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EVALUATING HYDROLOGICALLY CONNECTED SURFACE WATER AND GROUNDWATER USING A GROUNDWATER MODEL[1]

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ABSTRACT: Determination of the nature and extent of the connection between groundwater and surface water is of paramount importance to managing water supplies. The development of analyses that detail the surface water-groundwater system may lead to more effective utilization of available water. A tool was developed to help determine the effects of groundwater and surface water interactions. The software tool includes two graphic user interfaces to allow full compatibility with numerical MODFLOW groundwater models. This case study shows the tool, in conjunction with MODFLOW groundwater models and carefully designed scenarios, can successfully calculate the rates of stream-groundwater interactions, thereby providing the basis for designating management areas with the most significant hydrologic impact. This tool can be applied in other regions with similar settings and needs for integrated water management.

(KEY TERMS: integrated water management; hydrologically connected area; stream depletion; MODFLOW; Zone Budget; Nebraska.)

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INTRODUCTION

Surface water and groundwater interactions that result in a single integrated resource have long been acknowledged in the scientific community. The interaction between groundwater and surface water affects stream discharge, water quality, geomorphic evolution, and ecosystem services (Sophocleous, 2010). Anthropogenic influences on this interaction include land-use modifications that affect recharge rates, groundwater pumping, and depletion to streamflow. For example, over-appropriation of streams can reduce the groundwater levels, and conversely extraction of groundwater often depletes streamflow. However, statutory and legal frameworks often designated surface water and groundwater as separate water resources (Sophocleous *et al.*, 1995; Winter *et al.*, 1998; Hoffman and Zellmer, 2013). Inability to integrate both water resources as a single resource into one management framework often causes negative implications such as reduction in streamflow, aquifer drawdown, water conflicts between users, and insufficient environmental flows

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(Steward *et al.*, 2013). Therefore, modern water resource management requires the coordinated planning of groundwater use and surface water use, also known as Integrated Water Management (IWM). Other equivalent and frequently used alternative terms include Integrated Water Resource Management (Biswas, 2004) or Conjunctive Water Management (Blomquist *et al.*, 2001).

Integrated Water Management is the most widely used management strategy to tackle global water conflicts where water demands often surpass supplies (Biswas, 2004; Rassam *et al.*, 2013). The U.S. State of Nebraska, as the leading state in IWM (Viessman, 2007), focuses on the broadly connected groundwater and surface water supplies (Nebraska Department of Natural Resources (NDNR), 2006). The majority of Nebraska streams are base-flow dominant, and groundwater contributions are the dominant source of water to the system that supports surface water irrigation and many ecological and recreational services. Historically, the development of groundwater in some basins (e.g., the Republican River Basin) had led to substantial river depletions and reduced outflow to downstream users.

Understanding the extent and magnitude of the connectivity between streams and adjacent aquifers is one of the key challenges for the effective management of integrated water resources (Winter *et al.*, 1998; Sophocleous, 2002). The nature of these relationships and varied temporal effects between the fast-response surface water system and the slow-response groundwater system are dependent on a number of factors, such as the hydraulic properties of the aquifer/stream system, the density and distribution of the stream network, the proximity of groundwater pumping to streams, and the severity of anthropogenic modifications. Among numerous existing approaches (e.g., hydrographs, hydrochemistry, analytical, and numerical flow modeling), numerical modeling has been adopted with exceptional frequency as a decision support tool for planning and managing water resources (Bejranonda *et al.*, 2013). Delineating hydrologically connected area is regarded as one of the most important steps in IWM of Nebraska.

The hydrologically connected area in the context of this article is defined as "the geographic area for the purposes of management, within which surface water-groundwater interactions occur at specified rates, within a given time frame" (Groundwater Management and Protection Act (GMPA), 2004). The delineation of this area utilizes the stream depletion factor (SDF), which calculates the potential of water pumped from a groundwater well to deplete streamflow (Jenkins, 1968; Fredericks *et al.*, 1998). The potential for depletive effects is a concept frequently utilized by Nebraska to designate areas where management actions will exert the greatest impacts. To facilitate the determination as a policy-based decision, the Nebraska Department of Natural Resources (NDNR) considers hydrologically connected area to be the area in which pumping of a well for 50 years would deplete streamflow by at least 10% of the amount pumped. In Nebraska, the hydrologically connected area is also known as the "10/50 Area" (hydrologically connected area and 10/50 area will be used interchangeably hereafter).

