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# Journal Pre-proofs

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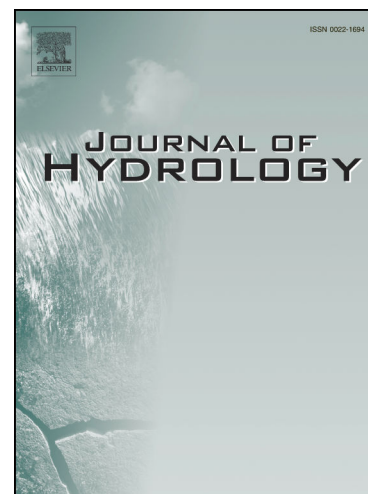
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1 **Worth of hydraulic and water chemistry observation data in terms**  
2 **of the reliability of surface water-groundwater exchange flux**  
3 **predictions under varied flow conditions**

4  
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16

**17 Abstract**

18 This study assesses the worth of routinely collected hydraulic data (groundwater head, stream  
19 stage and streamflow) and lesser collected water chemistry data (Radon-222, Carbon-14,  
20 electrical conductivity (EC)) in the context of making regional-scale surface water-groundwater  
21 (SW-GW) exchange flux predictions. Using integrated SW-GW flow and transport numerical  
22 models, first-order, second-moment (FOSM) analyses were employed to assess the extent of the  
23 uncertainty reduction or lack thereof in SW-GW exchange flux predictions following acquisition  
24 of hydraulic and water chemistry observation data. With a case study of the Campaspe River in  
25 the Murray-Darling Basin (Australia), we explored the apparent information content of these  
26 data during low, regular and high streamflow conditions. Also, a range of spatial and temporal  
27 prediction scales were considered: catchment-wide and reach-based spatial scales and annual and  
28 monthly temporal scales. Generally, the data worth evaluations showed significant variability  
29 across predictions that were dependent on the spatiotemporal scale of the SW-GW exchange, the  
30 magnitude and direction of the SW-GW exchange flux and the prevailing streamflow conditions.  
31 These dependencies serve to emphasise the importance of prediction specificity with respect to  
32 SW-GW exchange. Among existing data, the most worth was found in Radon-222, groundwater  
33 hydraulic head, EC, and streamflow data showing average reductions in uncertainty of 41%,  
34 38%, 32%, and 23% respectively. Assessment of type and spatiotemporal locations of potential  
35 data showed Radon-222 to be the next most important observation type across many predictions  
36 in locations with data paucity of all data types. Hydraulic observation data types were found to  
37 inform SW-GW exchange flux best under high- and regular- streamflow conditions when the  
38 magnitude of exchange fluxes were largest, whereas the water chemistry data was of highest

39 value for low- and regular- streamflow conditions where groundwater is discharging to the  
40 stream.

Journal Pre-proofs

## 41 **1 Introduction**

42 Observation data underpins effective water resource management, and managers have  
43 significant responsibility in decisions around data collection strategies. Conjunctive surface  
44 water (SW) and groundwater (GW) resource management requires having a quantitative insight  
45 into SW-GW exchange flux. Furthermore, the models that support such management are often  
46 required to provide the SW-GW exchange across multiple spatiotemporal scales.

47 Numerous methods exist for SW-GW exchange flux measurement and estimation  
48 (Fleckenstein et al. 2010; Kalbus et al. 2006). Means of estimating SW-GW exchange include  
49 direct methods (e.g., seepage meters), aimed at measuring the actual SW-GW exchange flux in-  
50 stream at a point. Direct methods are limited to very small spatial scales less than a few square  
51 metres and cannot be extrapolated to reach or regional scale SW-GW exchange (Cook 2015).  
52 Furthermore, such methods are limited by difficulty in identifying net SW-GW exchange – as  
53 opposed to hyporheic flow – and thus have limited utility at larger spatial scales (e.g. kilometre  
54 scale and greater).

55 The estimation of SW-GW exchange along stream reaches, as opposed to at a point,  
56 include methods based on stream water balance, hydraulic head gradient, river chemistry and  
57 ground water chemistry (see review by Cook 2015). The stream's water balance (through  
58 differential gauging) can be used where the SW-GW exchange is a significant component of the  
59 stream's water balance, greater than any uncertainties associated with other components of the  
60 balance. SW-GW exchange can be estimated by Darcian flux based on the average hydraulic  
61 head gradient across the stream and the average hydraulic conductivity of the streambed/aquifer.  
62 The exchange can also be estimated with stable and radioactive geochemical tracers (Cook  
63 2013), requiring information on features such as the flow in the stream, stream geometry, and

