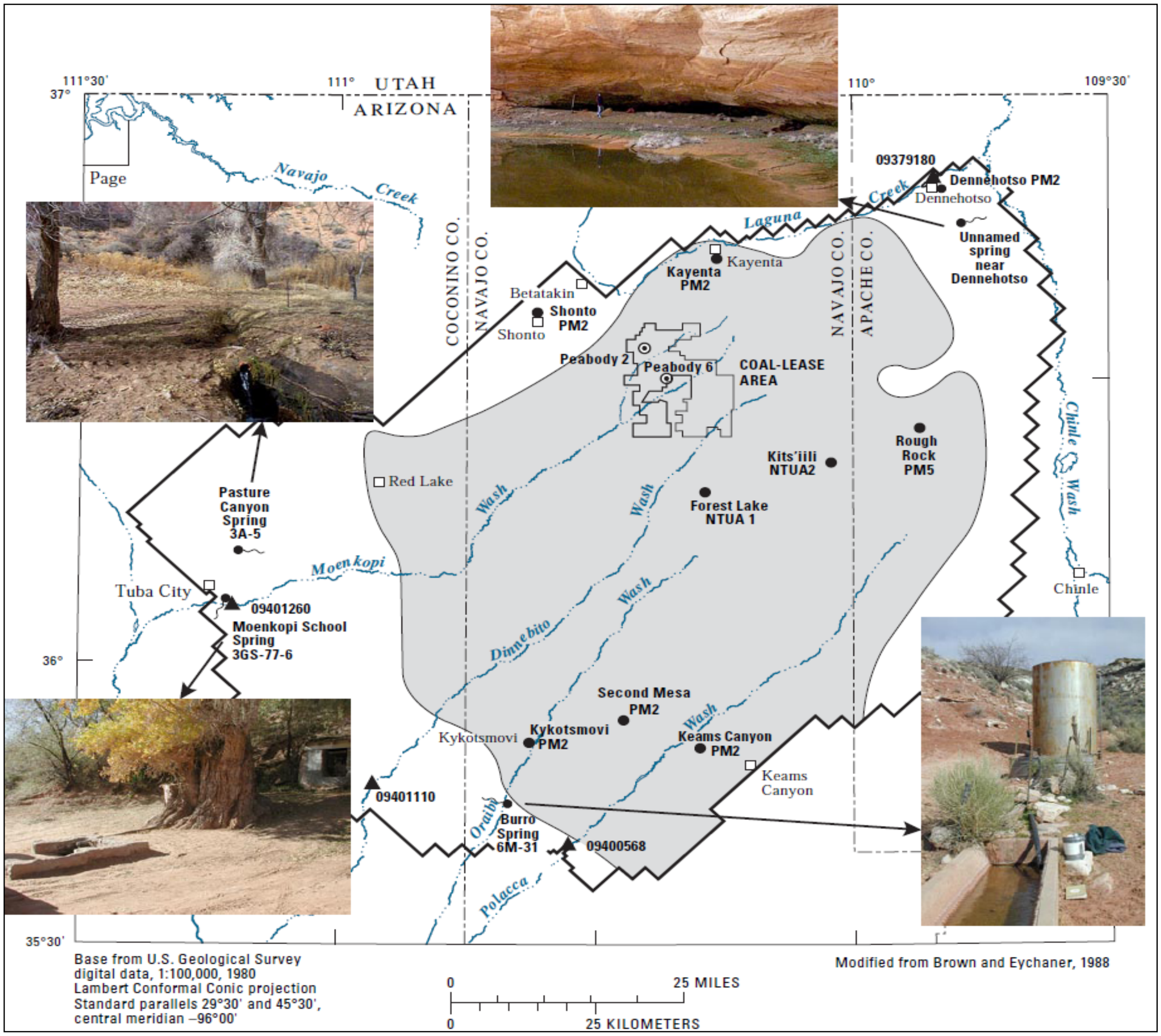
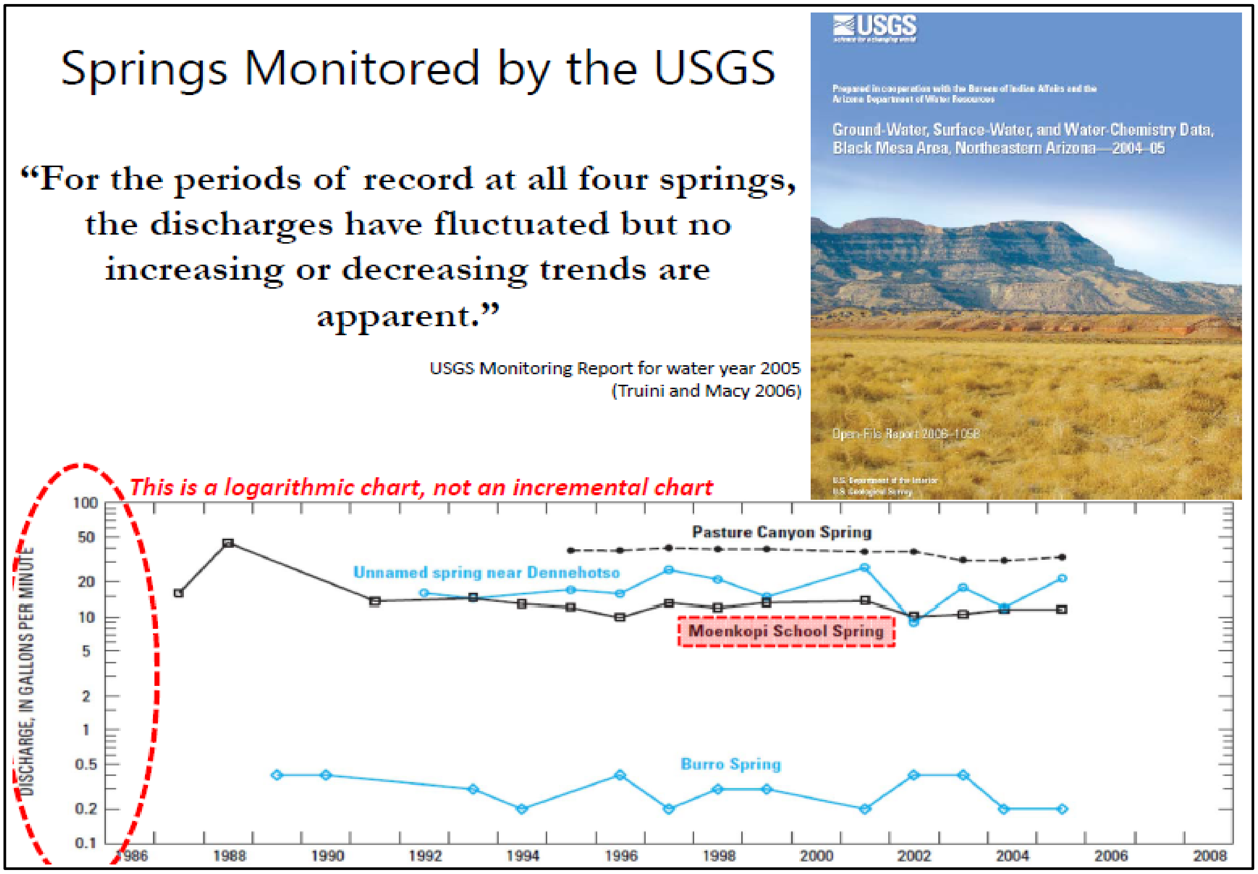


Figure 9. Locations of the four springs monitored by the USGS Black Mesa Monitoring Program (from Macy 2010).

Through water-year 2005, the USGS monitoring reports used logarithmic charts (Figure 10) to illustrate spring-discharge from the N-aquifer, and no appreciable trends were apparent at that time (see USGS monitoring reports 1984-2006). Concurrently, OSM’s 2006 evaluation of the mine’s impact on the N-aquifer concluded that material damage to springs had not occurred (OSM 2006; OSM-EIS 2004, 2006).

Later that year, it was revealed to the USGS that the logarithmic charts unintentionally concealed negative trends (i.e., in logarithmic charts, the unit of measure, circled in red (Figure 10) increases *exponentially* rather than incrementally. As such, if the measured value has small changes within the higher range of the parameter’s values, as in the case of Moenkopi School Spring, any trends in the data may be inadvertently concealed, which is evident when comparing discharge data for Moenkopi School Spring in an incremental chart, Figure 11).

Subsequently, USGS began illustrating spring-discharge using incremental charts (Truini and Macy 2008, 2007; Macy 2010, 2009).



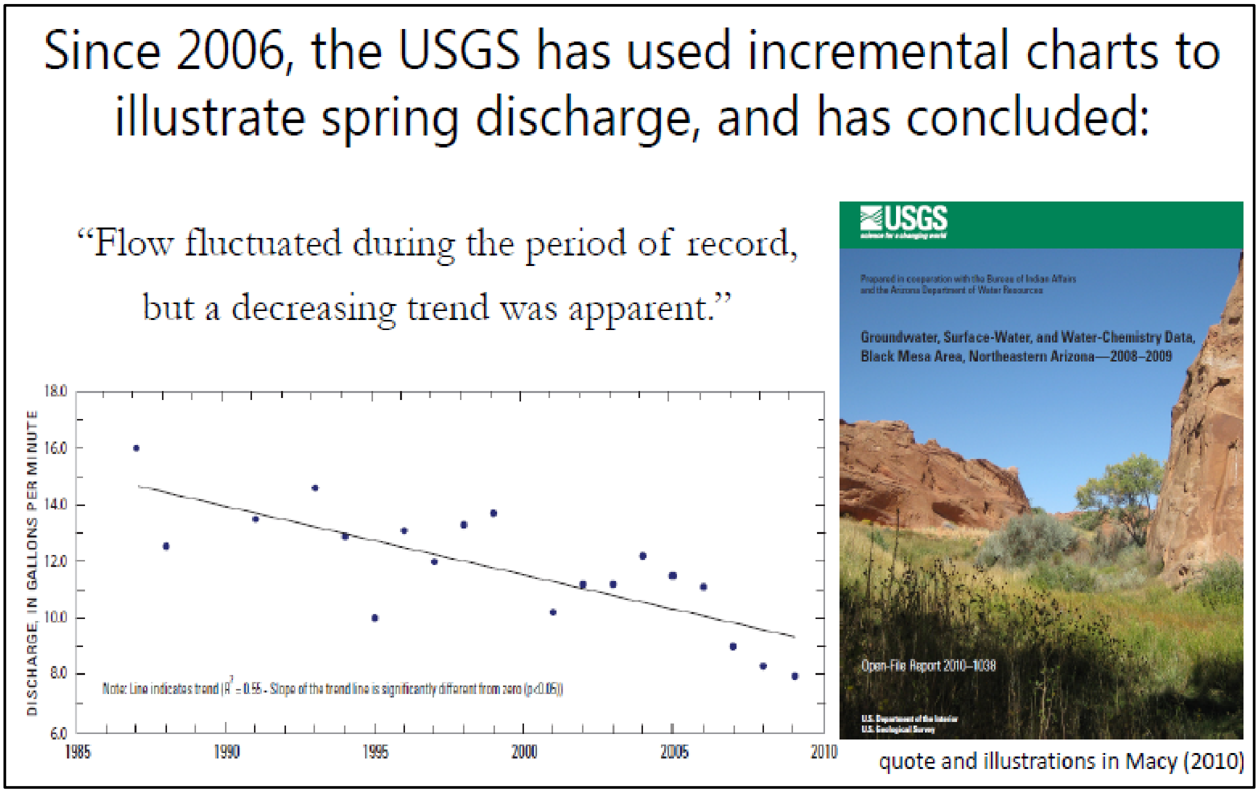
Springs Monitored by the USGS

“For the periods of record at all four springs, the discharges have fluctuated but no increasing or decreasing trends are apparent.”

USGS Monitoring Report for water year 2005
(Truini and Macy 2006)

This is a logarithmic chart, not an incremental chart

Figure 10. USGS’s logarithmic chart of spring discharge (adapted from Truini and Macy 2006). The y-axis, circled in red, increases exponentially rather than incrementally, which inadvertently concealed the declining trends, as is the case for Moenkopi School Spring, for the periods of record (1987-2005). Beginning in water-year 2006, the USGS began using incremental charts to illustrate the rate of spring discharge over time (see Figure 11).



Since 2006, the USGS has used incremental charts to illustrate spring discharge, and has concluded:

"Flow fluctuated during the period of record, but a decreasing trend was apparent."

quote and illustrations in Macy (2010)

Figure 11. Quote, incremental chart, and cover illustration are adapted from Macy (2010). Beginning with water-year 2006, the use of incremental charts express declining trends for numerous N-aquifer springs, as is the case for Moenkopi School Spring, demonstrated in the incremental chart for the period of record 1987-2009.

Recall that Moenkopi School Spring is located near the Hopi village of Lower Moenkopi, along the bank of Moenkopi Wash, approximately 60 miles downstream of the mine, and it is in the western-most portion of the unconfined N-aquifer. According to Peabody's consultants, "Drawdown at Tuba City is solely caused by pumping from local community wells… There are no impacts at Tuba City from PWCC pumpage in either the 2D or 3D model" (HSIGeoTrans and WEHE 1999: 8-7 and 8-8).

The chart on bottom left corner of Figure 11 demonstrates that the rate of discharge (in gallons per minute) varied for the period (1987-2009) but expresses a declining trend (R^2= 0.55). The highest discharge (16 gpm) occurred the first year of record and lowest discharge (8.0 gpm) occurred during the most recent year of record. Mean discharge for the period is 11.81 gpm, which is 26.2% lower than the first-year's rate (1987).

If this decline expresses a stronger relationship with mining withdrawals than either municipal withdrawals or precipitation, then OSM's CHIA criterion has been exceeded by 16.2%.

REGRESSION OF MOENKOPI SCHOOL SPRING AND PEABODY WITHDRAWALS[7]

The regression of spring discharge to Peabody withdrawals (Figure 12) demonstrates a strong, indirect, linear relationship between decreasing discharge and increasing Peabody withdrawals: $r = -0.84$; $R^2 = 0.71$; $p < 0.0001$.

To clarify, with the data that are available, 71% of the variability in discharge from Moenkopi School Spring (a declining trend) can be accounted for on the basis of the variability in Peabody withdrawals (an increasing trend). The null hypothesis (Peabody withdrawals do not affect discharge from Moenkopi School Spring) is rejected because the chance that the demonstrated relationship (R^2) does *not* actually exist is less than 0.01% (*p*).

To date, OSM's conclusion that the mine's groundwater withdrawals have had no effect on N-aquifer springs has not changed (OSM-EA 2011; OSM-CHIA 2008, 1989; OSM-EIS 2008, 1990; OSM 2006, 2004, 2000, 1998).

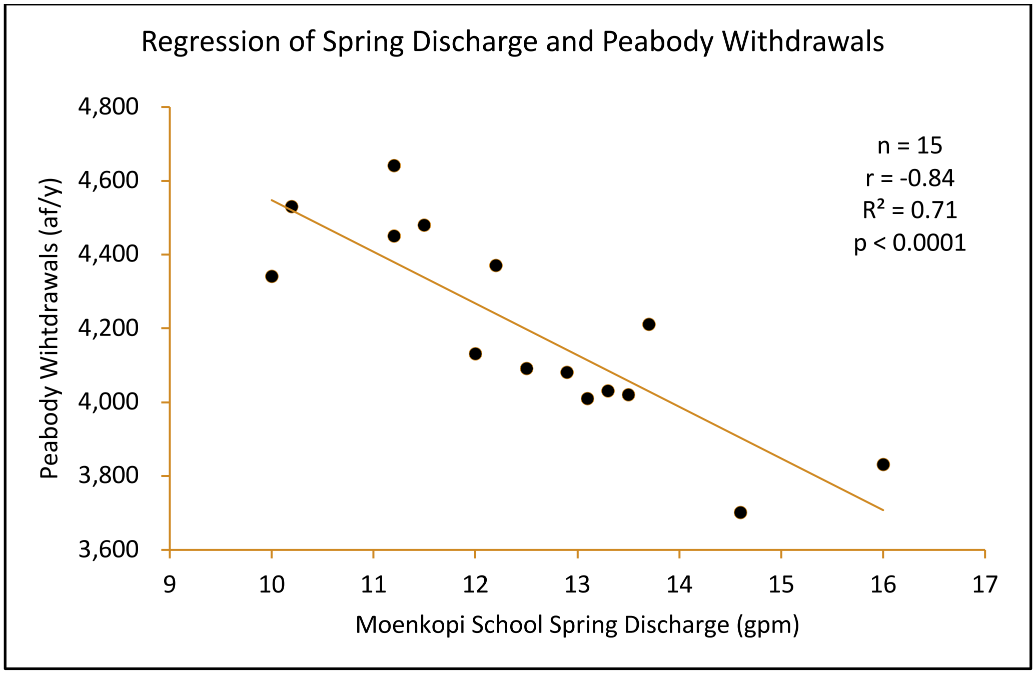


Figure 12. Regression of discharge from Moenkopi School Spring and Peabody Withdrawals (discharge and withdrawal data from Macy 2010).

REGRESSION OF MOENKOPI SCHOOL SPRING AND TUBA CITY WITHDRAWALS

Moenkopi School Spring is within five miles of the wells that comprise the Tuba City well system. The regression of spring discharge to Tuba City withdrawals (Figure 13) demonstrate that, for the period of record, there is *no* statistically significant relationship between spring discharge and local withdrawals: $r = -0.30$; $R^2 = 0.09$; $p = 0.28$.

To clarify, with the data that are available, 9% of the variability in discharge from Moenkopi School Spring (a declining trend) can be accounted for on the basis of the

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[7] Analysis for the period 1987-2005; Peabody withdrawals for water-years 2006, 2007, 2008 are statistical outliers and are not included in the regression (Peabody reduced its withdrawals 70% in 2006). See *Appendix B* for the statistical explanation of outliers.

variability in Tuba City withdrawals (an increasing trend). However, the null hypothesis (Tuba City withdrawals do not affect discharge from Moenkopi School Spring) is *not* rejected because there is a 28% chance (*p*) that the demonstrated relationship (R^2) occurred by chance.

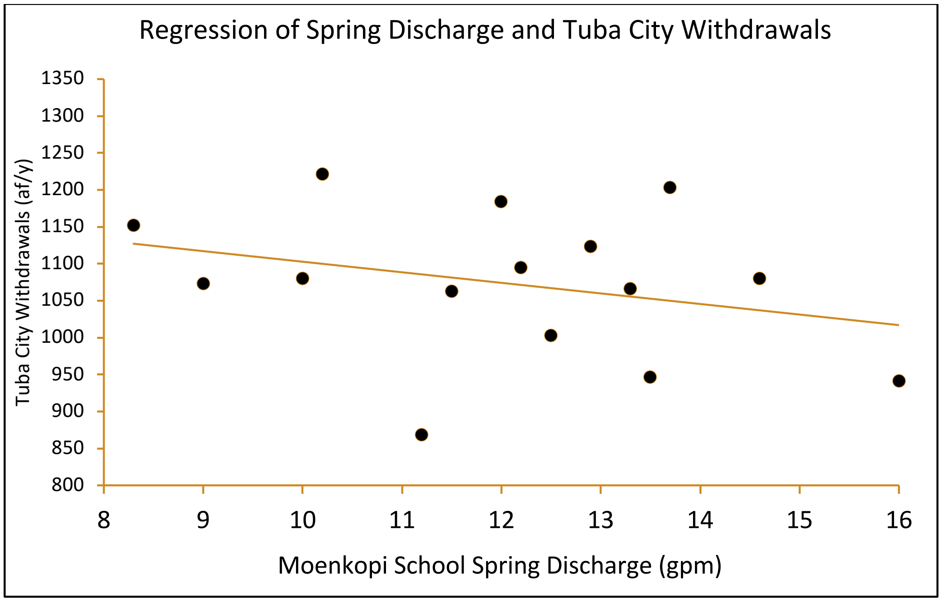

Figure 13. Regression of Moenkopi School Spring discharge & Tuba City Withdrawals ($r = -0.30$; $R^2 = 0.09$; $p = 0.28$)

REGRESSION OF MOENKOPI SCHOOL SPRING AND TUBA CITY PRECIPITATION

The regression of discharge from Moenkopi School Spring and local precipitation at Tuba City (Figure 14) demonstrate that there is no statistically significant relationship between discharge and rainfall in the area: the null hypothesis (Precipitation at Tuba City does not affect discharge from Moenkopi School Spring) is *not* rejected because there is a 17% chance (*p*) that the demonstrated relationship (R^2) occurred by chance[8].

