Groundwater

Methods Note/

Simulating Groundwater Interaction with a Surface Water Network Using Connected Linear Networks

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Abstract

Simulating the interaction of groundwater with surface water networks using traditional boundary packages available with MODFLOW-USG can be challenging for complex systems. Often several package types are required as they are typically purpose built. Moreover, these packages generally do not interact with one another which complicates accounting of groundwater discharge at different points within the system. Here, we demonstrate that see 1.17 the connected linear network (CLN) package of MODFLOW-USG, and advances therein in USG-Transport, can be used to simulate groundwater interaction with a complex surface water network comprised of creeks, ponds, wetlands, and springs, in a manner that is comparable with these other packages, but with additional benefits, including explicit routing 4.1 of water between the features.

Introduction

This article demonstrates the utility of simulating the interaction of a groundwater system with a complex surface water network comprised of creeks, ponds, wetlands, and springs using the connected linear network (CLN) package available with USG-Transport, formerly MODFLOW-USG (Panday et al. 2017; Panday 2021). Traditionally, in practice, a variety of packages are required to represent these different surface water features when using USG-Transport. These packages are purpose built and do not always interact with one another. These packages include the streamflow-routing (SFR; Niswonger and Prudic 2005, Prudic et al. 2004), lake (LAK; Merritt and Konikow 2000), river (RIV), constant-head (CHD), and drain (DRN) or drain-return (DRT; Banta 2000) packages developed for previous releases of MODFLOW (Harbaugh et al. 2000; Harbaugh 2005). Except for the SFR and LAK packages, these packages only simulate the groundwater exchange between the surface water and aquifer systems and do not route water within or between the elements of the surface water network itself. 4.8

The CLN package provides a generic framework to calculate flow within a network of cylindrical features and the exchange with a porous medium (Panday 2021). Flow within the CLN network is calculated using laminar or turbulent flow equations, while the flow between a CLN node and a groundwater flow (GWF) cell is calculated using conductance or Thiem equations. The MODFLOW-USG code released by the U.S. Geological Survey (USGS) only uses the laminar flow equation in the CLN domain, while the USG-Transport enhancements include Manning's, Darcy–Weisbach, and Hazen–Williams turbulent flow equations. The CLN system is a separate flow process that is solved simultaneously with the GWF process. While the CLN system is a boundary package to the GWF

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system, boundary conditions can be applied to the CLN system itself. For example, the well (WEL) package can be used to represent pumping from a vertical conduit or the CHD or DRN packages can be used to represent the outlet stage of a creek.[4.3]

Simulating wells and creeks with the CLN package is common practice and are suggested applications in Panday (2021). These types of CLN networks are referred to by Panday (2021) as one-dimensional (1D) because flow is calculated in the longitudinal direction of the conceptual pipe or cylinder. Here, we use dimensionality to describe the intraconnectivity of CLN nodes representing a surface water feature. A 1D feature is tessellated in one direction, that is, its CLN nodes are connected in sequence from one to the next, like a multilayer well or creek (Figure 1). A two-dimensional (2D) feature is tessellated in two directions, that is, the discretization of the feature mirrors the underlying GWF grid. The calculated flow between each connected CLN node is still longitudinal, but their intraconnectivity mimics a 2D grid. The connectivity of nodes is input to the CLN package using an IA/JA-array specification as is done for the finite-difference GWF grid in the USG-Transport discretization (DIS) package. The IA array is a count of the number of connections for each CLN node, while the JA array lists the other CLN nodes connected to a CLN node. This specification style provides the framework necessary to represent complex networks involving 1D and 2D features and their interconnectivity. Moreover, multiple GWF cells can be assigned to a CLN node and the conductance terms for each specified independently.

The flexibility afforded by the connectivity specification, coupled with the variety of flow formulations available, was the motivation to evaluate the use of CLNs to represent complex surface water networks comprised of 1D and 2D features.

