Modelling Groundwater Flow in a Variably-Connected Aquifer-Stream System

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To

William Milne-Home (Bill)

The exemplary scholar and friend to whom I am deeply in debt.

For his continuous support, encouragement, and guidance

And to

Shatha,

Rahaf, Qoot, Dhoha, and Shahd

(my "small" family)

For their patience, sacrifices, and continuous support which ensured the successful completion of this challenging research

CERTIFICATE OF AUTHORSHIP / ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Jamal Khaled Nejem

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Symbol	Description	Chapter
s	drawdown in the aquifer at radius r, at time t	2
Q	flow of the well; well pumping rate; the constant discharge of the well	2, 3
Q_r	rate of river depletion at any time since pumping started	2
ΔQ	stream depletion flowrate	2
Q_w	constant discharge of the well from time $t = 0$ to $t = \infty$	2
K	aquifer permeability (or hydraulic conductivity); effective hydraulic conductivity	2
K'	hydraulic conductivity of the confining bed	2
K_r	hydraulic conductivity in the saturated zone	2
K_i	hydraulic conductivity at initial moisture content	2
K_h	horizontal hydraulic conductivity	2, 3, 4, 7
K_x , K_y	horizontal hydraulic conductivities in x- and y- direction respectively	2, 3, 4, 7
K_v	vertical hydraulic conductivity	2, 3, 4, 7
K_z	vertical hydraulic conductivity in z-direction	2, 3, 4, 7
K_{rw}	relative permeability, that is a function of water saturation	7
D	saturated thickness of the aquifer; depth of soil profile between initial water table location and bottom of river bed; saturated depth of flow	2
1D, 2D, 3D	one- two- and three-dimensional	2, 3, 4, 7
r	a radius measured from the centre of the well	2

Symbol	Description	Chapter
V	volume of water yielded by unit area of the aquifer if the pressure is dropped one unit depth	2
t	time, from beginning of pumping	2
e	base of natural logarithms	2
λ	a time variable; leakage coefficient; streambed leakage	2
E_1	exponential integral	2
x_1	well distance from river edge	2
x	a rectangular coordinate measured from the centre of the well	2
x_0	effective distance from the pumped well to the streambank	2
q	flow contribution of the river; stream depletion rate	2
$P(z)$	probability integral or error function	2
$erf(z)$	error function	2
$erfc(z)$	complementary error function	2
z, U	argument of error function or its complement	2
B	leakage factor; channel half-width	2
T	aquifer transmissivity	2
b'	thickness of the confining bed where vertical leakage occurs in proportion to drawdown	2
m	weighted mean of the saturation depth	2
ε, S_y	aquifer specific yield	2, 4, 6, 7
S	storage coefficient	2, 7
Ss	specific storage of the porous material	7

Symbol	Description	Chapter
S_w	degree of saturation of water, that is a function of the pressure head	7
a	retardation coefficient (i.e. leakance) of the semipervious streambed	2
l	the shortest distance between the well and stream edge	2
L	stream leakance; distance between the well and the stream	2
SDF	stream depletion factor	2
Δh	head difference between the aquifer and the stream	2, 3, 6, 7
MSDR	maximum stream depletion rate	2
SDR	transient stream depletion rate	2
q(t)	flow rate (infiltration discharge) through the river bed; lateral specific discharge; lateral flux	2
q_0	infiltration discharge per half unit length of river at the instant the wetting front meets the saturated zone (aquifer)	2
e	initial aquifer average saturated thickness	2
W	width of river; volumetric flux per unit volume and represents sources and/or sinks of water per unit of time	2, 7
h(0,t)	head in aquifer at x = 0 (river bank; x increasing away from river; axis of symmetry on opposite river bank)	2
h(x, t)	position of the water table	
H	depth of water above base of river bed (river stage)	2
$f(\xi, t)$	local infiltration rate	2
ξ	coordinate across channel bottom, origin at channel centreline	2
$\Delta\theta$	fillable pore space	2