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[8] OSM also found no discernible relationship between precipitation and discharge in the Tuba City/Moenkopi area (OSM-CHIA 1989). In fact, OSM found an inverse relationship: the (pre-mining) period of higher precipitation correlated with low-flow characteristics while the (post-mining) period of low precipitation correlated with high-flow characteristics.

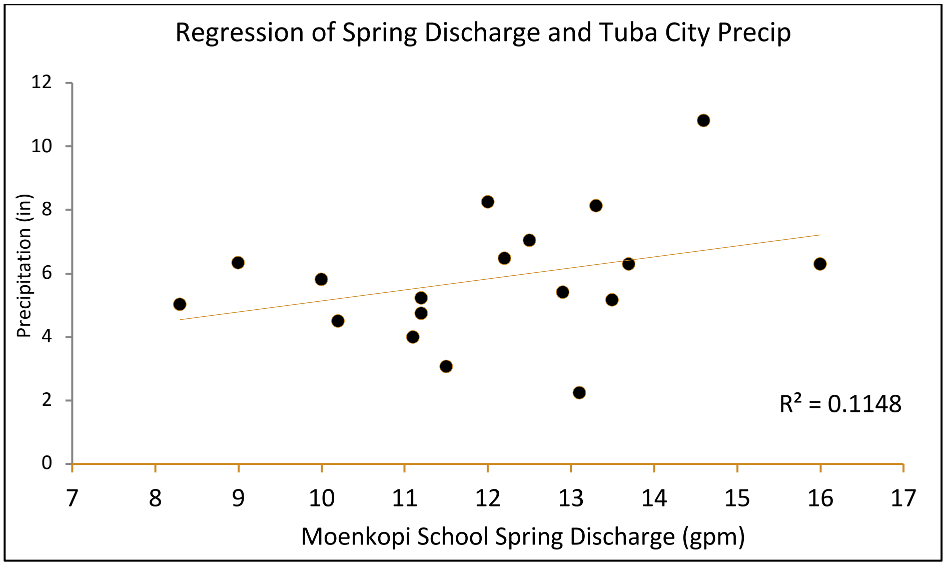

Figure 14. Regression of Moenkopi School Spring discharge & Tuba City Precipitation ($R^2 = 0.11$; $p = 0.17$). Precipitation data for the Tuba City weather station from the Desert Research Institute: http://www.wrcc.dri.edu/.

SPRING DISCHARGE & GROUNDWATER QUALITY

> *The sandstone aquifers supplying water to the Peabody wells contain a vast quantity in storage, which is isolated from water in the relatively shallow local wells on the mesa by impermeable formations overlying the Navajo, Kayenta, and other deep formations*.
>
> United States Bureau of Reclamation (USBR 1971)
> *Environmental Statement for the Black Mesa-Kayenta Mine*

> *Effects of induced leakage of poorer quality water from the overlying D-aquifer system on N-aquifer water quality. The water quality from Peabody and Tribal wells completed in the N-aquifer has been periodically monitored by the USGS since 1967. The thrust of the N-aquifer water quality monitoring effort has been towards assessing if vertical leakage from the overlying D-aquifer system is significant. The concentration of dissolved solids, chloride, and sulfate ions in the D-aquifer is about 7 times, 11 times, and 30 times greater, respectively, than in the N-aquifer. If the N-aquifer water level declines are inducing large amounts of vertical leakage from the D-aquifer system, there should be marked changes with time in these parameter concentrations.*
>
> Peabody Western Coal Company (PCC-PHC 1985: 46)
> Determination of *Probably Hydrologic Consequences*

Peabody's 1985 PHC concluded that "there is no evidence to suggest that significant vertical leakage is occurring from the D-aquifer system into the N-aquifer system" (PCC-PHC 1985: 46). OSM subsequently generated the material damage criterion for water quality: *a value of leakage from the overlying D-aquifer, caused by mine-related withdrawals, is not to exceed 10%*.

Like the criterion for structural stability and spring discharge, groundwater model simulations provide the basis for the evaluation of water-quality. The simulation showed that municipal pumping caused leakage of 239 acre-feet per year, and the simulation of both municipal *and* industrial pumping showed leakage increasing to 243 af/y. Thus, because the mine would increase leakage from the overlying D-aquifer by merely 4 acre-feet per year, "any effect on water quality would be negligible due to a 2 million to 1 dilution and no material damage to water quality would occur" (OSM-CHIA 1989: 7-4).

OSM reiterates its findings in the 1990 EIS: "This is further substantiated by the 1989 USGS monitoring program progress report (Hart and Sottilare 1989) which concludes that no impacts are observable from leakage of the D-aquifer to the N-aquifer. OSM concludes that the potential for degradation… is considered to be minor over both the short and the long-term" (OSM-EIS 1990: IV-34). OSM upheld this conclusion in 2006, stating, "material damage to the N-aquifer, caused by mining, with respect to leakage from the overlying D-aquifer, has not occurred" (OSM 2006).

The N-aquifer models were not developed to simulate *any* chemical quality parameters: they have no capacity to simulate changes in the N-aquifer's hydrogeochemical quality over time. Rather, OSM predetermined that mining will not diminish the water-quality because the model's pumping scenarios showed negligible leakage from the overlying D-aquifer. In short, OSM has argued that because the models simulated little mining-induced leakage, the mine will not impact the N-aquifer's chemical quality and future evaluation of the criterion is unnecessary.

The quantification of leakage between aquifers that are thousands of feet deep requires intensive investigation into vertical hydraulic conductivities between the aquifers, water measurements from the aquifers, and other hydrogeological information that are not available because the D-aquifer *has never been monitored* and investigation of its leakage characteristics did not begin until 2003 (see Truini and Longsworth 2003; Truini and Macy 2005). OSM acknowledged this limitation: "Neither the USGS nor PWCC monitors water-levels in the confined portion of the D-aquifer as part of its monitoring effort. D-aquifer water-level information would be needed to directly evaluate the change in leakage from the D-aquifer to the N-aquifer" (OSM 2006: 7).

In review of USGS monitoring data, two wells (Rough Rock PM5 and Keams Canyon PM2) show TDS-levels exceeding the EPA's recommended drinking water limit and "appreciably higher levels of chloride" at 97 mg/L and 113 mg/L, respectively (OSM 2006). Monitoring reports show arsenic in Keams Canyon PM2 at 40.3 µg/L (exceeding the EPA's standard for Maximum Contaminant Level of 10 µg/L; see Truini and Macy 2007), significant increases in TDS, Chloride, and Sulfate at Moenkopi School Spring (Figure 15, blue data points and trend line; see Macy 2010).

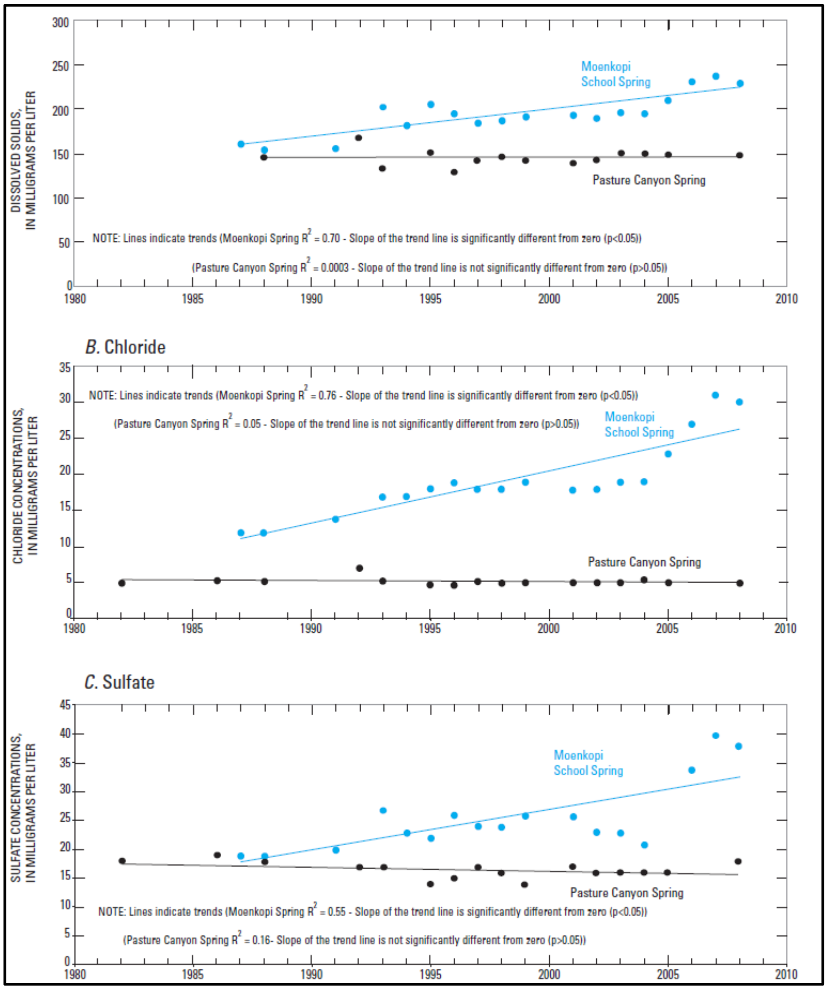

Figure 15. Water chemistry data for select springs (from Macy 2009)

Nevertheless, because OSM concluded that mining-activities will generate only an additional 4 acre-feet of leakage per year, it maintains that material damage to the N-aquifer's groundwater quality has not and will not occur (OSM-CHIA 1989).

Regression analysis was performed to elucidate if any relationships exist between the water quality of Moenkopi School Spring discharge and the rates of mining withdrawals, local municipal withdrawals, or local precipitation.

Recall the analyses performed earlier in this section demonstrating a strong, indirect, linear relationship between the rate of spring discharge and the rate of Peabody withdrawals ($r = -0.84$; $R^2 = 0.71$; $p < 0.0001$), and no statistically significant relationship between the rates of spring discharge and local community withdrawals ($r = -0.30$; $R^2 = 0.09$; $p = 0.28$).

Similarly, the regression of the water quality in Moenkopi School Spring expresses a moderately strong relationship with the rate of Peabody withdrawals (Table 1, below), while there are no statistically significant relationships with either the rate of local withdrawals from the Tuba City well system or local precipitation in the Tuba City / Moenkopi area.

Table 1. Correlation between Moenkopi School Spring’s water quality and Peabody withdrawals

TDS		**Chloride**		**Sulfate**	
r =	-0.75	r =	-0.77	r =	-0.69
R2 =	0.56	R2 =	0.59	R2 =	0.47
p =	0.0002	p <	0.0001	p =	0.001

Data for TDS, chloride, and sulfates in Moenkopi School Spring, and withdrawal data, are from Macy (2010)

Peabody and OSM on Mine-Related Impacts to springs (1989 – 2011)

*"As new information develops, existing data sets are strengthened,
and impact predictions are evaluated and modified as may be necessary"* (Klein 2011)

OSM's 1989 CHIA:

"No material damage to spring discharge to the hydrologic balance is projected to occur for N-aquifer spring discharge." (OSM-CHIA 1989: 7-5)

OSM's 1990 EIS:

"Spring discharges in Pasture Canyon would not change as a result of mine-related withdrawals. Simulated outflow from the N-aquifer to Moenkopi Wash, west of Black Mesa through Blue Canyon to Moenkopi, would decrease by 1 to 2 percent under all pumping scenarios. Community pumping would have a slightly greater effect on the outflow to Moenkopi Wash than would varying the duration of pumping at the mine; therefore, the short- and long-term impact of the mine on Moenkopi Wash baseflow discharge from the N-aquifer would be negligible." (OSM-EIS 1990: IV-28)

"Simulated water level decline in [Tuba City/Moenkopi] are due only to community pumping. OSM concludes that under all alternatives there would be negligible short and long-term impacts in the Tuba City/Moenkopi area due to mine-related pumping" (OSM-EIS 1990: IV-29)

Peabody's groundwater model:

"Drawdown at Tuba City has zero effect caused by PWCC." (HSIGeoTrans & WEHE 1999: 6-14)

OSM's 2006 Annual Report

"Although CHIA criterion number 3 is based on computer simulation of spring flow, monitoring data from the USGS report are discussed in this section for informational purposes… OSM continues to caution relating USGS spring monitoring data to PWCC impacts due to the proximity and prevalence of non-PWCC pumping near the USGS monitored springs. Therefore, OSM concludes that material damage to the hydrologic balance of the N-aquifer, caused by mining, with respect to N-aquifer spring flow, has not occurred." (OSM 2006: 9)

OSM's 2008 EIS:

"The USGS concludes that "for the consistent periods of record at all four springs, the discharges have fluctuated but long-term trends are no apparent" (USGS 2005). It appears that pumping to-date has not measurably reduced the monitored N-aquifer spring flow. However, modeling of N-aquifer groundwater discharge suggests that as future non-mining-related groundwater pumping in proximity to some of these springs increases, flows from springs could be impacted (GeoTrans 2006)." (OSM-EIS 2008: 4-32; emphasis added).

OSM's 2008 CHIA:

"Because the springs in the vicinity of Tuba City and Moenkopi area lie considerably outside of the confined region of N-aquifer, there have been and will be no impacts to these springs attributable to mining… Therefore, PWCC's proposed operation of [the Black Mesa mining complex] is designed to prevent material damage to the quantity of water discharging from N-aquifer springs and its corresponding uses." (OSM-CHIA 2008: 86-87)

Peabody's 2010 PHC:

"Further, the discharge rate of these springs are likely to be more sensitive to changes in local recharge than to drawdown caused by distant pumping… Because of the character of these springs and of the groundwater system, the effects of Peabody's pumping are expected to be negligible. Measurement of pumping effects on these springs will be difficult because of the expected small magnitude of these effects, seasonal changes to precipitation and evapotranspiration rates, and longer term changes in local precipitation rates." (OSM-EA 2011: 76)

OSM's 2011 EA:

"Monitoring data shows that PWCC pumping to date has not measurably reduced the monitored N-aquifer spring flow… Discharge measurements measured at both Moenkopi School Spring and Pasture Canyon Spring are strongly influenced by local community pumping stresses… modeling of N-aquifer groundwater discharge suggests that as future non-mining-related groundwater pumping near some of these springs increases, flows from spring could be affected (GeoTrans 2006)." (OSM-EA 2011: 107)

"The USGS concludes that "for the consistent periods of record for all four springs, the discharges have fluctuated but long term trends are not apparent" (USGS 1985-2005)." (in OSM-EA 2011: B-26; emphasis added)

THE 2008 CHIA[9]

As explained earlier in this report, OSM's 1989 *cumulative hydrologic impact assessment* (CHIA) was developed to keep "the big picture of hydrologic impacts before the regulatory authority at all times, so that if the accumulated impacts reach potentially damaging magnitudes, they can be dealt with in a timely manner" (OSM 1985: II-1).

By 2005, the *big picture* at Black Mesa included at least three significant issues: (1) the material damage threshold for spring discharge had been crossed; (2) the material damage threshold for structural stability had been crossed; and (3) the material damage criteria for water quality and discharge to streams had never been evaluated as OSM originally intended.

On 28 December 2008, OSM posted a link on the agency website to a *new* CHIA for Peabody's coal mining operation on Black Mesa (OSM-CHIA 2008). The *Technical Rational* of the revision explains:

> OSM determined that a new CHIA for the Black Mesa Complex was warranted. This CHIA reevaluates impact mechanisms, methodologies for impact assessment, and updates material damage criteria. The need to supersede and replace the 1989 CHIA was prompted by a significant reduction in the quantity of N-Aquifer water to be used during the [Life of Mine], the analysis of 20+ additional years of detailed hydrologic data, and several new hydrologic studies completed since 1989. In addition, the 1989 CHIA included some information and criteria that have necessitated revision based on additional information about the hydrologic balance. Recent data provide far more information than was available for completion of the 1989 CHIA. (OSM-CHIA 2008: 3)

The 2008 CHIA includes new definitions, new *cumulative impact area* boundaries, and new criteria for material damage (i.e. the 1989 criteria for material damage were eliminated with this revision; see OSM-CHIA 2008).

2008 DEFINITIONS

The original 1989 CHIA explicitly defined the term *material damage* in conformance with the 1985 *Draft Guidelines for Preparation of a Cumulative Hydrologic Impact Assessment* developed by OSM (OSM-CHIA 1989: 1-1; for *Draft Guidelines*, see OSM 1985). The 1985 guidelines explained: "Material damage to the hydrologic balance means, with respect to CHIA, the changes to the hydrologic balance caused by surface mining and reclamation operations to the extent that these changes would significantly affect present and potential uses as designated by the regulatory authority (OSM-CHIA 1989: 5-1; referencing the definition provided in OSM 1985).

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[9] Unless otherwise noted, the information in this section comes from OSM-CHIA (2008).

In the 2008 CHIA revision, however, OSM explains that the *Surface Mining Reclamation and Control Act* of 1977 (SMCRA) does not define the *phrase* “Material damage to the hydrologic balance” (OSM-CHIA 2008: 2), and the revision makes no reference to the definition used in the 1989 CHIA or to OSM’s 1985 *Guidelines for preparing CHIA* (OSM 1985). Rather, OSM states:

> The CHIA process cannot reasonably be extended to include remote and speculative impacts: rather, it should be defined to enable the regulatory authority to reach a decision for permit approval… Material damage implies that mining cannot proceed because the impact is deemed too severe. Examples of material damage are *permanent destruction of a major regional aquifer* and *long-term contamination of an aquifer* in use for which there is no suitable replacement water supply. (OSM-CHIA 2008: 2; emphasis added)

To clarify, in the revised 2008 CHIA, material damage requires “permanent destruction” and “long-term contamination” to the N-aquifer (caused by mining) unless a suitable replacement water supply can be identified. It is at this point—*after* it has been determined that permanent destruction or contamination has occurred—that OSM would conclude that material damage had occurred. And with this new definition, OSM asserts its discretionary authority, “except for water quality standards and effluent limitations established at 30 CFR Part 816.42, the determination of material damage criteria is left to the regulatory authority” (OSM-CHIA 2008: 2).

2008 CUMULATIVE IMPACT AREA FOR GROUNDWATER

In 1989, the groundwater cumulative impact area (CIA) encompassed 4,800 mi^2 of the Black Mesa and Blanding Hydrologic Basins, as conceptualized in the USGS groundwater model (Eychaner 1981, 1983; Brown and Eychaner 1988).

In 2008, OSM uses the spatial parameters of Peabody model as the boundary of the groundwater impact area: 7,450 mi^2, an increase from the former CIA of 2,650 mi^2 (HSIGeoTrans & WEHE 1999; Brown and Eychaner 1988).

> In order to evaluate all potential impacts from PWCC well field pumping, OSM believes the entire area included in the detailed aquifer model should be included in the CIA. Therefore, the groundwater CIA for the N- and D-aquifers is the area contained within the 3D model boundary. (OSM-CHIA 2008)

Although the rate of groundwater pumping was recently reduced from its prior average of 4,000 af/y to a projected 1,236 af/y from 2006 through 2026 (a 72% reduction), OSM *increased* the Groundwater CIA from 4,800 mi^2 to 7,450 mi^2 (a 64% increase).

However, N-aquifer springs are no longer categorized as a *groundwater* impact; they are now designated within their own category as a *surface-water* impact.

2008 CUMULATIVE IMPACT AREA FOR SURFACE-WATER (SPRINGS ONLY)

In the 1989 CHIA, springs were categorized within the groundwater impact area[10]; the 2008 CHIA revision categorizes springs as a *surface water* impact area, which has been vastly reduced from 3,800 mi^2 in 1989 (OSM-CHIA 1989) to 304 mi^2 in 2008, a 92% reduction (OSM-CHIA 2008).

> The groundwater model predictions indicate that, outside of these two narrow areas, N-Aquifer will either remain confined and produce no springs (on the sides facing BMC) or unconfined and unaffected by PWCC pumping (on the side opposite the BMC). The CIA is drawn only around the area where potentially affected springs might exist although the flow from these springs could theoretically impact flows downstream of this zone in the major washes if the baseline discharge is appreciable. (OSM-CHIA 2008: 81-82)

As a consequence, three of the original four springs associated with the N-aquifer—Moenkopi School Spring, Pasture Canyon Spring, and Unnamed Spring near Dennehotso—are no longer within a CIA, and thus their condition will no longer be evaluated for material damage caused by mining. Only Burro Spring falls within the boundary of the new CIA.