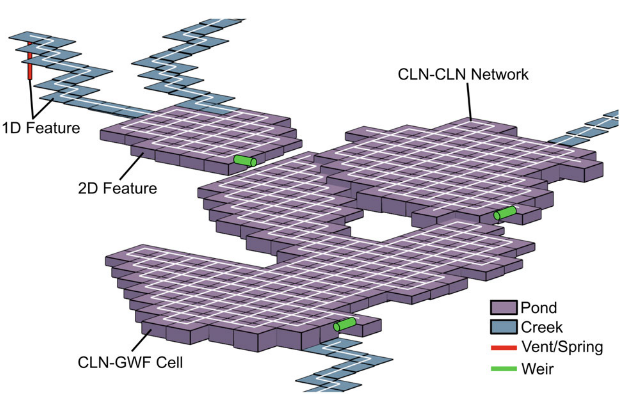

Figure 1. Illustration of feature intraconnectivity. In blue are model cells for which a creek CLN node is specified, and in purple are GWF cells corresponding to pond CLN nodes. The white lines are the corresponding CLN network. Creek intraconnectivity is one-dimensional; a CLN node is connected to at most one other CLN node upstream and downstream. Pond intraconnectivity is two-dimensional; a CLN node is connected to the four neighboring CLN nodes mimicking the connectivity of the GWF grid.

Method

To demonstrate the utility of using the CLN package to simulate a connected surface water network we converted a model originally developed using the SFR, LAK, DRT, and CLN packages to one using the CLN package, exclusively. The calculated flows within and to the different feature types were then compared.

The original model was developed to evaluate the effects pumping would have on nearby springs, creeks, ponds, and wetlands. It is a steady-state model and the area of interest includes two creeks that flow through a succession of wetlands, and for one creek, a series of small ponds, before ultimately discharging to a river (Figure 2). There are three ponds, and the level of each is controlled by a weir. At the headwaters of some wetlands, springs are mapped. These springs are the result of a discontinuity in the subsurface that creates discrete pathways, vents, for groundwater flow. Groundwater discharges to these features before ultimately flowing to the river.

The surface water network was originally simulated using the SFR, LAK, DRT, and CLN packages available with USG-Transport. The creeks were simulated with the SFR package, and the small ponds with the LAK package. The weirs at the outlet of each pond were simulated using the SFR package. The spring vents were simulated as vertical conduits between the requisite model layers using the CLN package. The stream-connected groundwater slope wetlands were simulated with a hydraulic conductivity zone to represent the peats and fine-grained sediments in the wetlands. The vertical hydraulic conductivity of these sediments controls the rate of groundwater discharge to these features. Thus, a low-resistance bed was specified in the DRT package with a uniform high conductance of 10,000 ft^2/d (0.01 m^2/s).

The necessary connections linking the creeks, ponds, and weirs were originally set within the SFR package. The CLN and DRT packages were linked to the creek network using a series of high-conductivity SFR segments placed along each creek. To route groundwater from the vents to the creeks, a high-conductivity SFR segment was placed in the first model layer at each spring location and connected to the corresponding creek segment. To account for the groundwater flowing through the wetlands to the creeks, the DRT cells were manually grouped based on their location along a creek with the flow return cell for each set to a high-conductivity SFR segment which was in turn connected to a creek segment. With this approach we were able to use the gaging capabilities of the SFR package to compare model calculated baseflow with estimates at each staff gage (Figure 2). However, this approach requires an *a-prior* interpretation of the flow within the wetlands to the creeks. For the most part, there is little consequence in doing this; the groundwater just needs to be returned upstream of the correct gage for accounting purposes.

A version of this model was then developed using the CLN package to represent all the features of the surface water network. Manning's turbulent flow equation was used for the CLN domain. The creeks, vents, and

