Mine Closure 2023 - Behrooz Abbasi, Jeff Parshley, Andy Fourie & Mark Tibbett (eds)
© 2023 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-7-2
doi:10.36487/ACG_repo/2315_062

Estimating baseline water levels for mine closure

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Abstract

Baseline hydrologic data, such as groundwater levels in wells, are required to understand mine-induced impacts to the environment, both during mining operations and closure. Baseline data have natural temporal variability; however, capturing the full range of variability in baseline data is challenging. Using long-term (1900–present) climatic data, a baseline water-level record can be constructed that provides an understanding of the expected range of natural temporal variability.

This paper presents an analytical approach for constructing a theoretical long-term (1900–2023) water-level record, using the Turquoise Ridge Mine Complex in northern Nevada as an example. The approach relies on an underlying conceptual model of groundwater recharge and discharge. Recharge and discharge are assumed to be in a state of dynamic equilibrium, where water levels fluctuate over annual-to-decadal timescales but have a century-scale steady-state condition. The baseline water-level record compares favourably to measured water levels, thus successfully validating the approach.

Keywords: *closure criteria, baseline data, natural variability, water-level trends*

1 Introduction

Baseline (or background) data are required to understand potential mine-induced impacts to the environment, both during mining operations and closure. During operations, baseline data are used to address hydrologic questions, such as whether drawdown from mine-induced pumping has affected nearby water users or groundwater-dependent ecosystems. In this example, baseline data define natural water-level variability so that subtle water-level declines can be correctly attributed to natural variability or pumping. From the mine-closure perspective, baseline data are used as a benchmark when developing closure alternatives for mine facilities. Closure-alternative analyses compare baseline data to future projections of water quantity and quality to ensure that the mine site will not pose a risk to human health or the environment during closure.

Baseline data have natural temporal variability. Collecting a representative distribution that captures the full range of variability in baseline data is challenging. Furthermore, baseline data are often, if not always, incorrectly regarded as a fixed value (mean or median) that represents a hypothetical background condition without considering the range of natural variability.

Baseline hydrologic data include, but are not limited to, climatic data, groundwater levels, and surface-water flows. High-resolution, long-term (1900–present) climatic data are available from many web-based services (e.g., Climate Engine, Climate Research Unit, National Centers for Environmental Information, Western Regional Climate Center). Even though long-term water-level and flow records are rare, long-term climatic data can be used to construct a baseline water-level record that provides an understanding of the expected range in natural temporal variability.

This paper presents an analytical approach for constructing a theoretical long-term (1900–present) water-level record, using the Turquoise Ridge Mine Complex in northern Nevada as an example. The approach relies on an underlying conceptual model that assumes groundwater recharge and discharge are in a state of dynamic equilibrium. The baseline water-level record is validated by qualitative comparison to measured water-level data affected only by natural hydrologic stresses.

1.1 Site description

The Turquoise Ridge Complex consists of the Turquoise Ridge (TR) and Twin Creeks (TC) Mines. The Complex is within the Basin and Range Province in Northern Nevada (Harrill and Prudic, 1998), which is characterized by extensional tectonic forces that cause down-dropped fault blocks to form valleys and upthrown fault blocks to form intervening mountain ranges. The Turquoise Ridge Complex is on the Kelly Creek valley floor, which is bounded on the west and east by the Osgood and Snowstorm Mountains, respectively (Figure 1). Land-surface altitudes range from 1,300–1,600 m above mean sea level (m amsl) on the Kelly Creek valley floor. Land-surface altitudes are up to 2,645 m amsl at Adam Peak in the Osgood Mountains and up to 2,560 m amsl at Kelly Creek Mountain in the Snowstorm Mountains.

Groundwater flows from highland recharge areas in the Osgood and Snowstorm Mountains toward the Kelly Creek valley floor (Figure 1). Groundwater beneath Kelly Creek valley flows south-southwest to discharge at the Humboldt River.