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[10] In the 1989 CHIA (section 7.2.2, *Groundwater: N-Aquifer System*), it explains, “The hydrologic concerns raised for the N-aquifer involve impacts on wells and springs, diminution of water quantity and degradation of water quality” (see OSM-CHIA 1989: p.7-3).

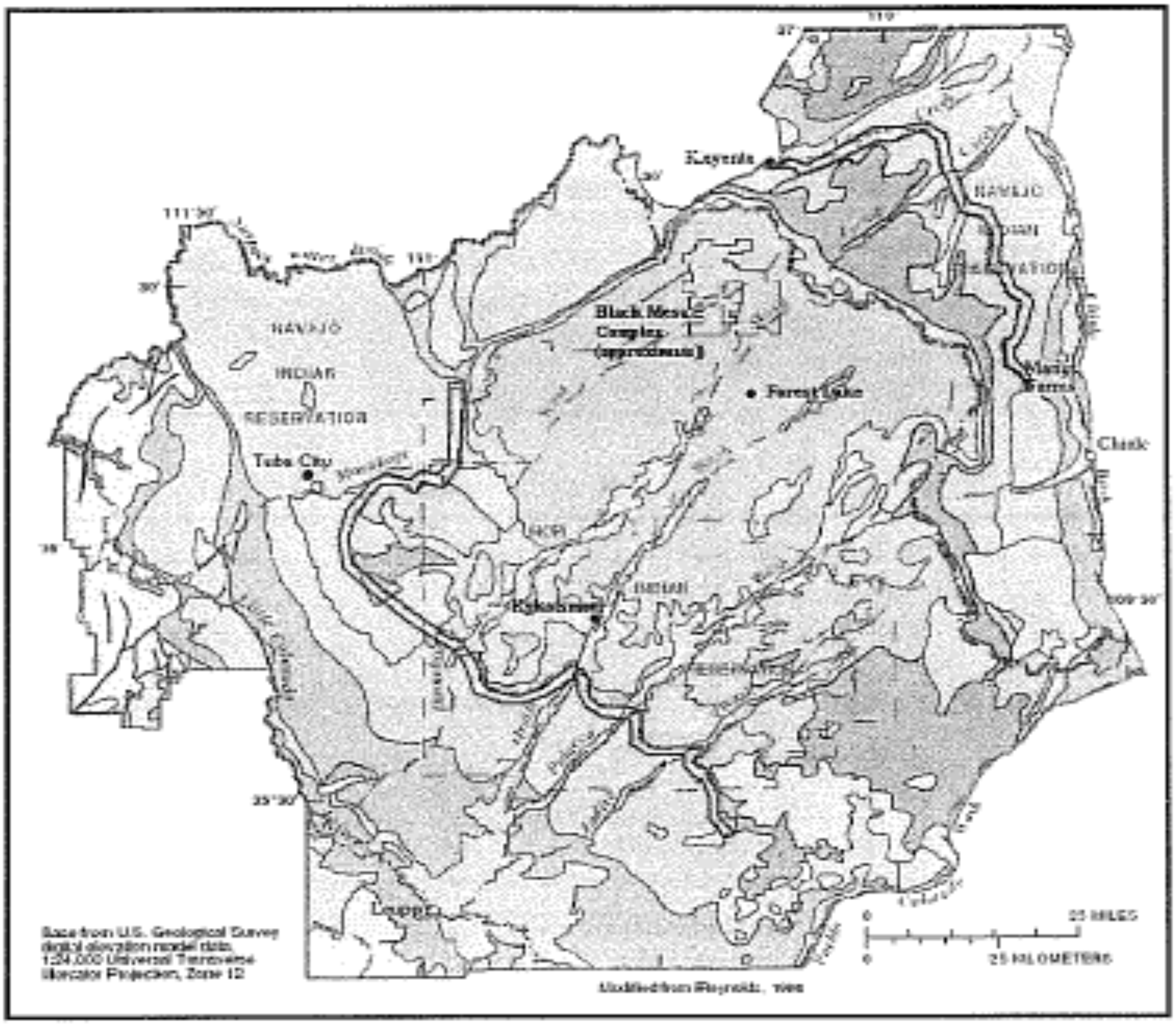

Figure 15. The two narrow, bold lines to the northeast and southwest of the confined boundary area delineates OSM's revised Surface Water Impact Area for springs; only springs located within these two narrow strips will continue to be evaluated by OSM (OSM-CHIA 2008).

2008 CHIA ELIMINATES THE 1989 MATERIAL DAMAGE CRITERIA

The 2008 CHIA criteria were established based on the Peabody model simulations (HSIGeoTrans & WEHE 1999; GeoTrans 2005). OSM developed six entirely new criteria, but three of them will not be evaluated because OSM determined that they are not relevant to industrial groundwater withdrawals (OSM-CHIA 2008).

(1) STRUCTURAL STABILITY

In 1989, the first criterion for material damage to the N-aquifer, caused by mining, was for structural stability: *the potentiometric surface must remain at least 100 feet above the top of the confined N-aquifer* (OSM-CHIA 1989).

In the 2008 CHIA, the material damage criterion for structural stability has been completely removed from regulatory purview. OSM explains:

> Pumping of the confined N-Aquifer system by PWCC has reduced the potentiometric surface but could not cause material damage, because PWCC's

> Maximum drawdown impact occurred in 2006. PWCC reduced its rate of N-Aquifer pumping by approximately 70% at the end of 2005. Water levels in the N-Aquifer system are currently recovering… Model results and ongoing monitoring demonstrate that there is and will be no impairment to the use of N-aquifer from PWCC pumping… Because no material damage has occurred to date and the confined N-aquifer water levels are now rising due to significant reduction in PWCC pumping, material damage has been prevented… OSM knows of no aquifers like N-Aquifer that have experienced any structural instability due to groundwater pumping. And now that N-Aquifer is recovering from past higher pumping rates, with no documented instability, future structural impacts are even less likely than they were previously. *Therefore, OSM will set no material damage criterion for the structural stability of N-Aquifer.* (OSM-CHIA 2008: 71; emphasis added)

As a consequence of the 2008 CHIA revision and the implementation of the new *material damage* criteria, the water-level decline in Kayenta BM3 (which is more than 106 feet below the 1989 CHIA damage-threshold; is six feet below the top of the N-aquifer; has a strong, statistically significant, linear relationship with Peabody withdrawals; and has no statistically significant relationship with municipal withdrawals) cannot be attributed to the mine.

(2) WATER QUALITY

In 1989, the second criterion was for water quality: *leakage from the overlying D-aquifer, caused by mine-related withdrawals, not to exceed 10%* (OSM-CHIA 1989).

In the 2008 CHIA, only water quality within the Peabody lease area, monitored by Peabody, will be evaluated for material damage. The mine's impact on water quality will not be considered anywhere outside of the Peabody leasehold (OSM-CHIA 2008; see pp. 71-88). OSM explains:

> Measured and predicted drawdown in the areas of the community wells is a combination of pumping from the PWCC and the communities… To date, no significant water quality impacts to the community wells have been attributed to PWCC pumping. As water levels continue to recover from the large reduction in PWCC pumping that began in late 2005, the potential for increased leakage from D-Aquifer to N-Aquifer will diminish[11]. *Therefore, no material damage criterion will be set for the southern region of the N-Aquifer.* (OSM-CHIA 2008: 76; emphasis added)

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[11] Here, while OSM concludes that leakage from the D-aquifer should decline due to Peabody's reduced withdrawals, concurrently, the Peabody model simulations include at least 4,000 af/y of leakage from the D-aquifer aquifer as natural recharge (i.e. not caused by mining) to the N-aquifer. Thus, OSM is arguing that the N-aquifer is benefitting from two mutually exclusive benefits: (1) an increased recharge estimate due to the discovery of 4,000 af/y of natural leakage and, simultaneously (2) predicting decreased leakage to the N-aquifer due to Peabody's reduced withdrawals.

As a consequence of the implementation of the 2008 CHIA, the declining water quality trends identified at Keams Canyon*,* Rough Rock, and in the discharge from Moenkopi School Spring, cannot be attributed to the mine[12].

(3) DISCHARGE FROM SPRINGS

In 1989, the third criterion was for evaluating the mine's impact on discharge from springs: *decline in spring discharge, caused by mining, not to exceed 10%* (OSM-CHIA 1989).

In 2008, as a regulated component of the N-aquifer's water-budget, the spring-discharge parameter was removed from the groundwater *cumulative impact area*, re-classified as a surface-water impact, and placed within the surface-water c*umulative impact area* – which OSM reduced by 92% (from 3,800 mi^2 to 304 mi^2).

This classification change and spatial reduction removes three of the four springs monitored by the USGS from a *cumulative impact area*, and thus from regulatory oversight: "OSM acknowledges that other N-aquifer springs do exist, but they are not within the CIA and will not be impacted by PWCC pumping" (OSM-CHIA 2008: 81).

The remaining spring (Burro), has a new and arguably insurmountable criterion for material damage. OSM explains:

> OSM would declare material damage to N-Aquifer spring quantity if OSM determined that PWCC pumping reduced discharge from the N-Aquifer to any wash (including springs, streams, etc.) within the CIA *by more than 10% for 10 consecutive years.* This reduction would be measured using the calibrated PWCC groundwater flow model, which will be continually updated with annual monitoring data… *The PWCC model will be used for this purpose instead of direct spring measurements* partly because only one aquifer spring (Burro Spring) within the CIA is consistently gaged [*sic*] and *data from this spring indicate that there has been no statistically significant impact from PWCC pumping… Model predictions indicate that the majority of drawdown of N-Aquifer in the southern part of Black Mesa would derive from local pumping sources.* Furthermore, calculations indicate a miniscule impact from PWCC pumping to streams that receive a fractional amount of their flow from N-aquifer springs. *Therefore PWCC's proposed operation of the BMC is designed to prevent material damage to the quantity of water discharging from N-Aquifer springs and its corresponding uses.* (OSM-CHIA 2008: 87; emphasis added).

As a consequence, the declining discharge from Moenkopi School Spring (26.2% since measurements began in 1987) cannot be attributed to the mine despite its strong, statistically significant relationship with Peabody's increasing withdrawals (r = -0.84; R^2

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[12] In 2006, two wells (Rough Rock PM5 and Keams Canyon PM2) had TDS-levels exceeding the EPA's recommended drinking water limit, as well as "appreciably higher levels of chloride" at 97 mg/L and 113 mg/L, respectively (OSM 2006). In 2007, the USGS reported the concentration of arsenic at Keams Canyon (PM2) at 40.3 µg/L, which exceeds the EPA's standard for Maximum Contaminant Level of 10 µg/L (Truini and Macy 2007). In 2008, the USGS reported significant increasing trends TDS, Chloride, and Sulfate at Moenkopi School Spring (Macy 2010).

= 0.71; $p < 0.0001$), and in spite of the fact that it has *no* statistically significant relationship with municipal withdrawals from the Tuba City well system.

OSM implores, "Because springs in the vicinity of Tuba City and Moenkopi area lie considerably outside of the confined region of N-aquifer, there have been and will be no impacts to these springs attributable to mining" (OSM-CHIA 2008: 86).

Burro spring will continue to be evaluated for material damage, and OSM will use the Peabody model simulations rather than actual monitoring data as the basis of its evaluation. However, as the Peabody model report explains (next section), spring discharge is not well known, and "a regional scale model cannot currently be developed for the basin that will accurately predict the impacts of pumping on individual springs" (HSIGeoTrans & WEHE 1999: 5-23).

(4) DISCHARGE TO STREAMS

In 1989, the fourth criterion was for evaluating the mine's impact on discharge to streams. This criterion will continue to be evaluated, however, its threshold for material damage has changed*: if OSM determines that the Peabody model simulations have demonstrated that Peabody's groundwater withdrawals have decreased discharge to streams by 10% for 10 consecutive years, then material damage has occurred* (OSM-CHIA 2008).

However, as the Peabody model report explains (next section), because discharge to streams is not well known, the Peabody model cannot accurately simulate discharge to streams (HSIGeoTrans and WEHE 1999: 5-24).

And with regard to Tuba City and Moenkopi specifically, "improvements to the model in this area would be needed if it were to be used as a water-resource management tool for the Tuba City and Moenkopi area…. the predicted wash discharge values derived from the model for this area are not reliable" (HSIGeoTrans and WEHE 1999: 5-52, 53).

> Evaluation of the model indicates that it successfully simulates historic water-level response to pumping in the N-aquifer. It also produces N-aquifer drawdowns that are essentially the same as the USGS model. This model has been accepted by OSM for use in evaluating impacts due to mine-related pumpage.
>
> OSM (2006: 4-25)
> Draft Environmental Impact Statement

> Modelers must contend with the practical reality that model results, more than other expressions of professional judgment, have the capacity to appear more certain, more precise, and more authoritative than they really are. Many people who are using or relying upon the results [of groundwater models] are not fully aware of the assumptions and idealizations that are incorporated into them or of the limitations of the state of the art. There is a danger that some may infer from the smoothness of the computer graphics or the number of decimal places that appear on the tabulation of the calculations a level of accuracy that far exceeds that of the model. There are inherent inaccuracies in the theoretical equations, the boundary conditions, and other conditions and in the codes. Special care therefore must be taken in the presentation of modeling results. Modelers must understand the legal framework within which their work is used. Similarly, decision-makers, whether they operate agencies or in courts, must understand the limitations of models.
>
> National Research Council (1990)

According to Peabody, "The latest study, and to date the most significant study is the development of the three-dimensional model of the N-aquifer, and Peabody sponsored that model. That model cost us about three-million dollars to develop and took almost three years; it is the most comprehensive tool to use to measure the impacts of our water use" (Dunfee 2002).

According to Peabody's hydrology consultants, the 3D model "was designed to evaluate the effects on the groundwater system caused by pumping of water from both PWCC's well field and at Tribal communities. The evaluations included effects on stream discharge, recharge, leakance, and water levels throughout the basin. The model… was not designed to evaluate impacts at individual springs or wells" (HSIGeoTrans and WEHE 1999: 1-5).

They further assert, "This particular model is extremely unusual. We can actually look at the results and compare it to what's really happening in nature. And it's happening — the model predicts what's going on" [13] (Johnson 2002).

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[13] This comment was included in Peabody's (2002) promotional video *The Miracle on Black Mesa*. The model was completed in 1999; thus, this statement affirming the model's predictive accuracy was made approximately 2-3 years after the model was calibrated: *Principle of Groundwater Development:* Evaluating a groundwater model's prediction accuracy shortly after it was calibrated misleadingly demonstrates the model's "forced empirical accuracy" which is generated by the calibration process, and is not indicative of the model's prediction accuracy (See chapters 4 and 5 for detailed explanation and literature review).

(footnote continued)

According to OSM, the Peabody model was calibrated and rigorously "validated with a complex and comprehensive data set"[14] (OSM-CHIA 2008).

> The 3D model considers the cumulative effect of all groundwater use from PWCC, Navajo Nation, and Hopi community pumping centers on the N- and D-Aquifers and associated discharge to local washes. The 3D model predictions were also validated against field measured water levels from 1996 to 2003 (the 3D model was calibrated in 1996) to assist in determining the appropriateness of utilizing the 3D model for predictive purposes. The model validation and previous calibrations to field data demonstrate that the 3D model is an appropriate tool for assessing PWCC water quantity impacts from groundwater pumping at the PWCC well field. (OSM-CHIA 2008)

In 2011, OSM reiterated that the model had been "validated in 2005 and again in 2011" (Klein 2011).

CONCEPTUAL ACCURACY AND PREDICTIVE RELIABILITY [15]

This Peabody's model's improved performance is attributed to many significant changes in its conceptualization of the N-aquifer: "…previous modeling assumptions and conceptual model pictures were not primarily relied upon, and a new and fresh approach was undertaken. Although the 2D models constitute a significant and reliable picture of the N-aquifer, it was important to remain open-minded to new ideas and concepts of the flow regime" (HSIGeoTrans & WEHE 1999: 1-4).

Despite its profound changes, the model's simulations rendered the same results as the USGS model. According to Peabody's hydrology consultants, the model demonstrated that the mine's effects are (1) constrained to the central, confined portion of the N-aquifer; (2) "imperceptible" in the unconfined portion of the aquifer; and (3) have no influence near Tuba City and Moenkopi (OSM-CHIA 2008; OSM-EIS 2008, 2006; HSIGeoTrans and WEHE 1999):

> Changes in water levels caused by PWCC pumping are nearly imperceptible along the margins of the basin where the aquifer is unconfined (i.e. water levels are below the top of the aquifer)… Along the Laguna Creek, pumping by PWCC is predicted to deplete stream flows by less than one percent… At Pasture Canyon, near Tuba City, effects caused by PWCC are effectively zero. Effects from community pumping are higher at both places. The largest effects from PWCC pumping are along Moenkopi Wash, but are still less than one percent… For both estimates of recharge, predicted

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[14] A postaudit must be performed if validation is understood to mean that the model can reliably make long-term predictions. From a scientific standpoint, a groundwater model cannot be "validated" because an accurate conceptual model requires accurate and complete field characterization—which is always incomplete—and accurate knowledge of future stressors—which is always unobtainable (see Oreskes et al 1994; Anderson and Woessner 1992; Konikow 1986).

[15] Unless otherwise referenced, the information in this section comes from the model report (HSIGeoTrans & WEHE 1999).

> effects to water-levels caused by PWCC are limited to the central, confined portion of the basin. Along the margins, where the aquifer is unconfined, changes in water-levels are attributable to community pumping… the results from the 3D model are consistent with the results from the previous 2D modeling efforts. (HSIGeoTrans & WEHE 1999: ES 5, 6)

However, there is reason to question the conceptual accuracy and predictive reliability of Peabody's $3 million, 3-year model. Seven of the most salient issues are briefly summarized here.

STORAGE

The area of the Peabody model is 55% (2,000 mi^2) larger than the USGS model, and the overlying D-aquifer and Carmel Formation was integrated into the N-aquifer, doubling groundwater stored in the N-aquifer by 2.5 times (totaling 400 million acre-feet). To clarify, as the Peabody model has conceptualized the N-aquifer, it includes (1) the distinct and overlying D-aquifer, (2) the intervening Carmel Formation, and (3) the distinct N-aquifer. These integrated formations are what Peabody refers to as "the seven geologic layers comprising the Navajo Aquifer *system*" (emphasis added). Confusingly, Peabody refers to the distinct geologic formations comprising the D-aquifer, N-aquifer, and Carmel Formation as the N-aquifer *system* and, subsequently, as simply the N-aquifer (HSIGeoTrans and WEHE 1999).

RECHARGE

Peabody's complex recharge estimate, which increased by more than 25% (or totaling exactly 17,726 acre-feet per year), is reported to be the most accurate estimate to date:

> Based on review of past studies, nearby regional model results, and available published methods summarized above, a quasi-physically based, distributed method was developed to estimate recharge for the study area… Ultimately, this method relies upon the model calibration to estimate the range of basin-scale recharge. The recharge distribution is believed to be more representative of actual conditions than in past studies because it more accurately addresses differences in surface geology, soil type and distribution, and precipitation throughout the recharge area. (HSIGeoTrans & WEHE 1999: 4-24, 25)

However, Peabody's "quasi-physically based, distributed method" of estimating N-aquifer recharge—upon which Peabody's *water-budget* model is based—did not work. "The plan to estimate the recharge rate using the model was not successful because of uncertainty in the discharge rates" (p.5-12); the calibration "process determined that the model is not a useful tool for reliably determining the recharge rate" (p. 5-48).

Further, the report expresses great inconsistency in references to its own *alternative* recharge estimate. The section titled *Determination of Recharge Rates* (p. 4-35) explains that a "conservatively low" recharge estimate of 17,726 acre-feet per year is used even though it more realistically ranges from 42,355 to 51,629 af/y. Simultaneously, the *Introduction* (p. 1-13) explains that this estimate "may be low by 4 to 5 times" (or 70,904 – 88,630 af/y), while the S*ummary and Conclusions* (p. 8-6) states that recharge "may be 2 to 4 times higher" than its estimate (35,452 – 70,904 af/y).

As such, Peabody has determined that natural recharge to the N-aquifer occurs annually at a rate between approximately 18,000 and 90,000 acre-feet per year[16] (HSIGeoTrans and WEHE 1999).