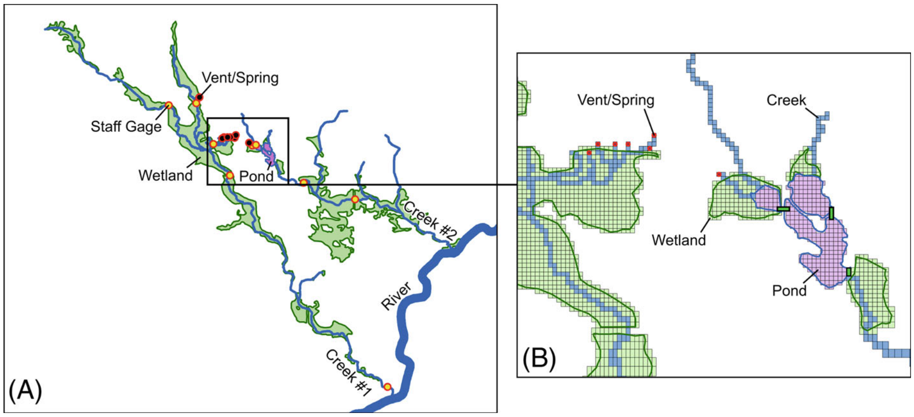

Figure 2. (A) The surface water network represented in the models. The thick blue line is the river, and the thin blue lines are the creeks. The mapped wetlands are shown in green and the ponds in purple. The black dots outlined in red are the locations of the mapped springs, and the yellow dots outlined in red are the locations of staff gages at which flow was measured. (B) Model representation of the surface water network in the vicinity of the springs and ponds. The vents are shown in red and the weirs at the outlet of each pond are shown as green lines outlined in black.

weirs were represented as 1D features; and the ponds and wetlands as 2D features. The intraconnectivity of CLN nodes for each feature mimicked the connections in the IA/JA array of the GWF grid, where GWF cell number was replaced with the corresponding CLN node number. The interconnectivity between the different features was also determined using this approach. Moreover, the flexibility afforded by the IA/JA specifications in the CLN package made it straightforward to directly connect the vertical vent features with the horizontal creek features. For the conversion from the LAK package, the cells inactivated to define each pond were retained and the required seepage faces with periphery GWF cells in layer 1 and underlying cells in layer 2 were specified in the CLN package as shown in Figure 3.

Cylindrical Conduits, Wetted Perimeter, and Equivalent Conductance

For each of the boundary packages used in the models the volumetric flow between the surface water feature and the aquifer is calculated as the product of a conductance term, C [L^2 T^{-1}], and the difference in head between the two, $h_s - h_a$; where h_s is the head in the surface water feature [L], and h_a is the head in the aquifer [L]. The conductance term is a function of the area of the seepage face between the two processes. The conductance terms for the different packages are calculated as follows (Merritt and Konikow 2000; Prudic et al. 2004; Panday 2021):

$$C = \begin{cases} \frac{K_b w L}{b}, & \text{SFR, DRT} \\ \frac{A}{\frac{b}{K_b} + \frac{\Delta l}{K_a}}, & \text{LAK} \\ \frac{K_b P_w L}{b}, & \text{CLN} \end{cases} \quad (1)$$

where K_b is the hydraulic conductivity of the feature bed [L T^{-1}], b is the bed thickness [L], w is the bed width [L], L is the bed length [L], A is the area of the seepage face,

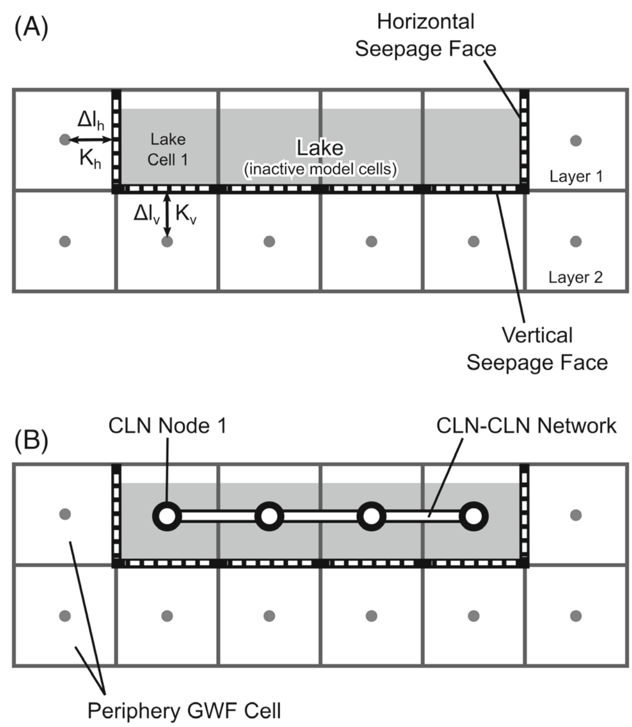

Figure 3. Conceptual seepage faces due to horizontal and vertical flow between a lake and the aquifer for (A) the LAK package, determined implicitly from the inactivated cells assigned to a lake; and (B) the CLN package, in which the seepage faces must be listed explicitly. Lake Cell 1 in (A) includes both a horizontal and vertical seepage face, and the same is true for CLN Node 1 in (B).

