MODFLOW’s River Package.

Part 1. A Critique

Abstract

Most widely used integrated hydrologic models were conceived and their development started some 50-60 years ago. These models have undertaken many major improvements since. However they still describe the flow interaction between streams and aquifers using the primitive early concepts. Most users seem unaware of the limitations of these concepts, which use parameters that are empirical and can only be obtained by calibration. In this Part1 the shortcomings of the methodology are shown in great details. In the article reference is made specifically to the code MODFLOW. Most of the other integrated hydrologic models used for large-scale regional studies apply essentially the same methodology to estimate seepage.

In a second Part means are presented by which improvements can be introduced in the procedures.

1. Introduction

Large-scale integrated hydrologic models such as MODFLOW (McDonald, and Harbaugh, 1988) are very comprehensive and complex. They try to be as physically based as possible but they nevertheless remain highly conceptual. Most users are not much aware of the limitations of the concepts, which use parameters that are empirical and can be obtained only by calibration.

This article explores why in the river package (McDonald, and Harbaugh, 1988, specifically Book 6, Chapter A1) the methodology does not provide a proper physical representation of the stream-aquifer flow exchange. The MODFLOW document does not provide clear discussions of the physical basis for the provided formulae. Rather it reads more like a Users' Manual to input data in order to run the computer FORTRAN program. As a consequence the names of the variables such as aquifer hydraulic conductivity, riverbed conductivity, riverbed thickness, head in the aquifer, etc., are provided as FORTRAN symbols. Because in this article and in many previous articles (e.g. Morel-Seytoux et al. 2016; Morel-Seytoux et al., 2018) other approaches are discussed, more mathematical symbols, less closely associated with MODFLOW's FORTRAN program, are introduced.

The new symbols are introduced in parenthesis next to MODFLOW's original FORTRAN variable names.

First a summary of the procedures used in the River Package is presented. Next the methodology behind the procedures and their shortcomings are described in some details. (In a separate second part ways are suggested to improve MODFLOW's River Package and, more generally, ways to improve the calculation of seepage for other models as well).

2. Summary of procedures in River Package

There are essentially three procedures depending upon, whether:

(1) there exists a clogging layer in the riverbed, and the connection between the stream and the aquifer is saturated, or

(2) there exists a clogging layer in the riverbed, and the connection between the stream and the aquifer is unsaturated, or

(3) there is no clogging layer and the connection is always saturated

For ease of reference with MODFLOW's original document the equations quoted from MODFLOW's chapter 6 have kept their original numbers, always involving the chapter number 6 before the equation number.

Generally the seepage discharge is estimated with an expression of the form:

$$QRIV = CRIV(HRIV - h_{ijk}) \quad (6\text{-}5)$$

or in more mathematical notation: $Q_S^{\mathrm{mod}} = C_{riv}(h_S - h_f)$ (6-5 math)

There are however a few exceptions to that equation.

$HRIV$ (h_S) is the head in the river, h_{ijk} (h_f) is the head at the node in the cell underlying the river reach (i.e the aquifer cell that contains the river reach, the river cell) and $CRIV(C_{riv})$ is the hydraulic conductance of the river-aquifer interconnection (L^2T^{-1} i.e. dimension of a transmissivity).

2.1 There is a tight riverbed and the hydraulic connection is saturated

If there is a tight riverbed a formula is given to determine $CRIV$:

$$CRIV = \frac{KLW}{M} \quad (\text{6-6}) \quad \text{or} \quad C_{riv} = \frac{K_{rcl} L_R W}{e_{rcl}} \quad (\text{6-6 math})$$

where K (K_{rcl}) is the hydraulic conductivity of the riverbed material (the clogging layer), L (L_R) is the length of the river reach at it crosses the node (that is the length within the aquifer cell that contains the reach, the river cell), W (same as $2B$) is the (bottom) width of the river reach and M (e_{rcl}) is the thickness of the riverbed material. CRIV is referred to as the river conductance (dimension of transmissivity) and $\frac{K}{M} = \frac{K_{rcl}}{e_{rcl}} = \Lambda_{\mathrm{mod}}$ (1) as the leakance coefficient (dimension inverse of a time).