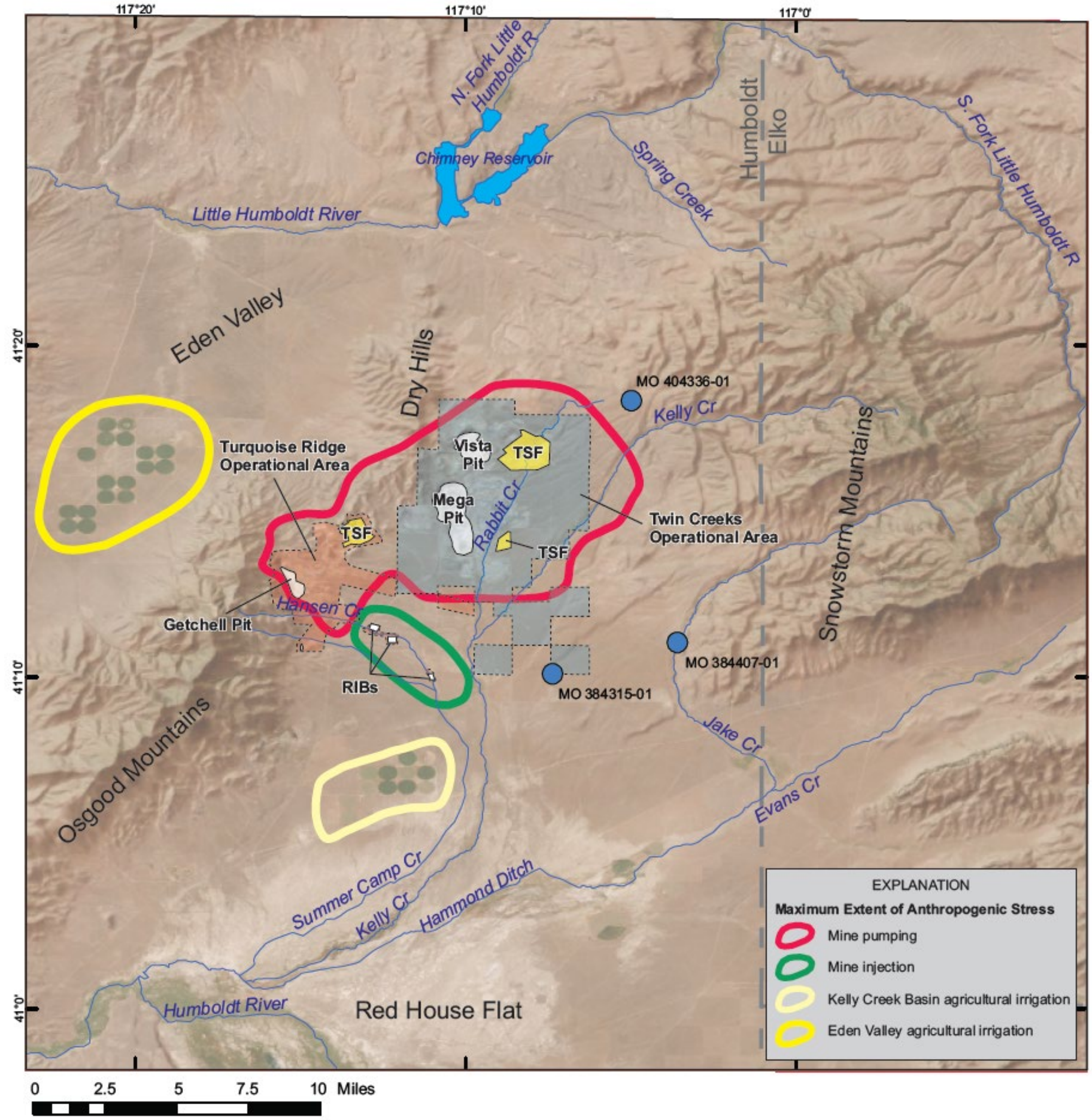

Figure 1 Physiography, well locations, and mine-site features at Turquoise Ridge Complex, northern Nevada

1.2 Climate

The study area is a semi-arid steppe climate characterized by dry, hot summers and cold winters. The region has low annual precipitation, low relative humidity, clear skies, and large diurnal temperature variations because of the dryness of the air. Average summertime maximum temperatures range from 14–26°C, and average wintertime minimum temperatures range from -12 to 6°C (NOAAa, 2023). Average annual precipitation ranges from 0.6 m in the Osgood and Snowstorm Mountains [Climate Engine, 2023, (Lat,Lon: 41.1953N,117.2922W)] to 0.3 m on the Kelly Creek valley floor [Climate Engine, 2023, (Lat,Lon: 41.2368N,117.2219W)].

