Comparison of Electromagnetic and Natural Potential Geophysical Investigations near the Emperious Tailings Pile
Creede, Colorado

Above: Electromagnetic Method Investigation

Left: Natural Potential Method Investigation

Willow Creek Reclamation Committee

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EXECUTIVE SUMMARY

The Willow Creek Reclamation Committee installed a series of monitoring wells in the lower floodplain area of Willow Creek to investigate groundwater contamination in the vicinity of the Emperious tailings pile. Several wells have produced samples with high conductivity and significant concentrations of metal contaminants.

Non-intrusive geophysical methods were examined as a potential cost-effective means that could more fully characterize the spatial extent of contaminated groundwater. Several different methods are available, and the success and utility of different methods may depend on local geologic and aquifer conditions. Therefore, studies of a limited portion of the floodplain were conducted with two different geophysical methods in order to evaluate the effectiveness of each method to characterize contaminated groundwater in the area. The results of each study were used to place several new monitoring wells in the floodplain, and water quality data from the new wells was, in turn, used to compare the predictive success of each method.

The URS Corporation performed an investigation in the floodplain area using an electromagnetic method between June 13 and June 16, 2002. The electromagnetic method study produced results in the form of "quadrature" and "inphase" data. Karst Geophysics, Inc. used a natural potential method to investigate the floodplain area between May 6 and May 14, 2002. The present report provides a brief comparison of the effectiveness of the two geophysical techniques to identify areas of contaminated ground water and also provides some interpretation of study results.

Water quality results from the new wells were consistent with the electromagnetic method results. However, water quality in the new wells did not correspond as well with the natural potential anomalies. Electromagnetic quadrature results appeared to be more directly related to contaminant levels than electromagnetic inphase results. Therefore, the electromagnetic quadrature method appeared to be the most effective geophysical technique method to identify contaminated ground water in the lower floodplain area of Willow Creek.

The EM quadrature method results indicated that an area of contaminated groundwater may be present along the north and east side of the study area to the northeast of the railroad grade and near highway 149. The contaminated ground water may be related to the Emperious tailings pile, or could possibly be coming from an intersection with the Amethyst vein. The primary channel of Willow Creek may be a losing stream in the study area. There are some indications that groundwater contamination could be mixing or diffusing somewhat with the creek water in a transverse direction. However, more study is needed to verify these possibilities.

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INTRODUCTION

The Willow Creek watershed is located in the eastern San Juan Mountains in southwestern Colorado. Willow Creek enters the Rio Grande just below the town of Creede. Figure 1 shows the location of Creede. The Willow Creek watershed is seriously impacted by historic mining activities. The Willow Creek Reclamation Committee (WCRC) was formed in 1999 to direct a community-based effort aimed at improving water quality and physical habitat in the watershed as part of a long-term management program to restore aquatic resources and protect the Rio Grande from future fish kills.

The alluvial floodplain area below the town of Creede and near the Emperious tailings pile is identified as an area of concern for water quality contamination. Figure 1 also displays an aerial view of the Emperious tailings pile and the lower Willow Creek watershed. The Emperious tailings pile originated as a retention pond for mill tailings in the 1930's that was used extensively until it was regraded and capped with alluvial materials in the late 1980's (WCRC 2003). The impounded mill tailings might be a significant potential source of contaminated groundwater that could be migrating towards Willow Creek or the Rio Grande.

The WCRC installed a series of monitoring wells in the floodplain area to investigate groundwater contamination in the vicinity of the Emperious tailings pile. A shallow alluvial aquifer was observed, and several wells produced samples with high conductivity and significant concentrations of metal contaminants. Table 1 presents water quality data for monitoring wells that were installed prior to the current study. Presented values are the average of selected water quality constituents from the November 18, 2002 and April 3, 2003 sampling events. For a complete description of groundwater quality monitoring results, please see the "Report on Characterization of Groundwater in the Alluvial Deposits Beneath the Floodplain of Willow Creek Below Creede" that was produced by the WCRC in 2003. Monitoring wells with significantly higher contaminant levels are described by WCRC (2003) as "contaminated" (noted with bold text) while other wells are described as "clean". The water quality descriptions noted in the table are referenced in figures in the results section of this report.