2.2 There is a tight riverbed and the hydraulic connection is unsaturated

If there is a tight riverbed there is a possibility for the connection to become unsaturated. MODFLOW’s criterion for incipient desaturation is that the head in the (aquifer) river cell falls below the elevation of the bottom of the riverbed (clogging layer). Eq.(6.5) still applies but the variable $h_{ijk}(h_f)$ is replaced by the elevation of the bottom of the riverbed RBOT (h_{brb}) thus:

$$QRIV = CRIV(HRIV - RBOT) = LW_p \frac{K}{M}(HRIV - RBOT) \qquad (6\text{-}7)$$

or $$Q_S^{\mathrm{mod}} = C_{riv}(h_S - h_{brb}) = L_R W_p \Lambda_{\mathrm{mod}}(h_S - h_{brb}) \qquad (6\text{-}7 \text{ math})$$

As soon as and as long as $h_{ijk} \le RBOT$ Eq.(6-7) applies

(or as soon and as long as $h_f \le h_{brb}$ Eq.(6-7 math) applies).

2.3 There is no tight riverbed

In that case the connection is always saturated.

$$QRIV = \frac{K_{aq}}{1} LW_p(HRIV - h_{ijk}) = \Lambda_{\mathrm{mod}} LW_p(HRIV - h_{ijk}) \quad (6\text{-}9)$$

with $\Lambda_{\mathrm{mod}} = \frac{K_{aq}}{1} = \frac{K_V}{1}$ (2)

$K_{aq} = K_V$ is the aquifer (vertical) conductivity, or

$$Q_S^{\mathrm{mod}} = \frac{K_V}{1} L_R W_p(h_S - h_F) = \Lambda_{\mathrm{mod}} L_R W_p(h_S - h_F) \quad (6\text{-}9 \text{ math})$$

3. Shortcomings of the methodology in River Package

3.1 There is a tight riverbed and the hydraulic connection is saturated.

The formula in such a case for the seepage discharge $QRIV\,(Q_S)$ is assumed of the form: $Q_S^{\mathrm{mod}} = C_{riv}(h_S - h_f) = \dfrac{K_{rcl} L_R W}{e_{rcl}}(h_S - h_f)$ (6.5 math)

Actually in MODFLOW W is a fictitious width which is actually the wetted perimeter of the actual cross-section represented by a rectangle with width the wetted perimeter of the actual cross-section and impervious sides (see Figure 6-5 in Appendix 1 online; the relevant figures of River Package are provided in Appendix 1 online). Thus the procedure may underestimate the seepage taking place from the sides when the river penetrates the aquifer deeply and when there is a significant amount of anisotropy in the aquifer. (Naturally this effect is somewhat compensated in MODFLOW by flattening the sides to an horizontal position, especially if there is no anisotropy in the aquifer. Still the vertical flow is more inhibited than the sideflow especially if the impervious bottom of the aquifer is not very deep below the river bottom. In that case the vertical flow faces a hard resistance to turn horizontal; see Figure 6-5).

In addition the formula states that the seepage is proportional to the head difference between the river head and the river cell head. However that river cell head is the average head for a cell whose size in practice greatly exceeds the river width. It does not represent the actual head that exists right below the river bottom. Essentially the procedure assumes that there is no added vertical resistance to flow below the bottom of the clogging layer down to the center of the river cell. Once that vertical flow has hit the center of the river cell the typical finite difference procedure assumes that the flow has no difficulty to turn horizontal without any added resistance.

Finally how does one estimate the clogging layer conductance? MODFLOW does not provide any suggestion on how to obtain it. It is usually calibrated.