In this article, we outlined a computer program that can be used to assist in determining the geographic extents of the hydrologically connected area and the nature of surface water-groundwater relationships by identifying the rate of water movement between the systems. In a policy context, this rate of interaction helps define areas of management focus, which are the hydrologically connected areas. This tool is expected to fill the gaps between the development of groundwater models and application of the models for water resource management.

METHOD

To delineate the scientifically defensible 10/50 area, NDNR reviewed available numerical models to assess the validity and appropriateness for hydrologic connectivity analyses. After selection of a numerical model, NDNR relied on a process known as "Cycle Well Analysis" (CWA) to conduct the analysis. The results of the CWA are used to address the following questions: in which geographic area along the streams are the groundwater and surface water regarded as hydrologically connected (extent); and what percentage of stream depletion can be caused by newly installed pumping wells (magnitude). Since the above process is typically applied to the multi-basin numerical models with tens of thousands of model grid cells, it is expected that a manual step-by-step implementation of CWA is not plausible.

The basic design principle of the CWA tool is to place a hypothetical well into each model grid cell, run the groundwater model developed using MODFLOW, and then the Zone Budget program in a cyclical manner. MODFLOW is a finite-differential groundwater flow modeling program commonly used to assess the effects of pumping on streamflow and aquifer levels (Harbaugh and McDonald, 1996). Zone Budget is a MODFLOW post-processing program that computes subregional water budgets using results produced by MODFLOW (Harbaugh, 1990). It is noted that the Zone Budget allows the stream depletion to be summarized at the levels of subregions or subbasins, and the groundwater model should be appropriate for a 50-year model simulation. Water budget outputs from each cycle are compared with those from the baseline run (i.e., the original model run without the hypothetical well). The stream depletion factor is computed as the ratio of stream depletion difference in net flow out to streams between the run with the hypothetical well and the baseline run to the total pumpage of the hypothetical well. Figure 1 shows the conceptual procedure to implement the CWA process, in which the blue and red arrows indicate the baseline and scenario runs respectively and the green and orange arrows denote the calculation of the basinwide and subbasin level 10/50 areas.

The tool was developed using Visual Basic .NET with compatibility with Windows 7, Windows Server 2008, and their later versions. It features two Graphic User Interfaces (GUIs), the Basic (Figure 2A) and Advanced modes (Figure 2B), which can be used to meet the needs of users with different levels of professional knowledge on groundwater models. The Basic mode can be used to test the same pumping rate for each hypothetical well that is either located at predefined cross sections or determined by a user-input list. But, the Advanced mode has greater flexibility to allow the input of a user-compiled cycle well list where the layer number, pumping rates, and row/column of the model grids can be customized by a user. The MODFLOW and Zone Budget programs can be activated and implemented through a few user-defined inputs in the software GUIs. In addition, this modeling tool requires extra pre-processing and post-processing steps. The pre-processing requires modification of the existing Well file that defines the locations and pumping rate for each model grid cell. The computation of the long-term SDF and the determination of the 10/50 area depend on the process of the post-processing using a separate program CWA Summary Analysis Tool (Figure 2C). This software tool may help water resource managers and technical staff who are not familiar with running groundwater models.

For technical details about the implementation of the program, please refer to the Supporting Information.

CASE STUDY

The case study region encompasses approximately 36,800 square kilometers, which includes portions of the Loup and Elkhorn River Basins of central Nebraska. About 60% of the area is overlain by the Nebraska Sandhills, the largest sand-dune area in North America (Keech and Bentall, 1971). The Loup and Elkhorn Rivers provide surface water flows for irrigation, hydropower production, recreation, and wildlife habitat. A transient numerical groundwater model, namely the Central Nebraska (CENEB) model, was developed based on MODFLOW-NWT for this region. It is a one-layer model with a total of 359 stress periods (ranging from 1940 to 2011). The documentation of this CENEB model is accessible at http://www.dnr.nebraska.gov/iwm/central-nebraska-groundwater-flow-model-august-2013.

