Identifying environmental impacts of underground construction

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Abstract Dewatering of the groundwater resource and associated reduced flow of surface water features are potential negative impacts when constructing underground facilities. Little work has been done to develop methods for the early detection of environmental impacts on water resources where major underground construction is being undertaken. Recognizing this, prior to construction of two rock tunnels in the southwestern USA, a 3-year preconstruction program was implemented to monitor over 100 wells, springs, and streams in the project area that might be affected. This preconstruction monitoring phase has established data for a hydrologic reference which indicates a high degree of spatial and temporal variability. This variability must be accounted for when trying to identify construction-related impacts. The project area was subdivided into areas of similar characteristics based on geologic and hydrologic features. Measurements from features within each unit were then normalized and aggregated to derive a single representative flow parameter. This representative flow was then correlated to precipitation and major stream flow records to allow for a method of estimating unimpacted flow and groundwater levels during and after construction. Application of this method proved useful in determining and enabling a quick response to construction-related impacts.

Résumé L'épuisement des ressources en eau souterraine et le phénomène conséquent de la baisse du régime des eaux de surface sont des impacts potentiels et négatifs lies à la construction souterraine. Peu d'études ont porté sur le développement de méthodes de détection des impacts environnementaux sur les ressources hydrologiques, lorsque de grandes constructions souterraines sont planifiées. Dés lors, avant la construction de deux tunnels dans la roche dans le Sud-Ouest des USA, un programme de pré construction sur trois ans, visant le suivi d'une centaine de puits, sources et cours d'eau, a été mis en place. Cette phase de surveillance précédant la construction, a permis d'établir un état de référence hydrologique révélant entre autre l'importance de la variabilité spatiale et temporelle. Cette variabilité doit être prise en compte lorsque l'on s'essaye à la définition des impacts. La zone d'étude a été subdivisée par entités présentant des caractéristiques géologiques et hydrologiques communs. Les mesures de ces différentes entités ont été ensuite normalisées et agrégées de manière à n'en sortir qu'un seul et unique paramètre d'écoulement. Cet écoulement représentatif a été corrélé aux enregistrements de débits et de précipitation, permettant la mise en place d'une méthode d'estimation de l'impact pendant et après la construction, sur les niveaux piézométriques et les débits. Il est prouvé que cette méthode est fort utile, apportant une réponse rapide à la caractérisation des impacts.

Resumen El drenaje de recursos de agua subterránea con la reducción asociada de flujo de agua superficial constituyen impactos potenciales negativos cuando se construyen instalaciones subterráneas. Se ha hecho poco trabajo para desarrollar métodos que permitan la detección temprana de impactos ambientales en los recursos hídricos donde se están desarrollando construcciones subterráneas grandes. Tomando esto en cuenta se implementó, con anticipación de tres años antes del inicio de la obra, un programa de monitoreo abarcando más de 100 pozos, manantiales, y arroyos, en el área donde se construirían dos túneles en roca en el suroeste de Estados Unidos. Esta fase de monitoreo en la etapa de pre-construcción estableció datos para un marco hidrológico el cual indica un alto grado de variabilidad temporal y espacial. Debe de explicarse esta variabilidad cuando se trata de identificar los impactos relacionados con la construcción. El área del proyecto se dividió en áreas de características similares en base a las características hidrológicas y geológicas. Se normalizaron las mediciones de ciertas características dentro de cada unidad y se agregaron para derivar un parámetro único de flujo representativo. Este flujo representativo se correlacionó con la lluvia y los registros de caudales de los ríos principales para estimar un método que permita calcular flujos sin impacto y niveles de agua

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subterránea durante y después de la construcción. La aplicación de este método mostró ser útil en determinar y permitir una respuesta rápida a impactos relacionados con la construcción.

Keywords Groundwater protection · Environmental impact detection · Underground excavation

Introduction

Historically, groundwater studies associated with the design and construction of large underground structures have focused primarily on methods for the control of water inflows during excavation and for keeping the completed structure free of water. However, within the last 30 years, the impact of such activities on the environment has become a major consideration. Impacts on the groundwater resources of an area by underground excavations may be minimized by such planned constraints as pre-excavation grouting and the installation of an impermeable lining of the final excavation. However, such measures may not be sufficient for avoiding claims of environmental impacts, particularly in areas of existing water shortages and/or marginal supplies.

Today, the cost of delays and impact compensations that may result from inadequate understanding of the environment fully justify investigating and evaluating the conditions, as well as establishing a monitoring system to measure possible impacts. The most effective response to environmental concerns is based on an understanding of the respective environment, accompanied by adequate supporting data.

The approach begins with developing a good understanding of the water resources, collecting a database with which to establish the hydrologic characteristics prior to construction, and early establishment of a resource-monitoring program. With this completed prior to construction, the resource monitoring program can be organized to provide early detection of an impact during construction. Methods for minimizing and preventing impacts to the environment should be planned for and be made available to support response to impact alerts. In the following, the factors to consider and the general methodology for establishing a procedure for early identification of impacts is described. The experience of applying such a program to the large tunneling project, which was the incentive for developing the methodology, is then presented as a case study.

Characteristics of the water resource

Investigation of the groundwater resource in the vicinity of the proposed project should commence as soon as possible once the project is proposed. Although good understanding of the occurrence and movement of groundwater in the area may be acquired from available reports, it is seldom that previous studies are sufficiently specific to the project area to provide a basis for measuring possible impacts. Field investigation and exploration to measure the aquifer characteristics and to define the likely area of possible impact is needed. Transmissivity and storativity of the water-bearing materials will largely determine the maximum (i.e., critical) distance at which monitoring wells may provide early detection of an impact. Directional permeability can distort the effective distance and discontinuities such as faults, and can interfere with it, either as a barrier to, or as a conduit for water inflows. Measuring the aquifer characteristics and identifying the occurrence of faults that could affect water inflows is an important aspect of the preconstruction investigations. It cannot be emphasized enough that collection of sufficient data is needed to demonstrate the hydrology (i.e., recharge and storage capacities, seasonal fluctuations) of the resource unaffected by construction activities.