<u>3.2 There is a tight riverbed and the hydraulic connection is unsaturated.</u>

While there is such a relatively tight riverbed if the water-table head drops below the elevation of the riverbed the seepage discharge is described as:

$$QRIV = CRIV(HRIV - RBOT) = LW_p \frac{K}{M}(HRIV - RBOT) \tag{6-7}$$

or

$$Q_S^{\mathrm{mod}} = C_{riv}(h_S - h_{brb}) = L_R W_p \Lambda_{\mathrm{mod}}(h_S - h_{brb}) \tag{6-7 math}$$

where $RBOT$ (h_{rbb}) is the elevation of the riverbed bottom. The connection is now assumed unsaturated. Again it is assumed that the average head in the river cell represents the head just below the clogging layer. That criterion for incipient desaturation is incorrect. Desaturation will occur when the head just below the clogging layer falls to a value equal to the elevation of the river bottom minus the capillary drainage entry pressure of the aquifer material. That value is not the head in the river cell. With a continued unsaturated connection as head in the river cell further declines that head just below the clogging layer will drop further and the unsaturated flow process will continually change. The river seepage through the clogging layer will not recharge the aquifer instantaneously. The procedure in River Package does not distinguish between river seepage and aquifer recharge. It assumes that they are identical.

3.3 Absence of a relatively tight riverbed

«The application of Eqs.(6-5) and (6-7) is the most difficult in situations where a discrete riverbed does not exist…..One approach is to assume that the maximum seepage from the stream is the seepage in the aquifer in a column of water in which unity head gradient occurs» (pages 6-10, 6-11). If the head gradient in that vertical column is $\frac{dh}{dl}$ the seepage discharge is: $Q = K_{aq} LW \frac{dh}{dl}$ and for $\frac{dh}{dl} = 1$ then $Q_{\max} = K_{aq} LW$. The text in the report is not very clear but the reasoning seems to be that the discharge will be $Q_{\max}$

when the head gradient is one thus when h_{ijk} is such that $HRIV - h_{ijk} = 1$ in other words $h_{\max} = HRIV - 1 = RBOT$. Otherwise if h_{ijk} exceeds that value the discharge will be proportional to the ratio $\frac{dh}{dl} = \frac{HRIV - h_{ijk}}{1}$ and the discharge will be: $QRIV = Q_{\max}(\frac{HRIV - h_{ijk}}{1}) = K_{aq}LW(\frac{HRIV - h_{ijk}}{1})$

$$= K_{aq}LW(\frac{HRIV - h_{ijk}}{HRIV - h_{\max}}) = K_{aq}LW(\frac{HRIV - h_{ijk}}{HRIV - RBOT}) \quad (6\text{-}9)$$

with the result that $CRIV = \frac{K_{aq}LW}{HRIV - RBOT}$ (6-9a). When $h_{ijk} = HRIV$ the discharge is zero and it takes its maximum value when $h_{ijk} = h_{\max} = HRIV - 1$ while varying linearly when the head is between these two values. It is presumed that as the head drops below $h_{\max}$ the discharge will remain at its maximum value.

It is unfortunate that the same name, RBOT, is given here to a symbol that is not related at all to the elevation of the riverbed bottom but is simply $h_{\max} = HRIV - 1$ so that the denominator in Eq.(6-9) is 1 and effectively $CRIV = \frac{K_{aq}LW}{1}$ (6-9b).

What the package does not discuss at all is the situation when there is no tight riverbed material and the head in the aquifer exceeds the head in the river. All the previous discussion was premised upon having an essentially downward flow below the river bottom. In the case of a gaining river it seems that there is no alternative but to assume the presence of a riverbed (tight) material.

3.3 . Needed iteration

« At the start of each iteration, terms representing river seepage are added to the flow equation for each cell containing a river reach….Because this process is done at the start of each iteration, the most current value of head (h_{ijk}) is the value from the previous iteration. Thus the check for which river seepage equation to use lags behind the seepage calculations by one iteration». (page 6-12). What is referred to here is the fact that the equation to define the seepage is either Eq.(6-5) or Eq.(6-7) but which equation to use depends upon the value of h_{ijk}. Since such value itself varies from iteration to iteration there is a possibility that the process might oscillate. What is not mentioned in the discussion is the other iteration process because the river head will depend upon the seepage, thus upon h_{ijk}, and vice versa h_{ijk} will depend upon the river head, since by mass balance it depends on seepage. There is an even greater possibility for oscillation for this iteration cycle, whether under a saturated or unsaturated condition.