The hydrogeology of the Basin reflects the nature of the eolian and fluvial origin of the recent sediments. The primary aquifer in the Loup Basin is the Ogallala Formation, which consists of poorly sorted,

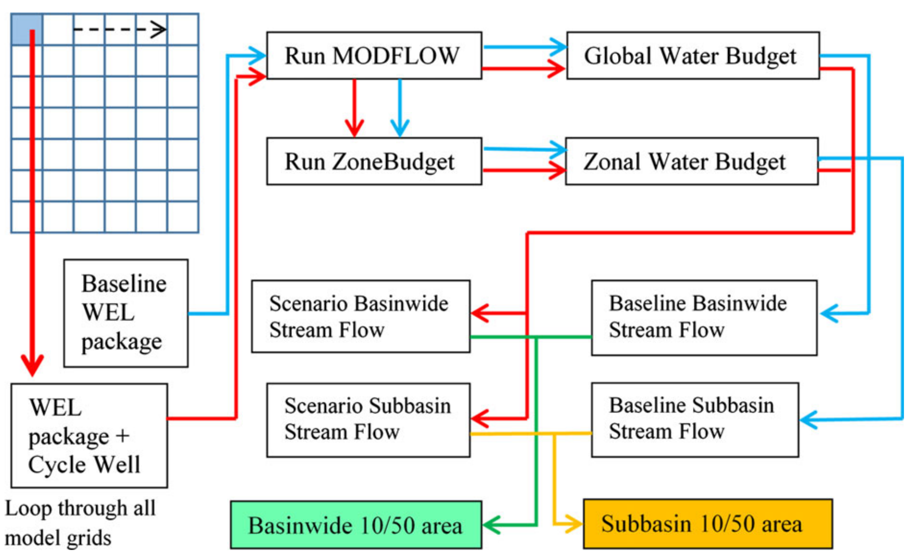

FIGURE 1. Conceptual Procedure for the Cycle Well Analysis.