1.3 Geology and hydrogeology

Geologic units are categorized as Quaternary alluvium, Tertiary volcanics, Mesozoic intrusive rocks, or undifferentiated Paleozoic rocks (Itasca, 2022). Quaternary alluvium consists of unconsolidated gravel, sand, silt, and clay. Alluvium occurs on the valley floors, along ephemeral and perennial channels, and forms alluvial fans on the flanks of the Osgood and Snowstorm Mountains. Tertiary volcanics consist of fractured rhyolitic, andesitic, and basaltic lava flows. These lava flows occur throughout the Snowstorm Mountains and are on the northern and southern parts of the Osgood Mountains. Mesozoic intrusives consist of (1) a granodiorite stock within the central part of the Osgood Mountains; and (2) dacitic dikes and sills, some of which crosscut the TC Mega Pit. Undifferentiated Paleozoic rocks consist of fractured carbonate and siliciclastic rocks, predominantly limestone, chert, greenstone, quartzite, shale, siltstone, and sandstone.

Alluvium and undifferentiated Paleozoic rocks form the primary aquifers in the study area (Itasca, 2022). The alluvial aquifer is recharged mostly by surface-water infiltration beneath ephemeral channels either along alluvial fans or on Kelly Creek valley floor. On the valley floor, alluvial-aquifer recharge mostly occurs along ephemeral reaches of Jake Creek, Kelly Creek, Rabbit Creek, and the Humboldt River. Paleozoic rocks form a fractured bedrock aquifer, which receives groundwater recharge directly at outcrops within highland areas, or indirectly from alluvial or volcanic aquifers. Tertiary volcanics form a secondary fractured-rock aquifer that occurs locally along the western range front of the Snowstorm Mountains. Mesozoic intrusive rock has low transmissivity and forms localized confining units.

1.4 Mining history

At TR Mine, gold mining activity began when the historic Getchell Pits were mined from 1937–1968. Mining ceased from 1968 to 1994. In 1992, dewatering wells were installed around the perimeter of the Getchell Pits to prepare for underground (UG) mining. Getchell Pit UG mining occurred from 1994–2008 and TR UG mining commenced in 1996 and continues today (2023). From 1992–2000, active dewatering occurred for UG mining. However, since 2000, when the dewatering wells became dry, dewatering has been done by passive-sump pumping in UG workings. Since 1993, excess groundwater withdrawals, which are not used for mine-water consumptive use, are treated at the TR water treatment plant (WTP) for arsenic reduction and discharged to the environment at three rapid infiltration basins (RIBs).

At TC Mine, gold was discovered at Mega Pit in 1984, but mining operations did not begin until 1987. Active dewatering occurred during mining of Mega Pit from 1989–2011. From 2012–2023, open pit and UG mining has occurred at Vista Pit. Since 1993, excess groundwater withdrawals, which are not used for mine-water consumptive use, are treated at the TC WTP and discharged to Rabbit Creek, a tributary to Kelly Creek.

1.5 Maximum extent of mining and non-mining stresses

The maximum extent of mine-induced pumping-drawdown and injection was determined from a water-level trend analysis (Jackson, 2023), InSAR-based drawdown analysis (Bell and Katzenstein, 2011), and groundwater-flow model results (Itasca, 2022). Results from these studies indicate that pumping centers from TC and TR Mines have coalesced (Figure 1). Mine-water injection into RIBs has caused a local mounding of the water table (Figure 1). The localized mound forms a hydraulic barrier that impedes the southern propagation of mine-induced pumping toward Kelly Creek Basin irrigation area and the Humboldt River. Non-mine irrigation pumping has caused localized areas of pumping-drawdown that are centered within the main irrigation areas (Figure 1). Isolated irrigation pumping areas are supported by the analysis of water-level trends in wells between irrigation pumping areas and the Turquoise Mine Complex (Jackson, 2023).

2 Methods

Water levels in wells fluctuate naturally in response to recharge events. Therefore, to construct a baseline water-level record, an estimation of the historic temporal recharge distribution is required. Recharge was estimated by summing winter precipitation from a long-term (100+ year) precipitation record and then computing the standardized precipitation index, as described below.

