Appendix

Background Information and Methodology to Support Estimation of Sustainable Groundwater Abstraction using GEFIS

Aditya Sood and Karen G. Villholth

Background

When assessing environmental flow requirements (EFR) of rivers, and adapting appropriate management strategies to comply with EFR, it is critical to understand the changes that may impact river flows. These could be river abstractions and discharges, land use changes, river diversion and impoundment, as well as groundwater abstraction in the catchment or river basin. The link between groundwater and surface water flow can be significant, implying that if groundwater is pumped near a river, it may significantly influence and reduce river flow (Barlow and Leake, 2012) (Figure A1). This is because in many, especially perennial rivers, groundwater provides part of the flow in the river, a flow component called base flow (BF) (Figure A1). By implication, management of rivers and EFR is closely linked to groundwater management, and to ensure sustainable outcomes, in most cases, management of both water resources are required. This is referred to as conjunctive water management (Barlow and Leake, 2012).

In order to support this process, and ensuring long-term EFR as well as sustainable groundwater abstraction, according to set environmental standards, these guidelines explicitly include assessment of EFR and their linkage to groundwater abstraction limits.

This appendix explains briefly the methodology for assessing groundwater abstraction limits under given environmental management standards, while also adhering to associated EFR. For more detailed information on the methodology, reference is given to Sood et al. (2017).

Methodology and Assumptions

It is important to understand the assumptions made to be able to use the GEFIS model for calculating sustainable groundwater withdrawals.

It is assumed that rivers are perennial, and that at any given time, the flow in a river can be divided into a surface runoff (SR) and a groundwater (baseflow (BF)) component. BF is the contribution to the river by the adjoining aquifer. For this to be true, it is assumed that the aquifer is always hydraulically connected to the flow in the river and that the water table in the aquifer is higher than the river water surface (Figure A1), i.e. the water from the aquifer flows into the river. Such a river is called a 'gaining river'.

The surface water component of the river discharge is derived from surface runoff or water from the soil horizon, so-called interflow. Combined, the surface water and groundwater components constitute the river discharge. The distribution of flow between the two components may vary from river to river, from location to location within a river and may vary seasonally or with climatic or other changes. Flow in a perennial river in the dry season or after a prolonged period of no precipitation may constitute mostly of the groundwater component (Barlow and Leake, 2012).