Table 1. Selected Water Quality Data from Pre-Study Monitoring Wells

Well	Desc.	Cond. (umhos/cm)	TDS (mg/L)	dCd (ug/L)	dZn (ug/L)	dPb (ug/L)	dCu (ug/L)	dAl (ug/L)	SO4 (mg/L)	field pH
MWFP5	clean	239	165	16	6553	4.3	<1	18	75	6.23
MWFP7	clean	222	150	15	8120	9.1	<1	163	69	6.19
MWFP8	**contam.**	**3880**	**4695**	**725**	**537850**	**<2**	**534**	**85397**	**2340**	**3.22**
MWFP9	**contam.**	**4490**	**5419**	**421**	**603825**	**7.0**	**29**	**32296**	**3105**	**4.20**
MWFP10	**contam.**	**3760**	**4662**	**1192**	**530725**	**4.3**	**1019**	**113763**	**2617**	**3.17**
MWFP11	**contam.**	**3060**	**3691**	**970**	**438025**	**5.5**	**358**	**80417**	**1878**	**3.72**

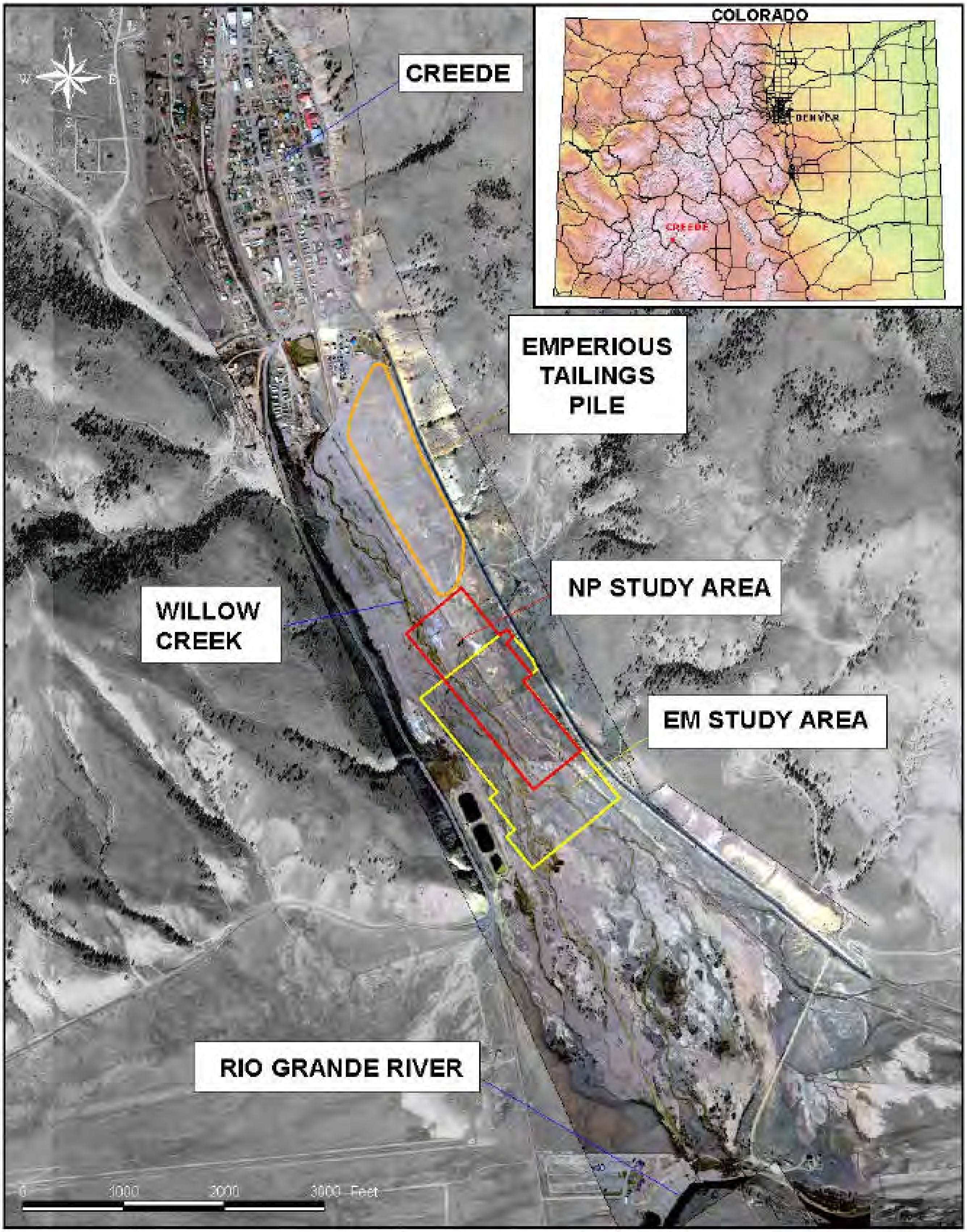

Figure 1. Location of Creede, Lower Willow Creek, and NP and EM Study Areas

Non-intrusive geophysical methods were examined as a potential cost-effective means that could more fully characterize the spatial extent of contaminated groundwater. Several different methods are available, and the success and utility of different methods may depend on local geologic and aquifer conditions. Therefore, studies of a limited portion of the floodplain were conducted with two different geophysical methods in order to evaluate the effectiveness of each method to characterize contaminated groundwater in the area. The results of each study were used to place several new monitoring wells in the floodplain, and water quality data from the new wells was, in turn, used to compare the predictive success of each method.