LEAKAGE

Although the overlying and poorer quality D-aquifer has never been monitored and the rate of leakage into the N-aquifer has never been ascertained (heretofore believed to be prevented by the "impermeable" Carmel Formation), Peabody concludes that leakage is more than 4,000 af/y (p. 5-51) and considers it as is natural recharge to the N-aquifer. This estimate is notable because it is approximately equivalent to Peabody's withdrawal rate for the period 1972-2005 (i.e. theoretically, under the *safe-yield* water-budget paradigm, the impact of Peabody's withdrawals on the N-aquifer is negated by this rate of naturally occurring leakage alone).

DISCHARGE

A discharge estimate for the N-aquifer was not attempted (p. 5-24) because spring discharge is not well known (pp. 4-42, 5-24), stream discharge is not well known (p. 4-43), evapotranspiration is not well known (p. 5-24), "Natural recharge and discharge rates are not well known" (p. 5-31), and because reliable measurements are "difficult", "expensive", and "unfeasible to obtain" (pp. 5-1, 5-24, 5-6). As such, the model makes no improvements in understanding discharge as a component of the water budget[17].

Recall that undesired *capture* (the unwanted decrease in discharge) can occur at very low withdrawal rates: the time it takes for withdrawals to affect discharge depends upon *aquifer diffusivity*: a function of transmissivity, storage coefficient, and distance from the pumping site to the discharge location. Understanding discharge is central to understanding aquifer dynamics (see Chapters 4: *Groundwater,* and 5: *The Water Budget Myth* in this study).

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[16] In 1997, the USGS used geochemical analyses to estimate recharge at approximately 2,500 to 3,500 acre-feet per year. Furthermore, 90% of the groundwater in storage is between 10,000 and 35,000 years old, and may exceed 35,000 years old where it discharges near Moenkopi (Lopes and Hoffman 1997).

[17] The current inadequacy of discharge data was equally inadequate in 1966 when Peabody proposed to pump groundwater from the N-aquifer. Since that time, Peabody has made no effort to improve this deficiency. And although, according to Peabody Energy (2002) and Brian Dunfee (2002), Peabody's Manager of Environmental Engineering, Peabody invested $3 million and three years in its groundwater model of the N-aquifer (HSIGeoTrans and WEHE 1999) and produced a video promoting its operations on Black Mesa (Peabody 2002: *The Miracle on Black Mesa*), the company describes the acquisition of N-aquifer discharge data as too expensive and unfeasible to obtain (pp. 5-61, 5-24). Ironically, Peabody—now the world's largest and wealthiest private sector coal company—has an extensive catalogue of N-aquifer springs although it has never attempted to measure the discharge parameter: there are 634 springs catalogued in Peabody's database; 419 springs occur within the model's boundary area; 110 springs are associated with the N-aquifer; 70 springs have been measured for discharge; however, only 21 have been measured more than once, but these measuring stations were temporary. USGS has monitored four N-aquifer springs since 1982, but these measurements have been inconsistent (pp. 4-42 and 5-21). Although the Black Mesa-Kayenta Coal Mine has been operating since 1968, Peabody has concluded that "A regional scale model cannot currently be developed for the basin that will accurately predict impacts of pumping on individual springs" because the data are insufficient (p. 5-23).

CALIBRATION

The model could not be successfully calibrated without the introduction of four geological formations that *do not exist* in the actual N-aquifer. For example, the report explains: "To achieve sufficient drawdown at BM5 and BM6 without simulating excessive drawdown at BM1, additional material zones in the Navajo Sandstone were created" (p. 5-36). The report continues, "While there is no independent geological evidence of the existence of the "Covered Central Navajo" zone, other attempts to simulate the observed drawdown at BM5 and BM6 were not successful… a test using higher conductivity zones along Moenkopi, Dinnebito, Polacca, Oraibi, and Jadito Washes produced better agreement at BM6 (in Dinnebito Wash) but poorer agreement at BM5 (in Oraibi Wash)" (HSIGeoTrans WEHE 1999: 5-38).

SIMULATIONS

The model cannot accurately simulate discharge from springs (p. 5-23); it cannot accurately simulate discharge to streams (p. 5-52); it cannot accurately simulate the water level in individual wells (p. 1-5); and simulated rates of discharge near Tuba City and Moenkopi—the area of primary discharge from the N-aquifer—are unreliable (p.5-52).

PARAMETERS

Hydrogeological parameter values used in the Peabody model were extrapolated from as many as five other models of "regional" aquifer's that are not connected to the N-aquifer or Black Mesa hydrologic basin. According to the Peabody model report, these other models "provided insight and confirmation" of the values used in the Peabody model. The five groundwater models included: Kaiparowits Plateau, Utah; Kane and Washington County, Utah; Monument Valley, Arizona and Utah border area; Lake Powell Region, Arizona and Utah border area; and San Juan Basin, northwestern New Mexico (HSIGeoTrans and WEHE 1999: 1-9).

To summarize, Peabody integrated the D-aquifer into the N-aquifer (increasing groundwater in storage by 2.5 times); included parameter values that were extrapolated from models of aquifers are not connected to Black Mesa's hydrologic basin; determined that leakage from the overlying D-aquifer (previously asserted to be prevented by the "impermeable" Carmel Formation) naturally recharges the N-aquifer at a rate sufficient to compensate for the volume of Peabody's withdrawals; required the integration of four geological formations that do not exist in the actual N-aquifer (to be successfully calibrated); concludes that recharge ranges between 18,000 and 90,000 af/y although its intended estimation method did not work; and a discharge estimate was not attempted because all vectors of discharge are poorly understood (HSIGeoTrans and WEHE 1999).

PREFACE

The argument that Peabody's reduced rate of groundwater withdrawals (beginning in 2006) has prevented any future mine-related impacts to the N-aquifer ignores numerous principles of groundwater engineering, specifically, and natural resource overexploitation, in general: (1) it fails to acknowledge the cumulative mine-related impacts to date; (2) given the *time-lag effect*, cumulative impacts may continue their declining trajectories despite the reduced rate of stress on the system[18]; and finally, (3) due to the biological and physical complexity of large-scale systems, neither renewable natural resources nor ecosystems recover to pre-development conditions once stressors are removed[19]. Finally, when 90% of the resource in question is fossil groundwater (between 10,000 and 35,000 years old (Lopes and Hoffman 1997)), predicted recoveries to pre-development conditions via "*reclamation*" are misleading to the public and have little scientific merit (Bredehoeft and Durbin 2009; Walker and Salt 2006; Berkes et al. 2003; Gunderson and Holling 2002; Ludwig et al. 1993).

In 2010, seeking renewal of its surface mining permit for the Kayenta Coal Mine, Peabody Western Coal Company submitted its determination of *Probable Hydrologic Consequences* (PHC) that would result from the proposed actions (PWCC-PHC 2010). Following OSM's review of the PHC, the agency entered its *Finding of No Significant Impact* (OSM-FONSI 2011) and an environmental consulting firm, under OSM's direction, prepared an *environmental assessment* (EA) as required by the *National Environmental Policy Act* (OSM-EA 2011).

Because the 2010 PHC and 2011 EA embody much of the same material and prediction information, and because both are based on simulations generated by Peabody's groundwater model (evaluated in the previous section), these reports are reviewed together throughout this section.

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[18] If equilibrium of a hydrologic basin is uncertain, then determining sustainable rates of development is precluded by the *time to full capture* problem: "large systems pose a challenge to the water manager… (1) a large groundwater system creates a delayed response between the observation of an impact and its maximum effect and (2) there is a long time lag between changing the stress and observing an impact at a distant boundary." (Bredehoeft and Durbin 2009).

[19] Developments in the ecological sciences illustrate that the bio-physical complexity of natural systems precludes the conventional command-and-control approach to natural resource exploitation and ecosystem management (Ludwig et al. 1993, Ludwig 2000; Holling 1973, 1986, 1995; Gunderson and Holling 2002; Berkes et al. 2003). The only scientific "truths" about the properties that govern complex social-ecological systems make their replication impossible and their control illusory. They are distinguished by *multiple equilibria* (within the range of different "stability domains" toward which the system may drift when conditions change), *emergent properties* (properties unique to one scale may be coupled to properties at other scales with many feedback mechanisms between them), *nested scales* in space and time (a small watershed is an ecosystem, but it is also a part of a larger watershed, etc.), *self-organization* (open systems will reorganize at critical points of instability), and they express *episodic* or *discontinuous* behavior. Finally, ecosystems do not necessarily reestablish former characteristics, recovery to former conditions, or return to their former trajectories once development stressors are lifted (Holling and Gunderson 2002; Berkes et al. 2003; Mitchell 2009; Jorgenson 1997).

In 2008, OSM explicitly stated that the mine's maximum impact occurred in 2006, that water-levels were recovering, that water levels were rising, and that there had been and will be no mine-related impacts on the N-aquifer:

> …PWCC's Maximum drawdown impact occurred in 2006. PWCC reduced its rate of N-Aquifer pumping by approximately 70% at the end of 2005. Water levels in the N-Aquifer system are currently recovering. When maximum decline occurred in 2006, the N-aquifer remained completely saturated with substantial pressure head. Model results and ongoing monitoring demonstrate that there is and will be no impairment to the use of N-aquifer from PWCC pumping… Because no material damage has occurred to date and the confined N-aquifer water levels are now rising due to significant reduction in PWCC pumping, material damage has been prevented… And now that N-Aquifer is recovering from past higher pumping rates, with no documented instability, future structural impacts are even less likely than they were previously. (OSM-CHIA 2008: 71)

Figure 16 (following page) demonstrates that data from "ongoing monitoring" conflicts with most of OSM's assertions (the red-dashed line indicates water year 2006, when Peabody's reduction in withdrawals began). Peabody's "maximum drawdown impact" did not occur in 2006; the mine's withdrawal effects have not yet been realized; maximum drawdown has not occurred because most wells that were in decline at the end of 2005 continue to decline in 2011.

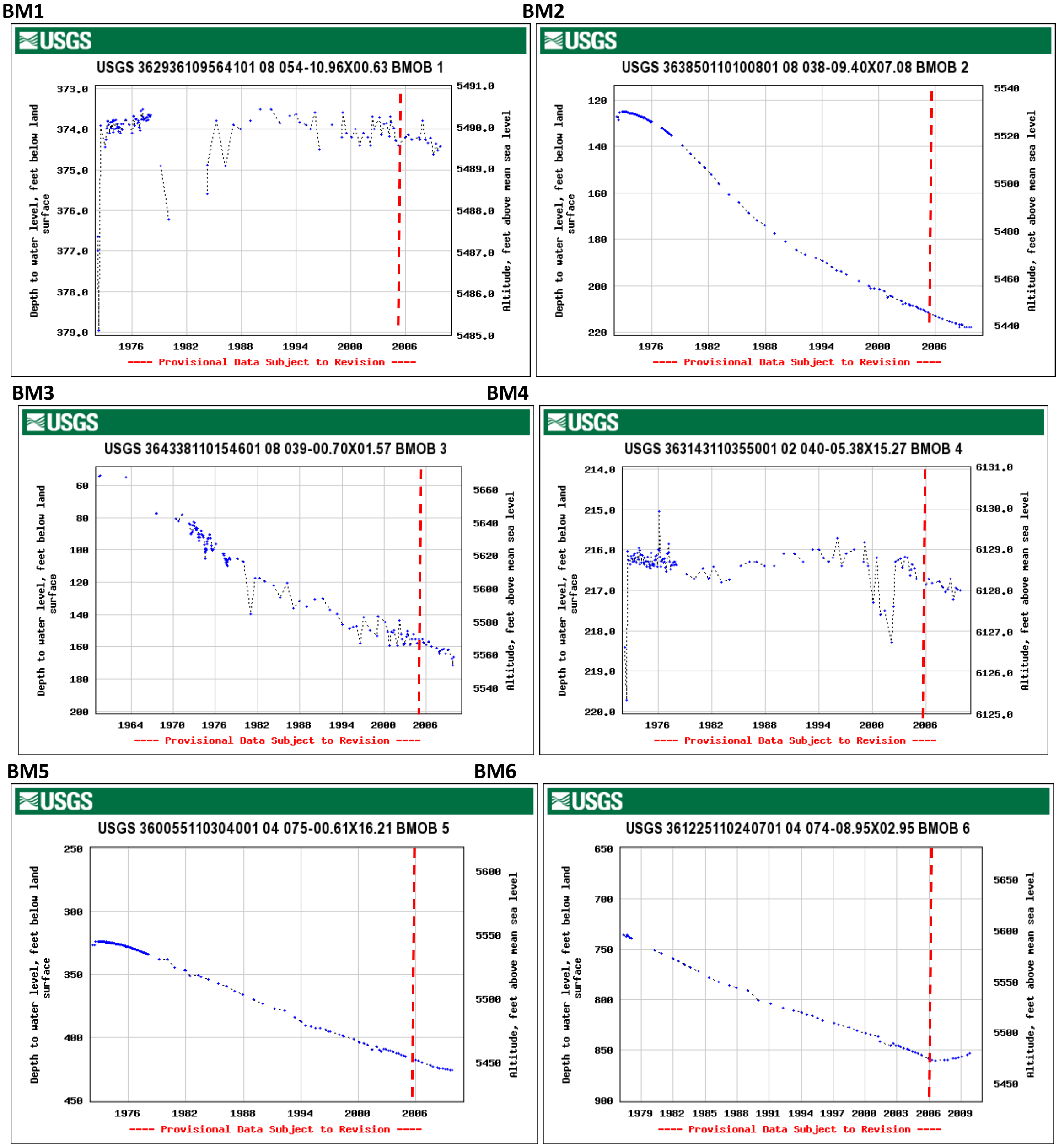

Figure 16. Water Level Data for the six USGS observation wells[20] (BMMP 2010)

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[20] OSM (CHIA 2008) concludes that BM1 and BM4 are not influenced by Peabody withdrawals because they are outside the confined/unconfined boundary. Given the principle of Superposition, this is contestable; both express a slight decreasing trend since the late 1980s. Only BM6—the well closest to the mine and in the immediate path of flow from the recharge area (Shonto) to the mine, and then to BM6—signals recovery. BM6 is not influenced by any municipal pumping. Recovery at BM5 is indeterminable at this point in time; however, the temporal difference between recovery at BM5 and BM6 demonstrates the aquifer's time-lag over this short distance (hydrographs from BMMP 2010).

PEABODY'S 2010 PHC

Peabody argues that the impact-predictions in its 2010 PHC are strong for the following reasons:

(1) they are "based on data measured before and during the period of [mine] pumping" (PWCC-PHC 2010: 39);
(2) the groundwater models which "are based on these data" and are "the best tools available for determining the individual contribution of each pumping stress on the observed or measured effects" (PWCC-PHC 2010: 39);
(3) S.S. Papadopulos and Associates (1993) reviewed the USGS model and concluded that it "is clearly appropriate for the purpose of evaluating impacts due to pumping by Peabody", and that "Peabody's impacts on surface-water features (such as streams and springs) was minimal because water was predominantly coming from aquifer storage" (PWCC-PHC 2010: 41); and because
(4) Peabody made a substantial revision to the existing data set in its development of a 3D groundwater model of the N-aquifer, which was successfully calibrated to the USGS's six BM-series observation wells: "The four models match the observed water-level changes at the six BM monitoring wells quite well" (PWCC-PHC 2010: 54).

Thus, the development and refinement of the USGS model, the Peabody model, and the integration of annual monitoring data into the models comprise the data set with which the mine-related have been predicted.

The PHC does not provide the thoroughness about the Peabody model's limitations and uncertainties that are found in the model's report itself (HSIGeoTrans & WEHE 1999; GeoTrans 2005). In contrast to the previous section, *Peabody's Groundwater Model*, the PHC does not explain that (1) the model could not be successfully calibrated without the integration of four geological features that do not exist in the actual N-aquifer; (2) the model's method for estimating recharge did not work; (3) the model did not attempt to estimate discharge from the N-aquifer because discharge data are limited; (4) the model extrapolated parameter values from models' of aquifers that are not associated with the Black Mesa hydrologic basin; etc.

Although recharge, discharge, and leakage between the D- and N-aquifer's remain highly uncertain, Peabody argues that the rate of Peabody's withdrawals within the lease-hold provides "a data set which, if properly evaluated, provides considerable information about the aquifer, and about the response of the aquifer to pumping. These measurements also provide information with which to estimate the effects of future water use. It is important to use appropriate tools to interpret this information" (PWCC-PHC 2010: 39).

With the veracity of the PHC's predictions established, Peabody reasserts the pre-existing conclusions pertaining to the mine's impact on water-level and spring discharge:

> "In summary, the data indicate that there is no risk to the structural integrity of the aquifer resulting from projected drawdown. Similarly, compaction has been and will be insignificant, and any compaction is expected to be insignificant." (PWCC-PHC 2010: 79)
>
> "Further, the discharge rate of these springs are likely to be more sensitive to changes in local recharge than to drawdown caused by distant pumping… Because of the character of these springs and of the groundwater system, the effects of Peabody's pumping are expected to be negligible. Measurement of pumping effects on these springs will be difficult because of the expected small magnitude of these effects, seasonal changes to precipitation and evapotranspiration rates, and longer term changes in local precipitation rates." (OSM-EA 2011: 76)

In conflict with OSM's previous and subsequent conclusion that water-levels are currently recovering, and in conflict with its own model simulations, the Peabody PHC explains that two observation wells (BM2, south of Kayenta, and BM3, in Kayenta) continue to decline.

In regard to BM2, the PHC states: "in recent years, *measured* drawdown has been occurring more rapidly than predicted drawdown. The *simulations* show a small response to the reduction in pumping by Peabody in 2006. The *measured* values show that the rate of drawdown has decreased but that water levels have not yet started to rise" (PWCC-PHC 2010: 47; emphasis added).

In regard to BM3, the PHC states: "Effects of reduced pumpage by Peabody are not apparent in the data. The *simulations* show a slight decrease in the rate of drawdown" (PWCC-PHC 2010: 54; emphasis added).

Concurrently, with this information—and in congruence with the lag-time effect—it can be stated that, as of 2011, the mine's impact on water-level at Kayenta has not yet reached its maximum impact, despite Peabody's withdrawal reduction.

OSM'S 2011 EA

CHERRY PICKING

As in 2008, OSM's 2011 EA explicitly states that water levels in the N-aquifer are recovering, despite the current monitoring data that conflict with this assertion, and despite the statements in Peabody's 2010 PHC, upon which OSM's conclusions are based:

> "Groundwater levels are recovering because less groundwater has been used by PWCC since the coal slurry pipeline was discontinued in 2005… The simulated groundwater level recovery is relatively small near the boundary between the confined and unconfined conditions in the N-aquifer, as total drawdown prior to

> 2005 was also small near this boundary. The greatest difference in groundwater levels occur near the communities, where local pumping is predicted to cause continued drawdowns." (OSM-EA: 2011: 105)

And as in 2008, the agency's 2011 EA quotes outdated monitoring data regarding the trends in spring discharge.

> Monitoring data shows that PWCC pumping to date has not measurably reduced the monitored N-aquifer spring flow… Discharge measurements measured at both Moenkopi School Spring and Pasture Canyon Spring are strongly influenced by local community pumping stresses… modeling of N-aquifer groundwater discharge suggests that as future non-mining-related groundwater pumping near some of these springs increases, flows from spring could be affected (GeoTrans 2006).
>
> (OSM-EA 2011: 107)

As has been demonstrated in this report (see Figures 10 and 11; section on spring discharge), through water-year 2005 the USGS used logarithmic charts to illustrate spring discharge, inadvertently concealing the negative trends in numerous springs. Since water-year 2006, the USGS has used incremental charts to illustrate spring discharge and has concluded (since that time) that concluded that declining trends are apparent.

However, in asserting OSM's conclusion about the mine's impact on N-aquifer springs, the agency references the USGS monitoring reports for the years 1985 through 2005 (which reported no apparent trends in spring discharge), and does not include in its reference ***the most recent*** USGS monitoring reports for years 2006, 2007, 2008, and 2009 (which reported that declining trends in spring discharge are apparent). Quoting the 2005 USGS monitoring report, OSM's 2011 EA asserts:

> "The USGS concludes that "for the consistent periods of record for all four springs, the discharges have fluctuated but long term trends are not apparent" (**USGS 1985-2005**)".
>
> (OSM-EA 2011: B-26; emphasis added)

Finally, as in the 2008 CHIA, the 2011 EA states that Peabody's groundwater model will be used to evaluate the mine's impact on spring discharge (rather than monitoring data). However, the EA also explains: "the model does not attempt to simulate individual spring flows, which typically occur within a limited local area" (OSM-EA 2010: B-4).