4. Crude nature of the approximations in the River Package

The early MODFLOW developers were fully aware of the crude nature of some of the approximations. As shown in Figure 6-5 (Appendix 1) the river cross-section of the river is made rectangular with a flat bottom and impervious sides. Thus the approach neglects the possibility of deep penetration of the river into the aquifer material with significant flow taking place from the sides.

In addition «the assumption is made that measurable head losses between the river and the aquifer are limited to those across the riverbed layer itself—that is, that no substantial head loss occurs between the bottom of the riverbed layer and the point represented by the underlying model node.» (page 6-6). This may be the case only if the riverbed is excessively tight. As stated by Rushton (2007) : "The MODFLOW approach assumes that head losses between the stream and the aquifer node representing the stream are limited to those across the streambed itself; fine-grid model solutions show that typically less than one-third of the loss occurs across the streambed, the remaining loss is due to the converging flows" (i.e. the turning factor, Morel-Seytoux, 2009) "in the aquifer in the vicinity of the river channel".

As the aquifer head drops a time may occur when the connection will become unsaturated. However the desaturation will not be caused by the average head in a large aquifer river cell but by the head at the base of the riverbed. When the river cell that contains the river reach has dimensions that greatly exceed the width of the river that assumption is very crude. In addition desaturation does not occur at the base of the riverbed when the pressure there is atmospheric but when the capillary pressure there is the entry pressure in drainage. Also as water drains from the created unsaturated zone above the water-table, recharge rate to the water-table will be different from the seepage rate.

When there is no riverbed clogging layer the assumption that flow takes place as gravity free flow vertically is physically incorrect. The assumption amounts to assume that the aquifer has no impervious bottom and is open there to the free atmosphere. It is flowing as water would flow in a laboratory soil column under a maintained small head at the top and allowing the water to drain freely at the bottom. The reality is that the downward moving water will hit the phreatic surface, will encounter a strong resistance as the aquifer bottom is impervious, will have to turn and the flow is far from being one dimensional vertical. In this case River Package has the potential to greatly underestimate the resistance to seepage flow.

5. Alternative to estimate seepage using the full refined 3-dimensional capability of MODFLOW

In theory one could use the 3-dimensional capability of the model to simulate the seepage accurately at least when the connection is saturated. A very fine grid would be laid in the lateral (horizontal direction perpendicular to the stream) and vertical directions. In the case of unsaturated flow it would not be possible because MODFLOW does not solve the unsaturated flow equation (Richards' equation). At any rate even in the case of saturated flow it is not practical for large-scale regional studies where the water-table aquifer bed is typically treated as a **single** calculation layer and the lateral size of the cells is much larger than the width of the river (Hanson, 2017; Woolfenden and Nishikawa, 2014).

6. Conclusion

This first part has highlighted the shortcomings of the method currently utilized in many groundwater models to estimate river seepage or gain from the aquifer. In a second part means are presented by which improvements can be introduced in the procedures. Accuracy and numerical efficiency will be improved. The second article describes in details the proposed alternatives for both the saturated and the unsaturated connections. These new procedures could be incorporated simply within the original codes.

7. Bibliography

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Appendix 1. Excerpts from MODFLOW–2005, The U.S. Geological Survey Modular Ground-Water Model. River Package