The URS Corporation (Denver, CO) performed an investigation in the floodplain area using an electromagnetic (EM) method between June 13 and June 16, 2002 (URS 2002). Karst Geophysics, Inc. (Golden, CO) used a natural potential (NP) method to investigate the floodplain area between May 6 and May 14, 2002 (Karst 2002). NP was also used to investigate subsurface flows along short sections of East Willow Creek on May 11 and along the north bank of the Rio Grande on May 30. The NP investigations along East Willow Creek encompassed private and Forest Service land downstream of the Solomon mine. The WCRC previously installed two shallow wells in that area to monitor for contamination in the groundwater. NP readings were taken in the water along the west bank to locate possible subsurface inflows. NP anomalies primarily indicated metal objects within the stream, but there were four other sites at which the readings might have indicated inflows. The Rio Grande NP readings were taken in soil along the north bank between the mouth of Willow Creek and the Wason Ranch. Six prominent anomalies were discovered that could relate to subsurface water flowing between nearby ponds and the river. No comparisons of geophysical methods can be made in these two areas, because EM surveys were not conducted along East Willow Creek or the Rio Grande; however, these results may warrant further evaluation to determine if the NP survey was an accurate detection method for subsurface flows in these areas.

The present report provides a brief comparison of the data produced by the EM and NP studies as well as some interpretation of study results. However, much of the information in the current report is drawn directly from the project study reports; refer to the respective project reports for complete information about the studies.

METHODS

Grid Layout

A grid was laid out and surveyed by personnel from Ducks Unlimited and the Willow Creek Reclamation Committee in order to spatially tie readings from the geophysical studies. The grid was about 1100 feet wide and extended from an area near monitoring well MWFP8 down-valley about 2100 feet to the south and east. Wooden stakes and plastic pin flags were placed on a 100 foot spacing on the southwest to northeast transects, and transects were surveyed every 100 or 200 feet to the south and east. Three additional transects were laid out during the NP study continuing up-valley to the northwest at 200 foot intervals. The grid locations for the EM and NP studies are also shown in Figure 1.

Topographic contours were created using elevation data from the Ducks Unlimited grid survey. Coordinates for monitoring wells were confirmed using differentially corrected GPS so that well location could be accurately mapped in GIS. Figures from the EM and NP studies were digitally scanned and georeferenced in GIS using the survey grid locations so that the results from the studies could be overlain and compared.

Natural Potential Method

Natural electric currents cause detectable potential (voltage) differences that can be detected on the earth's surface. Currents can result from chemical reactions around natural conductors (e.g. metals), moving fluids, diffusion-adsorption processes, localized heating, and chemical gradients in the subsurface.

Fluid flowing through a granular medium produces a voltage drop along its path that is proportional to the driving pressure of the fluid and is dependant on a range of liquid and soil properties. This potential is the principal signal that is utilized for groundwater mapping using the natural potential (NP) method. NP responses can result from both vertical and lateral ground water flow.

With the NP method, a reference electrode is positioned in the soil at a base station. Milli-volt readings are then taken along a transect using a roving electrode that is connected to the reference electrode by a long wire. The electrodes are placed in shallow holes to contact moister soil. The roving electrode consisted of a cluster of 3-1.25 inch diameter electrodes that were sampled twice so that each data point consisted of an average of 6 readings. Changes in the ambient electric field were monitored by 2 electrodes placed 250 feet apart, and NP readings were taken next to the reference electrode between each transect. NP data were then corrected by removing background NP changes due to solar heating and ambient noise.

NP profiles were generated for each transect. Adjacent profiles were "stacked", and NP anomalies that appeared related across two or more transects were traced and identified as anomaly trends. NP data were also contoured, but Karst preferred the traced anomaly trends to the contours for interpretation. Please see Karst (2002) for additional details.

Electromagnetic Method

The electromagnetic method (EM) produces data related to the electrical conductivity of the subsurface. A transmitter coil is used to generate a time-varying magnetic field into the ground. A receiver measures the transmitted primary field as well as secondary fields that are produced in the ground by small eddy currents. Two data components are produced by the EM measurements; the quadrature phase component and the inphase component. The quadrature component is linearly related to the ground conductivity and is therefore most responsive to geologic variations. The inphase component is a ratio of the secondary magnetic field to the primary field and is more sensitive to electrically conductive materials such as metallic objects or ground water with a high conductivity than the quadrature measurement.

The EM study was conducted using a Geonics EM-31 instrument. Readings from the instrument are influenced by the subsurface to a maximum depth of about 15 feet. Groundwater levels in monitoring wells in the area range from about 3 to 13 feet (except for MWFP6 which is dry), and it was considered that this penetration depth was sufficient.