2.1 Compiled precipitation data

Century-scale (1900–2023) precipitation data were compiled from Winnemucca Airport precipitation station (Station ID: USW00024128; NOAAb, 2023). The Winnemucca Airport precipitation record was used as a proxy for precipitation and recharge patterns on Kelly Creek valley floor, which is where the Turquoise Ridge Complex is situated. Winnemucca Airport precipitation is assumed representative of Kelly Creek valley floor precipitation and recharge patterns because the Winnemucca Airport station is (1) in close proximity (~ 60 km) of the Turquoise Ridge Complex; and (2) at an altitude of 1,310.6 m, which is similar to altitudes on Kelly Creek valley floor that range from 1,300–1,600 m. Even though the century-scale Winnemucca Airport precipitation record may not be identical to the true magnitude of precipitation in the recharge areas surrounding the Turquoise Ridge Complex, the relative temporal distribution of dry and wet years is assumed similar. This assumption is validated in section 4.

2.2 Recharge estimation using standardized precipitation index

In Nevada, most recharge is derived during the winter months (October–March) from greater-than-average precipitation when evapotranspiration approaches zero (Winograd et al., 1998; Smith et al., 2017). Precipitation thresholds can be used as a proxy for recharge events. Jackson et al. (2022) developed a statistical-based method for estimating precipitation thresholds that represent recharge events. The method requires computing a standardized precipitation index (SPI) from long-term precipitation records. An SPI has values ranging from −3 to 3, where values represent the number of standard deviations by which precipitation deviates from the long-term mean, assuming precipitation is normally distributed (McKee et al., 1993; Guttman, 1999). Because precipitation is generally not normally distributed, the SPI is computed by transforming a long-term precipitation record using a Gamma distribution and then fitting the transformed precipitation data to a normal distribution (Guttman, 1999).

Potential recharge was estimated from the Winnemucca Airport precipitation record (1900–2023) by summing precipitation during the winter months (October 1–March 31) (Figure 2A) and computing the six-month (winter) SPI (Figure 2B). Winter SPI values greater than 1 indicate wet climatic conditions (Figure 2C; Guttman 1999). Therefore, in the study area, winter SPI values greater than 1 are assumed to represent wet winters that could contribute recharge to the groundwater system. For example, Winnemucca Airport winter precipitation greater than 0.17 m (winter SPI = 1) represents potential recharge during wet winters, whereas winter precipitation less than 0.17 m is assumed to be evapotranspired (Figure 2C).