SPRING DISCHARGE

Recall that, in the 1989 CHIA, OSM categorized mine-related impacts to spring discharge as a *groundwater* impact, and in OSM's 2008 CHIA, OSM removed spring discharge from the groundwater impact area and categorized it as a *surface-water* impact. However, because the surface-water cumulative impact area was reduced by 92%, Moenkopi School spring is no longer in an impact area and thus has been removed from future consideration of mine-related impacts (OSM-CHIA 2008, 1989).

Interestingly, In the 2011 EA, OSM addresses the mine's impact on spring discharge as an impact on *groundwater* resources. The EA states: "Measured N-aquifer springs include Moenkopi School Spring, Pasture Canyon, Burro, and the Unnamed Spring near Dennehotso" (see OSM-EA 2011: section C.1.1 Hydrologic Impacts, Region of Influence, Groundwater, p. B-14). OSM must address the mine's impact on Moenkopi School Spring if it is categorized as a potential groundwater impact. However, because OSM's 2011 CHIA has not been released at the time of this study, it is unknown whether or not spring discharge will be categorized in the context of the 2008 CHIA or the 2011 EA.

IMPACT AT KAYENTA

In regard to water-level decline near Kayenta, OSM's 2011 EA states: "The comparison of simulated and measured values is more difficult at BM3 because the impacts of variable local pumping and resultant high variability of water levels in the well… Effects of reduced pumpage by PWCC are not apparent in the data." (OSM-EA 2010: B-6).

This statement conflicts with OSM's conclusion that "Groundwater levels are recovering because less groundwater has been used by PWCC since the coal slurry pipeline was discontinued in 2005" (OSM-EA: 2011: 105). To the contrary, it has been shown that most N-aquifer wells are continuing to decline.

WEPO / ALLUVIAL AQUIFER IMPACTS

Recently, much concern has been expressed about the decline in surface water sources near the mine lease area (to streams and springs). The 2011 EA states:

> "In 2003, land subsidence features in the form of sinkholes, cracks, and slumps were reported near Forest Lake… After investigation… all of the subsidence features of concern were determined to be either in or adjacent to unconsolidated alluvial valley deposits and due to surface water entering and eroding desiccation features following an extended period of drought. These features are unrelated to the mining or water productions facilities on the PWCC lease area." (OSM-EA 2011: B-32).

Peabody's 2010 PHC acknowledges the prior and potential future impacts on the alluvial and Wepo aquifers in response to mining activities. The following information comes directly from the 2010 PHC (PWCC-PHC 2010).

1. Historic and recent records indicate that all areas to be mined "have already or will intercept the upper part of the Wepo aquifer for some period during the life of the mining areas" (p.1)

2. Groundwater flow has been and will be intercepted by coal pits dug for coal extraction.
3. Groundwater flow direction is altered because the water-gradient rapidly changes toward the direction of the pits (induced groundwater recharge may occur from the alluvial aquifer at higher elevations than the Wepo).
4. Groundwater filling the pits is removed (predicted up to 37 acre-feet per year) in order to commence mining activities (groundwater continues to be drawn toward the pits).
5. Drawdowns in the Wepo formation, in response to mining activities, are predicted to be as great as 60 feet.
6. Longer-term impacts are predicted to be experienced due to the replacement of spoil material in the mined-out pits.
7. Infiltration in these reclaimed areas ***will allow little or no recharge*** to the Wepo aquifer ("but the impact will be of little significance to the local well users" (p.26)). Replacement of spoil may also block flow within the system.
8. Resaturation of replacement spoil (reclaimed areas) may take as long as 100 years.
9. Maximum drawdown in specific pits is expected to be 115 feet (J-16 & J-19).
10. "Following the resaturation period [up to 100 years], Groundwater levels will recovery to pre-mining levels" (p.26)
11. Impacts to groundwater quality will have long-term, localized impacts in these areas (Wepo aquifer within the leasehold boundary area only).
12. The significance of this impact is minor because "there are no present water users of the Wepo aquifer within the leasehold." (p. 35).
13. Other areas of the Wepo aquifer can cause local decline in the alluvial aquifer system… portions of the alluvial aquifer system (Reed Valley, Red Peak Valley, Upper Moenkopi, and Dinnebito aquifers) could potentially be affected to the extent that drawdowns exceed natural water level fluctuations" (p. 35)

Given the manner in which these mining actions have and are predicted to inhibit and redirect the flow of the Wepo and Alluvial aquifers, it is plausible that they are contributing to the discharge declines near Forest Lake and other locations near the mine.

SUMMARY

This report demonstrated declining trends in the N-aquifer's water-level, spring discharge, and water-quality at rates that exceed OSM's 1989 criteria for material damage. It also demonstrated strong, statistically significant relationships between the rate of Peabody's withdrawals and the declining trends in water-level, spring discharge, and water quality. Finally, it demonstrated that there are no statistically significant relationships between the declining trends and either municipal withdrawals or local precipitation. As such, by the standards developed by OSM in 1989, the data show that material damage to the N-aquifer, caused by mining, has occurred.

However, in 2008, OSM terminated all four of its original (1989) material damage criteria and implemented three new criteria (OSM-CHIA 2008). The agency explained that *there have been and will be no impacts to the N-aquifer in response to Peabody's groundwater pumping* and, given OSM's reduced rate of withdrawals that began in 2006, the mine cannot adversely impact outside of the mine's leasehold. As a consequence of these revisions, OSM will no longer evaluate the mine's impact on the groundwater resources near the tribal communities, despite the statistical evidence in this report (also submitted to OSM in July 2011) that counter OSM's conclusions.

Moreover, this report also demonstrated that, due to the *time-lag effect*, many of the mine-related impacts identified in this study continue to decline, have expressed no recovery to date, and have yet to express the mine's maximum impact. In short, OSM has neither acknowledged the mine's cumulative impacts nor asserted realistic recovery periods for any these groundwater parameters. Rather, OSM implores that the N-aquifer is recovering and that water-levels are rising (monitoring data do not support this conclusion).

Given OSM's discretionary authority, only the discharge from one spring (Burro) and the streams in the unconfined areas will continue to be evaluated for material damage caused by mining; however, OSM's new criteria for material damage have insurmountable damage-thresholds and actual monitoring data will *not be used* to determine their condition. Rather, the simulation results of a groundwater model—*which are generated by the company being regulated and are incapable of simulating discharge from springs or discharge to streams*—will be used to determine the mine's impact on Burro Spring and N-aquifer steams until Peabody's new mining permit expires in 2026 (OSM-CHIA 2008; HSIGeoTrans & WEHE 1999).

Since 1989, OSM has equated the simulations of groundwater models with the actual condition of the N-aquifer, despite the fact that (1) monitoring data consistently diverged from and conflicted with the model simulations; (2) two of OSM's original four thresholds for *material damage* had been crossed; and (3) the other two criteria had never been evaluated as intended. Concurrently, OSM disregarded the conflicting monitoring data, attributed the adverse trends to municipal withdrawals or drought, and has rejected any further consideration that the declining trends could be associated with mine operations (Klein 2011; EA 2011; OSM-EIS 2008, 2006, 1990; OSM-CHIA 2008, 1989; OSM, 2006, 2004, 2000, 1998).

This study found OSM, the lead Regulatory Authority of the Black Mesa-Kayenta Coal Mine, consistently rationalizing the negation of conflicting information with the argument that the current knowledge about the N-aquifer is far greater than prior knowledge of the N-aquifer and, as such, there is no need to evaluate OSM's prior predictions. In short, the *new* data and *new* predictions are comprehensive and accurate, in comparison to the old data and old predictions (see Klein 2011). However, this report demonstrated that throughout the period 1984-2011, OSM has never modified any of its mine-related impact-predictions in reflection of any new information about the N-aquifer.

Collectively, there is no substantive evidence or line of reasoning that would lead to the conclusion that the Regulatory Authority's objective has been "to ensure that the public and the environment is protected" (OSM 2008). To the contrary, in consideration of the history of OSM's discretionary decision-making, it might be argued that the agency has become so rigid in defending its pre-existing conclusions that, ultimately, it eliminated its own oversight responsibilities in order to prevent any further debate on the issue.

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APPENDIX A: LITERATURE REVIEW ON GROUNDWATER MODELING

THE VALUE, LIMITATION, AND PREDICTIVE RELIABILITY OF GROUNDWATER MODELS

Konikow and Bredehoeft (1992) explain that, like hypotheses, groundwater models are generated as a means of suggesting explanations for observed phenomena and predicting causal relationships between phenomena: understanding of a groundwater basin increases when the model is iteratively tested, falsified, and refined over time to develop a more accurate representation of the system.

Groundwater models expose “uncertainties and facilitate discussion of possible responses, which may include various precautionary actions, steps to increase or maintain social flexibility and ecological resilience, and/or research and monitoring schemes to reduce uncertainty” (Carpenter et al. 2002).

A *conceptual groundwater model* is a simplified explanation of the structural and functional properties that characterize a hydrogeological system. A *mathematical groundwater model* quantifies the properties and variables of the conceptual model and integrates them into differential equations in order to increase understanding of the system’s overall behavior. A *Deterministic groundwater model* is a mathematical model created to describe specific cause-and-effect relationships that affect the system’s mass balance; generally, they are used to replicate conditions prior to development and predict conditions throughout the development period and after its cessation (Konikow and Bredehoeft 1992; Bredehoeft 2006).

> The underlying philosophy of process-simulating deterministic-modeling… is that, given a comprehensive understanding of the processes by which stresses on a system produce subsequent responses in that system, a system’s response to any set of stresses can be defined or predetermined through that understanding of the governing (or controlling) processes, even if the magnitude of the new stresses fall outside of the range of historically observed stresses. Predictions made this way assume an understanding of cause-and-effect relations. The accuracy of such deterministic forecasts thus depends, in part, upon how closely our concepts of the governing processes reflect the processes that actually control the system’s behavior. (Konikow 1986)

The accuracy of deterministic groundwater models comes into question when regulatory agencies and the public require assurance that potential impacts from a proposed project have not been underestimated; because decision-makers rely upon impact-assessments to approve or disapprove projects that could adversely affect social and ecological systems, concern regarding the predictive reliability or “correctness” of groundwater models is warranted (Hassan 2004; Woessner and Anderson 1996; Oreskes et al. 1994; Sargent 1990).

Consequently, modelers have pursued methods for testing the veracity of their models: “the notion has emerged that numerical models can be “verified” or “validated”... Claims about verification and validation of model results are now routinely found in the published literature” (Oreskes et al. 1994).

However, procedural inconsistency, semantic confusion, and disagreement regarding model capabilities continue to hinder the modeling process, problematize policy-decisions, and foster public skepticism (NRC 1990, 2000; Leijnse and Hassanizadeh 1994; Konikow and Bredehoeft 1992; Anderson and Woessner 1992a, 1992b).

Some modelers argue that because every groundwater model is designed to address a unique problem, “engineering-confidence” in a model’s veracity is sufficient for preventing adverse impacts (de Marsily et al. 1993; McCombie and McKinley 1993), and faith in this capacity is well promoted: “Hydrogeologists and engineers engrossed in developing and applying ground water models tend to represent the results of their work as “the answer”, as a “highly probable solution”, or a “reasonable probability”” (Woessner and Anderson 1996).

Others argue that the *engineering-confidence* standard is delusory: such subjectivity fails to acknowledge the range of uncertainties that characterizes complex systems and consistently leads to unforeseeable problems at unknowable scales (Holling 1978; National Research Council 1990, 2000; Westley et al. 2002; Bredehoeft et al. 1982; Bredehoeft 1997, 2002; Bredehoeft and Durbin 2009; Konikow and Bredehoeft 1992; Sophocleous 1997; Alley and Leake 2004; Alley et al. 1999; Oreskes et al. 1994; Anderson and Woessner 1992a, 1992b; Anderson 1995; Anderson and Lu 2005; Woessner and Anderson 1996).

“Acceptability of ground water models should be determined by using confirming observations to support subjective judgment. The judgment is made in the context of the stated purpose of the model and the nature of the supporting observations associated with each component of the modeling process” (Woessner and Anderson 1996). The National Research Council[21] (1990) acknowledges the inherent limitations of deterministic groundwater models, adding:

> Modelers must contend with the practical reality that model results, more than other expressions of professional judgment, have the capacity to appear more certain, more precise, and more authoritative than they really are. Many people who are using or relying upon the results [of groundwater models] are not fully aware of the assumptions and idealizations that are incorporated into them or of the limitations of the state of the art. There is a danger that some may infer from the smoothness of the computer graphics or the number of decimal places that appear on the tabulation of the calculations a level of accuracy that far exceeds that of the model. There are inherent inaccuracies in the theoretical equations, the boundary conditions, and other conditions and in the codes. Special care therefore must be taken in the presentation of modeling results. Modelers must understand the legal framework within which their work is used. Similarly, decision-makers, whether they operate agencies or in courts, must understand the limitations of models. (NRC 1990)

PROTOCOL

There is no standard protocol for groundwater system-modeling, ascertaining model validity, or reporting simulation-results. Consequently, agreement upon standards for accepting the conceptual accuracy and predictive-reliability of a deterministic groundwater model continues to be the source of much contention (Anderson and Woessner 1992a; Hassan 2004).

Because there are numerous interpretations of the terms *verification* and *validation*, there are numerous approaches for conducting these processes and disparate standards for gauging their attainment: “Both words imply authentication of both the truth and accuracy of the model” (Konikow and Bredehoeft 1992). When the terms are used interchangeably “to indicate

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[21] *Ground Water Models: Scientific and Regulatory Applications*. NRC members “are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The Members of the committee responsible for the report were chosen for their special competence and with regard to appropriate balance” (NRC 1990).

that model predictions are consistent with observational data… modelers misleadingly imply that validation and verification are synonymous, and that validation establishes the veracity of the model" (Oreskes et al. 1994).

Further, it is often mistakenly assumed that once a model has been *calibrated*, it has also been *validated*, and thus the model is perceived as an acceptable tool for predicting the future conditions of a hydrological basin (Freyberg 1988; Konikow and Bredehoeft 1992). However, Verification, calibration, and validation are three distinct processes, and all three are required for determining the biophysical-accuracy and predictive-reliability of a groundwater model.

"The principal question asked by model reviewers is, "Does the model adequately represent the system conditions such that an answer to the question posed by the modeler or regulator is possible?" To date, the criteria for judging the adequacy of a modeling effort have only been partially established" (Woessner and Anderson 1996).

Given the inherent complexity of groundwater systems and the subjectivity required in the modeling process, Woessner and Anderson (1996) have proposed three underlying principles for modelers and model-users to keep in mind:

(1) Groundwater modeling is inherently uncertain.
(2) Model acceptability should be based upon the strength and number of actual observations that confirm the model's predictions.
(3) Subjective judgment determines if a model appropriately represents the system.

Anderson and Woessner (1992a) offer a modeling protocol (Figure 20) that is widely referenced in the groundwater modeling literature.

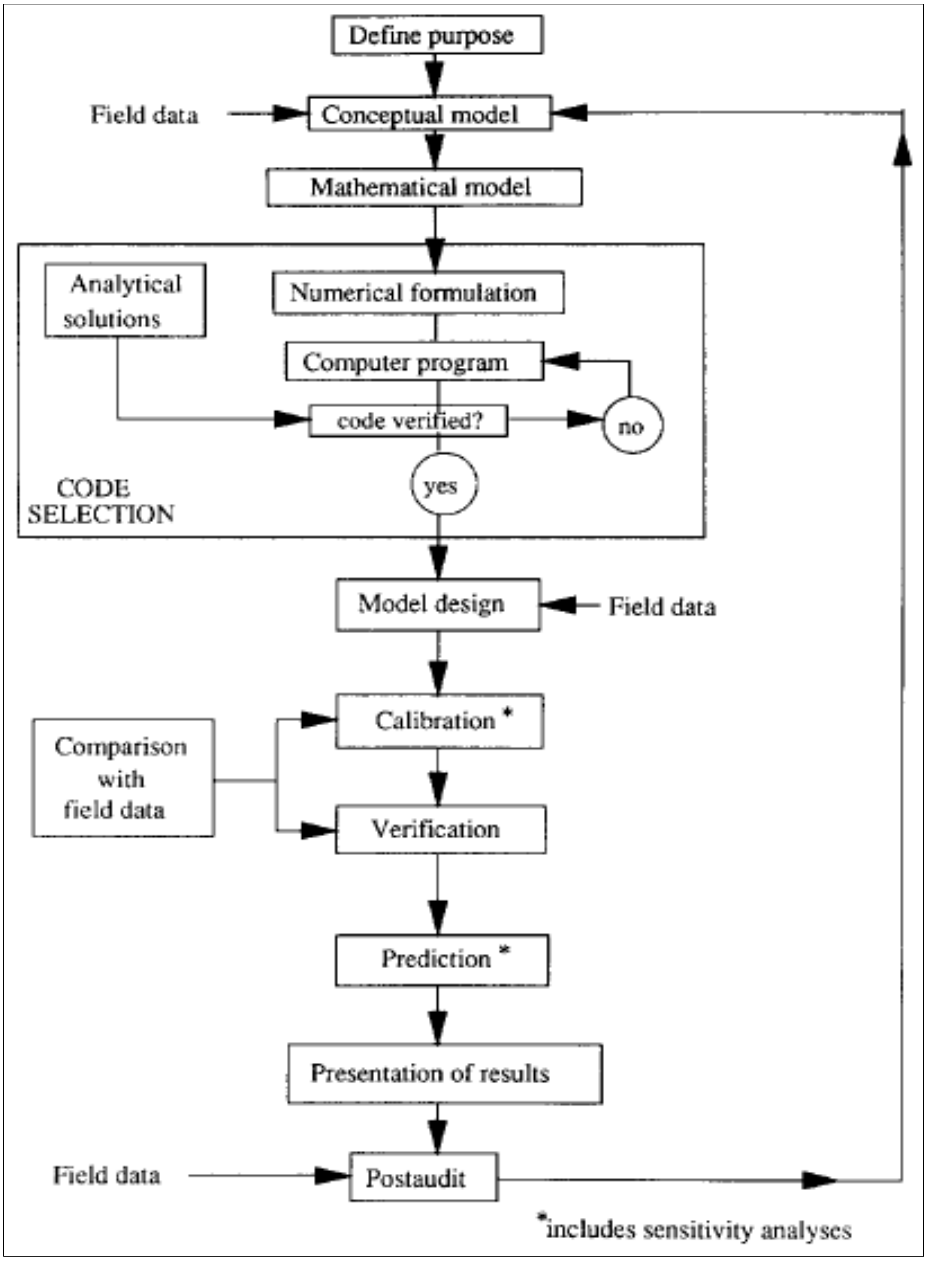

Figure 1. A groundwater modeling protocol (Anderson and Woessner 1992a)

CALIBRATION

Calibration of a groundwater model determines the level of accuracy that a model can reproduce *historical conditions* within a predetermined range of acceptability. Because determining the actual distribution of aquifer parameters is both technically and economically unfeasible, calibration is a method of subjectively selecting a set of parameter values through manual trial and error (or automated programs) for the system. Referred to as *history matching,* the process forces the model to reproduce historical conditions by changing parameter values until an “acceptable” range of accuracy is achieved; “There are no rules other than one’s judgment” (Konikow 1986; Konikow and Bredehoeft 1992, 1993).

Calibration does not result in a unique set of parameters; i.e., different combinations of parameter values can produce the same results. The process addresses the unique “inverse problem” to groundwater modeling (Oreskes et al. 1994): the dependent variables (e.g. hydraulic head) are well known while the independent variables (e.g. parameters, boundary conditions, etc.) are not, thus requiring the subjective “tuning” to force an acceptable level of “empirical accuracy” (van Fraassen 1980).

Calibrated models are often presented, either implicitly or explicitly, as *empirically adequate* representations of the system—that is, as *valid* representation of the system—but this is misleading. Konikow (1986) acknowledges one consistent source of model error when calibration is equated with validation:

> It should be recognized that when model parameters have been adjusted during calibration to obtain “best fit” to historical data, there is a bias towards extrapolating existing trends when predicting future conditions, in part because predictions of future stresses are often based on existing trends…. Concepts inherent in a given model may be adequate over the observed range of stresses, but may prove to be oversimplified of invalid approximations under a new and previously inexperienced type or magnitude of stresses.

Oreskes et al. (1994) explain that the necessity to refine a calibrated model “suggests that the *empirical adequacy* of numerical models is forced… Consider the difference between stating that a model is “verified” and stating that it has “forced empirical accuracy””.