Generally, EM values are not used to directly interpret subsurface conditions. However, measurements above a general background value are considered anomalous and variations indicate changes in subsurface conditions. Contaminated and conductive groundwaters usually produce large anomalies. However, anomalies can also be produced by metallic debris, structures, and utilities. Dry soil and rock are generally less conductive, but EM changes can indicate layers with different porosity or lithology.

Data were collected along each transect and cross-transect line with an average density of about 2 feet. Data were tied to the surveyed grid markers, and results were color contoured using computer software. Please see URS (2002) for additional details.

RESULTS

Natural Potential Method
The transverse NP profiles identified several peaks that were characteristic of anomalies. Several peaks were more or less consistent between profiles, and several NP trends were identified in the longitudinal direction. Figure 2 overlays the NP trends that were identified by Karst on an aerial photo of the floodplain area with other GIS information. Numbers, as identified by Karst (2002), indicating consistent trends are included on the figures using similar display colors. Topographic contours were generated using the EM grid survey and are also included on the figures to show ground surface elevations in feet above mean sea level.

The strongest and most distinct NP trend was identified as Trend 1 (shown in orange in Figure 2). At the northern end of the study area, Trend 1 is in line with contaminated well MWFP10. The trend continues to the southeast following the western edge of the railroad tracks before crossing to the eastern side of the tracks near contaminated well MWFP8. The trend follows the eastern edge of the railroad tracks to the southeast extent of the study area and matches the curve of the tracks. Much of the lower portion of trend 1 to the east of the railroad tracks coincides with a dry overflow channel containing fine-grained sediments. These fines are atypical of the surrounding area and may be derived from tailings. Karst noted that the principal anomaly trend could be either the effect of the fine-grained, dry sediments, or the expression of an underflow channel containing materials derived from the tailings. Similar NP readings before and after a bucket of the material was placed in an undisturbed area suggested that the fines were not responsible for trend 1. Also, it is noted that the railroad grade is older than the tailings pile, and sediments derived from the tailings pile should not extend under the tracks. NP trend 1 could also be related to the railroad tracks or rails that could have been discarded and buried. However, Karst did not expect the railroad to affect readings as the tracks are elevated above the ground and noted that no evidence of buried rails was visible.

Trend 6 may be related to discharge from a topographic basin. Karst noted that the basin area was excavated below stream level to supply material to cap the tailings pile. The extent of the basin is apparent from the topographic contours, and areas of mud from ponded water can be noted in the aerial photos. Surface channels containing fine sediments similar to those associated with trend 1 were also associated with trend 6. The northern end of trend 6 is in line with contaminated well MWFP8. Monitoring well MWFP6 is located near the central portion of trend 6 but is dry.

Trends 2 and 3 were identified near the northeast corner of the study area. The trends straddle contaminated monitoring wells MWFP9. Although the trend direction appears in line with trend 6, the trends are relatively short and NP responses did not continue to trend 6.

Trends 4, 5, and 7 were identified to the west of the railroad grade. Trend 4 envelops monitoring wells “clean” wells MWFP5 and MWFP7. These trends appear related to subsurface flow of relatively cleaner water from the creek.

Electromagnetic Method

Contours generated from EM quadrature measurements are presented in Figure 3 and contours generated from EM inphase measurements are presented in Figure 4. The anomalous trends identified by the NP study, monitoring wells, and topographic contours are also overlain. The location of active creek channels and the railroad tracks were plotted on top of the color contours for reference.

Both the EM quadrature and inphase measurements indicate anomalous values in the northeast portion of the study area nearest the tailings pile and to the southeast along the east side of the valley. This indicates that contaminated or high-conductivity groundwater may be present in this area. URS noted that if the eastern part of the valley is fault controlled, contaminated groundwater emanating from the tailings pile could be migrating southeast along the fault.

The anomalous EM area is most extensive and apparent in the quadrature measurements. Quadrature measurements may be more influenced by geologic characteristics than inphase measurements, and geologic differences between the tailings area and the alluvial floodplain or possible areas of shallow bedrock along the margin of the valley could also influence the quadrature results. An area of slightly anomalous inphase measurements follows the Willow Creek channel area which may indicate a higher groundwater table due to the creek bed and a "loosing" stream reach. A line of blue-colored dipoles can be noted from the quadrature measurements that are related to the railroad tracks.

The EM results, especially the EM quadrature results, correspond well with water quality data from the monitoring wells that were installed prior to the study. The "clean" wells MWFP5 and MWFP7 are located within areas of low EM quadrature response indicated by blue and green colors. As mentioned earlier, EM inphase response are slightly higher in this area indicating that inphase results may be responding to the presence of cleaner water from Willow Creek rather than contaminant levels. Monitoring well MWFP8 is a contaminated well and is located within an anomalous purple area indicated by both the EM quadrature and inphase measurements. Well MWFP6 is currently dry and is located within an area with lower EM readings.