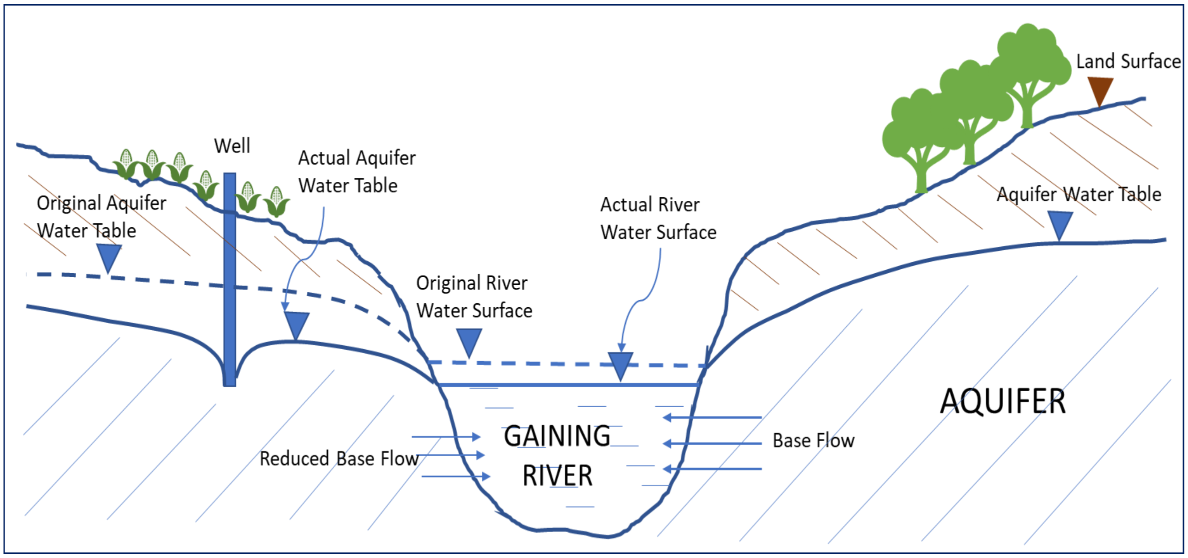

Figure A1: Schematic of a gaining river and the impact of groundwater pumping on base flow.

To quantify contribution of groundwater to river flow, a base flow separation technique is used to divide river flow into BF and SR components. The data source for the river flow data were model data from the PCR-GLOBWB model for the time period 1960-2010 (Sood et al., 2017). A recursive digital filter method, which is a numerical method that uses a computer algorithm to separate the BF from a time series of river flow, is used in GEFIS (Figure A2). Since the algorithm is not based on physical characteristics of the area of interest, it uses a fitting parameter (β) that captures these characteristics (Ebrahim and Villholth, 2017). The BF separation routine is sensitive to this parameter, i.e. getting the right value for this parameter is critical to get the correct contribution of aquifer flow to the river. Hence, it was calculated individually for each grid in GEFIS through calibration to the modelled river and base flow time series. It is important to note that this method strictly separates 'slow' flow (i.e. flows not driven by rainfall events) from 'quick' flow (i.e. flow resulting from rainfall events). It does not necessarily separate BF from SR because slow flows could have other sources such as snowmelt or releases from upstream dams. However, this further distinction between sources of flow to a river was not considered, since snowmelt data are not available at global distributed scale, and the PCR-GLOBWB model simulations used do not consider river impoundment.

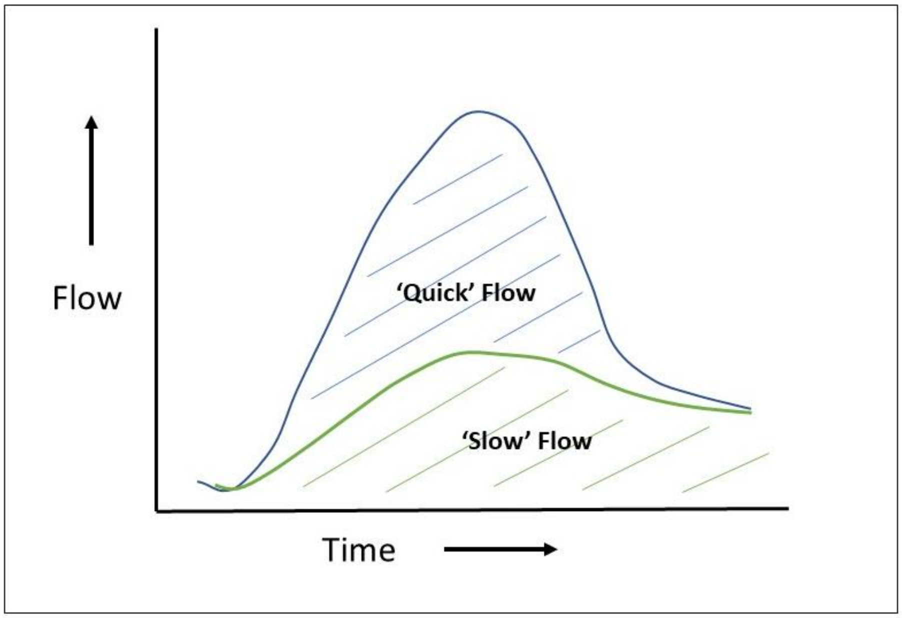

Figure A2: Flow hydrograph showing 'quick' flow and 'slow' flow components.