Any model used to predict system behavior should be routinely recalibrated to incorporate new information, changes in the stresses, or revision of the conceptual model; this is generally recognized as part of the *verification* process (Konikow and Bredehoeft 1992, Konikow 1986; Anderson and Woessner 1992a; Anderson et al. 1993).

“Calibration to a number of different stress conditions or time periods provides additional confirming observations that strengthen the use of the model to predict future conditions” (Woessner and Anderson 1996).

A common misperception is that more data and more sophisticated models will result in increased understanding of the system (NRC 1990). As groundwater models have evolved to integrate greater complexity, parameterization of has grown equally complex:

> The model complexity and the subsequent high-dimensional parameterization make objective calibration very difficult, if not impossible. The fitting process that is used to determine modeling parameters can be guided by the principle of parsimony… the best model is the simplest model… while still accounting for the system processes and characteristics evident in the observation. (Hassan 2004, also see Hill 1998).

VERIFICATION

“The purpose of model verification is to establish greater confidence in the model by using the set of calibrated parameter values and stresses to reproduce a second set of field data”; if there is no second set of independent (transient-state) data, the model cannot be verified; a calibrated model may be unverified but its predictions will be less reliable (Anderson and Woessner 1992b).

A model is said to be *verified* if it produces an acceptable match to the independent data without changing the calibrated parameter values[22] (Anderson and Woessner 1992a, 1992b; Woessner and Anderson 1996). Oreskes et al. (1994) argue that, because the word *verify* (from Latin *verus*, meaning *true*) is literally defined as "an assertion or establishment of truth", a *verified* model implies that the model has been confirmed as a true representation of the system, which is unobtainable: "To say that a model is verified is to say that its truth has been demonstrated, which implies its reliability as a basis for decision-making. However, it is impossible to demonstrate the truth of any proposition, except in a closed system." Woessner and Anderson (1996) affirm this position:

> "the incompleteness of data and the non-uniqueness of model parameterization leave doubt as to the usefulness of models. We believe the realization that a groundwater model can not be verified allows for the acceptance of a degree of uncertainty in modeling results. The reasonableness of the modeling effort can only be supported by a large number of confirming observations that remove reasonable doubt."

VALIDATION

> …It is the central tenet of modern scientific method that hypotheses, including models, can never be proved right; they can only be proved wrong. This is why the frequent claims of—and demands for—"valid" models in ecological management, impact assessment, and policy design, are so unsound. (Holling 1978: 95)
>
> …Any scientist who is asked to use a model to verify or validate a predetermined result should be suspicious. (Oreskes et al. 1994)
>
> All models are wrong, some models are useful. (Box 1979)

There continues to be significant disagreement regarding the procedure and purpose for *validating* groundwater models. For example, while Niedermeyer (1998) defines validation in the context of verified calibration-accuracy as discussed in the previous section — "The reliability of model predictions is determined by the accuracy of the calibration… If the model is capable of reproducing the measured data for only one significantly different additional… system-state, the model is said to be validated" — Konikow and Bredehoeft (1992) assert that the calibration process itself indicates a model's uncertainty: "If a model is validated, it follows that the model is valid. A logical inference is that a model certified as valid can make reliable predictions, without qualifications. Yet, accepting that one needs to calibrate a site-specific groundwater model is tantamount to acknowledging the impossibility of validating such a model."

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[22] Verification of the groundwater *model* should not be confused with either the verification of the model's *governing equations,* or *code* verification, which the modeler performs earlier in the process (Anderson and Woessner 1992a; Anderson et al. 1993).

In the groundwater literature, the issue continues to be largely semantic. If, by definition, validation implies that a model is “founded in truth” and is “logically correct” (Hassan 2004), or if it implies that a model “can make reliable predictions, without qualifications”, then groundwater models cannot be validated (Konikow and Bredehoeft 1992, 1993). “Complete confirmation is logically precluded by the fallacy of affirming the consequent and by incomplete access to natural phenomena. Models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic” (Oreskes et al. 1994).

While there is consensus that *absolute* validity is not even a theoretical possibility (Hassan 2004; Oreskes et al. 1994; Konikow and Bredehoeft 1992; Konikow 1995; El-Kadi 1995), some practitioners object to rigid standards and procedures for model validation, arguing that high levels of predictive accuracy is superfluous and that “engineering confidence” is sufficient for the goals of groundwater development (de Marsily et al. 1993; McCombie and McKinley 1993).

Discrepancies regarding the validation-process have significant implications for the regulatory-standards to which model-reliability is held (Hassan 2004; Sargent 1990). The International Atomic Energy Agency (IAEA), US Nuclear Regulatory Commission, International Nuclide Transport Code Intercomparison Study, and INTRAVAL all define validation in the subjective context of a model’s “goodness of fit”, “correctness” or “sufficient” representation. However, these definitions fail to assess the accuracy of the model’s *calculations* (Flavelle 1992).

In 1988, the IAEA updated its definition to include calculation-assessment, stating that validation is a “comparison of model predictions with independent field observation and experimental measurements. A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy” (IAEA 1988). Yet, the *acceptableness* of a model is no less a subjective measure than is *goodness of fit*. The National Research Council (1990) concluded:

> Since rigorous statistical validation tests are generally not appropriate in groundwater applications, model validation is typically an ad hoc exercise that does not have a firm scientific foundation… This leads us to ask how we can distinguish a “good fit” that is based on artificial manipulation of an overparameterized model from a “good fit” that is based on an accurate description of [biophysical] processes… (NRC 1990)

It is axiomatic that models of complex systems cannot be *validated*: they can only be invalidated and refined over time by testing the extent to which they diverge from reality (Holdgate 1978; Holling 1978; Konikow and Bredehoeft 1992). In deterministic groundwater models, *calibration* is commonly used as the basis for sizing sustainable rates of exploitation. However, because the parameter-solution is non-unique, successful comparisons can result from an erroneous model: the iterative process of comparing model-predictions to field observations only *reveals* errors—it does not signify the absence of errors (Konikow and Bredehoeft 1992; Greenberg et al. 1976).

“There are cases in hydrology… where our understanding of processes may be great, but predictive ability is low, and other cases where understanding is minimal, but predictive accuracy is very high. In any event, *the accuracy of the prediction cannot be assessed until after the predicted period of time has passed*” (Konikow and Bredehoeft 1992; emphasis added).

If validation is interpreted to mean that a model can reliably predict the system's future behavior (i.e. *predictive validation*), then it can only be achieved by performing a *postaudit* (Anderson and Woessner 1992b). However, in this context, validation is unlikely: "The issue of validation is mainly a regulatory one, not a scientific one… Because our understanding of a system will always be incomplete, a model can never be proven valid from a scientific standpoint" (Anderson and Woessner 1992b).

SENSITIVITY ANALYSIS

Sensitivity analyses are performed to determine the significance of model-parameters and their influence upon the modeled-system's processes when the parameters are changed. "When parameters that cause increases or decreases in model results are identified, a judgment as to the importance of these variations is made... If the modeling process supports the selection of the final model calibrated parameters, the sensitivity analysis results confirm parameter values are reasonable" (Woessner and Anderson 1996).

According to the National Research Council (1990), sensitivity analysis establishes "the extent to which uncertainty in a given parameter contributes to uncertainty in prediction. Such analyses in many instances can provide the justification for carry out additional field and laboratory studies."

POSTAUDIT

Where *calibration* and *verification* procedures demonstrate that a groundwater model can reproduce past behavior, *validation* tests a model's accuracy in predicting future conditions (Anderson and Woessner 1992: 168). *Predictive-validation*—the process of performing a Postaudit—compares a model's simulation-results to field observations after the predicted period has passed: "A model cannot be considered validated until sufficient testing has been performed to ensure an acceptable level of predictive accuracy… validation requires a postaudit… some 20 years or more after the model has been run" (Anderson 1995: 82).

Groundwater models often provide the bases for required regulatory-studies such as environmental impact assessments (EIA) and cumulative hydrologic impact assessments (CHIA). Ironically, while the literature on EIA-audits is "extensive", very few audits have been documented: "The fact that audits are rare is often attributed to institutional problems: audits are neither required by law nor routinely funded" (Wilson 1998).

Because there has been little research on either the efficacy of prediction techniques or audit methods, "it is possible for predictive techniques to be transferred from one EIS to another without authors ever knowing how well the techniques perform, or how appropriate they are for the intended application" (Tomlinson and Atkinson 1987; also see Wood 2000).

In general, the few postaudits that have been documented occur only after citizens, local scientists, or monitors observe unexpected signs of change; the subsequent "informal audits" investigate the specific observations, making them more practical than "scientific audits", which are (rarely) designed congruently with the original EIA predictions for monitors to track over time (Wilson 1998). Thus, the federally required process for predetermining environmental impacts prior to the approval of permits "is failing to maximize its potential to "learn from experience"" (Wood 2000).

Wilson (1998) developed a nine-step audit-methodology, but this particular method involves “qualitative judgments” about predictions and outcomes. Recommending the same subjective approach that problematizes the EIA process (“minor impacts only”; “impact observed, but insignificant”, etc.), the approach does nothing to ameliorate concerns for and perceptions of prediction-bias.

Further, while the literature calls for more postaudits as a means of improving the *process* for performing impact assessments, nowhere in the literature is it acknowledge that no matter how much the process is improved, the belief that a “reasonable” forecast of future impacts can be ascertained (from an assessment conducted at a single point in time) is delusory (Holling 1978; O’Brien 2002; Lindstrom and Smith 2002; Suskind et al. 2001; Kraft 2006; Ludwig et al. 1993).

To date, only a handful of postaudits have been documented; at best, they express only moderate confidence in model predictions; model errors are consistently attributed to flawed conceptual models and inaccurate estimation of future stressors — both attributable to unavailable data (Konikow and Bredehoeft 1974; Robertson 1974; Lewis and Goldstein 1982; Konikow and Person 1985; Konikow and Patten 1985; Konikow 1986; Person and Konikow 1986; Alley and Emery 1986; Freyberg 1988; Flavelle et al. 1990; Flavelle et al. 1991; Weaver et al. 1996; Stewart and Langevin’s 1999; Anderson and Lu 2005).

> It is likely that there have been hundreds of predictive modeling studies performed since the 1960s. The fact that only five postaudits are reported in the literature suggests that, at least in the USA, models are often used in a crisis mode rather than a management mode. In other words, a model is constructed to answer some pressing question so that a management decision can be made. After the model has served its purpose, it is ‘shelved’ and forgotten or discarded. Most models constructed in the USA are not used for management of the groundwater system on a day to day, month-to-month, or even year-to-year basis. (Anderson and Woessner 1992b)

While the literature illustrates the unreliability of groundwater models, it also demonstrates the value of the postaudit (Brown 1996; Anderson and Woessner 1992a, 1992b; Hassan 2004).

> A major value of the postaudit is that the evaluation of the nature and magnitude of predictive errors may itself lead to a large increase in the understanding of the system and in the value of a subsequently revised model. As new information becomes available, previous forecasts could and should be modified. Feedback from preliminary models not only helps an investigator to set improved priorities for the collection of additional data, but also helps test hypotheses concerning governing processes in order to develop an improved conceptual model of the system and problem of concern. (Konikow 1995: 76).

Konikow (1986) continues to be the most widely referenced postaudit. The study assessed the predictive reliability of a 1968 model built upon forty years of data (1923-1964) on Arizona’s lower Santa Cruz and Salt River Valleys; the calibrated model was used to make predictions though 1974. Konikow concluded that model error was introduced through the inability to predict future stressors and to recognize how a system's historical behavior (under a prior stress-regime) may change under future regimes.

Konikow (1986) illustrated the problem of using a single set of parameter values to predict behavior. Ironically, because the predictions in the original 1968 model showed profound water-level declines throughout the Santa Cruz and Salt River Valleys, significant effort was successfully generated to decrease groundwater pumping throughout the region; this social response to the model's dire predictions was not considered in the model itself, and thus was included among the sources that led to prediction error.

Freyberg (1988) showed that groundwater managers often couple predictive-reliability with the calibration process; Konikow and Bredehoeft (1992) illustrated that model calibration or "history matching" in no way infers predictive reliability; Konikow and Patten (1985) and Anderson and Woessner (1992a, 1992b) illustrated that deterministic models are generally unreliable over the long-term and that predictive errors are usually traceable to a flawed conceptual model and unknowable future stressors. Finally, Brown (1996) explained that although postaudits offer valuable insights for revising model-errors, subsequent improvements takes place only after (1) the model has been accepted, (2) development actions have commenced, and (3) the prediction period has passed.

CONCEPTUAL ACCURACY, PREDICTIVE RELIABILITY, AND MODEL ERROR

In a review of the groundwater modeling literature, Hassan (2004) distilled six factors where error may be introduced into groundwater models, inhibiting their predictive reliability. First, model errors generally exist in three forms: (1) conceptual errors; (2) numerical errors (i.e. the misuse of the equation-solving algorithm); and (3) uncertainties or inadequacies in input data, which are generally attributable to a misinterpretation of aquifer dynamics. When error is apparent, discerning its source is extremely difficult (Hassan 2004; Konikow and Bredehoeft 1992; Konikow and Patten 1985; Konikow 1986; Anderson and Woessner 1992a).

Second, the complexity of large, deep, multi-layered geologic environments means that data required to accurately replication the systems are unavailable; this includes basic parameter values (i.e., porosity, transmissivity, diffusivity, yield, retention, head, gradient, etc.); thickness and permeability of confining layers; deep groundwater inflow from other aquifers; groundwater discharge to streams and springs; evapotranspiration from plants; clearly identified aquifer boundaries; knowledge of appropriate scales for assessing cumulative impacts; and knowledge of the randomness of geologic and hydrogeologic processes over time (Moench 2004; AWWA 2003; El-Kadi 1995; Anderson and Woessner 1992a, 1992b). Even if an extensive database for a particular site exists, "they are often limited in relation to the variety of conditions and parameters that need to be monitored and characterized" (Hassan 2004).

Third, this complexity precludes the determination of the model's conceptual accuracy: "When heterogeneity is significant and data are limited, as is the case in many field sites, there may be no way of judging the model predictions or declaring any degree of satisfaction about the model" (Hassan 2004).

Fourth, knowledge of future stressors and their significance within the altered landscape is unknowable; and fifth, the "significance" of these impacts, and the determination of who will be affected by them, is defined by the entity modeling the system. Thus, *procedural* subjectivity is confounded by the *personal* subjectivity of the modeler: all affected parties are not equal[23].

Fifth, the iterative process of long-term model validation can be extremely expensive. According to the National Research Council (1990), because limited resources generally preclude the collection of the enormous amount of data that would be required to replicate a large-scale system and test the model's veracity, modelers often extrapolate from historical data that were not collected with the intention of being used in mathematical models.

Given such uncertainty, it has been argued that using simulations to determine sustainable rates of development is a misuse of model applications: software-engineers and groundwater-modelers have argued that ascertaining the validity of a model is extremely difficult, that evidence of predictive reliability must always be questioned, and software programs should not be used to determine development (Konikow 1986, 1995; Konikow and Bredehoeft 1992, 1993; van der Heijde and Elnawawy 1992; van der Heijde et al. 1985; van der Heijde and Park 1986; van der Heijde et al. 1993; van der Heijde 1995; El-Kadi 1995; Tsang 1987, 1991; Massmann and Hagley 1995).

Nonetheless, many resource managers continue to assert remarkable confidence in the conceptual and predictive accuracy of their models, but such confidence are delusory:

> Our present understanding of the many processes affecting groundwater is sufficiently adequate to allow us, in theory, to predict responses in a groundwater system. In practice, we are severely limited by the inadequacy of available data to describe aquifer properties and historical stresses and responses, and by an inability to predict future stresses. Overall, extreme caution is required in making, presenting, and accepting predictions of future groundwater behavior. (Konikow 1995)

In order for a model to be accepted as a tool for predicting reliable future conditions of a system, then numerous assumptions must be accepted. However, the range of assumptions that are required in replicating a large-scale system makes the introduction of errors an inherent aspect of the modeling process. At the most basic level, these assumptions include: conceptual accuracy; climatic stability; biological and physical variables function as "norms" (averages); spatial and temporal scales are appropriate for all issues and concerns; and the parameters, conditions, and alterations that have been *insignificant* under past and present conditions will continue to be insignificant under future conditions (Milly et al. 2008; AWWA 2003; Konikow 1986, 1992, 1995; El-Kadi 1995; Konikow and Bredehoeft 1992; Anderson and Woessner 1992a, 1992b).

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[23] Moench (2004) explains that the identification of certain model variables is not an issue of objective mathematical realities, but rather, of subjective perspectives. Suppose that a team of hydrological consultants has determined that the amount of recharge which is "available" for a proposed groundwater development project (i.e. the capture) will reduce the surface-flow of a nearby wash by one-third. The consultants determined that this reduction is "insignificant" to the area's social-ecological-systems because the model-simulations showed that the wash would re-gain any lost-stream before the distant, downstream communities would be affected. Being completely unaffected by the worst-case scenario, the consultants also determine that the downstream communities are not within the project's impact area. Subsequently, the project was permitted because the hydrologists showed that no adverse impacts would result from the project. However, the model may not have included adequate spatial and temporal variables, and it did not simulate the effects of an immediate ten-year drought (the average precipitation rate for the area was used in all simulations); for the stakeholders downstream, the unexpected impacts may have profound and immeasurable implications.

The literature acknowledges this subjectivity; generally, it attributes conflicting perspectives to disciplinary training and professional influence. More clearly stated, underlying any conflicting perspectives, it is assumed that the modeler is, at least, being virtuous to the goal of portraying the groundwater system accurately.

However, given the (1) the political and economic influence of private interests and (2) the legal loopholes of regulatory requirements, there is the potential that embedded within a groundwater model's complexity is the intention to generate optimistic simulation-results rather demonstrate an accurate portrayal of system dynamics (this form of *subjectivity* is not necessarily distilled through verification and regulatory procedures).

> …companies pay consultants handsome fees to obtain lucrative permits to pump [groundwater]. After a Perrier hydrologist in Wisconsin concluded that the company's pumping would not damage the environment, the Sheboygan Press editorialized, "Pardon us for being skeptical, but what else could he say given that he's on the company payroll."
>
> In Florida, Perrier proposed to pump 657 million gallons per year from a well near a spring, yet the company's hydrologist testified at a 1999 hearing that "[you] will not be able to detect a change in the nearby river's flow." My hydrologist colleague… contemptuously dismisses hydrologists who make such extravagant claims as "hydrostitutes". (Glennon 2002: 10)

And Despite Hassan's (2004) confidence in the public's "competency" to understand bio-physical uncertainty in modeling and regulatory processes, the literature in Political Ecology, Public Policy, Environmental Justice, Risk Assessment, etc. is robust with evidence that political and economic influences are highly proficient in obscuring the significance of scientific uncertainty, in misrepresenting the reliability of deterministic-models, and in misleading the public about the significance of cumulative impacts (see *Theory* section in the Introduction).

The *Safe Yield* Water-Budget methodology is one approach in which expert *certainty* and model reliability are implied in order to convey misleading conclusions.

RECHARGE, SAFE YIELD, AND THE WATER-BUDGET MYTH

The *safe yield* water-budget paradigm assumes that if the volume of groundwater withdrawn from an aquifer is less than the rate of natural recharge, then development will be sustainable; if withdrawals *equal* recharge, then discharge will be stopped but storage will remain intact, and is thus sustainable; and if withdrawals exceed recharge, then discharge will be stopped, storage will be depleted, and development is not sustainable (i.e. *groundwater mining*). However, despite the apparent logic of the water-budget paradigm, the method flouts the fundamental principles of hydrogeological engineering:

> Water-resource scientists are concerned that some basic principles are being overlooked by water managers…. Perhaps the most common misconception in groundwater hydrology is that a water budget of an area determines the magnitude of possible groundwater development. Several well-known hydrologists have addressed this misconception and attempted to dispel it. Somehow, though, it

> persists and continues to color decisions by the water-management community. (Bredehoeft et al. 1982)

According to the U.S. Geological Survey, the water-budget paradigm “is an oversimplification of the information that is needed to understand the effects of developing a groundwater system… A pre-development water-budget by itself is of limited value in determining the amount of groundwater that can be withdrawn on a sustained basis” (Alley et al. 1999).

Balleau and Mayer (1988) explain that “It would be hydrologically inaccurate and economically inefficient to ignore the transition period and to assume that ground water is only of two types: 100 percent mined or 100 percent recharged”. Nonetheless, policy decision-makers prefer the method because its mathematical precision implies expert-consensus regarding sustainable groundwater exploitation (Ludwig et al. 1993).