A canvass of the area to locate and measure the water resource features (i.e., streams, springs and wells) is of first priority. The canvass must be completed early in the planning in order to establish the resource-monitoring program and to collect as much data on the groundwater hydrology as feasible prior to construction activity. Only with such data in hand, can monitoring of the resource during and following construction be effectively assessed as to whether or not any impact has occurred, and if so, to what degree it has occurred. Supporting data of an impact evaluation are critical for minimizing and avoiding claims of interference.

Resource-monitoring program

The first task of the resource-monitoring program is to collect preconstruction data on the resource features of the area and on hydrologic control variables that are independent of any impact by underground excavation. Correlations established between these data will be the reference (“baseline” conditions) for determining seasonal and annual fluctuations unaffected by construction activities. Precipitation in the resource area is the first independent control variable to consider. Water wells, springs and streams located beyond the area affected by construction can also provide an independent control.

Typically, the data will illustrate that seasonal and yearly fluctuations of the resource features are significant and are a complex response affected by many factors: groundwater, precipitation, soil moisture, geology. Because of this, effective detection of impacts cannot be made by comparing measurements during construction to a reference simply expressed as average conditions, or even as average seasonal conditions. The correlation under baseline conditions needs to provide a measure of the response of features to natural climatic fluctuations. If groundwater development is present in the area, a decline in groundwater levels in response to groundwater use must also be identified in the baseline data.

The second task is to maintain the monitoring program of the resource features and the control variables during the construction activities and continuing through a

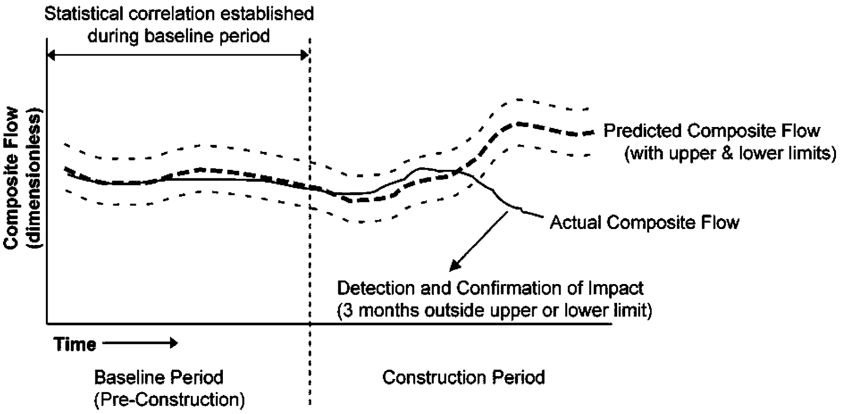

Fig. 1 Use of composite flow in identifying impacts

postconstruction phase. Comparison of these data with the baseline data correlations provides a basis for identifying normal fluctuations of the resource and early detection and assessment of any impacts by construction activities.

Impact detection

The means and speed with which a construction-related impact could be detected is largely governed by the magnitude of the impact. For example, a substantial drop in the water level of monitoring wells, together with a marked reduction in the flow in springs and streams associated with large inflows to the underground excavation would be quickly detected by field monitoring personnel, and with appropriate review, remedial measures would be implemented.

A more likely scenario would be that the water level in a monitoring well is marginally below its historical range and a distant spring shows signs of drying up, although the springs nearest to the well are flowing normally. A scenario such as this, unfortunately, can reasonably be expected; it could easily occur due entirely to the random variability inherent in hydrologic monitoring or, the old constraint, not enough data. Therefore, professional judgment will be needed to determine whether the spring is impacted from the excavation or not, applying a detailed understanding of the hydrogeology of the project area. Often, the most prudent course of action will be to monitor the feature in question more frequently to see if the apparent impact persists or was due to random variability.

Detecting possible impacts begins by defining baseline conditions, with statistical correlations between the resource features and the control variables, using the preconstruction data. Periodic monitoring of the resource features during construction is then evaluated against that correlation, and if the measurements indicate fluctuations beyond what can be attributed to “normal” conditions, an alert is established, and related features are more closely monitored to confirm whether or not remediation is justified. This approach incorporates and expands upon techniques employed in a US Geological Survey study (Rantz 1962) directed to flow measurements affected by dewatering during a tunnel excavation. In that study, measurements at individual hydrologic features within defined geographical units were combined to determine a representative flow for each unit. The composite flow parameter was found to respond to seasonal variations in precipitation in a much more predictable manner than the individual measurements at springs and streams. It was used effectively to assess whether or not the features had been affected by drainage during construction of the tunnel. Applying this approach, the area of concern may be subdivided for study purposes into one or more “hydrologic” units that include related resource features. The number of units will depend on the size and complexity of the area and composite flow parameters are constructed for each unit.

Measurements at each feature within a unit are first scaled to a common, dimensionless reference. Basic to such hydrologic analyses, each measurement represents a time increment (such as a month) of the annual cycle of hydrologic/climatic conditions. The dimensionless reference is the ratio of the flow measurement divided by the median flow for that feature. The resulting dimensionless values can be used to construct hydrographs that are comparable from feature to feature. A value of one represents the median flow for each feature. Half of all the values of each feature fall between zero and one, while the other half are greater than one.