Δl is the length of aquifer [L], K_a is the aquifer hydraulic conductivity [L T^{-1}], and P_w is the wetted perimeter of the upstream CLN node [L]. The conductance term for the vertical component of flow is linear in the SFR, LAK, and DRT packages, however, for the CLN package, regardless of flow component direction, conductance is nonlinear and depends on the wetted perimeter which is a function of the aquifer or surface water body head (Panday 2021):

$$P_w = \begin{cases} 0, & d \leq 0 \\ 2R\cos^{-1}\left(\frac{R-d}{R}\right), & 0 < d \leq R \\ 2R\left[\pi - \cos^{-1}\left(\frac{d-R}{R}\right)\right], & R < d < 2R \\ 2\pi R, & d \geq 2R \end{cases} \quad (2)$$

where R is the radius of the CLN node [L], and d is the upstream depth [L] calculated as h-BOT; where BOT is the specified elevation of the CLN node, and h is the larger of h_s and h_a. Thus, if $h_s > h_a$, the surface water body is draining to the aquifer, and if $h_a > h_s$, the aquifer is discharging to the surface water body, across the wetted portion of the CLN node.

In the CLN package, because the seepage faces are represented as a circular feature as opposed to a rectangular one, and because the conductance terms are all nonlinear, it is not possible to derive equivalent terms to those in the traditional packages. However, from Equation 1, by scaling the area term, $P_w L$, by an estimate of the initial wetted perimeter, corresponding conductance terms can be approximated. From Equation 2, an initial estimate of the wetted perimeter requires an idea of the applicable depth condition, an appropriate equivalent conduit radius, and an estimate of the depth.

CLN Seepage Face Properties

The seepage face properties input to the CLN package that were used to convert from the standard packages are summarized in Table 1. Where possible, the property values input to the standard package were repeated in the CLN package. Because the input and conductance formulations are similar between the SFR and CLN packages, this conversion was straightforward and only required an estimate of the creek depth to calculate an appropriate conduit radius and initial estimate of the wetted perimeter. For the conversion from the LAK package, it was necessary to assume a bed thickness to calculate a bed conductivity from the specified leakance assigned to the ponds. The conduit radius assigned to each pond equaled their respective expected maximum depth, which was calculated as the initial stage, specified in the LAK package, less the minimum bathymetry elevation of all model cells comprising a pond. The conductance specified in the DRT package is uniform and was approximated in the CLN package by assigning a constant area, A_c, to each seepage face and scaling this area by an estimate of the wetted perimeter and input to the CLN package as the length term. The area specified corresponded to the area of the smallest model cell. The estimated wetted perimeter was calculated using Equation 2 by assuming a conduit radius of 10 ft (3 m), and a depth of 0.5 ft (0.15 m). This radius was assumed for numerical stability as the calculated stage in the CLN package is also a function of this radius. A large radius results in a shallower calculated depth which can cause numerical oscillations if the calculated stage in the CLN node and head in the aquifer cell are approximately equal. If the radius specified is too small, the calculated depth may exceed it or the diameter, which will change the condition applied in Equation 2 to calculate the wetted perimeter from the initial assumption of $d \leq R$.

Table 1
Seepage Face Properties Input to the CLN Package for the Converted Model

Original Package	CLN Package: Conduit Radius	Bed Conductivity	Bed Length	Bed Thickness	Notes
SFR	$\frac{d}{2} + \frac{w^2}{8d}$	$\frac{K_b w}{P_{est}}$	L	b	• Depth assumed to be 0.5 ft • Bed conductivity, width, length, and thickness taken from the SFR package • P_{est} calculated using Equation 2, where $0 < d \leq$ R
LAK	d	$\frac{1}{\frac{1}{k} + \frac{\Delta l}{K_a}}$	$\frac{A}{P_{est}}$	1 ft	• Depth based on initial stage and bathymetry in LAK package • Bed conductivity calculated from leakance, k, in LAK package and assumed 1 ft bed thickness • Bed conductivity calculated using aquifer lengths and conductivities indicated in Figure 3, for horizontal and vertical seepage faces, respectively • P_{est} calculated using Equation 2, where $0 < d \leq R$
DRT	10	$\frac{10{,}000}{\frac{A_c}{P_{est}}}$	$\frac{A_c}{P_{est}}$	1 ft	• Depth assumed to be 0.5 ft • Conduit radius[2] assumed to be 10 ft • Area, A_c, uniform, assumed to be 2500 ft^2 (area of smallest cell) as conductance in DRT package is uniform • P_{est} calculated using Equation 2, where $0 < d \leq R$