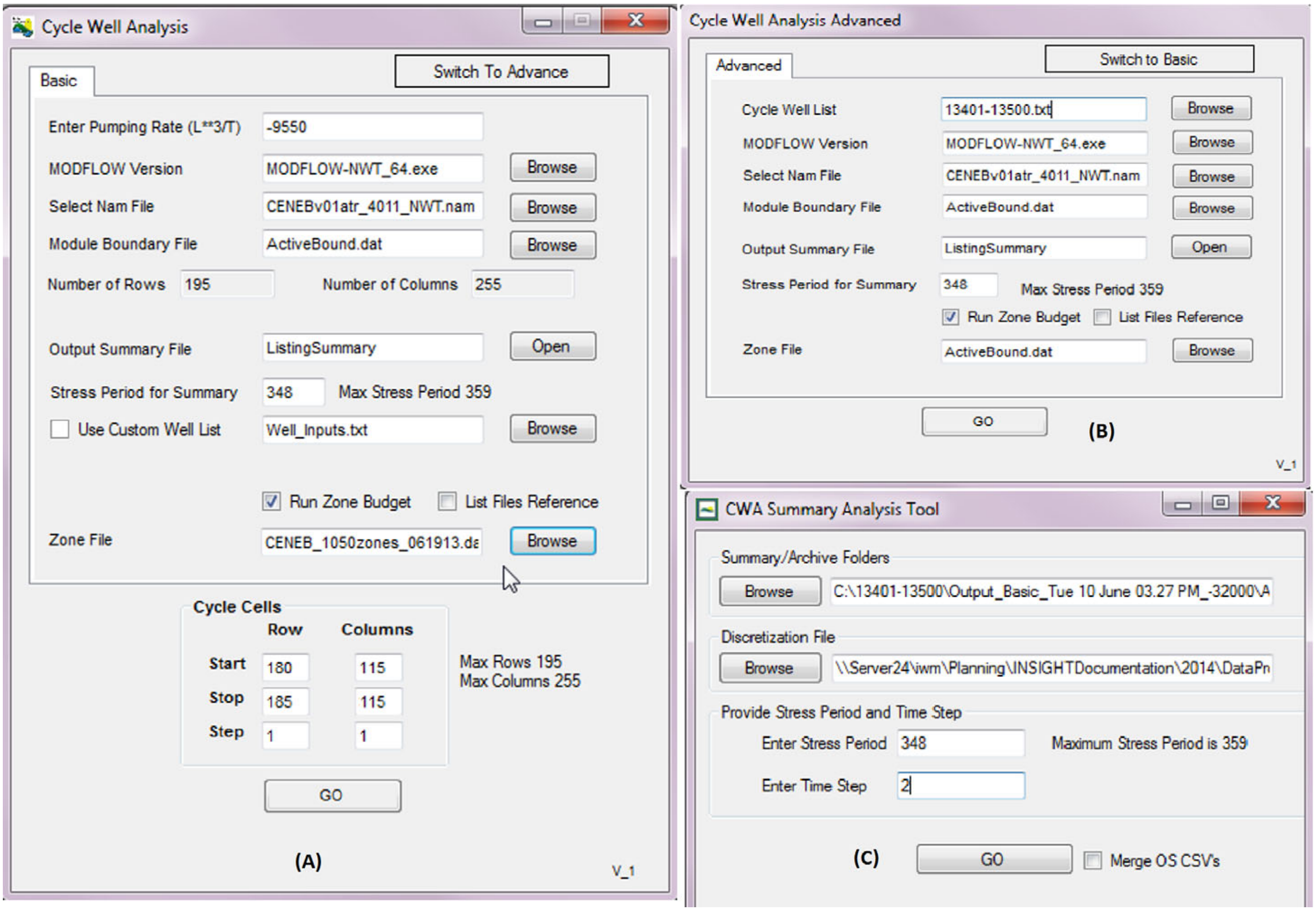

FIGURE 2. Basic and Advanced Graphic User Interfaces of the Cycle Well Analysis Tool and a Post-processing Tool.

generally unconsolidated clay, silt, sand, and gravel (Peterson *et al.*, 2008). The Ogallala Formation is part of a vast system of related sediments that make up the High Plains Aquifer. The eastern margin of the basin is underlain by undivided Quaternary-aged units of the Great Plains Aquifer. Large saturated thicknesses, high porosity and yield, and high hydraulic conductivity are common in the basin. The principal aquifer varies in saturated thickness from 0 to approximately 335 m, and depth to water from the land surface varies from 0 to more than 60 m. Most areas of the Basin have transmissivity values between 1,240 and 1,860 square meters per day. Specific yield ranges from less than 5 to greater than 20%. The principal aquifer is generally unconfined and is in hydrologic connection with the streams.

In this example, we assumed the hypothetical well pumped for the most recent 50 years. The pumping rate was set to occur at a constant rate of approximately 0.00313 m^3/s (equivalent to 9,550 ft^3 per day). This pumping rate was set based on an annual irrigation demand of 20.3 cm (8 inches) for a standard 48.6 ha (120 acre) farmland located in a central pivot.

After the pre-processing, the CWA program and the post-processing steps, a map of the SDF for this area was developed as shown in Figure 3. On this map, the area with SDF equal or above 0.1 was regarded as the area where groundwater and surface water are hydrologically connected.

To quantify the effects of the pumping rates on the SDF values, we conducted a sensitivity analysis by using a wide range of pumping rates from 1×10^{-4} m^3/s to 300×10^{-4} m^3/s. To reduce the computation time, we selected only every 20th cells for both rows and columns, and ended up with a total of 86 cells. The SDF values from these cells under different pumping rates were computed using the aforementioned processes, and plotted in Figure 4.