The value of the composite flow for each hydrologic unit is then established as the median of the dimensionless flow values for all the features within each hydrologic unit. This method smoothes the data and limits the effect of inconsistent discharge measurements. These inconsistencies may be due to errors in measurement, differences in the day or even the time of day that measurements were made at different features, or other unspecified causes. The resulting composite dimensionless flow provides a representation of the seasonal fluctuations of flow within the hydrologic unit. It is a reproducible flow parameter using the flow-measurement techniques employed at the monitored features, and can be expected to remain reasonably stable relative to regional climatic fluctuations. The composite flow parameter is subsequently used in a regression analysis to establish the baseline relationship

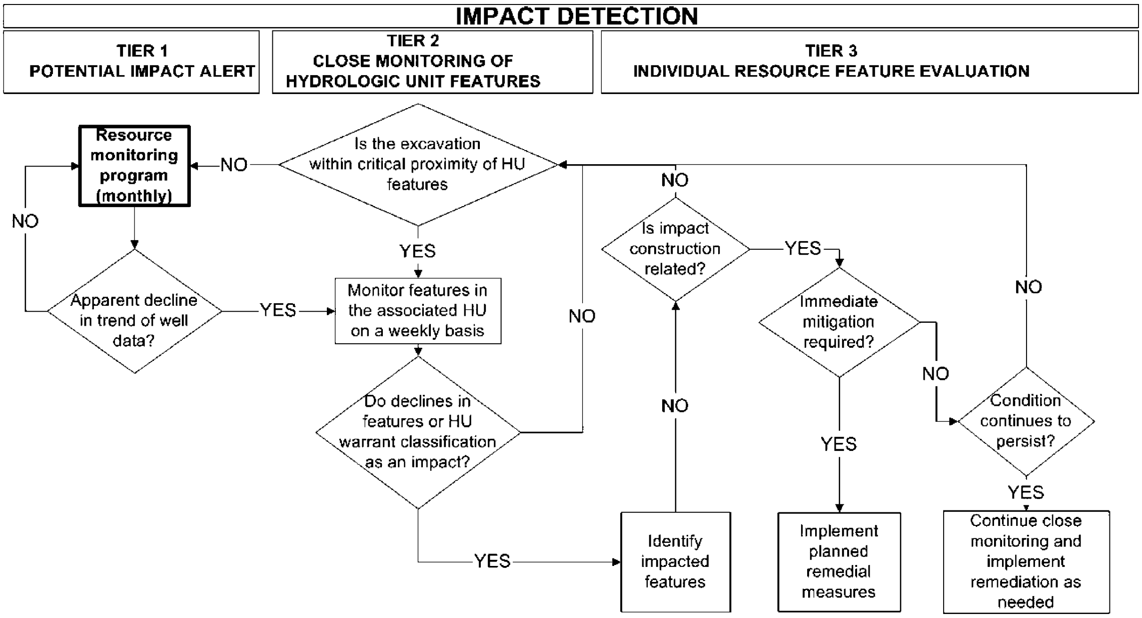

Fig. 2 Decision tree for determining and identifying construction related impacts

of flow within the hydrologic unit to the independent control variables such as precipitation, and possibly streamflows, springs or water wells outside the influence of construction.

The intended use of the composite flow is illustrated in Fig. 1. With the baseline correlation between the composite flow and the independent variable (i.e., precipitation) established, the composite flow during the construction period can be predicted. The actual composite values for the hydrologic unit are calculated and compared to the predicted values. Deviation from the predicted values is an indication of a possible impact developing within the hydrologic unit. The prediction interval around the predicted flow shows the margin of error within which it is acceptable for the actual composite flow to fall. Based on the level of confidence of the prediction, the actual composite flow should not fall outside of this interval for a statistically significant period; otherwise, it is an indication of a potential impact.

Fluctuations of groundwater levels in wells respond to the same parameters as surface flows, and developing baseline correlations of water levels may also be directed to the primary source of recharge—precipitation. The correlations will need to account for seasonal and annual fluctuations, most likely illustrated as cumulative departures from the mean of precipitation. An additional consideration in analyzing water-level fluctuations is the effect of groundwater use. Trends and fluctuations in water levels caused by the extraction can normally be accounted for with appropriate monitoring and documentation of the use.

The flows of small streams and springs tend to be highly variable and random deviations below historical range are likely, precluding early detection of an impact. Short-term groundwater level fluctuations, on the other hand, are normally small and an impact on the resource could be readily detected. Furthermore, because monitoring wells are in direct contact with the source of inflows to the underground excavation, they are most likely to register initial or early impact.

Impact detection procedure

A three-tiered procedure was developed with which the monitoring data can be analyzed systematically to provide an early alert, followed by closer monitoring to confirm the impact and to allow time to prepare an effective mitigation plan, if needed. A decision tree diagram of this procedure is shown in Fig. 2.

Tier 1: potential impact alert

The initial tier of detection is the first alert that an impact may be developing and serves notice to commence closer monitoring of the probable area (i.e., hydrologic unit) that could be affected. Groundwater levels are the most probable source of early indication of possible impacts. Monitoring wells in close proximity to the underground excavation are most likely to be in direct hydraulic contact with the source of inflows to the excavation, and are likely to register initial or early impact, similar to the interference effects of a pumping well. Features further away or hydraulically separated from the excavation may be impacted later or not at all.

Tier 2: close monitoring of hydrologic unit features

The second tier of detection directs closer, more frequent monitoring of features in the hydrologic unit associated with the alert. The objective is to confirm, as soon as is feasible, whether or not an impact is developing in the hydrologic unit. An impact may be identified at an