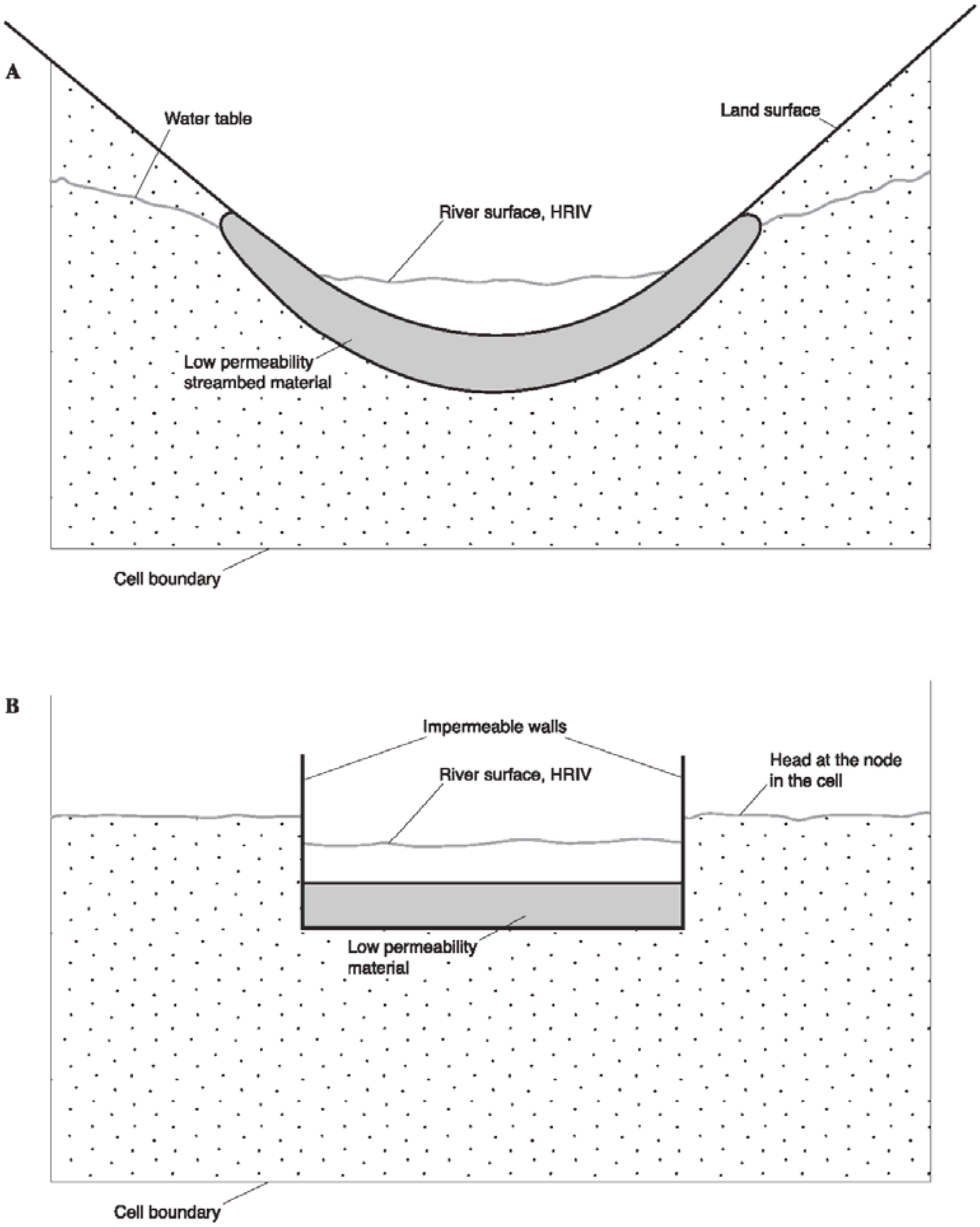

Figure 6-5. **(**A) Cross section of an aquifer containing a river and (B) conceptual representation of river-aquifer interconnection in a simulation. (From McDonald and Harbaugh, 1988.)