CLN Conduit Properties

In addition to the definition of the seepage faces, the CLN package requires specification of the conduit properties governing flow between the CLN nodes. This specification has two parts. In the first part, each CLN node is assigned a type and a length, and in the second part the radius and Manning's roughness coefficient are listed for each conduit type. Here, seven conduit types were defined. One for creeks, one for each of the ponds, one for the wetlands, one for the weirs, and one for the vents. The radius specified for each type was presented earlier.

For the creeks and weirs, the length of each CLN node and the Manning's coefficient were repeated using the values in the SFR package. For the ponds, a length of 50 ft (15 m), the cell width, was specified with a high roughness coefficient of 0.5. These values were used to ensure the calculated stage in each was controlled by their respective outlet weir. For the wetlands, the length was calculated as the square root of the cell area with a Manning's coefficient of 0.15. This roughness coefficient was used because it falls within the range of coefficients determined for different flood plains by Arcement and Schneider (1989).

Results

The flow through each seepage face calculated using both versions of the model were tabulated and a comparison for each boundary package type is shown graphically in Figure 4. The model calculated seepage rates for the creeks when simulated using the SFR and CLN packages are shown in Figure 4A. Generally, both packages calculate similar gaining and losing reaches with good correspondence in the calculated flow rate. There is a tendency to calculate higher flows using the CLN package, which is predominantly due to the differences in the conductance formulation and assumptions made here in approximating it when converting from the SFR to CLN package.

However, some of this difference is due to the fact that the flow system being solved is different between the two versions of the model. This difference is perhaps