While empirical precision is helpful in winning political buy-in, public-interests are not well served “by adopting an attractive fallacy that the natural recharge rate represents a safe rate of yield” (Balleau and Mayer 1988).

Sophocleous (1997) agreed, “policy-makers are primarily concerned about aquifer drawdown and surface-water depletion, both unrelated to the natural recharge rate. Despite its irrelevance, natural recharge is often used in groundwater policy to balance groundwater use under the banner of safe yield. Adopting such an attractive fallacy does not provide scientific credibility.”

Bredehoeft (1997) decried: “Sustainable groundwater development has almost nothing to do with recharge... However, I continue to hear my colleagues say they are studying the recharge in order to size a development… The water-budget as it is usually applied to scale development is a myth—Theis said this in 1940. Yet the profession continues to perpetuate this wrong paradigm.”

Five years later, Bredehoeft (2002) implored “...the myth goes on; it is so ingrained in the community’s collective thinking that nothing seems to derail it.”

Devlin and Sophocleous (2005) explained that despite the “conclusive theoretical proof” that the water-budget paradigm has no scientific merit, “it still persists”.

In 2008, Milly et al. (2008) explained that climate variability further exacerbates conventional methods of water management:

> Systems for management of water throughout the developed world have been designed and operated under the assumption of *stationarity*. Stationarity—the idea that natural systems fluctuate within an unchanging envelope of variability—is a foundational concept that permeates training and practice in water-resource engineering…. In view of the magnitude and ubiquity of the hydroclimatic change apparently now under way… we assert that stationarity is dead and should no longer serve as a central, default assumption in water-resource risk assessment and planning.

If *stationarity is dead*—that is, if the rate of precipitation cannot be assumed to fall within a predictable range for a specified area—then the paramount variable in all of groundwater management is a fixed uncertainty: “…if the climate is changing, as recent evidence suggests, then the assumption of equilibrium should be questioned” (Milly et al. 2008).

Bredehoeft and Durbin (2009) explain that if equilibrium of a hydrologic basin is uncertain, then the predetermination of sustainable rates of development is precluded by the *time to full capture* problem: "large systems pose a challenge to the water manager, especially when the water manager is committed to attempting to reach a new equilibrium state in which water levels will stabilize and the system can be maintained indefinitely." These attempts are mired by two realities: "(1) a large groundwater system creates a delayed response between the observation of an impact and its maximum effect and (2) there is a long time lag between changing the stress and observing an impact at a distant boundary."

DEBUNKING THE "SAFE YIELD" WATER-BUDGET METHODOLOGY

As Theis (1940) and many others[24] have concisely explained, once the pre-development water-budget has been calculated, *any* groundwater thereafter removed from the aquifer makes the budget invalid: new withdrawals upset the preexisting balance by depleting storage — pre-development equilibrium is lost and the system enters into a *transient*-equilibrium. A new equilibrium is reached only when water-levels throughout the system stabilize and storage is no longer depleted, at which point the effects of withdrawals have been absorbed and distributed elsewhere in the system.

At new equilibrium, groundwater-withdrawals no longer deplete storage but come from some combination of (1) decreased discharge from the aquifer (i.e., as springs, into streams, etc.), and (2) increased recharge into the aquifer (i.e., as *induced* recharge that is pulled in from overlying streams, adjacent aquifers, recharge projects, etc). The decrease in discharge plus induced-recharge (if any) is referred to as *capture*: the pumping-regime equals capture (Devlin and Sophocleous 2005; Bredehoeft 2002, 1997; Alley et al. 1999; Bredehoeft et al. 1982; Theis 1940).

Because *natural* recharge is dependent upon climate and induced-recharge is extremely difficult to discern from natural recharge and may be impossible to quantify, capture is usually a function of decreased discharge. "Once a new equilibrium is reached, the natural discharge is reduced by an amount equal to development—capture equals development. This statement has nothing to do with recharge. Often streams are depleted long before the pumping reaches the magnitude of the recharge" (Bredehoeft 1997: 929).

Bredehoeft and Durbin (2009) explain the most misunderstood aspect of the paradigm, "While the water budget describes the state of the system at a given time, it does not inform us about the time path the system will take to reach the new equilibrium state; the time path depends upon aquifer dynamics".

The time it takes for discharge to be influenced by pumpage depends upon aquifer *diffusivity*, a function of (1) transmissivity to storativity[25]; and (2) the distance from the pumping wells to discharge locations. Generally, the greater the distance that the pumping-wells are from the discharge-locations, the greater the time-period for discharge to be affected (Theis 1940; Bredehoeft et al. 1982; Bredehoeft 1997, 2002; USGS 1999; Balleau and Mayer 1988; Sophocleous 1997, 1998, 2000; Devlin and Sophocleous 2005).

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[24] Including, among others: Brown 1963; Lohman 1972; Bredehoeft et al. 1982; NAS 1982; Bredehoeft 1997, 2002; Balleau 1988; Balleau and Mayer 1988; Sophocleous 1997, 1998, 2000; Alley et al. 1999; Alley and Leake 1999; Devlin and Sophocleous 2005; Bredehoeft and Durbin2009; Leake 2009.

[25] *Transmissivity* is the flow capacity of an aquifer measured in volume per unit time per unit width. Equal to the product of hydraulic conductivity times the saturated thickness of the aquifer. *Storativity*, or the *storage coefficient* (SC), is the volume of water released per unit area of aquifer per unit drop in head; a confined aquifer's ability to store water is measured by its SC (Sophocleous 2000, 1998).

Bredehoeft and Durbin (2009) provide following example: in a simple aquifer[26], groundwater is being withdrawn at a rate of 100 cubic-feet per second (cfs), and Management wishes to maintain a spring that is discharging groundwater at the same rate of 100 cfs. Management establishes the criterion that if the spring's discharge decreases by 10%, then pumping will be stopped. The time it takes for groundwater pumping to reduce the spring's discharge rate by 10% is illustrated in Figure 19.

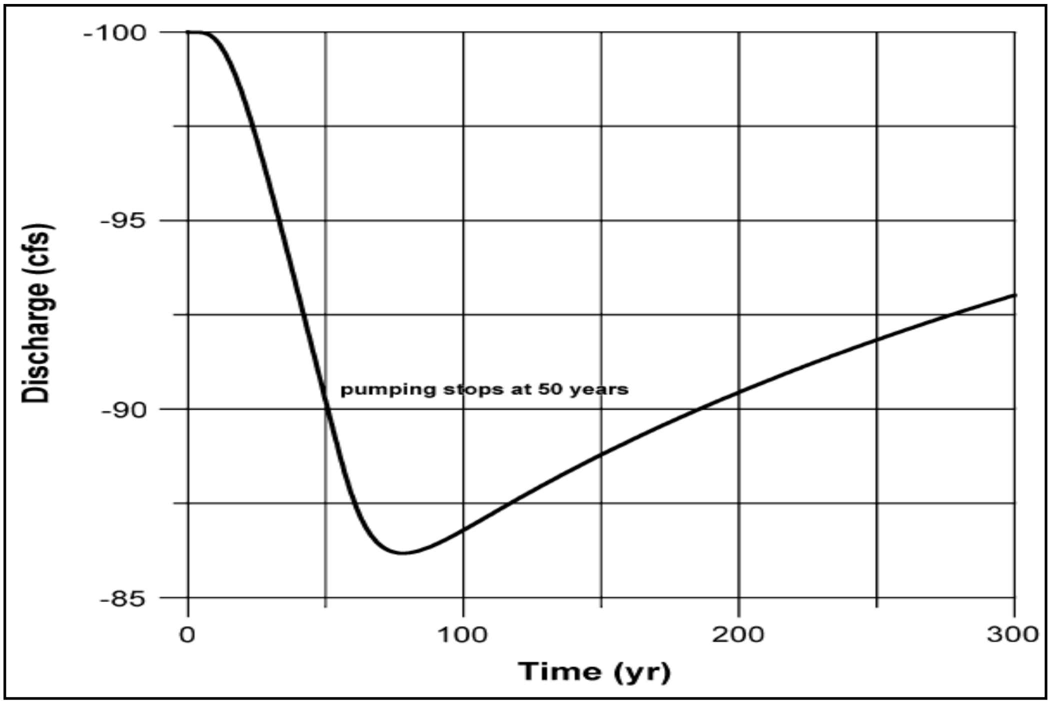

Figure 2. Discharge from a hypothetical aquifer (in Bredehoeft and Durbin 2009)

After fifty years of groundwater withdrawals, the spring's discharge rate decreased to 90 cfs (10%) and pumping was stopped. However, twenty-five years *after* pumping stopped, spring discharge continued to decline and reached its lowest discharge rate of 87 cfs. In other words, "the maximum drawdown at the spring created by pumping takes 25 years after pumping stops to work its way through the system" (Bredehoeft and Durbin 2009).

Further, although pumpage was *equal* to discharge, the system recovers very slowly *after* pumping is stopped: "during the 250 years since the pumping ceased, we have restored just more than 50% of the water that was removed from the storage during the pumping period. You can easily see that this simple system will take approximately 500 years to return to its original state" (Bredehoeft and Durbin 2009).

Numerous USGS hydrogeologists have explained the relatively straight-forward process that explains *capture*; classically trained hydrogeologists will recognize this as the *principle of superposition* or the *superposition calculation.* The superposition calculation requires: (1) distributions of transmissivity and storativity throughout the aquifer (i.e. *diffusivity*); (2) boundary conditions that will be reached by the cone of depression; and (3) the rate of

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[26] Parameters of this simple aquifer: Basin size = 50 X 25 miles; hydraulic conductivity = 0.00025 ft/s; saturated thickness = 2000 ft; transmissivity = .05 ft^2/s (~43,000 ft^2/d); storage coefficient = 0.1% to 10%; phreataphyte consumption = 100 cfs; well-field pumping = 100 cfs; recharge = 100 cfs.

pumping (Devlin and Sophocleous 2005; Bredehoeft 2002; Sophocleous 2000, 1998; Bredehoeft et al. 1982; Lohman 1972; Brown 1963; Theis 1940).

"Missing from the classical analysis is any mention of recharge. The recharge is taken into account by the initial hydraulic head (water table). The initial head is a solution to an initial boundary value problem that includes the recharge and discharge" (Bredehoeft 2002: 341). Figure 20 demonstrates the *capture* at a single location (e.g. at a spring) far from the pumping site: withdrawals have no effect on discharge, initially; over time, discharge decreases and continues to decline long after pumping stress is reduced or stopped.

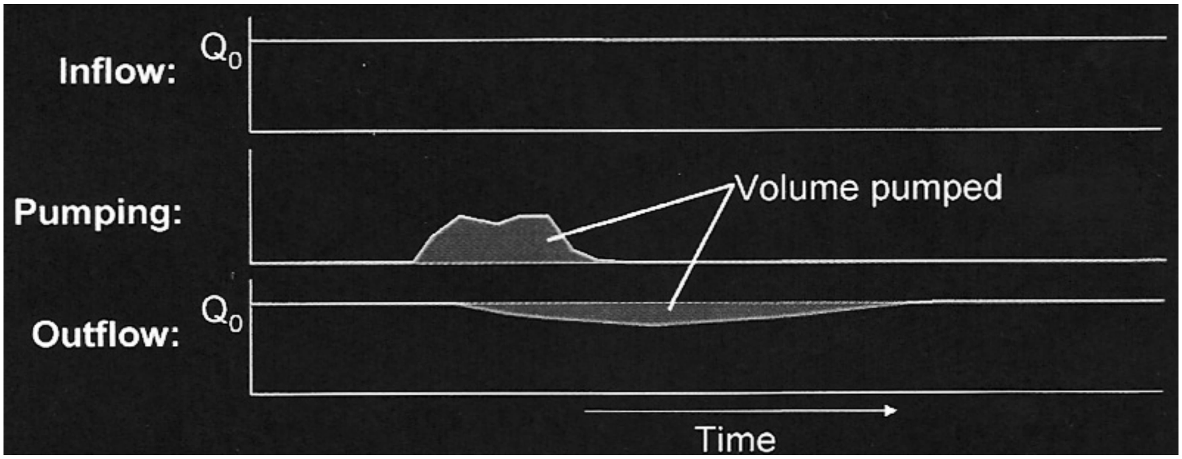

Figure 3. Withdrawals and recovery period (from Leake 2009)

Figure 21 provides a hypothetical, permeable alluvial-aquifer system underlying an island in a freshwater lake (from Bredehoeft 2002; also see Devlin and Sophocleous 2005; Bredehoeft et al. 1982; National Academy of Sciences 1982).

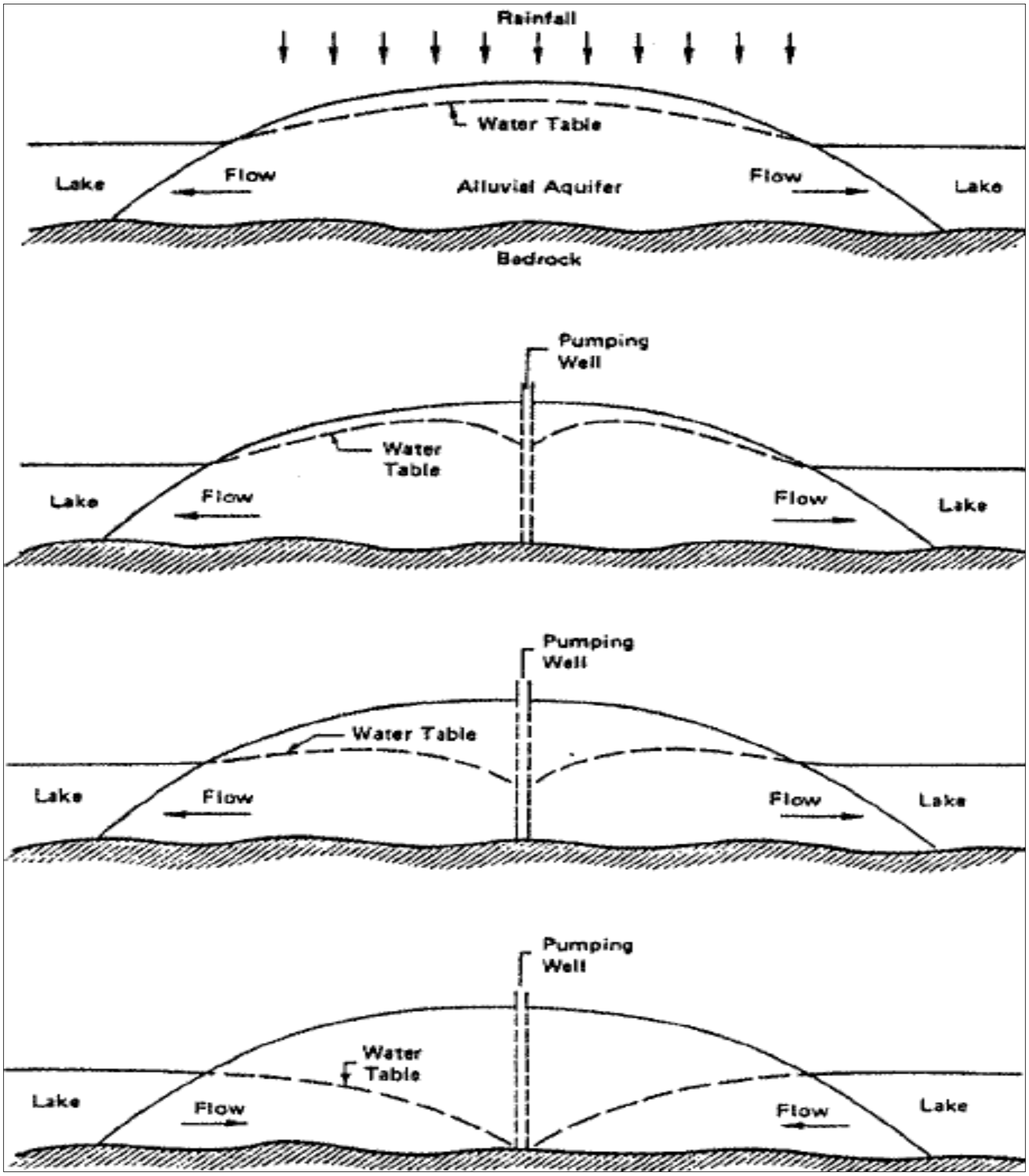

Figure 4. Pumping effects on flow (in Bredehoeft 2002, and NAS 1982)

At Stage 1 (top cross-section), the island-aquifer system is in equilibrium: recharge from rainfall is balanced by discharge from the permeable aquifer boundary at the shoreline into the lake. The aquifer's water-table is created by the distribution of recharge, discharge, and the transmissivity of the aquifer.

In stage 2, a well is installed, withdrawals come from storage (groundwater mining); a *cone of depression* begins to appear. Discharge is not affected: the cone of depression must *reach* the boundary to effect discharge. The time it takes for this to occur is a function of transmissivity, storativity, and boundary conditions.

In stage 3, the slope of the water-table is nearly flat at the shoreline, yet discharge is unaffected, and in stage 4, the slope of the water-table has decreased sufficiently that directional flow has reversed: discharge from the aquifer has ceased, water from the lake now flows into the aquifer: *induced recharge*.

It is significant to point out that the cone of depression has deepened to the base of the pump: depending upon hydrogeological properties of the system, it is possible that the well could have gone dry before discharge at the shoreline was affected

In this example, the pre-development water-table evolved as a function of recharge, discharge, and transmissivity (flow capacity). Prior to development (top cross-section), natural recharge (rainfall) is balanced by discharge to the lake through the permeable boundary; thus:

$$R_0 = D_0 \quad \textit{or} \quad R_0 - D_0 = 0$$

where R_0 and D_0 are the *natural* rates of recharge and discharge, respectively.

We may know transmissivity at a few points on the island, and the discharge rate where it comprises the baseflow of aquifer-related streams. With only this very limited information, we can estimate transmissivity for the *entire* aquifer. By applying Darcy's Law[27], the aquifer's discharge rate to the lake can be obtained at any point along the shore (aquifer boundary):

$$d = T\,(dh/dl)$$

where d is discharge at *a point* along the shore, T is Transmissivity at that point, and dh/dl is the hydraulic gradient (change in head over some distance: the *slope* of the water-table) at that point.

By employing the *point* discharge-rate (above) along the entire shoreline, we obtain *total discharge* (D_0) from the island-aquifer; this is expressed as:

$$\int T\,(dh/dl)\,ds = D_0$$

The well is now installed on the island and pumping begins. At any time, the water-budget for the island-aquifer *after pumping begins* is expressed as

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - P + (dV/dt) = 0$$

where ΔR_0 is the change in the mean rate of recharge, ΔD_0 is the change in the mean rate of discharge, P is the pumping rate, and dV/dt is the rate of change in storage (V is volume of water in storage and t is time). Recall that *natural* recharge equals discharge, so $R_0 - D_0 = 0$.

Thus, the above equation may be simplified:

$$\Delta R_0 + \Delta D_0 - P + (dV/dt) = 0$$

When the system reaches a new equilibrium, storage will no longer be depleted and water-levels stabilize; thus $dV/dt = 0$. At new equilibrium, our water-budget now expresses the *capture* attributable to pumping; i.e., the dynamic rate of sustainable withdrawals:

---

[27] Darcy's Law (1856): *the rate of flow is proportional to the pressure gradient in the water*. Thus, there is only one way to reduce flow to discharge areas: change the pressure gradient, which changes water-levels throughout the area between the wells and discharge area (Theis 1940; Bredehoeft et al. 1982, Bredehoeft 2002; Devlin and Sophocleous 2005).

$$\Delta R_0 + \Delta D_0 = P$$

It is significant to reiterate that natural recharge is dependent upon climatic conditions and is unlikely to be changed, and induced recharge may not occur at all. In such cases, $\Delta R_0 = 0$. Capture from discharge is the determining factor for sizing development:

$$P = \Delta D_0$$

“Notice that to determine sustainability we do not need to know the recharge. The recharge may be of interest, as are all the facets of the hydrologic budget, but it is not a determining factor in our analysis” (Bredehoeft 2002).

Devlin and Sophocleous (2005) explain that the *safe yield* paradigm implies that groundwater aquifers are fixed-directional-flow systems, analogous to a properly functioning kitchen sink: water enters through the faucet and leaves through the drain, but water never leaves through the faucet. While aquifers may behave like fixed-directional-flow systems under some conditions, conditions may change and cause unexpected impacts over the long-term. Unlike sinks, the point of discharge may become a point of recharge; this is seen in Figure 22 (unconfined aquifer ‘U’ and the confined aquifer ‘C’).