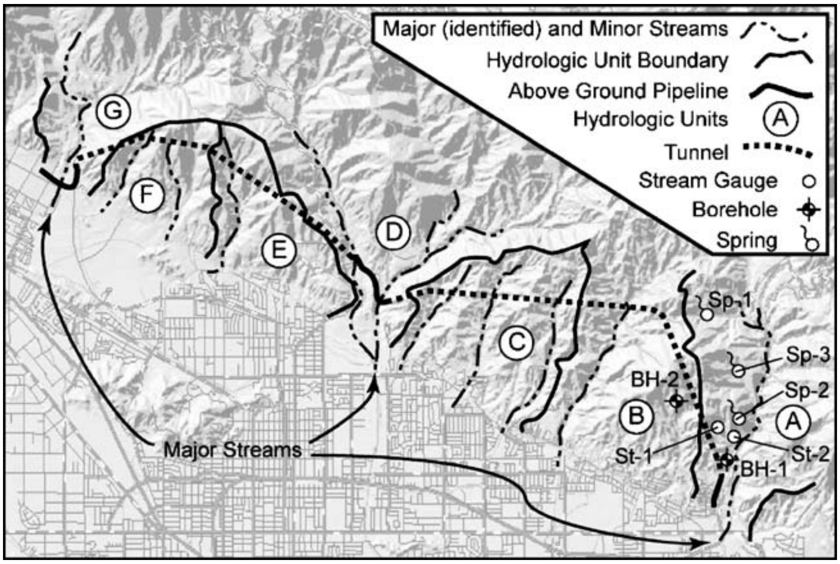

Fig. 3 Location map

individual feature before the impact is confirmed in the hydrologic unit. As soon as any impact is confirmed, the process of detection moves to tier 3.

Tier 3: individual feature evaluation

The third tier of detection is to identify individual features within each hydrologic unit that are impacted, and to determine if the impact is construction related. Because the natural fluctuation in flow at individual features is much greater than that of composite flow of the hydrologic unit, careful monitoring and field inspection will be needed to establish the degree of impact at individual features. Determining an impact will consider several factors including whether or not:

- Nearby monitoring wells are impacted
- The feature is in an impacted hydrologic unit
- Flow at the feature has fallen below the baseline minimum flow
- Flow at the feature is consistently low compared to nearby features
- Flow at the feature has abruptly decreased
- Underground excavation inflows near the feature are high
- Vegetation around the feature shows abnormal stress
- Water chemistry at the feature has changed

Judgment is expected to be a significant part of decisions at this level. It is quite conceivable that some of these factors may indicate an impact while others indicate that conditions are normal. The differences may need judgment to balance the conflicting evidence and make the final determination. Li and Kagami (1997) have illustrated the use of water-chemistry changes to identify tunnel construction impacts to springs.

If an impact to either the hydrologic unit or individual features is identified, factors that could cause the impact will be assessed. In addition to underground excavation, factors such as increased groundwater withdrawals or fires may cause an impact. If the observed impact is proved to be construction related and persists for a “significant” period, the need for remediation will be determined and appropriate measures implemented. The defining of what a significant period is should be established prior to construction, based on the hydrologic characteristics of the area. If the evaluation shows that the impact is not construction related, or if it shows that the impact does not persist, close monitoring may need to be continued until the cause is established.

Case study

Two 5.5-m-diameter tunnels of approximate equal length, and comprising a total length of 13 km, were planned beneath a mountainous, semi-arid region of the southwestern United States (Fig. 3). The tunnels, which are part of an extensive water-conveyance facility, were bored beneath the flanks of the mountain range to avoid transporting water through a highly developed urban area of the adjacent valley. Three major streams draining the slope of the mountains mark the boundaries of the tunnels and are the locale of the tunnel portals. Early in the planning stages of the project, it was realized that the construction, although temporary, could impact the water resources of this mountainous area. Groundwater is critical in sustaining the water sources of the flora and fauna of the area, as well as sourcing domestic wells. Because the tunnels are excavated in a complex of intrusives and metamorphics in which the occurrence and movement of groundwater occurs primarily within fractures and the storage capacity is relatively small, groundwater inflows to the tunnel could cause serious impacts.

Measures to control and minimize any such impacts included pre-excavation grouting in advance of tunnel excavation, and the addition of an impermeable lining to the final design of the tunnels. To further reduce the opportunity for inflow to the tunnel, installation of the lining was planned to follow, in practical terms, as close as possible behind the advancing excavated face. Additionally, it was decided that a pilot hole would be maintained in front of the tunnel face during construction to help anticipate potentially high inflows and guide the pre-excavation grouting. Even with these planned constraints, it was realized that measurable impacts could occur. A resource-monitoring program, maintained during and following construction to provide early warning should an impact develop, was recognized as a key provision in the effort to minimize and control any such impact. Establishing that program and determining the occurrence and extent of the groundwater resource was initiated early in the planning of the project.

Characteristics of the water resource

Determining the occurrence and movement of groundwater overlying the planned tunnels was an integral part of the alignment exploration. Together with mapping the surface geology, the area was canvassed to identify water resource features (streams, springs, wells) maintained by groundwater. Records of precipitation in the area, the source of recharge, were collected. In situ permeability testing of the rock mass was conducted in exploratory borings and correlated with rock-mass parameters such as fracture frequencies and depths of test intervals. Typical of the rock types present, the measured hydraulic conductivity of the materials underlying the area is low and the estimated storativity of the rock types is also low. Exploratory boreholes were completed as monitoring wells, providing a measure of the groundwater overlying the tunnel alignment. Estimates of anticipated tunnel inflows were calculated using methods presented by Goodman et al. (1965) and Heuer (1995).

Geologic investigation of the area determined that four large faults would be crossed by the tunnels and it seemed likely that they would be barriers to groundwater flow. Exploratory borings detected differential heads across only one of the faults. Regardless, in preparation of sudden inflows, construction procedures included careful monitoring of the pilot borings ahead of the excavation face as each fault was approached. As it turned out, although inflows up to 90 L/s did develop in the deeper portions of the tunnel, no sudden high inflows were encountered in respect to the faults encountered. At the one fault at which a differential head of about 60 m across the break was detected, only small inflows of less than 5 L/s were recorded.