Symbol	Description	Chapter
θ_s	volumetric soil moisture content at residual air saturation	2
θ_i	initial volumetric soil moisture content;	2
θ	drainable porosity of aquifer	2
θ_o	water content of the wetting zone	2
$\theta^{\sim}$	natural saturation water content	2
h_e	effective matric suction	2
$h(\xi, t)$	surface depth	2
$F(\xi, t)$	net change in total soil moisture above the moving wetting front	2
τ	variable of integration	2
Z_{rf}	infiltration distance	2
I	infiltration rate	2
I_0	recharge rate	2
HRV	Hadaquid River Valley	3, 7
P1, P2, P3	pumping bores (wells) at different locations; piezometers (PVC pipes) at three different depths in a pumping bore to measure groundwater level	3, 6, 7
BF	baseflow	3, 6
MF	MODFLOW model	3
Δ , Diff	percentage difference in water exchanged (in the river (or stream)-aquifer system) with respect to the bench mark model of mesh resolution 10x10 m	3
$\Delta_{\text{Grid i}}$	percentage difference in water exchanged in grid of i x i (in the river (or stream)-aquifer system) with respect to the bench mark model of mesh resolution 10x10 m	3
Q_{ixi}	water exchanged (in the river (or stream)-aquifer system) when the cell size is i x i m (selected values of i are 25, 50, 100, 150, and 250 m)	3
Q_{RIV}	river water flux	3

Symbol	Description	Chapter
$Q_{RIV, Grid\ i}$	river flux for a grid that has cell size of i x i	3
Q_{STR}	stream water flux	3
Q_{stream}	flowrate to the first up-stream cell	3
$Q_{STR, Grid\ i}$	stream flux for a grid that has cell size of i x i	3
QRIV	one-dimensional vertical flow between the river and the aquifer	7
MF	MODFLOW model	3
AHD	Australian Height Datum	4, 5, 6, 7
BoM	Bureau of Meteorology	4, 5, 6, 7
DNR	Department of Natural Resources	4, 5, 6
DWR	Department of Water Resources	6
DWE	Department of Water and Energy	4, 5, 6, 7
DECCW	Department of Environment, Climate Change, and Water	4, 6, 7
NOW	NSW Office of Water	4, 6, 7
AMG66	Australian Map Grid 1966	4, 5, 6, 7
$Rain_{avg}$	average rainfall	
GIS	Geographic Information System	4
RRM	Residual rainfall mass	6
$RAINmonth_i$	total monthly rainfall in month *i*	6
$\overline{RAINmonth}_i$	mean monthly rainfall for month *i* in all years	6
RSFM	Residual stream flow rate mass	6
$SFLOWmonth_i$	total monthly stream flow rate in month *i*	6
$\overline{SFLOWmonth}_i$	mean monthly stream flow rate for month *i* in all years	6
ML	Mega Litres (= 10^3 m^3)	1, 3, 4, 6, 7

Symbol	Description	Chapter
GWL	groundwater level in the bore	6
GUI	Graphical User Interface	2, 3, 6, 7
GV5	Groundwater Vistas, version 5.0	2, 3, 7
h	hydraulic head	2, 3, 6, 7
h_{mp}	height (elevation) of the measurement point	6
h_{gs}	height (elevation) of the ground surface	6
h_{sp}	height (elevation) of the standpipe	6
d	depth to groundwater as measured from the top of the standpipe (i.e. from the measurement point)	6
CRIV	riverbed conductance	7
k	hydraulic conductivity of the riverbed material	7
l	length of the river segment (i.e. reach) within each cell	7
w	width of the river reach within each cell of the mesh	7
m	thickness of the river reach within each cell of the mesh	7
HRIV	head of the river	7
RBOT	elevation of the river bottom	7
DEM	digital elevation model	7
Wi	dimensionless weighting fraction (ranges from 0 to 1) for each *i* measurement in *n* samplings of data;	7
hi	modelled head	7
Hi	measured head	7
Ri	Residual	7
SR	Sum of Residuals	7
SSQ	Sum of Squared Residuals	7, 8
MSR	Mean Sum of Residuals	7
SMSR	Scaled Mean Sum of Residuals	7, 8