In GEFIS, groundwater contributing to BF is conceptualized as a continuous shallow storage tank that supplies water to the river. The amount of water that flows into the river depends linearly on the size of the storage. As the size of the storage reduces, so does its contribution to the river. Since it is difficult to know the actual size of groundwater storage at global scale, for this work, only change in storage (and hence corresponding change in groundwater contribution) is considered. Since it is assumed that the aquifer is always connected to the river within the grid, GEFIS assessment only considers shallow aquifers[1]. In addition, it is assumed that the aquifer and river, in terms of flows and exchanges, are in a quazi-steady state, so that over longer time, the river responds to the pumping in the aquifer, even if in reality there will be a non-insignificant response time (Barlow and Leake, 2012).

The overall methodology is illustrated in Figure A3. Corresponding to a given Environmental Management Class (EMC), there is an acceptable reduction in streamflow that would preserve the EFR. Although the calculations are done with monthly data, the results are presented at average annual time scale. The new (reduced) river flow is shown in the figure as EFR. The hatched portion in the river channel depicts the water portion that can be sustainably withdrawn from the channel for that EFR and EMC. It can be conceptually divided into SR and BF withdrawal portions, as indicated in the red circle. The rectangle on the right side represents the aquifer storage, connected to the river channel that contributes to BF. The acceptable BF withdrawal for the EMC translates into an acceptable level of groundwater reduction in the aquifer storage (shaded portion) through a linear drainage constant, which is also characteristic

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[1] Shallow aquifers are those close to the ground surface and easily accessible. They are normally actively recharged by rainfall via infiltration. They lose water naturally due to evapotranspiration or due to infiltration to deeper aquifers or due to discharge to surface water bodies. The storage in shallow aquifers fluctuates depending on these processes as well as withdrawal patterns by humans.

for each grid (Sood et al., 2017)[2]. This shaded portion in the 'aquifer water storage' represents the sustainable aquifer water withdrawal to maintain EF for the specific EMC.

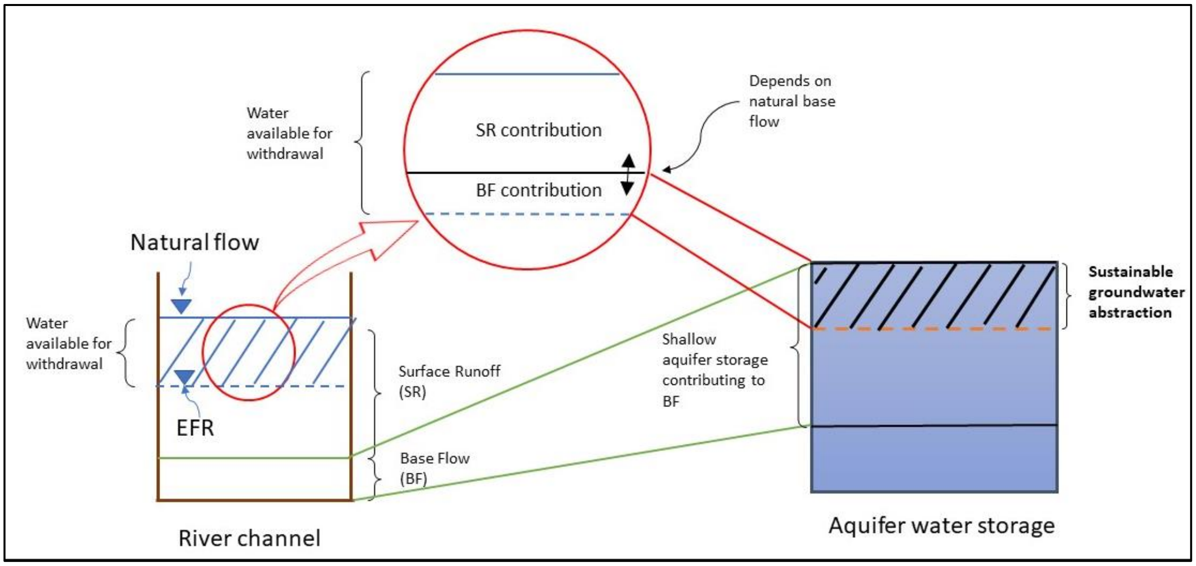

Figure A3: The schematic relationship between natural river flow, EFR, BF and aquifer water storage for natural conditions and for a desired EMC condition.