The three major streams bounding the tunnels are hydrologic boundaries (the central major stream separates the tunnel) limiting the extent of the groundwater body overlying each tunnel that could be impacted by tunnel construction. Based on these data, a conceptual hydrologic model of the two groundwater bodies overlying the planned tunnels was developed. Numerical analyses were then conducted to aid in assessing the impact of inflows to the tunnel with the planned methods of construction. Molinero et al. (2002) and Anna et al. (2003) present examples where numerical analysis has been conducted to aid in identifying the interaction between groundwater in fractured hydrogeological environments and the construction of a tunnel. Analyses derived from this study indicated that any impact on the groundwater would be minimized by controlling the inflow to the tunnel during construction to approximately 30 L/s. Should an impact on the resource develop in spite of the planned controls, early detection of the impact would allow time to prepare and implement mitigation measures to minimize the impact. The analyses indicated that interference to groundwater levels from inflows to the tunnels would be detectable at monitoring points within a distance of approximately 760 m of the excavation face. This was incorporated in the monitoring program and detection procedure as “critical proximity” for an early alert.

Monitoring program

The first step in the program was a survey to identify and classify water-resource features that are sustained, at least partially, by groundwater. The surveyed area in which features might be impacted by inflow to the tunnels, extends the length of the tunnels and approximately 2.5 km either side of the alignment. Resource features identified include 32 local streams, 25 springs, and 13 horizontal or vertical domestic wells. The records of eight established (USGS and local) precipitation stations within and adjacent to the survey area were identified as independent variables for data control and baseline correlations. Investigating the groundwater resource was an integral part of the tunnel alignment exploration and 25 boreholes were completed as monitoring wells. They were included in the program.

The early initiation of the monitoring program provided over 3 years of pre-construction monitoring data to provide a “baseline” period of data, illustrating yearly and seasonal fluctuations unaffected by construction. The monthly monitoring schedule was sufficient for providing close monitoring of baseline conditions.

Determining baseline conditions

Using site-specific conditions, the generic impact detection procedure was modified and the monitored area was subdivided into seven “hydrologic units”, based on surface drainages to better localize suspected resource impacts. The site-specific impact detection procedure is illustrated in Fig. 4. The resource features were matched to the appropriate unit and analyzed as related groups. Measurements of spring and stream flows in each unit were first normalized (see section Impact detection) and then aggregated to derive a representative composite flow parameter for that hydrologic unit. The composite flow of

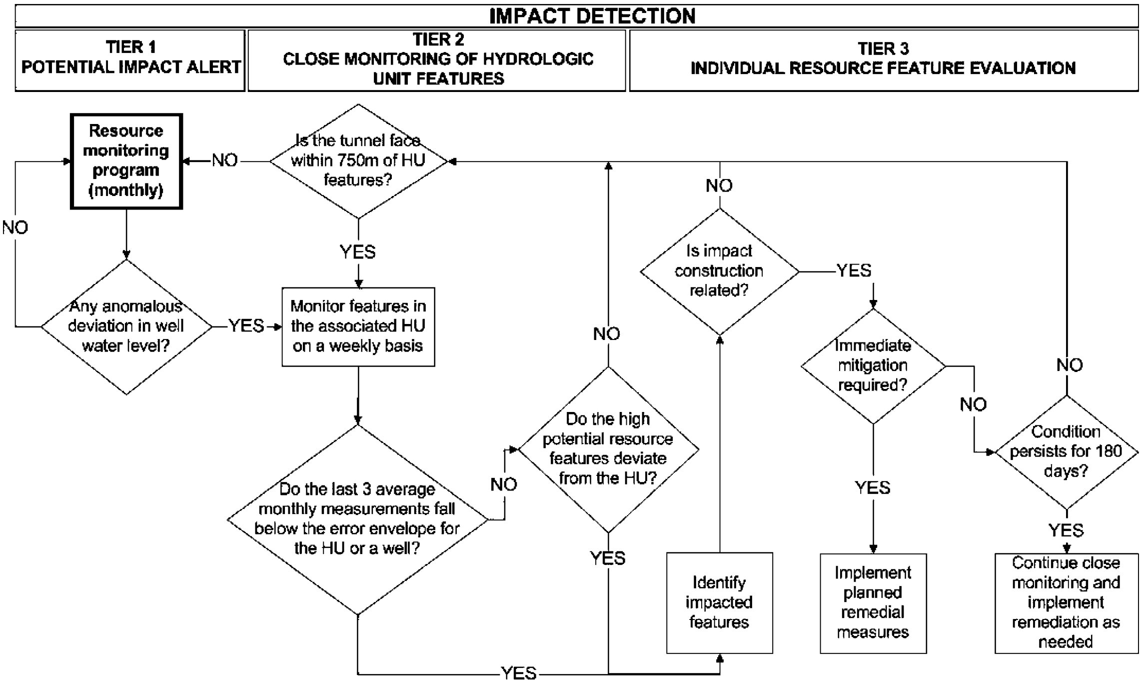

Fig. 4 Site-specific impact detection procedure

each hydrologic unit and the water levels of the monitoring wells were then correlated with control variables selected from nearby precipitation records and the flow records of the major streams bounding the tunnels project area. The individual resource features were classified as having a low, medium or high potential for being impacted by tunnel construction. This classification was based on a subjective assessment considering the following:

- Proximity to tunnel alignment
- Presence of a significant component of groundwater flow
- Proximity to faults
- Determination of whether or not those faults intercepted the tunnel

Selecting control (independent) variables

Long-term precipitation records were available from eight gauging stations and the process for determining those most suitable was to compute statistical correlations between the monthly precipitation and the composite flow for each of the seven hydrologic units. Because stream flow is, in large part, a composite response of a watershed to precipitation, a high correlation of flow to precipitation would indicate that a particular rain gauge is a good representation of the precipitation at that particular hydrologic unit. Two of the nine rain gauges had a high-correlation with the composite flow for all of the units, and the average of the rainfall at these two gauges was even higher than each one individually. As a result, the average of these two rain gauges was used as the first independent variable for control in predicting unimpaired resource conditions during construction.