Symbol	Description	Chapter
MSSQ	Mean Sum of Squares	7
RMS	Root Mean Square	7
RMFS	Root Mean Fraction Square	7
SRMFS	Scaled Root Mean Fraction Square	7, 8
SMSR	Scaled Root Mean Square	7, 8
SSQ_{Base}	SSQ of the base case	7
SSQ_{α}	SSQ produced from varying the base case parameters by applying a multiplier α (α can be 0.02, 0.1, 0.5, 2, or 10 depending on the parameter under consideration)	7
%ΔSSQ	percentage difference in the sum of squared residuals	7, 8

ABSTRACT

Catchments with variably-connected surface and subsurface flow systems are not uncommon in Australia or through various parts around the globe. Management of the available groundwater and surface water resources in such generic types of catchments is critical to ensure the sustainability of these valuable assets. This requires a decision making to be based on quantitative estimates of available volumes in the various interconnected water bodies, usually derived via suitable modelling. Fully coupled modelling of such systems still faces several complications such as: proper choice of spatial scale that better represents the interconnected system; availability and ease of access to the data required; availability of capable software to perform the simulation; and, occasionally certain jurisdictional conflicts- where these water bodies cross the trans-boundaries between neighbouring regions. Under these challenges, pseudo coupling- a less data-intensive but still rigorous modelling of aquifer-stream system- can provide estimates of acceptable accuracy for management decisions about the resource.

Therefore, the primary objectives of the present research were to investigate the effect of variable model cell dimensions on the resulting simulated aquifer-stream water balance estimates; and to develop a pseudo-coupled groundwater-surface water model of a representative catchment with an unregulated intermittent stream.

The first objective is to prove the effect of grid resolution on the calculated water balance components in modelling an interconnected aquifer-stream regime. Such analysis is of high importance for resolving double accounting and related issues in management of water allocations. This objective has been accomplished by pseudo coupling of MODFLOW with RIV and STR algorithms and MODFLOW-SURFACT with RIV applied to a synthetic aquifer-stream. Six cell resolutions (10x10, 25x25, 50x50, 100x100, 150x150, and 250x250 m) were developed for pumping and non-pumping scenarios. It was found that as the cell dimension increases, the difference in the exchanged fluxes between the river and the aquifer also increases and could be

more than 100% of the base case (i.e. the 10x10 m mesh, which has cell dimensions equal to the river width).

The outcomes of the grid variation experiment were applied to a three-dimensional flow model with grid resolution of 250 x 255 m for the entire aquifer-stream system in Zone 2 of Cox's Creek Catchment. The MODFLOW-SURFACT and RIV algorithm has been utilised in the pseudo-coupled simulation of the groundwater and surface water regimes over 24 years. The qualitative assessments and the quantitative calibration measures illustrated that the model could reproduce the observed groundwater level variations. The hydrographs support the observational inference that the lower aquifers are probably used for irrigation more than the upper one.

The contribution of Cox's Creek to the total inflow recharge is about 2852 ML/yr, which is nearly 13.4% of the total feed to the aquifers, and is around three times that from rainfall. The aquifers recharge the Cox's Creek by approximately 111 ML/yr (0.5% of the total groundwater outflow). The Creek receives the least amount of its flow from the underlying aquifers, a finding which supports the work of other researchers. The simulated monthly average leakage and baseflow of the Creek were 7.76 and 0.26 ML respectively throughout the simulation. These values provide further evidence that the Creek is generally a losing stream.

While the simulation model has been designed for Zone 2 in the Cox's Creek region, it has potential for application to other catchments with unregulated intermittent streams. Such merits should prove helpful to decision makers in managing water resources in regions of similar character.