64 hyporheic cycling. Electrical conductivity (EC) is one stable tracer that, given significant  
65 differences between the GW and SW EC can be used with end-member mixing analysis to  
66 estimate inflow of GW to a stream (Barthold et al. 2011). The presence of Radon-222 ( $^{222}\text{Rn}$ ) in  
67 SW is indicative of GW discharge (Ellins et al. 1990), in the absence of significant hyporheic  
68 flow. When the concentration of  $^{222}\text{Rn}$  in the GW is measured at multiple locations along a  
69 stream along with adequate sampling in the SW, then areas of GW discharge at the time of  
70 sampling can be pinpointed, and exchange fluxes estimated. As  $^{222}\text{Rn}$  is a gas with a half-life of  
71 3.8 days, it will only remain in the stream for short periods of time. The conservative nature of  
72 EC allows for differentiation of river water that briefly enters the streambed for a period before  
73 returning to the stream, which with accumulation of  $^{222}\text{Rn}$  could be otherwise misinterpreted as  
74 regional GW discharge. Thus it is possible that these two observation data types contain unique  
75 information (i.e. uncorrelated) with respect to SW-GW exchange fluxes, which will be tested  
76 herein.

77 The use of physically based numerical modelling of flow in SW-GW systems, which is  
78 commonly applied to support managing water resources, allows for groundwater hydraulic head,  
79 stream stage and streamflow data to be integrated (e.g., Schilling et al. 2018; Wöhling et al.  
80 2018). Furthermore, coupling of transport to such a flow model affords further integration of  
81 various stream chemistry and geochemical data, e.g. EC,  $^{222}\text{Rn}$  or  $^{14}\text{C}$ . Numerical models  
82 simulating SW-GW exchange that support water resources management provide an important  
83 basis for assessing the extent to which observations can build confidence in the prediction of  
84 SW-GW exchange, i.e., data worth (Fienen et al. 2010).

85 The level of confidence in regional scale predictions of SW-GW exchange flux obtained  
86 from various models is partly limited by the quality (measurement noise), quantity and types of

87 available data that inform such model predictions. Predictions of surface water-groundwater  
88 exchange at a regional scale are critical to support conjunctive management of surface and  
89 groundwater resources within strongly connected SW-GW systems, i.e. systems whereby change  
90 to management of a river has a notable impact on the underlying aquifer and vice versa.  
91 Determining the most informative observational data types and spatiotemporal quantities of such  
92 data is an ever increasing need for water resource management practitioners (Kikuchi 2017).

93         The use of numerical models as a tool to formally assess the benefit of different data  
94 types and optimal data acquisition/experimental design within a formal “data worth” assessment  
95 framework is continually growing in popularity (Kikuchi 2017). The problem of “data worth”, in  
96 the context of water resources modelling, can be defined in terms of the reduction or lack thereof  
97 in the uncertainty of any key prediction of management interest that is afforded through the  
98 acquisition of observation data. A popular method used is first-order, second-moment (FOSM)  
99 analysis, which assumes the model behaves linearly with respect to its input parameters and  
100 simulated outputs. This approach is commonly used because of its suitability to be applied in  
101 combination with complex models (which are often used to support environmental management)  
102 owing to its computational efficiency (e.g. Dausman et al. 2010; Fienen et al. 2010; Moore and  
103 Doherty 2005). Brunner et al. (2012) used this approach to explore the worth of groundwater  
104 hydraulic head, ET and soil moisture observations in informing regional scale groundwater  
105 models. Wallis et al. (2014) demonstrated the utility of a FOSM-based data worth analysis of  
106 bromide, temperature, methane and chloride in the context of aquifer injection trials following  
107 coal seam gas-related water production. Schilling et al. (2014) investigated the utility of novel  
108 tree ring data in reducing predictive uncertainty of SW-GW exchange. More recently, Zell et al.  
109 (2018) used a similar approach to analyse groundwater hydraulic head, stream discharge, SF<sub>6</sub>,



110 CFCs and  $^3\text{H}$  in GW transport times. Finally, Knowling et al. (2019b), explored the worth of  
111 tritium-derived mean-residence time data for forecasts of spring discharge.

112 In the current study, the worth of existing and potential different hydraulic and water  
113 chemistry data are quantitatively investigated in the context of SW-GW exchange flux  
114 predictions over monthly and annual timescales and over a range of length scales (whole of river  
115 (141 km) vs reach (0.8 - 40.4 km)), for a field site in south-eastern Australia (Campaspe River  
116 catchment). We specifically consider the worth of: groundwater hydraulic head, streamflow,  
117 stream stage/depth, stream EC, stream  $^{222}\text{Rn}$ , and groundwater  $^{14}\text{C}$  for such predictions. To the  
118 best of the authors' knowledge, the benefit or otherwise of these tracer methods have not been  
119 quantitatively evaluated compared to more traditional and routinely collected data types in the  
120 context of SW-GW exchanges at the regional scale. This paper aims to answer:

121 **Q1.** To what degree, if at all, does the addition/omission of existing hydraulic observation  
122 and/or chemical observation data reduce/increase the uncertainty of SW-GW exchange fluxes  
123 and what is the spatiotemporal variability of such reductions/increases during low, regular  
124 and high streamflow conditions?