DISCUSSIONS AND CONCLUSIONS

SDF values are known to be related to many hydrogeologic properties, including distributions of

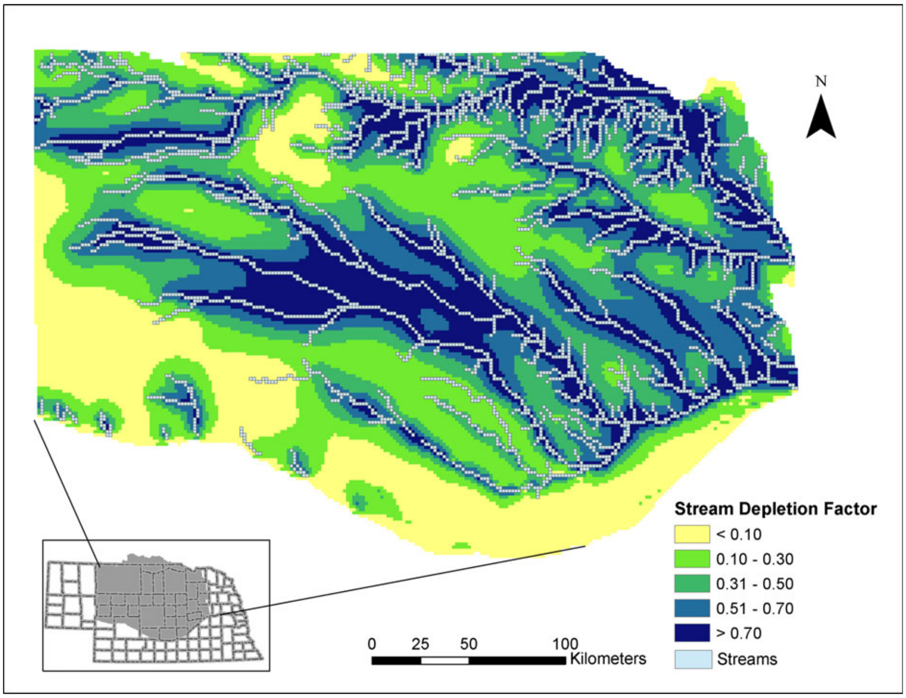

FIGURE 3. Stream Depletion Factor for Central Nebraska (study area was clipped to the boundary of Nebraska).

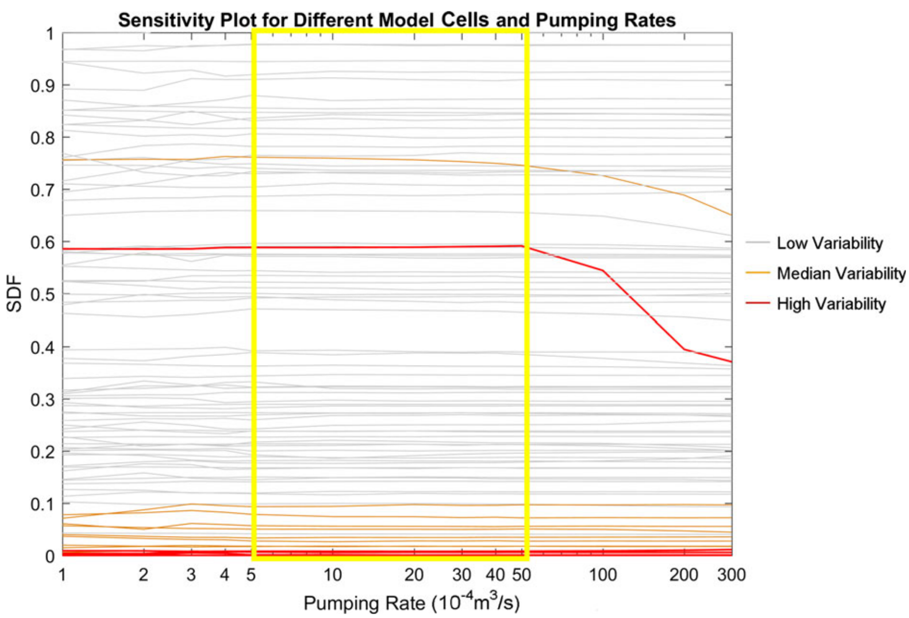

FIGURE 4. Sensitivity Test of Different Pumping Rates to Compute the Stream Depletion Factor (SDF) for the Central Nebraska Model.