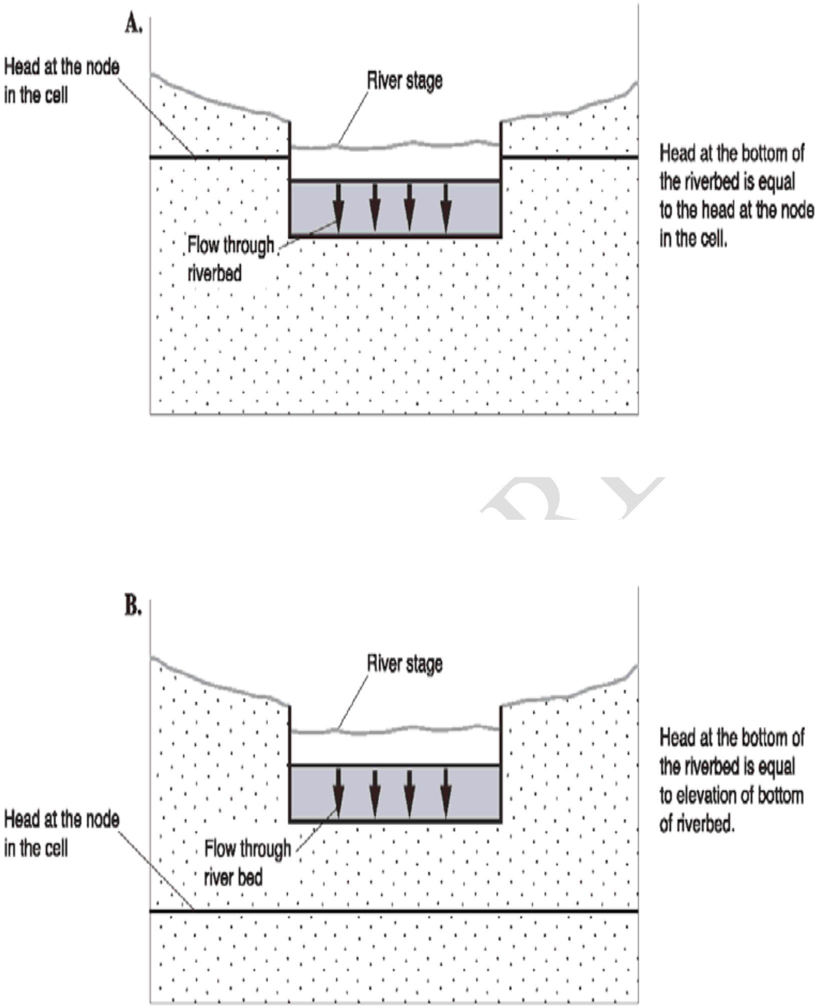

Figure 6-7. Cross sections showing the relation between head at the bottom of the riverbed layer and head in the cell. Head in the cell is equal to the water-table elevation. (Modified from McDonald and Harbaugh, 1988.)

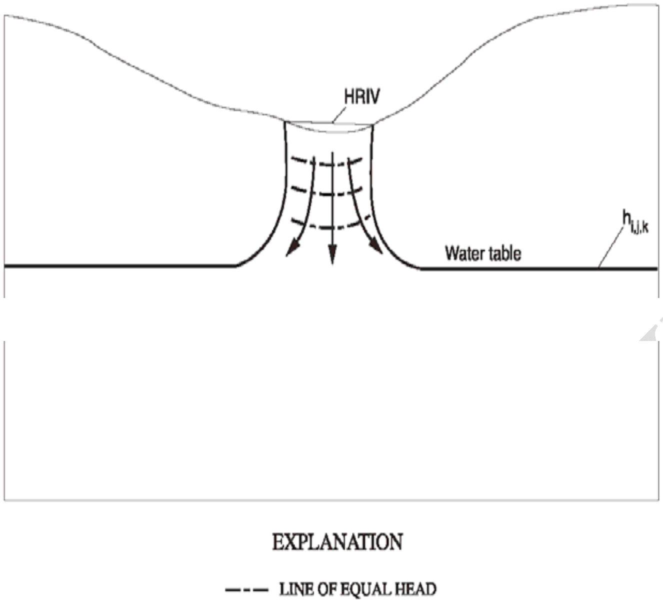

Figure 6-9. Limiting seepage from a river at unit hydraulic gradient. (Modified from McDonald and Harbaugh, 1988.)