The line separating the SR and BF contribution to water available for withdrawal (shown inside the circle in Figure 3) can be shifted up or down (indicating smaller/larger portion of BF contribution to abstractable water), which in turn will affect the amount of water that can be sustainably removed from the aquifer storage. In other words, if more river flow is abstracted as sustainable surface water abstraction, a corresponding reduction in groundwater abstraction will have to take place to maintain the overall EFR.

However, the distribution between groundwater and surface water to abstractable water depends on the natural base flow. Since base flow satisfies the EFR during the dry season, only a smaller amount of groundwater can be removed. This amount is determined as the groundwater equivalent to the amount of available water, which exceeds the base flow under the modified flow conditions (the black cross-hatched portion in the middle of Figure 4). Hence, if the available water under the given EMC is less than the base flow under the modified flow condition, groundwater cannot be taken out, and the available water can only be withdrawn from surface water in order to maintain the EFR. There is an assumption that the proportion of surface and groundwater flowing in the stream remains the same for natural flow and modified flows (i.e. between the two river channels in Figure A4).

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[2] The water in the aquifer is in reality interspersed between rocks and sediments. So that one volume of 'groundwater' corresponds to a larger volume of 'aquifer with water'. This is taken into account in the calculations when water is draining to the river.

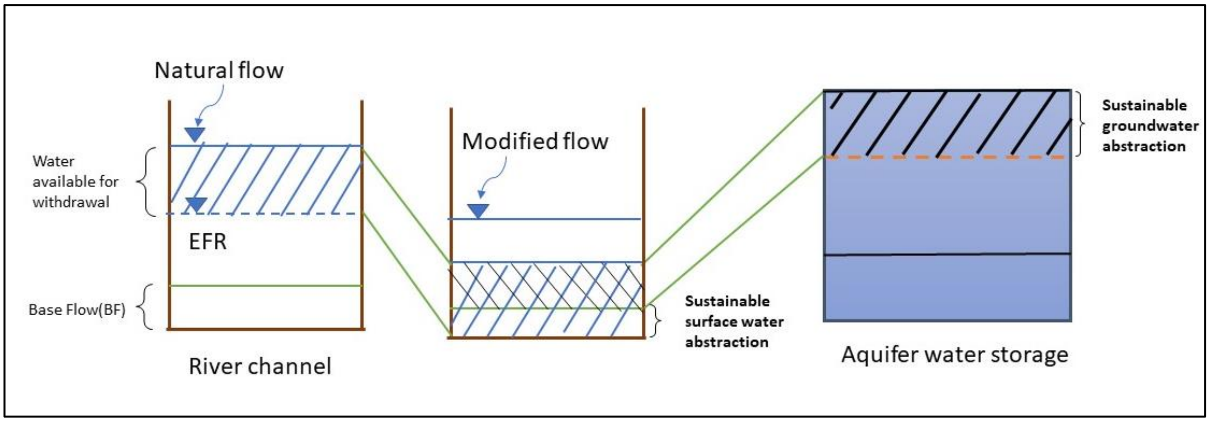

Figure A4: Schematic illustrating that groundwater can only be abstracted, if the water available for abstraction exceeds the reduced base flow under altered flow conditions.

There are situations where the above method and assumptions will lead to erroneous estimation of sustainable groundwater abstractions:

1. In case of snow-influenced grids, this method will underestimate sustainable groundwater abstraction. Since the separation method (discussed above) does not consider the source of 'slow' flow, some of the separated flow may actually be contributed from snowmelt. If some of the EFR is being met by snowmelt, the contribution of groundwater to EFR is reduced. In that case, more groundwater (than calculated in GEFIS) may be abstracted, while still meeting EFR.