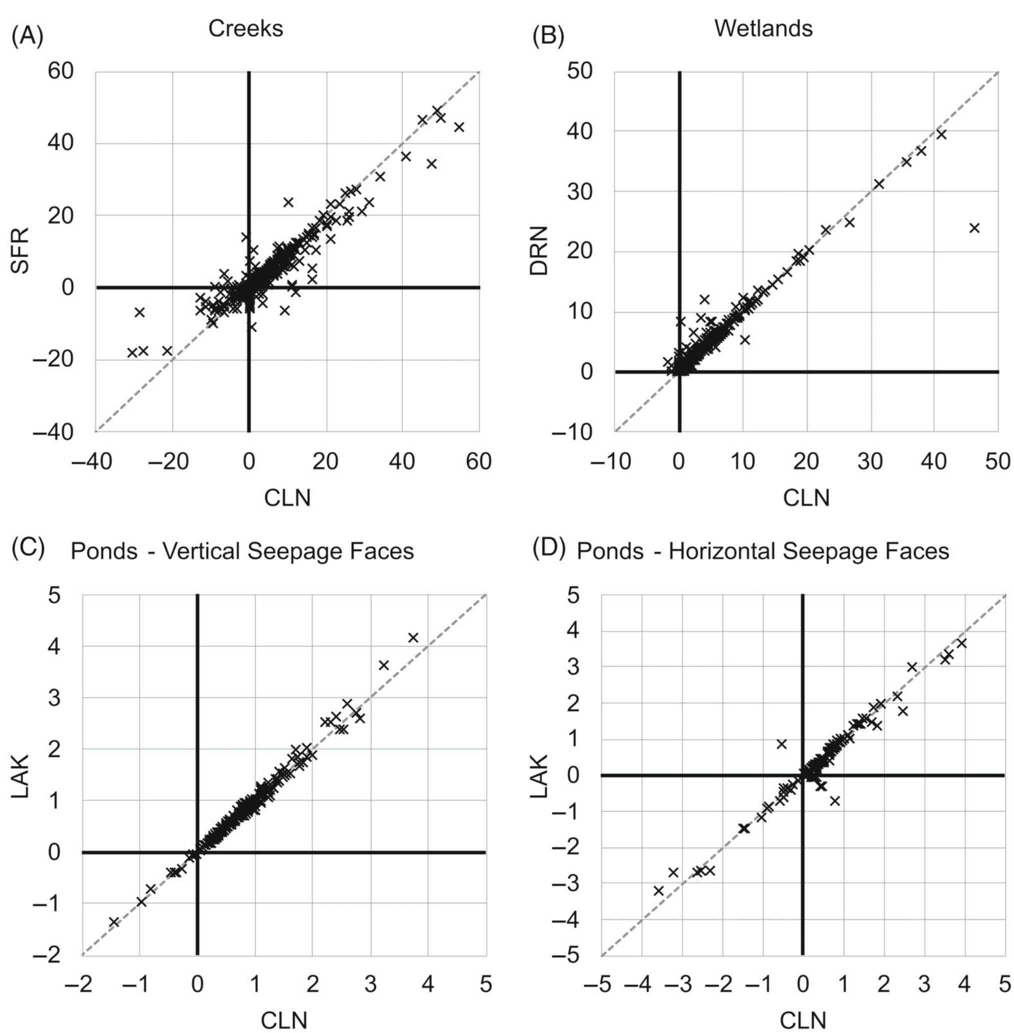

Figure 4. Plots of calculated flow through each seepage face simulated by (A) SFR and CLN packages for the creeks, (B) DRT and CLN packages for the wetlands, (C) LAK and CLN packages for vertical seepage faces of ponds, and (D) LAK and CLN packages for horizontal seepage faces of ponds. All flows are in gallons per minute.

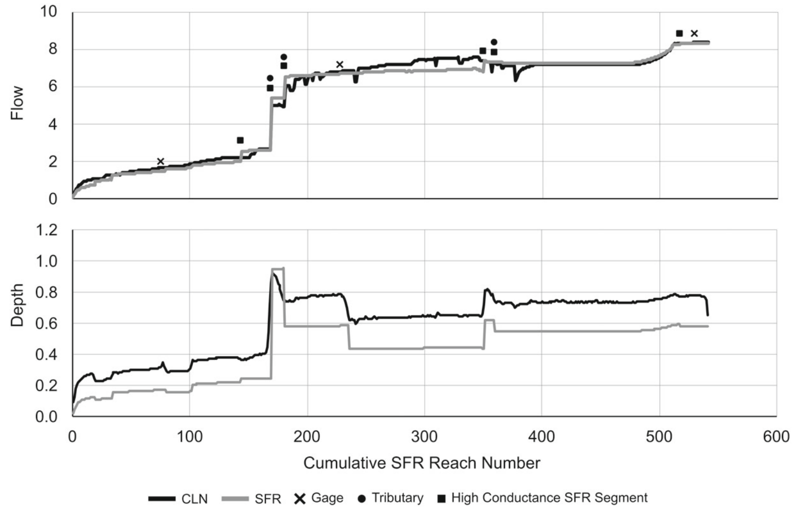

Figure 5. SFR (gray line) and CLN (black line) calculated flow and depth within Creek #1. The symbols indicate positions of interest along the creek: the crosses are the staff gage locations, the circles are where tributaries flow into the main branch, and the squares are the locations of high-conductance SFR segments that are used to route water from the wetlands to the creeks. Flow is in cubic feet per second.

most evident when looking at Figure 4B, in which the calculated flow through each seepage face is compared between the DRT and CLN packages. With the DRT package, it is assumed flow is one-way (GWF to DRT) between the two systems; groundwater can discharge to the wetlands, but that water is immediately routed to a creek. With the CLN package, flow is two-way, water that discharges to the wetlands can later recharge the groundwater system as it moves through the wetland due to variability in feature elevations. For some wetland seepage faces, negative flows (from CLN to GWF) are calculated for the CLN package.

The calculated flow through the vertical and horizontal seepage faces of the ponds correspond well between the two versions of the model, Figure 4C and 4D, respectively. The levels of these ponds are controlled by weirs. As a result, the initial estimate of the wetted perimeter is expected to be good, which means the conductance between the two packages are consistent for these seepage faces.