A review of the flow records for the three major streams bounding and passing through the project area determined that two of the streams had continuous, long-term flow data and that the flows were unlikely to be affected by construction because less than 10% of their drainage area was overlying the tunnel alignment. The average of monthly increments of flow measurements at these major streams was used as the second control variable. The primary reason for averaging the flow at the two stations was to reduce the reliance on a single gauge.

Correlations by statistical methods

Correlation of the baseline data with the two control variables through statistical methods was possible with most resource features and hydrologic units. The extensive baseline-monitoring period (up to 3 years for most features) and periodic monitoring provided sufficient data for establishing a basis for predicting stream flows and groundwater levels. However, the response of features is usually more complex than a simple direct response to an increment of precipitation. In the correlation analyses, it was found that features commonly showed a lagged response. Of the different forms of the control test in the analyses, five were found to be meaningful including: the concurrent increments of major streams flow, the 1-month lagged increments of stream flow, the concurrent increments of precipitation, the 2-months lagged increments of precipitation, and the CDMP (cumulative departure from the mean precipitation). Forward stepwise multiple-regression analyses were conducted with different combinations

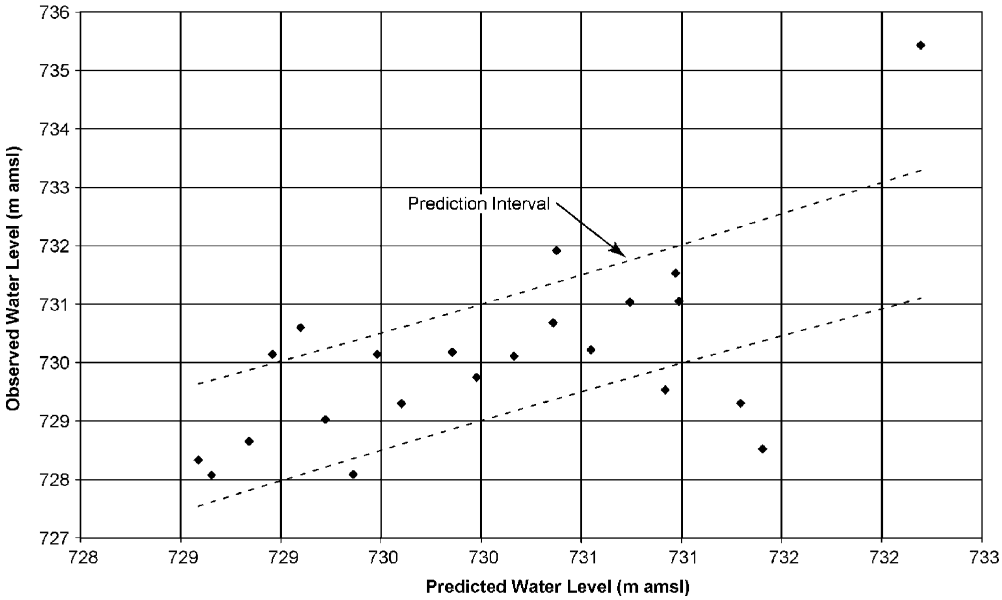

Fig. 5 Observed vs. predicted water levels for well BH-2 during the baseline period

of these forms of the independent (control) variables. Those combinations of the forms that were found to contribute to regression analyses, allowing a 95% or better confidence level, were used in the final relationships.

The prediction limit(s) are used here to determine the prediction interval within which individual measurements should fall. In order to be sufficiently narrow at a 95% confidence level, the criterion is such that for any three consecutive monthly measurements, at least one of those measurements would fall within the interval. Because the prediction error is essentially random, three consecutive measurements below the prediction limit would suggest the feature (i.e., hydrologic unit flow) had been adversely impacted. Because of the relatively slow response of the groundwater resource to an impact, an interval of less than 3 months (three measurements) to confirm an adverse impact allows sufficient time to prepare a program of remediation, should the impact persist and become large.

Groundwater levels

Statistical correlations between the monthly water levels in monitoring wells and the several forms of the control variables were made and it was found that the best correlation for nearly all wells was with the CDMP form of the precipitation. This is common and explained by the delay of recharge percolating through the vadose zone and the storage effect of the groundwater. Examples of the correlations are illustrated by the following equations:

$$\text{water level at well BH–1(m)}$$
$$= 0.1\,\text{CDMP}(1) + 541.54+/-(0.67)$$

$$\text{water level at well BH–2(m)}$$
$$= 0.21\,\text{CDMP}(1)+728.95+/-(1.31)$$

where CDMP (1) = the cumulative departure from the mean of precipitation (cm) lagged one month, and +/– (value) = standard error.

The cumulative departure from the mean precipitation is defined by the following equations:

$$\text{CDMP}_{(1)} = \text{precipitation}_{(t)} - \text{average precipitation} + \text{CDMP}_{(t-1)}$$

$$\text{CDMP}_{(1)} = \text{precipitation}_{(t)} - \text{average precipitation}$$

where: (*t*) = measurement at time t in months.

The water level data from the baseline period used in defining the statistical correlation along with the corresponding estimated water levels is presented in Fig. 5 for well BH-2.