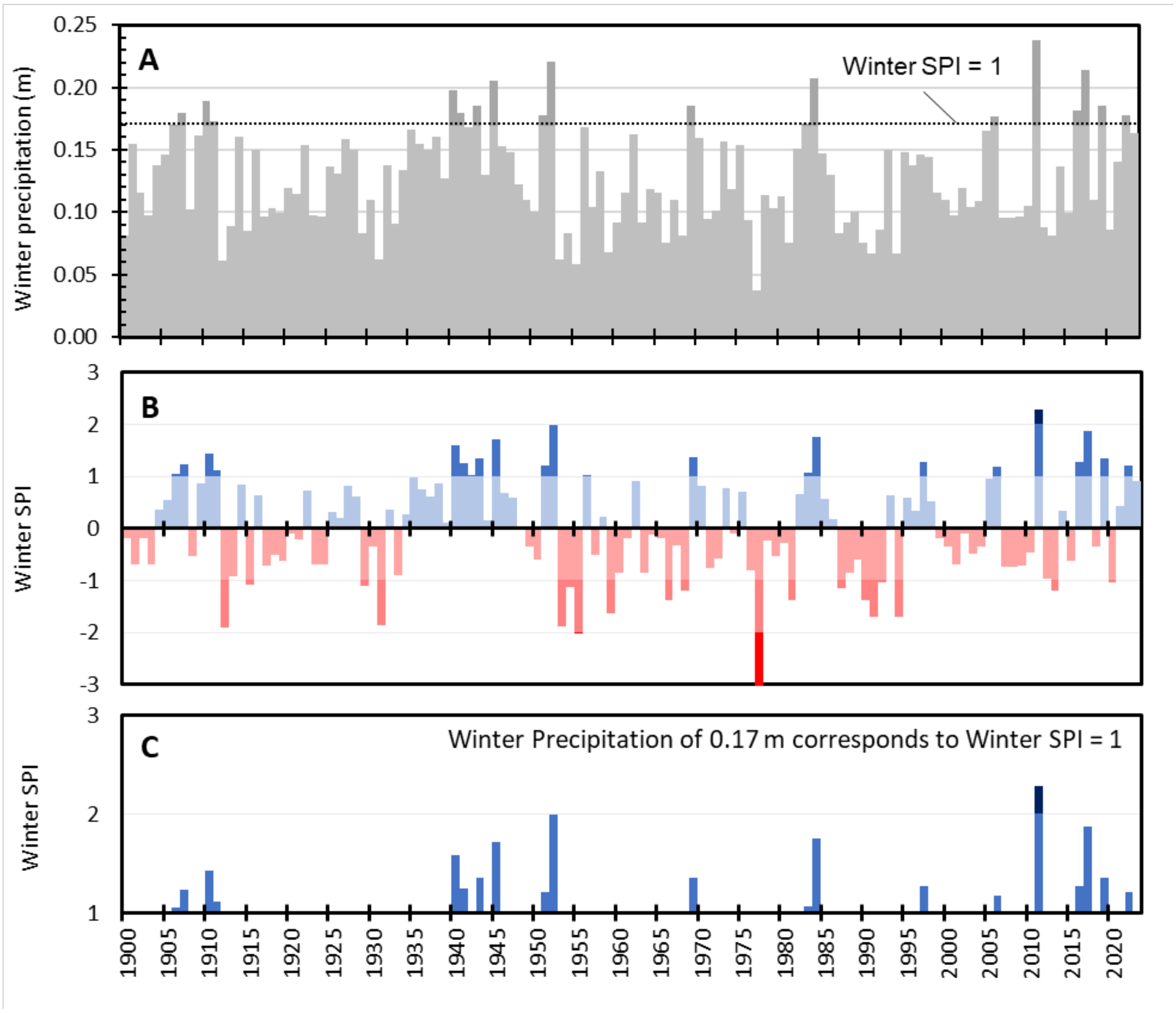

Figure 2 **Winnemucca Airport precipitation data. (A) Winter precipitation, summed from October 1 to March 31. (B) Winter Standardized Precipitation Index (SPI) computed using winter precipitation data. (C) Winter SPI values greater than 1, which show the relative magnitude and temporal distribution of recharge events**

3 Conceptual model of natural recharge and discharge

A conceptual model is developed herein to understand expected water-level trends from natural fluctuations in the groundwater system. Water-level trends affected only by natural hydrologic stresses, such as recharge and groundwater discharge to streams, springs, and phreatophytic areas, are assumed to be in a state of dynamic equilibrium. Dynamic equilibrium recognizes that water levels fluctuate over the short-term (years to decades) because of time-varying natural stresses, such as recharge. However, over a long (century) time scale, water levels are assumed to represent steady-state conditions. The steady-state timescale is assumed to be on the order of about a century. A century timescale is assumed because the study area is within the semi-arid Great Basin, which has large groundwater basins with long distances between recharge and discharge areas and, therefore, long timescales (Jackson and Fenelon, 2018). The conceptual model assumes that long-term cumulative recharge and discharge are balanced with a resultant net change of zero in long-term water levels and cumulative storage. Using this conceptual model, a long-term hypothetical water-level record is developed that represents expected water-level trends from natural fluctuations.

3.1 Aquifer stresses: recharge and discharge

Naturally occurring hydrologic stresses affecting decadal water-level trends in the study area are groundwater discharge to streams, springs, and phreatophytic areas and precipitation-derived recharge. Groundwater discharge in the study area occurs primarily as evapotranspiration from phreatophytes, which have nearly constant rates of annual discharge (Huntington et al., 2022). Groundwater discharge is constant with time because it is controlled by unchanging hydraulic properties of the groundwater system, and a nearly constant regional hydraulic gradient defined by long distances between recharge and discharge areas. On the contrary, precipitation-derived recharge varies temporally and spatially, and is the primary cause of decadal water-level changes in wells.

The conceptual model represents century-scale recharge patterns in the study area using the Winnemucca Airport precipitation record. Potential recharge does not indicate the absolute magnitude of recharge in the study area; rather, it represents the distribution of years when recharge occurred and the relative magnitudes. The recharge pattern in Figure 3A shows that the study area has experienced decadal dry and wet periods, with the most notable wet periods occurring in the 1910s, 1940s, and 2010s.