Comparison with New Monitoring Wells

After completion of the NP and EM studies, potential locations for the installation of new monitoring wells were suggested by Karst Geophysics and URS based on their study results. Karst Geophysics suggested the location of monitoring well MW17, where NP trend 1 and trend 6 appear to join near the southeast edge of the study area, would be contaminated. URS suggested the location of monitoring well 18, at a point that was indicated as significantly anomalous (purple) by the EM quadrature measurements and somewhat anomalous (red) in the EM inphase measurements, would be contaminated. Conversely, the location of each of these wells is not in areas suggested to be contaminated by the opposing study. The location of well MW17 is in an area of relatively low EM response, and well MW18 is not located within a significant NP anomaly trend. Both studies suggested that the location of monitoring well MW19 would be relatively uncontaminated. New monitoring wells were installed at these locations by the WCRC. Monitoring well MW20 was also installed at a location very near contaminated well MWFP9 for use in potential flux studies. Table 2 presents the average of selected water quality constituents from November 18, 2002 and April 3, 2003 from the new monitoring wells.

Table 2. Selected Water Quality Data from New Monitoring Wells

Well	**Desc.**	**Cond. (umhos/cm)**	**TDS (mg/L)**	**dCd (ug/L)**	**dZn (ug/L)**	**dPb (ug/L)**	**dCu (ug/L)**	**dAl (ug/L)**	**SO4 (mg/L)**	**field pH**
MW17	clean	357	280	23	20848	<2	5	753	163	4.16
MW18	**contam.**	**3220**	**6313**	**495**	**363925**	**4.0**	**689**	**27883**	**1160**	**5.00**
MW19	slight c.	987	765	374	109040	6.5	325	16838	525	4.06
MW20	**contam.**	**4255**	**5750**	**561**	**501900**	**28.5**	**236**	**25922**	**2915**	**4.12**

Water quality data from the new monitoring wells do not correspond well with the NP study results. Data from well MW17 indicate that the groundwater at this point is relatively clean. However, the water quality data does correspond well with the EM study results. Monitoring well MW18, located in a high EM response area, appears to be contaminated; while monitoring well MW17, located in an area of lower EM response, appears to be clean. The sample set (3 wells) is small for the purpose of statistical conclusions. However, water quality data from the new monitoring wells do support the EM study results more than the NP study results.

Both studies suggested that well MW19 would be clean. Monitoring well MW19 appears to be relatively "clean", although it is noted here with "slight contamination" as it has somewhat higher contamination levels. Although it is still within an area of lower EM quadrature response, well MW19 is located somewhat closer to an area of higher EM quadrature response than "clean" wells MWFP5 and MWFP7.

The general water quality descriptions of monitoring wells installed before and after the geophysical studies are also indicated along with NP and EM data on Figures 2, 3, and 4.