Hydrologic unit flow

A similar approach was undertaken for the composite flows of the hydrologic units. The composite flows are the dependent variable in a forward stepwise multiple-regression analysis. As with the monitoring wells, the analyses were made using different combinations of the several forms of the control variables. There is more variation between units as to the forms providing the “best fit”, and

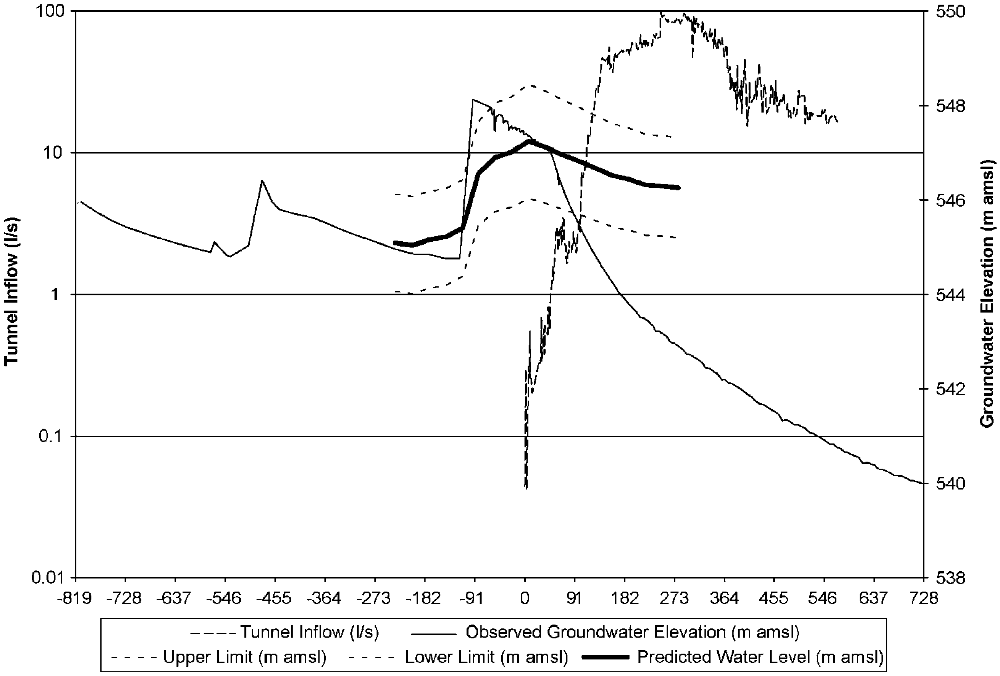

Fig. 6 Measured and predicted groundwater elevation in BH-1 and tunnel inflow record

all units but one rely on a combination of two or more forms. The 1-month-lagged stream flow and the CDMP are the most common forms included in the correlations. Examples of the prediction equations derived for two hydrologic units are as follows:

$$\text{Hydrologic unit A flow} = 1.2 \times 10^{-4} Q(1) + 0.058P + 0.45 \quad +/-(0.45)$$

$$\text{Hydrologic unit B flow} = 0.185P + .038\,\text{CDMP} + 0.081 \quad +/-(0.57)$$

where:

$Q(1)$	the 1-month-lagged flow in L/s at the two major bounding creeks
P	the monthly precipitation in cm
$P(2)$	the monthly precipitation in cm lagged two months
+/– (value)	the standard error

Detection of an impact

When tunnel construction actually began, it was probably the first time that such an extensive monitoring program and impact detection procedure had been implemented for such a purpose. As it turned out, the program was effective in recording the response of the resource during the construction and enabled quick identification of possible impacts. The sensitivity of the monitoring allowed ample time to allow the planning of possible remediation, if needed. Generally, the responses of the resources conformed to what had been expected. However, as is somewhat common in predicting the occurrence and movement of groundwater, some responses were unexpected. The construction began on the second of the two tunnels with a single heading from the eastern portal.

Excavation from the portal extended into the mountain more than 1,200 m in less than 100 days. Groundwater inflows during that period varied around 3.2 L/s. This portion of the tunnel is overlain by hydrologic unit A which covers an area of 4.4 km^2. There are 12 resource features in this unit and three monitoring wells. Although inflows of 3.2 L/s were expected to be insignificant, an apparent impact began to develop at well BH-1 after approximately 40 days of excavation. Although water-level interference was not expected to be discernable from such a low inflow, two other monitoring wells began to respond as well. Figure 6 details the water level hydrograph of well BH-1, together with the predicted water level and the prediction envelope. The tunnel inflow record is also illustrated. Following the impact detection, the break in slope (steepening) at well BH-1 signaled an alert that instigated weekly monitoring at features in hydrologic unit A.

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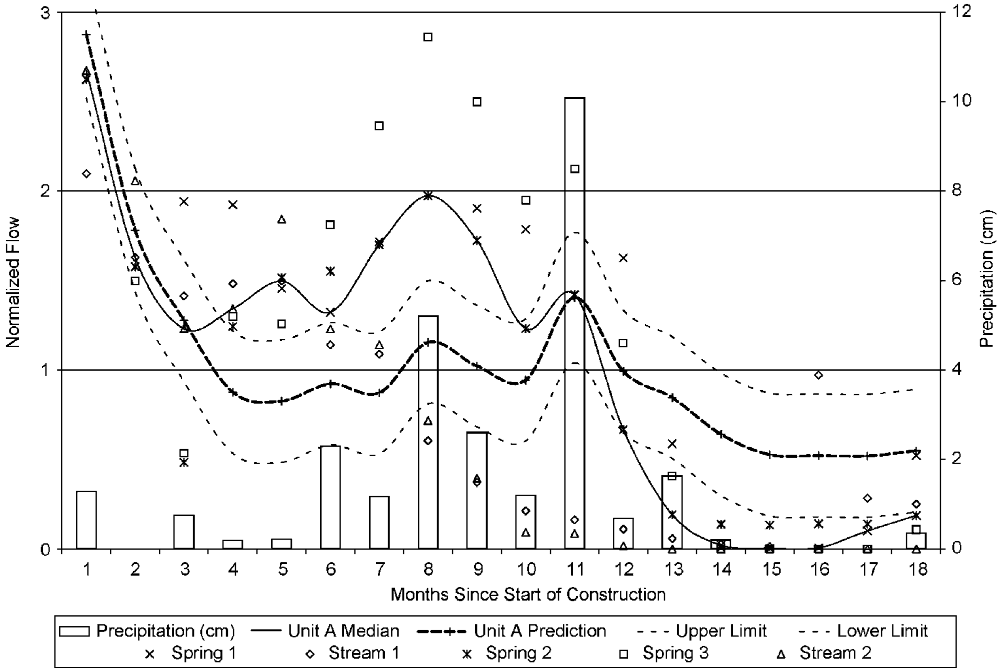