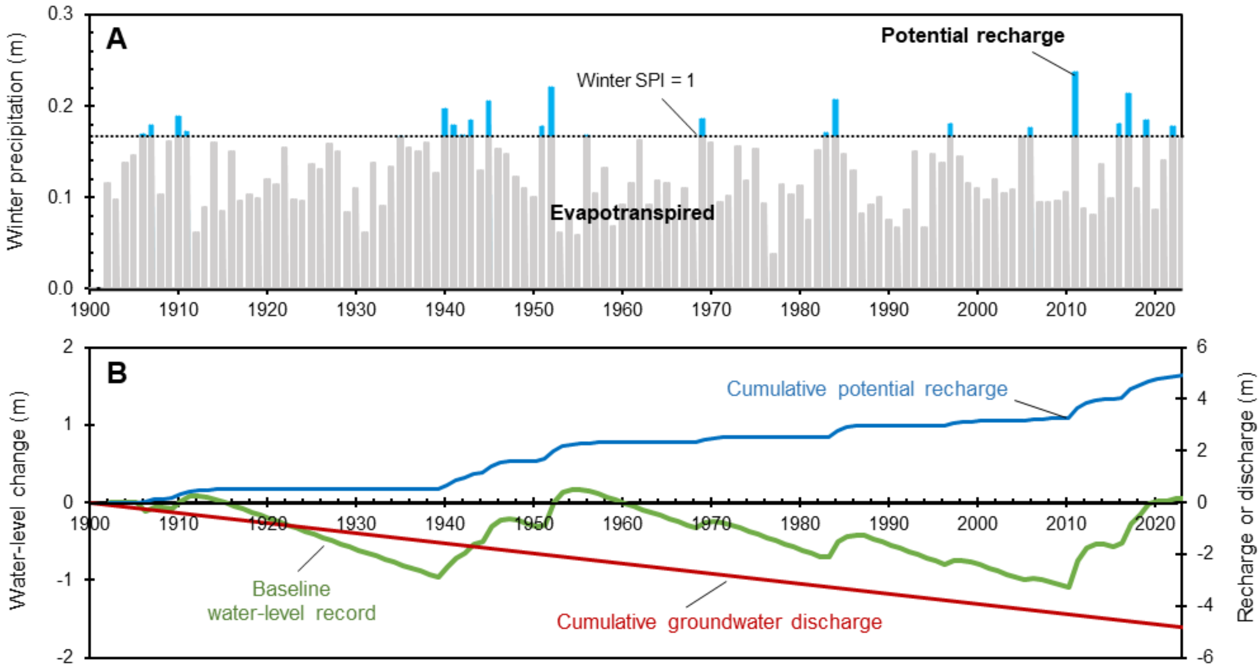

Figure 3 Steady-state conceptual model for the study area, 1900–2023. (A) Winter precipitation distribution and potential recharge during wet winters. (B) Baseline record of water-level change, cumulative potential recharge, and cumulative groundwater discharge

3.2 Baseline water-level record

A hypothetical, baseline water-level record was constructed assuming steady-state conditions over the 123-year record; that is, cumulative recharge equals cumulative aquifer discharge. The baseline water-level record is the sum of potential recharge and discharge (Figure 3B). Cumulative potential recharge with time is computed from summing winter precipitation greater than 0.17 m (i.e., winter SPI of 1) (Figure 3A). The discharge rate is assumed steady and was computed as total potential recharge from 1900 to 2023 divided by the 123-year period. Potential recharge and discharge were translated to water-level change by dividing values (in meters) by an assumed effective porosity of 10 percent (Figure 3B).

The baseline water-level record shows expected water-level trends, affected only by natural hydrologic stresses in the study area, using an assumed century-scale steady-state period. Consistent with the concept of long-term steady-state conditions, the net water-level change for the period of record is zero (Figure 3B). The baseline water-level record indicates that, during the first part of the 20th century, a declining trend likely occurred from 1910 to 1940 because of an absence of wet winters, which was followed by a rising trend during a wet period in the 1940s. Infrequent wet winters from 1950–2010 result in brief periods of water-level rise superimposed on a long-term declining trend (Figure 3B). Post-2010, natural water-level fluctuations are expected to have upward trends because the study area has been in a relatively wet period (Figure 3B).

If steady-state conditions occur on a century timescale, measured water-level trends are expected to be neutral or downward from 1990 to 2010 and upward post-2010 (Figure 3B). The magnitude and exact pattern of water-level trends will differ between the baseline water-level record and water-level records in study-area wells because of differing rock porosities, spatially varying recharge rates, and groundwater-discharge rates; however, the general water-level trends are expected to be similar (Figure 3B).