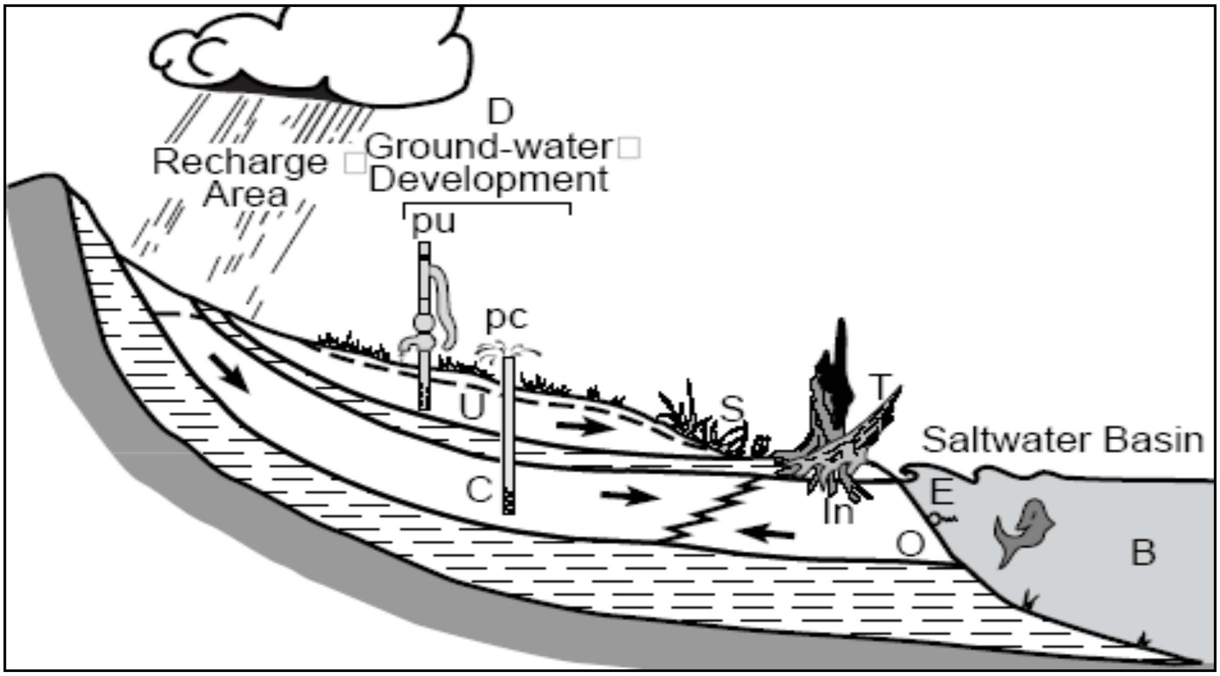

Figure 5. Adverse impacts from the water-budget (in Sophocleous 1998)

Development occurs (area D), including pumping from both confined and unconfined aquifers. Safe yield causes no decline in water-table (U) or head (C); reduction of outflow from U degrades the wetlands (T); reduces outflow from C into the saltwater basin (B) and induces saltwater intrusion into the freshwater aquifer (O), harming vegetation (T) and degrading the riparian area (E) (Sophocleous 1998).

Like the development strategies of other industries, the safe yield paradigm reflects the reasoning of economic-equilibrium theory, conceptualizing a groundwater basin as a fixed-directional system. Flows are quantified and, with the short-term reasoning fostered by return-on-investment incentives, we expend the extent of *capital* reserves that will still allow us to remain hydrologically solvent. Like crop yield, lumber yield, or fish yield — *safe yield* is a "single-product exploitation goal" (Sophocleous 1997), and a "single-variable intervention" (Westley et al. 2002). It represents a linear conceptualization of a natural system that is imposed upon nonlinear, complex, imbricate system.

Determining sustainable rates of development by focusing upon a single factor, such as recharge, is misleading. Numerous variables (aquifer structure, parameters, well location, pollution sources, current and future stressors, climatic variability, etc.) affect estimations. If development plans are not holistic, acknowledging the dynamic connectedness of various systems throughout the watershed—social, ecological, and hydrogeological—then human control may degrade the systems they intend to protect, through various scales of time and space (Sophocleous 1997; Westley et al. 2002; Holling and Gunderson 2002).

Given the time to new equilibrium, even *adaptive* monitoring-programs may not identify signals of change within a time-frame to prevent irreversible harm: "Monitoring for control… has fundamental problems. The maximum impacts are larger than those observed at the time pumping stops, and they occur sometime after the pumping stops. This is especially true if the monitoring occurs some distance away from the pumping. In addition, groundwater systems will be very slow to recover to their predevelopment state once pumping is stopped" (Bredehoeft and Durbin 2009).

Groundwater pumping causes slow and often undetectable changes that may not be captured in sophisticated models or vigilant monitoring efforts; it takes a great deal of time for a hydrogeological system to absorb the pumping stress and reach a new equilibrium; and the massive spatial extent of some systems further obscures signs of change. In the management office, however, the lack of perceivable problems is often attributed to technical skill and a comprehensive understanding of system dynamics: a high level of confidence in model-predictions is assumed, obscuring the evolving reality.

> …through initial success with command and control, managers lose sight of their original purposes, eliminate research and monitoring, and focus on efficiency of control. They then become isolated from the managed systems and inflexible in structure. Simultaneously, through overcapitalization, society becomes dependent upon command and control, demands it in greater intensity, and ignores the underlying ecological change or collapse that is developing. (Holling and Meffe 1998)

APPENDIX B: DESCRIPTIVE STATISTICS WITH OUTLIERS FOR PEABODY WITHDRAWALS

Data for Kayenta withdrawals are available from 1984-2008; data for spring discharge are available for the period 1987-2008; and Peabody withdrawal data are available for the period 1968 – 2008 (Chart 1, below). However, because withdrawals declined by approximately 70% after 2005, the regression of Peabody Withdrawals to discharge from Moenkopi School Spring (or to water-level in Kayenta well BM3), for example, is skewed by the three years of reduced withdrawals (Chart 2).

As might be expected, descriptive statistics for Peabody withdrawals (the period 1987-2008) express three outliers representing withdrawals for 2006, 2007, and 2008 (Chart 3). Due to these three years, the data are not distributed evenly under the normal fit; the box-plot expresses three outliers; and the three outliers skew the distribution.

It is not acceptable to remove outliers simply because data points appear to be anomalies in the data set. However, this is not the case here because these three years are not *anomalous* data points within the data set. Rather, Peabody made a management decision to change its withdrawal regime by decreasing withdrawals by 70%. In this case, the outliers are removed because they do not represent the data set's normal conditions.

With these three years removed from the data set (Chart 4), descriptive statistics express the small number of data points within the data set as distributed more evenly.

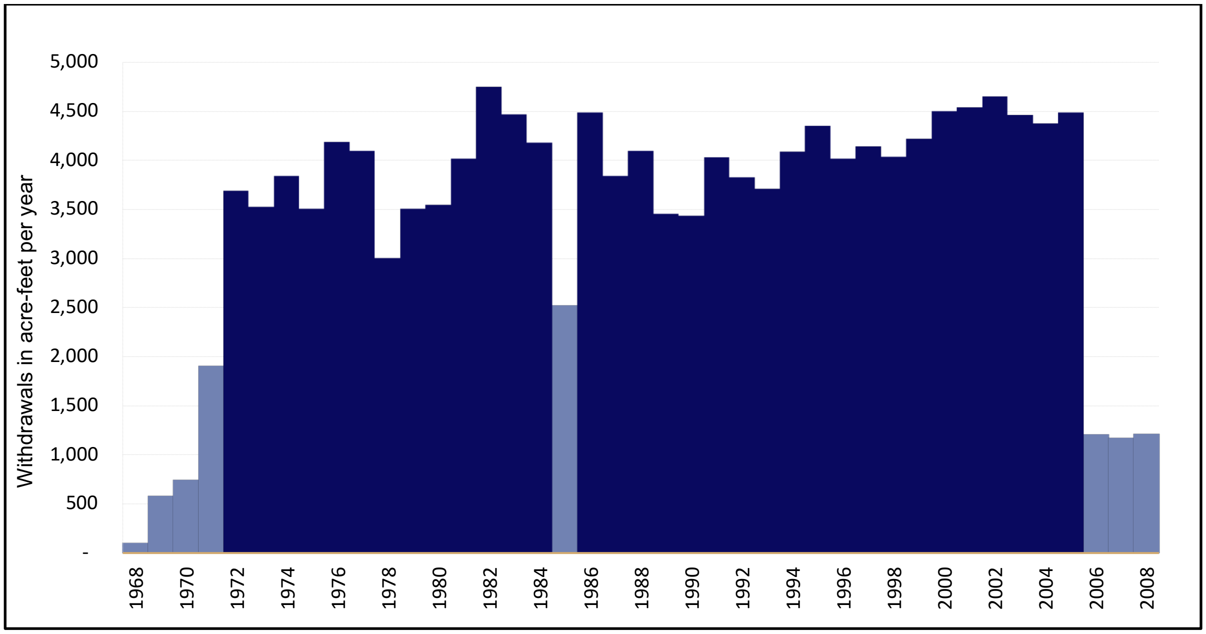

CHART 1

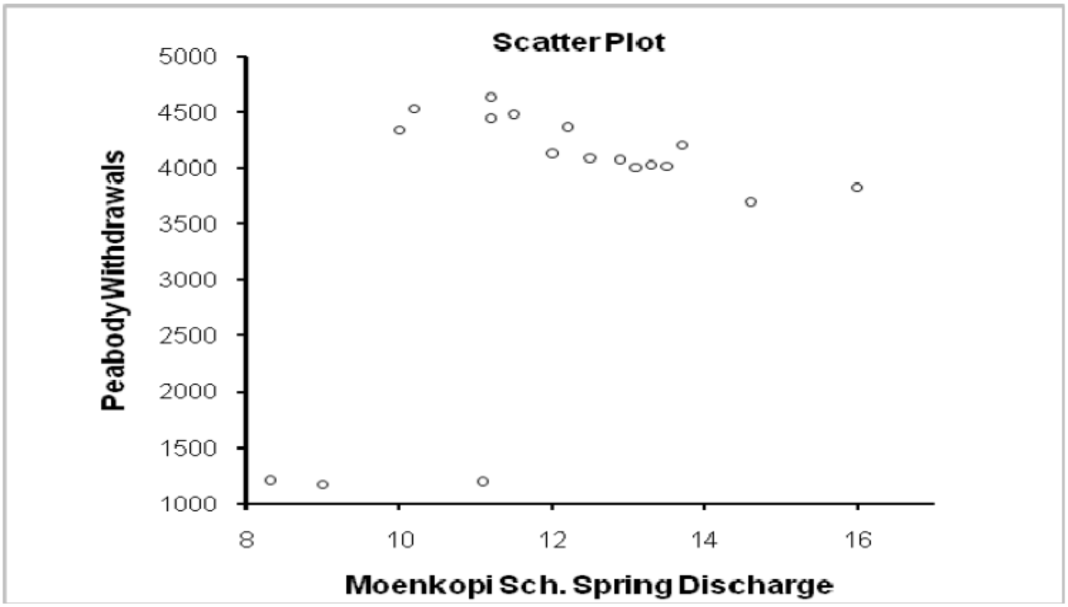

CHART 2

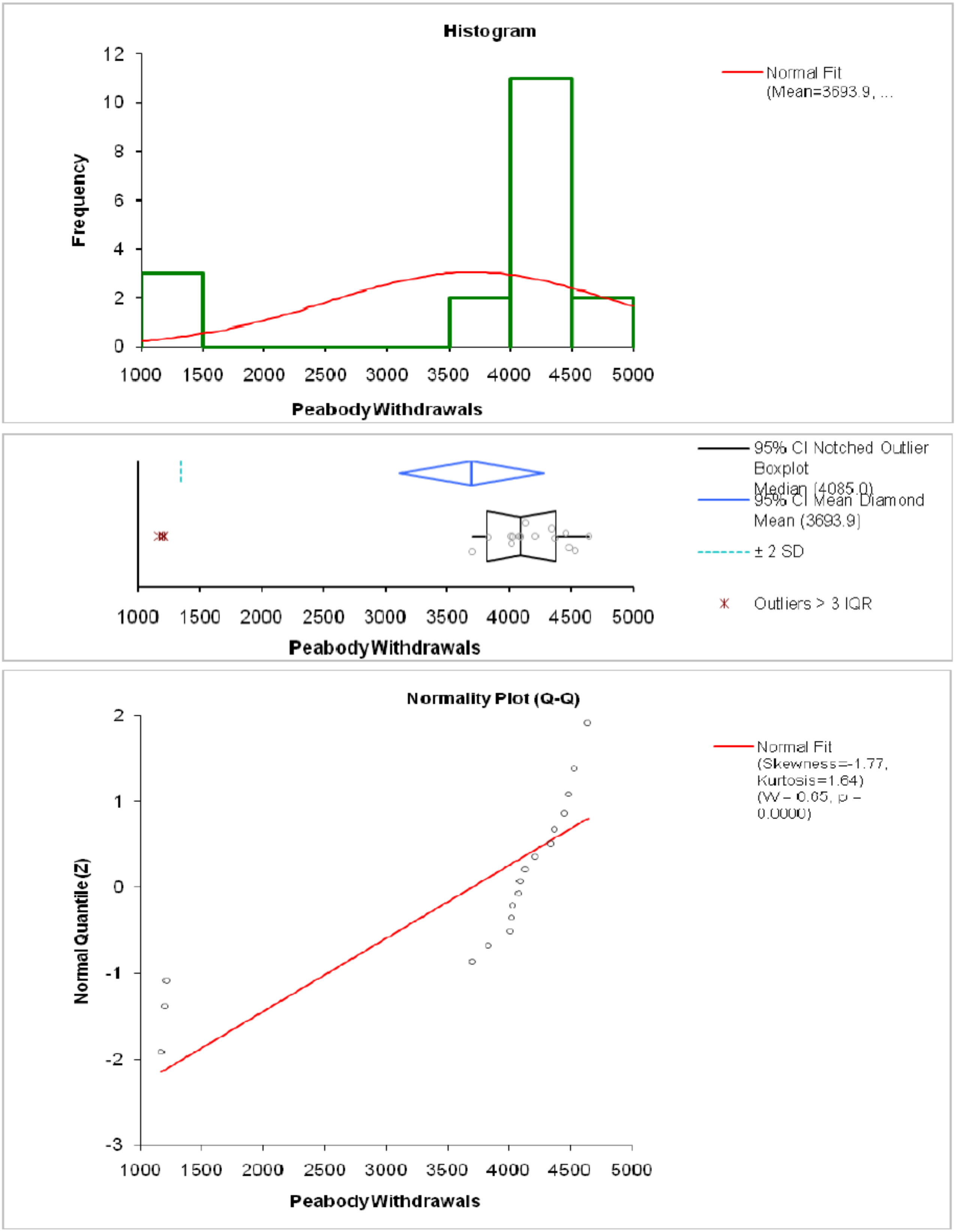
Histogram
Frequency
12
10
8
6
4
2
0
1000
1500
2000
2500
3000
3500
4000
4500
5000
Peabody Withdrawals
Normal Fit
(Mean=3693.9, ...
95% CI Notched Outlier Boxplot
Median (4085.0)
95% CI Mean Diamond
Mean (3693.9)
± 2 SD
Outliers > 3 IQR
1000
1500
2000
2500
3000
3500
4000
4500
5000
Peabody Withdrawals
Normality Plot (Q-Q)
Normal Quantile (Z)
2
1
0
-1
-2
-3
1000
1500
2000
2500
3000
3500
4000
4500
5000
Peabody Withdrawals
Normal Fit
(Skewness=-1.77, Kurtosis=1.64)
(W = 0.65, p = 0.0000)

CHART 3

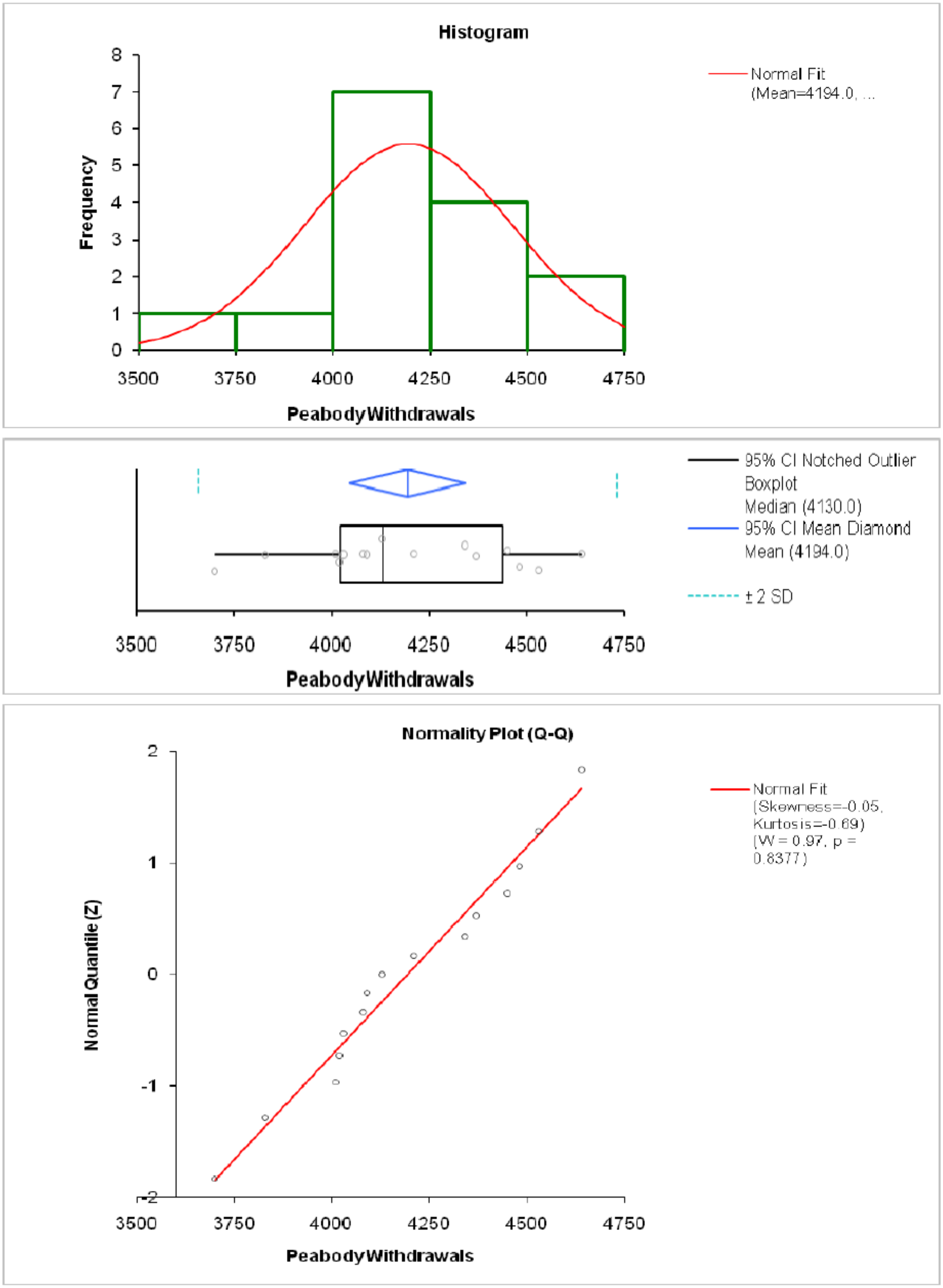
Histogram
Frequency
0
1
2
3
4
5
6
7
8
3500
3750
4000
4250
4500
4750
PeabodyWithdrawals
Normal Fit
(Mean=4194.0, ...
95% CI Notched Outlier Boxplot
Median (4130.0)
95% CI Mean Diamond
Mean (4194.0)
± 2 SD
3500
3750
4000
4250
4500
4750
PeabodyWithdrawals
Normality Plot (Q-Q)
Normal Quantile (Z)
-2
-1
0
1
2
3500
3750
4000
4250
4500
4750
PeabodyWithdrawals
Normal Fit
(Skewness=-0.05, Kurtosis=-0.69)
(W = 0.97, p = 0.8377)

CHART 4