125 **Q2.** Through consideration of potential future sampling locations and times, which hydraulic  
126 and/or chemical data should be targeted in the future to yield the best reductions in  
127 uncertainty of SW-GW exchange flux during low, regular and high streamflow conditions?

## 128 **2 Case Study: Campaspe River**

129 The Campaspe River, located in north-central Victoria, lies within the Murray-Darling  
130 Basin, shown in Figure 1. The river runs for 220 km, beginning in the hilly terrain of the Great  
131 Dividing Range and flowing down through undulating foothills to the wide flat riverine plain in

132 the north before it joins the Murray River; the river provides 0.9% of the inflow for the basin.  
133 The Campaspe River overlies a series of alluvial aquifers, namely the Coonambidgal Formation,  
134 Shepparton Formation, Calivil Formation and Renmark Group (the latter two also commonly  
135 referred to collectively as the Deep Lead aquifer) which interact with the river along its length.  
136 As shown in Figure 1, the hydrogeological units of the Lower Campaspe valley area are made up  
137 of a Palaeozoic basement of fractured and faulted rocks, overlain by the Renmark Group which  
138 contains a blanket of thinly bedded carbonaceous sand, silt, clay and peaty coal, then overlying  
139 this is the Calivil Formation comprising coarse grained quartzose sand and gravel sheet with  
140 minor kaolonite clay, and atop of the Calivil Formation the Shepparton Formation is made up of  
141 fine-grained clastics and polymitic sand and gravel. Finally, incised into the Shepparton  
142 Formation, the Coonambidgal Formation is made up of primarily light grey or brown silty clay,  
143 with sand beds often at the base (Arad and Evans 1987). The main groundwater resource in the  
144 Lower Campaspe Valley is the Deep Lead aquifer. Conjunctively managing both the Campaspe  
145 River and Deep Lead aquifer necessitates estimation of SW-GW exchange flux.

146 **Figure 1. Campaspe River study area (a), location of Campaspe River catchment within**  
147 **the Murray-Darling Basin (b), and 3D model of hydrogeological units within the study area**  
148 **(c).**

149 Average annual rainfall ranges from 424 to 746 mm, with the higher rainfall occurring at  
150 higher elevations above Lake Eppalock, and lower rainfall occurring in the Lower Campaspe  
151 Valley. On average, the highest rainfall occurs between June and August, with the driest months  
152 being January to March. As well as providing sustained flow, the Lake Eppalock dam  
153 (completed in 1964) allows enhanced recharge to the Lower Campaspe Valley, due to its use in  
154 providing irrigation water in the area. The focus of this study is the area downstream of Lake

155 Eppalock and all the way to where the Campaspe River joins the Murray River. Large diversions  
156 from the Campaspe River until recent years were made through offtakes from the Campaspe  
157 Weir (constructed in the late 1800s) in the Campaspe Irrigation District (CID). Significant  
158 groundwater pumping developed in the Lower Campaspe area in the 1960's.

### 159 *2.1 Existing and potential observation data*

160 Observation data types considered in this study include routinely collected and publicly  
161 available hydraulic data, i.e., streamflow (daily), stream stage (daily) and groundwater hydraulic  
162 head data (variable, usually quarterly) (Australian Bureau of Meteorology  
163 (<http://www.bom.gov.au>), Victorian Government (<http://data.water.vic.gov.au>)). We also used  
164 existing EC data from the Victorian Government at stream gauges (<http://data.water.vic.gov.au>).  
165 As part of this study we collected surface (multiple times) and groundwater (once)  $^{222}\text{Rn}$  data  
166 (spot sampling), and new groundwater  $^{14}\text{C}$  to supplement existing  $^{14}\text{C}$  data collected in previous  
167 studies (Cartwright et al. 2012; Cartwright et al. 2006; Cartwright et al. 2010) (spot sampling).  
168 All considered observation data sampling locations are shown in Figure 2, where it can be seen  
169 that the majority of groundwater head observations are located in the north of the study area. All  
170 data collected previously and part of this study is herein referred to as “existing data”, as opposed  
171 to “potential data” which herein refers to as yet uncollected data. A dense network of future  
172 potential observation locations (i.e. data not yet collected) was considered spanning the entire  
173 study area, which includes GW sampling locations for groundwater hydraulic head and  $^{14}\text{C}$  and  
174 SW sampling locations for stream stage, streamflow, stream  $^{222}\text{Rn}$  and stream EC. The potential  
175 locations were chosen with the aim of filling the spatial gaps in data, e.g. hydraulic head in the  
176 south of the study area.