4 Validation of baseline water-level record

The baseline water-level record was compared, qualitatively, to water-level trends from three study-area wells to validate the baseline record. The three selected wells are on Kelly Creek valley floor within 8 km of the Turquoise Ridge Complex. These wells have not been affected by irrigation pumping or mine-induced pumping-drawdown and injection (Figure 1). The three selected wells are either near Kelly Creek (MO 404336-01), along Jake Creek (MO 384407-01), or between Kelly and Jake Creeks near the center of the valley floor (MO 384315-01) (Figure 1). Wells MO 404336-01 and MO 384407-01 are open to fractured volcanic rocks, whereas well MO 384315-01 is open to alluvium (Jackson, 2023).

Periodic water-level data from the three wells were smoothed to better observe their water-level trends. Using water-level data from 1995–2023, water-year (Oct 1–Sep 30) averages were computed and then the datasets were normalized to 1. To qualitatively compare these data to the baseline water-level record, the baseline record also was normalized to 1 (Figure 4). Comparison of the baseline water-level record to measured data indicates that the baseline record replicates observed water-level trends in study-area wells affected only by natural stresses.

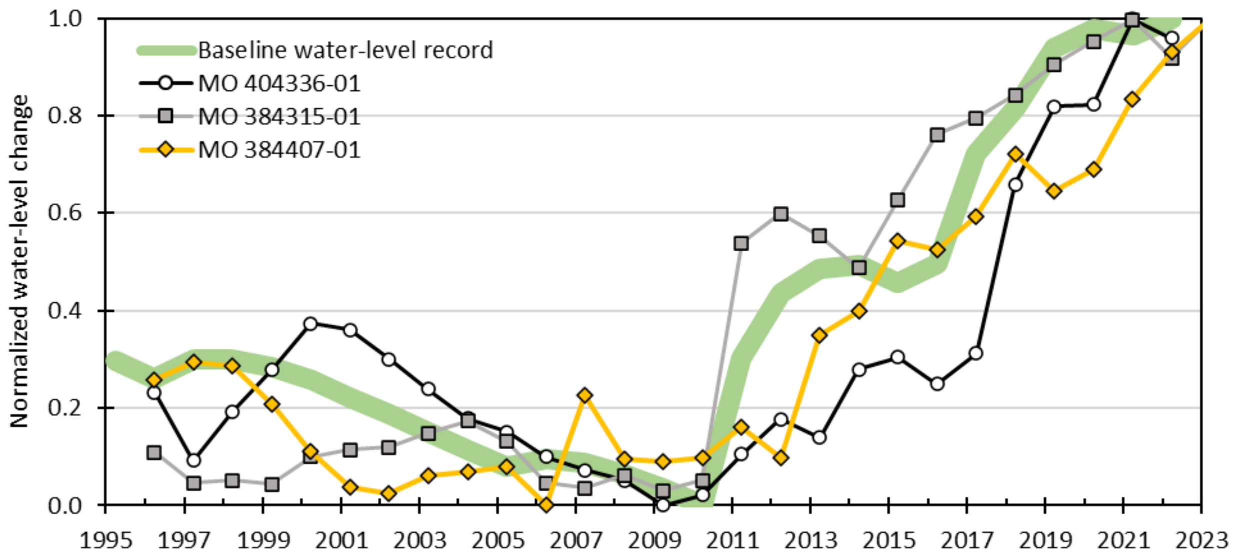

Figure 4 Comparison of normalized water-level data from three study-area wells to the normalized baseline water-level record

5 Conclusion

This paper presents an analytical approach for constructing a theoretical long-term (1900–2023) water-level record, which is a baseline dataset for understanding the expected range of natural temporal variability. The approach relies on an underlying conceptual model of groundwater recharge and discharge. Recharge and discharge are assumed to be in a state of dynamic equilibrium, where water levels fluctuate over annual-to-decadal timescales but have a century-scale steady-state (unchanging) condition. Using this conceptual model, a baseline (1900–2023) water-level record was constructed for the Turquoise Ridge Mine Complex in northern Nevada. The baseline record was validated by qualitative comparison to measured water-level data affected only by natural hydrologic stresses. The baseline water-level record compares favourably to measured water levels, thus successfully validating the approach.

Acknowledgement

The authors would like to thank their employer, Barrick Gold Corporation, for allowing us to publish the results of this study.

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