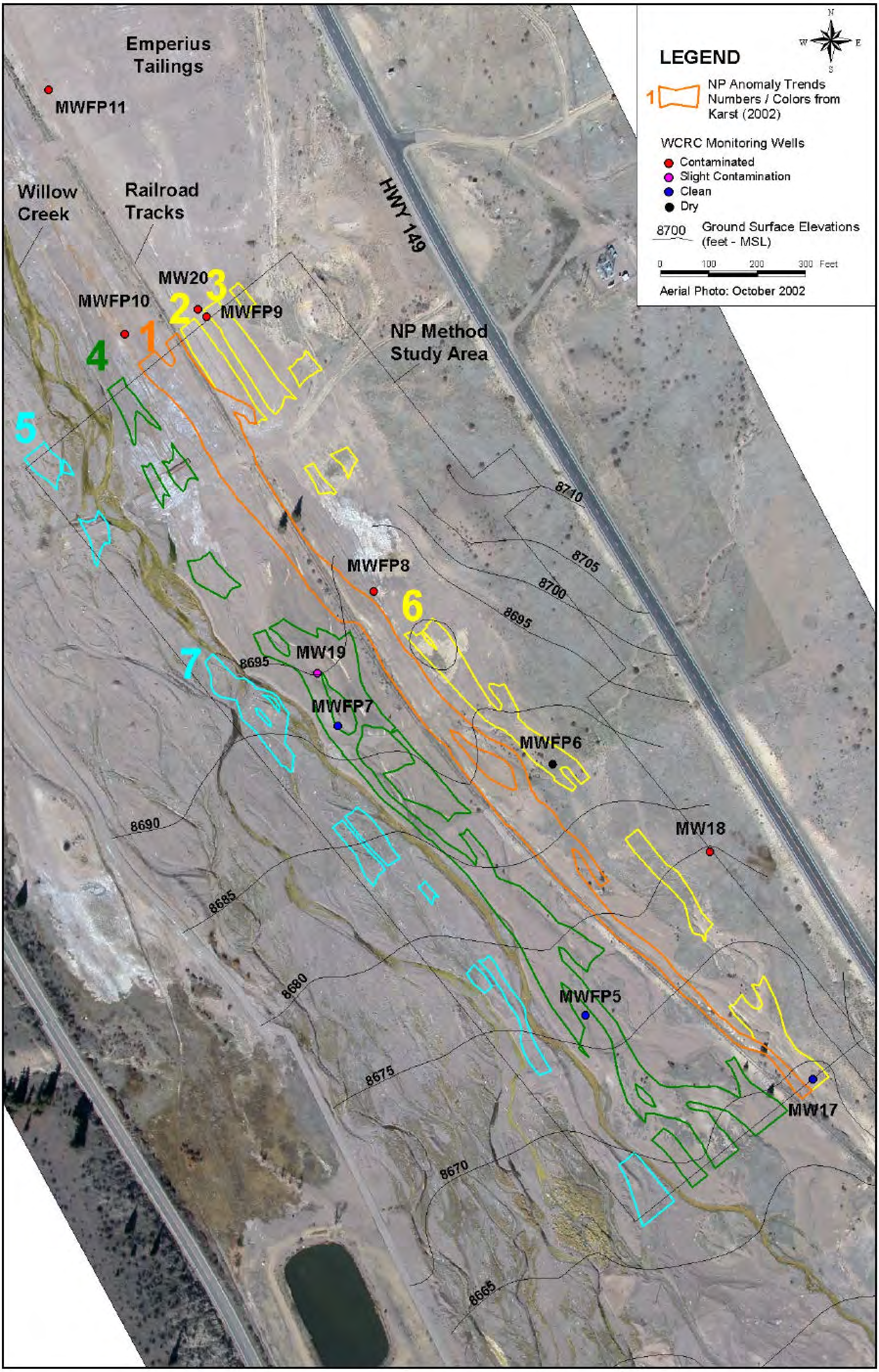

Figure 2. Comparison of NP Study Results and Water Quality of Monitoring Wells

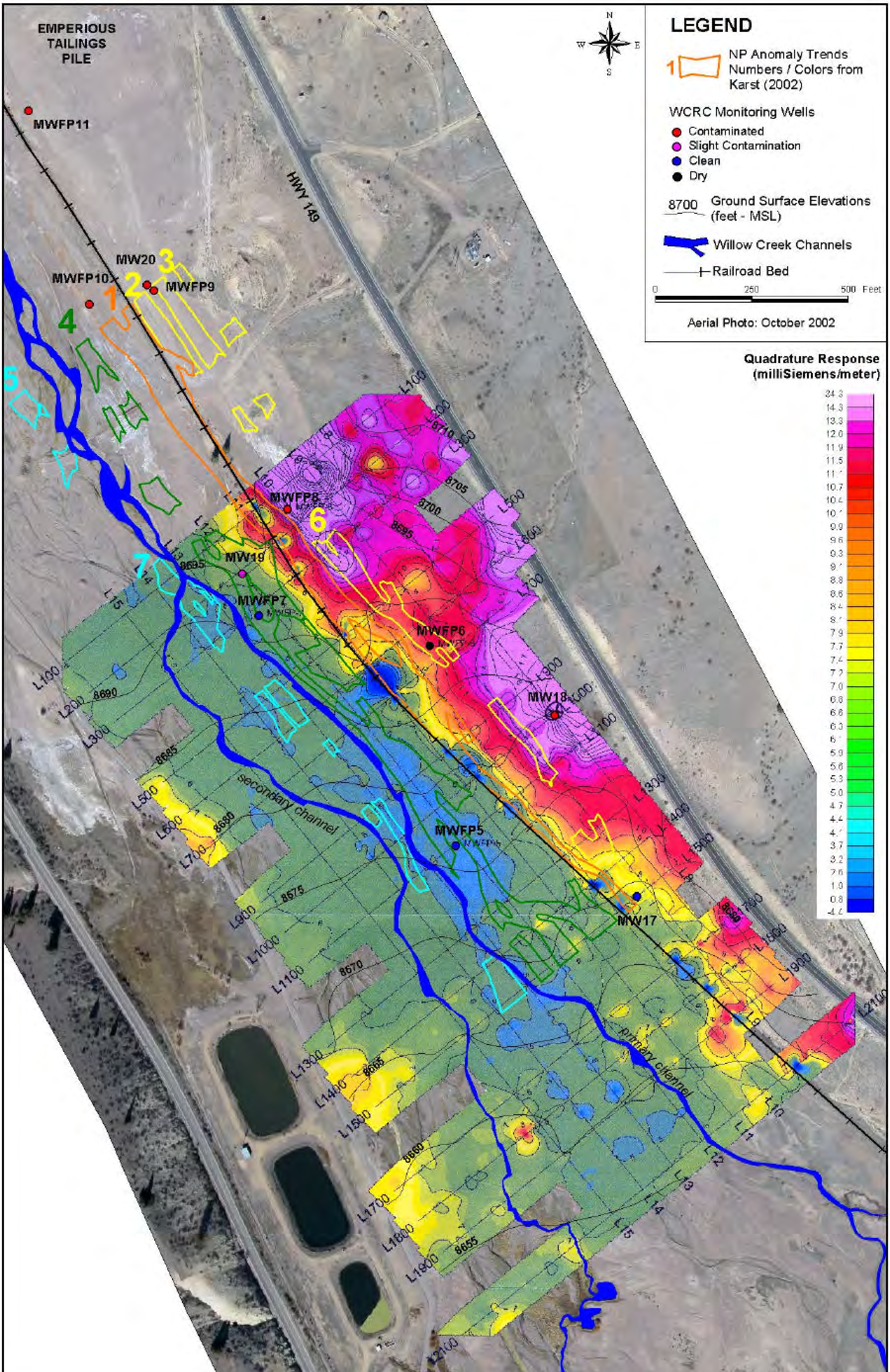

Figure 3. Comparison of EM Quadrature