The calculated flow and depth along the main branch of Creek #1 are shown in Figure 5 for both versions of the model. Generally, the calculated flows are consistent throughout its length. Of note are the jumps in the SFR solution due to the addition of the groundwater routed from the wetlands at the discrete high-conductance SFR segments. There is not a corresponding jump in the CLN solution as water is routed continuously between the creeks and the wetlands along their lengths. However, when the jump is due to the addition of flow from a tributary, there is a corresponding jump in the CLN solution of similar magnitude, which indicates that the total groundwater flow to the tributaries is consistent between the two models. Further, the calculated flow at the gage locations and creek outlet are similar between the two versions of the model. The depth calculated by the CLN package is greater than the SFR package, which is expected because of the difference in the shape of their respective cross sections.

Discussion

We have demonstrated that the CLN package is a viable alternative to more commonly used boundary packages to simulate the interaction of groundwater with complex surface water networks. To do this, we converted a groundwater flow model developed previously for USG-Transport that represented a network of creeks, ponds, weirs, wetlands, and springs using a combination of the SFR, LAK, DRT, and CLN packages to one that used the CLN package exclusively. We found that the flows through each seepage face calculated by both versions of the models compare well.

A direct comparison of the two versions of the model is not possible because all the conductance terms in the CLN package are nonlinear and were developed for cylindrical conduits as opposed to rectangular channels.

With the LAK package, the model grid is used to define the pond volume and aquifer cells are inactivated where a pond is specified. As a result, the horizontal and vertical discretization of the model in the vicinity of the ponds needs to reflect the spatial extent and bathymetry with the necessary accuracy (Merritt and Konikow 2000). This definition is not necessary with the CLN package; the bottom elevation and relative position of the feature are input to the package. As a result, it is not required to inactivate cells when using the CLN package to represent lakes and ponds, which is convenient, especially to represent shallow features.

We approximated conductance terms in the traditional package here to compare the two models, however, these terms may be part of a calibration process, or a cylindrical representation may be more appropriate than a rectangular one, in which case this conversion to an equivalent rectangular formulation is not necessary. Regardless, we demonstrate that the cylindrical formulation required with the CLN package can be used to approximate rectangular features if needed.

Some error may get introduced in the storage term for transient simulations when approximating a large water body with several CLN nodes. The error may be larger for smaller radius CLN cells that are meant to mimic the flat bottom of a large surface water feature.

For some hydrologic settings, representing the entirety of a surface water network with the CLN package is advantageous over the traditional packages in USG-Transport. These advantages include: the connectivity flexibility allowed for more natural connections between the different surface water features, especially for the vent/spring and wetland connectivity to the creeks; implicit routing of water within and between the different surface water features; and representation of shallow features like ponds and lakes without having to enforce model layering that approximates their bathymetry or inactivate model cells. Numerically, though, the CLN package is more computationally burdensome owing to the calculation of flow within the network and non-linearity of the conductance formulation, but it has been our experience that it is not prohibitively so. The run time for the standard package version of the model was 45 s and for the converted CLN version 2 min.

Conclusions

We have demonstrated that the CLN package is a viable alternative to more commonly used boundary packages to simulate the interaction of groundwater with complex surface water networks. The CLN package incorporates all the features of commonly used boundary packages (SFR, LAK, RIV, and DRN/DRT) with comparable input requirements within a single package, while providing additional capabilities. From a pragmatic perspective, it is straight forward to assemble the surface water boundary representation and interpret surface water and groundwater interactions using the CLN package.

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Our colleagues, Jim Rumbaugh and Marinko Karanovic, for incorporating aspects of this approach into their respective MODFLOW interfaces (Groundwater Vistas and Groundwater Desktop) which aided in the preparation and visualization of the models and figures, and Vivek Bedekar for his assistance in deriving equivalent conductance terms. Also, an anonymous reviewer whose constructive comments helped to significantly improve the manuscript.

Conflict of Interest

The authors declare no conflicts of interest.

Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article. Supporting Information is generally *not* peer reviewed.

Appendix S1: Derivation of conduit radius calculation used to convert from the SFR to the CLN package.

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