Fig. 7 Predicted and actual composite flow for hydrologic unit A

The weekly measurements of the features were transposed to dimensionless values for evaluation with the statistical prediction method. Approximately 3 months after the alert was identified, the dimensionless flow values of two streams (median flows of 0.8 and 0.5 L/s) began to fall to the bottom of the population of resource features in the unit. The distribution of the flow values (ratio of measured flow of each feature to the median of measurements at that feature for the baseline period) that contribute to the composite flow of the hydrologic unit should fall randomly about the median flow. If values of a feature consistently fall to the bottom of the population, it is an indication that it may be flowing at less than its median. Features exhibiting expected behavior would fall above the composite flow 50% of the time and below the composite flow 50% of the time. The persistence of flow values of these two streams at the bottom of the population indicated the streams are probably impacted. With the possibility of an impact, planning of mitigation measures for the two streams commenced, and the fauna

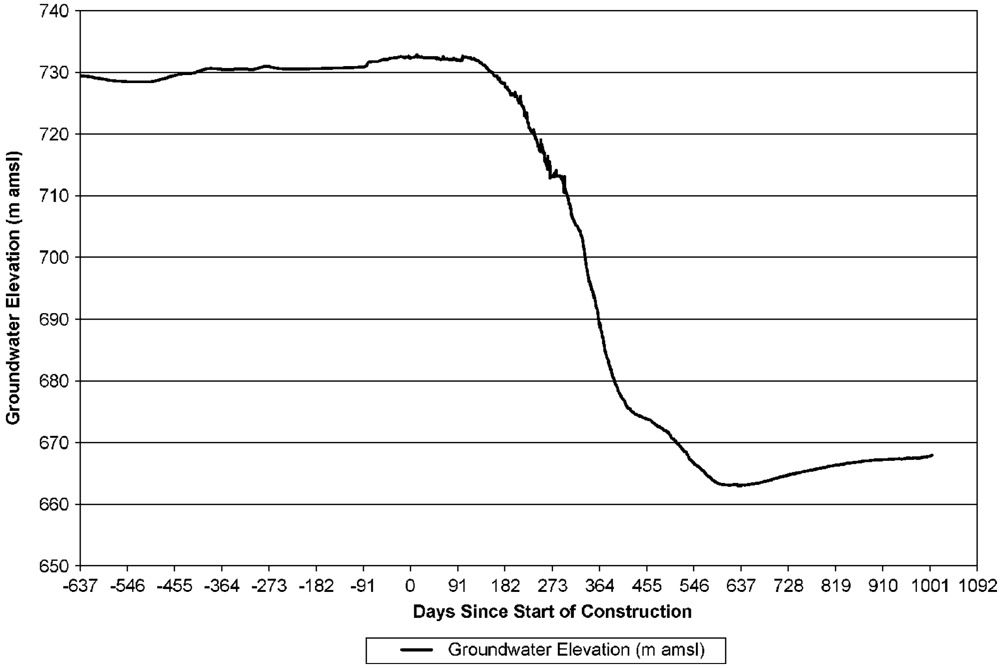

Fig. 8 Actual water level at well BH-2 showing recovery of water level

and flora in the vicinity of the streams were also closely monitored for possible impact.

Figure 7 illustrates the predicted composite flow of hydrologic unit A during excavation of the tunnel, based on the baseline statistical correlations and the prediction envelope. Superimposed on that graph, is the actual composite flow of the unit and the individual dimensionless flow values of the five features with which the composite flow is determined. It can be seen that with the measurement increment at 123 days of tunnel excavation, streams 1 and 2 had fallen to the bottom of the population. The continued persistence of these features at the bottom of the population confirmed that an impact had occurred. The impact began to be reflected in the unit composite flow after about 300 days, but was not confirmed until after about 1 year (380 days) when the flow fell outside the prediction envelope for three successive measurements.

Once an impact was established as indicated by the monitoring procedure, the plan for mitigation was implemented. The measures restored flow to the affected areas and impacts on the environment were minimized.

Concluding remarks

As shown in Fig. 6, reviewing the history of inflows to the tunnel after about 95 days of excavation inflows markedly increased above the 3.2 L/s that initially affected hydrologic unit A. This was more than 50 days after the alert of an impact was recognized in the water-level trend at well BH-1. As excavation of the tunnel progressed beyond unit A, penetrating deeper beneath the mountainous area, inflows increased considerably. They exceeded 90 L/s for a brief period. The monitoring wells in close proximity to the tunnel face recorded a clear transient response to those large inflows, as indicated by the hydrograph of well BH-2 in Fig. 8. There was no response detectable in the hydrograph of well BH-1 (Fig. 6) to this increased stress on the groundwater resource. Nor was there any response in the other wells overlying hydrologic unit A.

The responses at monitoring wells in close proximity to the excavation during the high inflows caused alerts in the corresponding hydrologic units. However, there were no impacts detected in any of the units from those alerts. The high inflows were controlled by grouting at the face, and eventually reduced to near-negligible amounts. Recovery of the groundwater resource began soon after the high inflows were controlled, as indicated by the reversal in trend of well BH-2 hydrograph (Fig. 8).

The program is considered to have been effective in meeting the objectives. The combination of characterizing the water resources, the implementation of a resource monitoring program and the establishment of a detection procedure to identify impacts to the groundwater placed the project manager in a position to act appropriately when it was determined that an impact had occurred. The impact detection procedure proved to be much more sensitive than had been anticipated and was able to detect an impact on the groundwater resource at low inflow rates.

Each underground engineering project will have unique aspects in regard to the environment and to the occurrence of groundwater resource. However, the guidelines set forth herein are a good basis from which to establish an effective monitoring system that will help minimize impacts on groundwater resources.

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