Results, NP Study Results, and Water Quality of Monitoring Wells

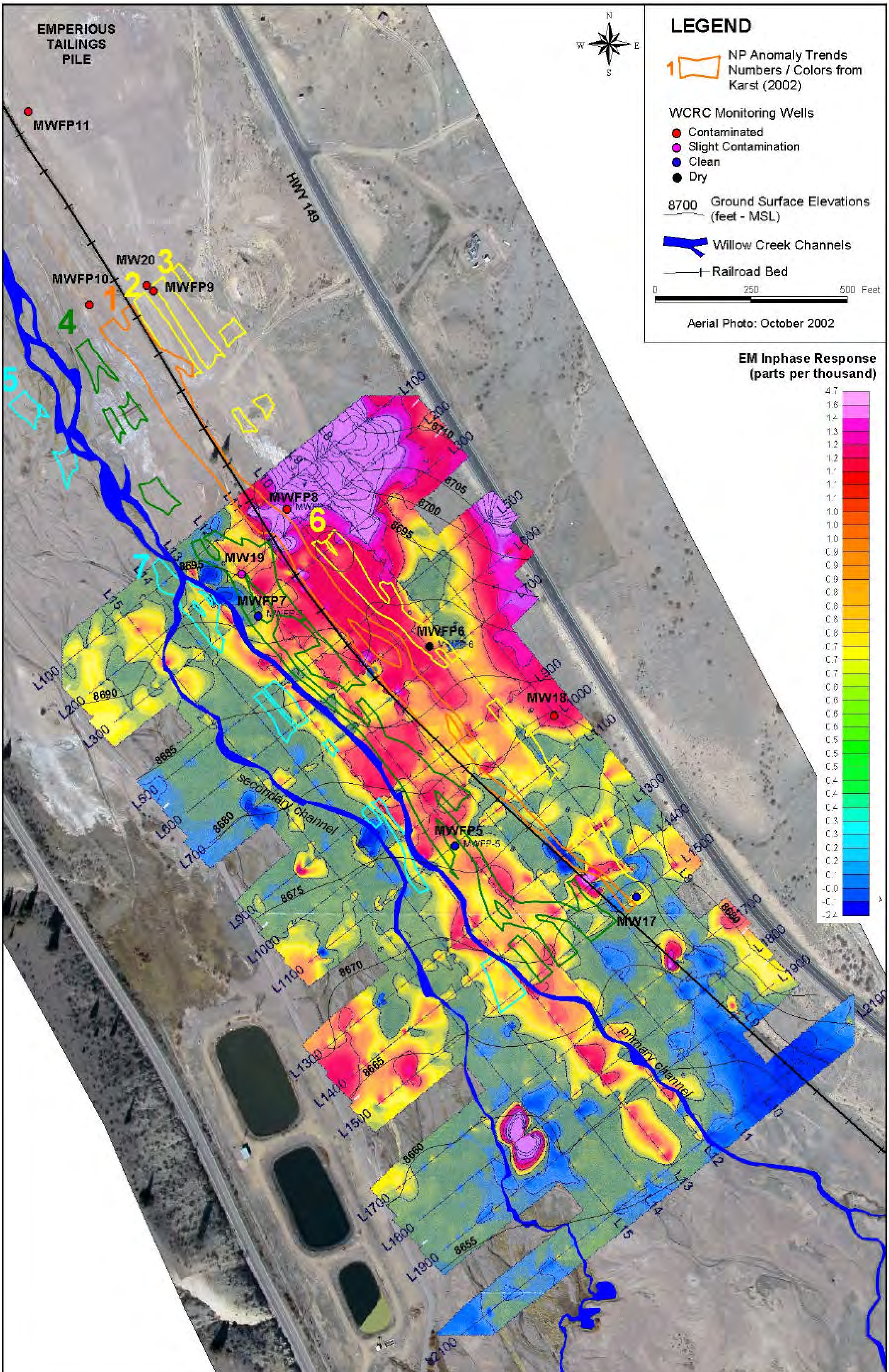

Figure 4. Comparison of EM Inphase Results, NP Study Results, and Water Quality of Monitoring Wells