hydraulic conductivity, specific storage, specific yield, and system geometry (Leake, 2011) as well as streambed properties and thickness. However, the sensitivity of the SDF values to the selection of pumping rate may be largely problem specific. We thus examined the effects of different pumping rates using the aforementioned approach. As shown in Figure 4, the 86 locations examined cover a wide range of SDF values from near 0 to around 1. The data series were divided into three groups, low variability (gray lines), median variability (orange color), and high variability (red color), based on the relative variability in the SDF results associated with different pumping rates (quantified as normalized standard deviation). A majority of selected model cells showed low variability, indicating the SDF values of most cells would not be strongly influenced by pumping rates. Among the median and high variability groups, nine out of ten cells with median variability and four out of five cells with high variability are located outside the "10/50 areas" with SDF values less than 0.1. Only two model cells with SDF values greater than 0.1 exhibited large declines in SDF at higher pumping rate of 0.01 m^3/s and above (orange and red lines).

In a close examination of the water budget for the two exceptions, we found that the reduction in stream depletion coincided with decreased groundwater evapotranspiration (ET). It was found that both cells are located adjacent to or on top of two stream tributaries where phreatophyte ET has been simulated (using methods in Harbaugh and McDonald, 1996). Larger pumping rates reduced the groundwater head to a level that is lower than the ET surface (a MODFLOW term for the extinction depth below which ET is cut off), and the resulting decrease in simulated ET helped compensate for stream depletion. Figure 4 also indicated there could be a pumping rate "window" associated with the least SDF variability ranging between 5×10^{-4} m^3/s and 50×10^{-4} m^3/s (shown in the yellow rectangle area). The variability tends to increase outside of this range.

A few conclusions can be cautiously drawn from this sensitivity test:

1. SDF values can be affected by the choice of pumping rate but not significantly for the entire geographic area overall;
2. The pumping rate selected should be neither too large nor too small, and the optimal values could be determined using a similar sensitivity test; and
3. The variability in SDF values associated with different pumping rates would not appreciably affect the determination of the "10/50 area" boundaries for this study.

In the State of Nebraska, the rule of "10/50" (i.e., 10% or greater stream depletion within 50 years) is applied to determine high-focus management areas, also known as hydrologically connected areas. The CWA program, along with a numerical groundwater model, may benefit other regulatory or management agencies to determine the degrees of interactions of surface water-groundwater systems, and define the hydrologically connected water resources. The CWA program was designed in a way to be compatible with alternative rules such as changing the percentage of depletion (10%) or incorporating different time frames.

The application of this program in other groundwater models in Nebraska also showed that it is beneficial to incorporate the 10/50 analysis during the development of a numerical groundwater model. With the tool, the sensitivity of the water budget in response to incremental pumping in each model grid can be tested and analyzed. For example, scenario models with incremental pumping added to adjacent cells theoretically should not result in dramatic difference in water budget discrepancies. Also, the SDF is expected to present smooth patterns with gradual spatial gradients in the vicinity of a stream. If the results show deviation from the expected patterns, it may indicate model design issues or discrepancies associated with water budget closure such as loose closure criteria. Thus, this tool can also provide an invaluable opportunity to test the model reliability in response to incremental stresses.

In addition, it is useful to note potential limitations of using the program for certain models. The assumption adopted by this tool may not be valid for areas with dry cells, the model grid cells that become inactive during certain periods of simulation. If model cells become dry, the assumption of long-term continuous pumping would be violated. The typical remedies include a reduction in the pumping rates, moving the pumping into other model layer(s) if available, or conversion from pumping wells to injection wells. The SDF can also be affected by extreme cases of large-scale groundwater development and limited streamflow when the stream loses all of its water to the aquifer and becomes ephemeral (Barlow and Leake, 2012). The streamflow would be completely depleted in a time period shorter than 50 years in such a case. Thus, this program should be used with caution in areas with widespread dry stream reaches. Currently, the CWA does not support parallel computing mode and increases in the rate of model simulations is only achieved by manually distributing multiple sessions of tasks to separate computers or servers. Future incorporation of parallel computing is being explored.

In summary, the CWA program provides a tool for water resource managers to understand and delineate hydrologically connected water resources. It has presented its utility and robustness for IWM in the State of Nebraska. With appropriate adjustments and precautions, this program may be applicable to other places with similar needs for water resources planning and management.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: The document provided technical details on the implementation of the Cycle Well Analysis tool.

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