2. As discussed above, it is assumed that the aquifers are feeding the rivers, and base flow provides perennial rivers. This may not always be true. There are ephemeral rivers, where the groundwater table may be below the rivers. In such cases, the rivers may lose water to the groundwater ('losing' instead of 'gaining' rivers). Such situation is more likely to be encountered in arid and semi-arid regions. In these cases, the groundwater does not contribute to EFR. There may be other issues to consider, while assessing abstractable water from such aquifers, and hence the methodology does not apply to these environments. In GEFIS, effort has been made to exclude such regions[3].

3. This methodology only considers shallow aquifers. Some abstraction may be made from deeper aquifers, but these systems may, or may not, be linked to surface water discharges, and so the methodology used for estimating allowable withdrawal from deep aquifers

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[3] In GEFIS, arid and semi-arid regions with negligible stream flows have been excluded from calculations. To define regions with negligible flows, land use was used as a proxy for arid regions. GlobCover 2009, developed by the European Space Agency, was used to obtain land use coverages (Sood et al., 2017). The following land use categories were excluded from the study: 'bare areas', 'water bodies', 'permanent snow and ice', 'closed to open grassland', 'closed to open shrubland' for North America and South America; and 'sparse vegetation' for Africa and Australia.

need special attention. This may involve recharge estimations and timescales for replenishment and discharge, which may be long, indicating high uncertainty in estimating sustainable abstraction limits for such aquifers using solely water balance criteria. Furthermore, some deeper aquifers may discharge to rivers, especially within large basins. However, here we assume that shallow aquifers are the main source of base flow to rivers, irrespective of basin size.

Applying GEFIS

Following steps may be followed when calculating sustainable groundwater abstraction using GEFIS:

1. Identify the region of interest. Smaller regions that fall within a single aquifer is ideal. For ease, a smaller river segment or a country may be selected. Identify grids (polygons) that constitute the area of interest.
2. Determine the EMC desired for the selected region of interest (as prescribed in the guidelines).
3. Use GEFIS to calculate sustainable groundwater abstraction for the grids within the polygon for the given EMC.[4]
4. Subtract estimated existing shallow groundwater abstraction for the area from the total allowable abstraction, to calculate residual allowable shallow groundwater withdrawal.
5. Use expert judgement to identify and calculate sustainable withdrawal from other groundwater sources (such as deep aquifers) within the area. Add those to the allowable abstraction in point 4.

Possible GEFIS Improvements

To account for the uncertainty and shortcomings in estimating sustainable groundwater abstraction mentioned above, the following adjustments of the methodology should be considered:

1. Classify grids based on snow-dominated processes. Include handling of snowmelt in snow-dominated grids to refine estimation of allowable groundwater abstraction
2. Create a data layer to show sustainable deep aquifer withdrawals

References

Barlow, P.M., and Leake, S.A., 2012. Streamflow depletion by wells—Understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey, Circular 1376, 84 p. htp://pubs.usgs.gov/circ/1376/.

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[4] If the grids are influenced by snow, this method would underestimate sustainable groundwater abstraction.

Ebrahim, G.Y. and Villholth, K.G., 2016. Estimating shallow groundwater availability in small catchments using streamflow recession and instream flow requirements of rivers in South Africa. J. Hyd., 541B, 754-765, DOI:10.1016/j.jhydrol.2016.07.032.

Sood, A., Smakhtin, V., Eriyagama, N., Villholth, K.G., Liyanage, N. Wada, Y., Ebrahim, G. and Dickens, C., 2017. Global environmental flow information for the sustainable development goals. Colombo, Sri Lanka: International Water Management Institute (IWMI). 37p. (IWMI Research Report 168). DOI: 10.5337/2017.201.