DISCUSSION

The EM quadrature results are consistent with contaminant levels in monitoring wells that were installed both before and after the study. The EM inphase corresponded relatively well with contaminated wells, but results were also fairly high along the Willow Creek bed and near "clean" wells MWFP5 and MWFP7. Therefore, the EM quadrature results appear to correspond best with groundwater contaminant levels, while EM inphase results may be more related to the saturated aquifer thickness than contaminant levels. Water quality from monitoring wells placed after the studies were not consistent with the NP results. Therefore, the EM quadrature method appears to be most effective to identify areas of contaminated groundwater in this area. The penetration of the EM method signal is limited to about 15 feet, but this penetration depth appeared sufficient in the study area.

Although the primary purpose of this report was to compare the effectiveness of the EM and NP methods, the EM quadrature results also provide useful information about groundwater contamination in the study area, and study results are examined briefly here.

The highest EM quadrature response extends along the north and east margins of the study area. Two areas of the highest EM quadrature response, with response ranging from about 13 to over 30 milliSiemens/meter, are indicated by the color purple in Figure 3 near wells MWFP8 and MW18. The high levels near MWFP8 may indicate an area of contaminated groundwater that could possibly be emanating from the Emperious tailings pile. This area of contaminated ground water could extend continuously along the east side of the study area. Dry well MWFP6 is located between the two areas of highest response, and the area of somewhat lower EM response may be related to a thinner saturated aquifer depth related to underling bedrock contours. URS (2002) suggested a fault to the south and east may be directing contaminated water to the second high level near well MW18. However, a fault does not likely offset the upper alluvial gravels. The small area of higher response at the eastern end of transects L500 and L600 at the edge of highway 149 suggests that the contaminated water near well MW18 may be coming from a source to the east of the highway. Bob Kirkham, a professional geologist that has worked in the area, suggested that the Amethyst vein could potentially intersect the alluvial valley and be producing contaminated water at this point (Kirkham pers. comm.).

The EM quadrature results appears to be directly related to contaminant levels in the ground water. According to the NP method description in Karst (2002), the NP method responds to moving water streams, diffusion-adsorption processes, and chemical gradients. Therefore, NP results may be less related to overall groundwater contaminant levels. It is conceivable that NP anomalies could be related to a flow, mixing or diffusion boundary in the transverse, rather than longitudinal, direction. Trends 1 and 6 may indicate mixing or diffusion of contaminants from the highly anomalous areas indicated by the EM results to the south and west, while trend 4, 5, and 7 may indicate flow away from the active creek channel. The somewhat higher contaminant levels in MW19 may indicate that contaminated groundwater to the northeast may be mixing with cleaner creek water to the southwest at this diffusion boundary. The higher EM inphase results along the primary Willow Creek channel may also indicate that Willow Creek is a losing reach within the study area. This would indicate that regional ground water flow may be more in a down valley direction towards the Rio Grande than inwards towards Willow Creek.

CONCLUSIONS

The EM results were consistent with contaminant levels that have been measured in monitoring wells in the study area. NP anomalies did not correspond as well with available well data. The EM quadrature results appeared to be more effective than EM inphase results at identifying areas of contaminated groundwater. Therefore, EM quadrature appears to be the most effective method to identify contaminated ground water in the lower floodplain area of Willow Creek, and should be used if a more extensive characterization of contaminated groundwater in the area is desired in the future. The success of the EM method may be related to the geologic and aquifer conditions of the area and may not be the most effective method in other areas.

The EM quadrature method results indicate that an area of contaminated groundwater may be present along the north and east side of the study area to the northeast of the railroad grade and near highway 149. The contaminated ground water may be related to the Emperious tailings pile, or could possibly be coming from an intersection with the Amethyst vein. Willow Creek may be a losing stream in the study area. There are some indications that groundwater contamination could be mixing or diffusing somewhat with the creek water in a transverse direction. However, more study is needed to verify these possibilities.

REFERENCES

Karst. 2002. Natural-Potential Survey along Willow Creek in Creede, Colorado. Karst Geophysics, Inc. Golden, CO.

Kirkham, B. 2003. Personal communication. Alamosa, CO.

URS. 2002. Geophysical Investigation near the Emperious Tailing Pile Creede, Colorado. URS Corporation. Denver, CO.

WCRC. 2003. Report on Characterization of Groundwater in the Alluvial Deposits Beneath the Floodplain of Willow Creek Below Creede. Creede, CO.