177 **Figure 2. Locations for observation data, including a) existing hydraulic (groundwater**  
178 **hydraulic head, stream stage and streamflow) and b) chemical (stream  $^{222}\text{Rn}$ ,  $^{14}\text{C}$ , stream**  
179 **EC) data. Potential future observation data (c) collection locations considered are also**  
180 **shown. The potential GW observations cover the extent of the aquifers, with gaps existing**  
181 **in the south of the study area due to the presence of only bedrock. The number of locations**  
182 **for each data type is shown in brackets in the legend.**

### 183 **3 Methodology**

#### 184 *3.1 Integrated SW-GW model setup*

185 The integrated SW-GW numerical models described below collectively serve as a tool for  
186 quantifying regional-scale SW-GW exchange flux prediction uncertainty and its reduction (or  
187 lack thereof) through the collection of various types of hydraulic and chemical data. A  
188 requirement for effective model usage in this context is that the models provide a robust basis for  
189 representing the primary processes and parameters on which predictions of interest may depend.  
190 For example, Fienen et al. (2010) showed that spatially distributed parameterisation schemes are  
191 necessary for effective predictive uncertainty estimation and to avoid corrupted data worth  
192 interpretations that may arise when adopting more parsimonious parameterisation schemes. As  
193 such, the numerical models employed here are physically based and highly parameterised (>  
194 1500 parameters), to allow simulation of surface and subsurface hydraulics (hydraulic head,  
195 stream stage and flow) and transport ( $^{222}\text{Rn}$ ,  $^{14}\text{C}$  and EC), and to robustly express uncertainty in  
196 regional-scale SW-GW exchange flux predictions (e.g., Hunt et al. 2007; Knowling et al. 2019a),  
197 respectively.

198           The integrated models considered herein comprise a series of SW-GW flow models and a  
199 series of SW-GW and SW solute transport models (Figure 3). The flow modelling in this study  
200 was carried out using MODFLOW-NWT (Niswonger et al. 2011). Assimilation of the hydraulic  
201 data (groundwater hydraulic head, streamflow, stream stage) is achieved through the integrated  
202 SW-GW flow models. The flow models simulate 3D saturated groundwater flow (ignoring  
203 unsaturated flow) and 1D surface flow routing through rivers (by the kinematic wave equation;  
204 SFR2 (Niswonger and Prudic 2005)). The flow model focuses representation of surface flow on  
205 the Campaspe River, ignoring some of the small tributaries that feed into the main river  
206 downstream of Lake Eppalock. This simplification is made as little flow arises from these  
207 tributaries other than in large rainfall events.

208           The flow solutions obtained from the steady and transient MODFLOW-NWT models  
209 were subsequently used to simulate transport of  $^{14}\text{C}$  using MT3D-USGS (Bedekar et al. 2016a;  
210 Bedekar et al. 2016b). Due to existing limitations in simulating radioactive decay and  
211 evapoconcentration with the stream flow transport (SFT) package of MT3D-USGS, the  
212 simulation of EC and  $^{222}\text{Rn}$  stream concentrations was carried out with an analytical steady-state  
213 transport model which accounts for evapoconcentration, decay and hyporheic exchange (similar  
214 to that of Cook et al. (2006) but rearranged to solve for concentration as shown in the Appendix)  
215 using the MODFLOW-simulated streamflows and SW-GW exchange fluxes as inputs. With this  
216 SW transport model, GW  $^{222}\text{Rn}$  and EC concentrations were treated as a static boundary (see  
217 Table 2). It is assumed that over the monthly time-step used in the flow model that the river is  
218 completely flushed and that all inflows (and corresponding concentrations) are steady, hence the  
219 use of the steady-state transport model.

220 The series of flow and transport models, shown in Figure 3, were used as a basis for  
221 representing the different hydraulic and chemical data types. Firstly, groundwater hydraulic  
222 head, streamflow, and stream depth/stage, are simulated under pre-clearance conditions in a  
223 steady-state flow model (SS) (MODFLOW-NWT). Secondly, transient SW-GW flow (TR) is  
224 simulated spanning the period 1840 to 2018. In the transient flow model, it is assumed that  
225 clearance of native trees and shrubs was immediate (1840) and that irrigation was static (using  
226 long term average).  $^{14}\text{C}$  was simulated in two models, firstly using the output from the SS flow  
227 model but simulating transport for 40,000 yrs ( $\text{TR1}_{\text{C14}}$ ) with an initial concentration of  $^{14}\text{C}$  set to  
228 0 PMC across the model domain; subsequently the final concentration of  $^{14}\text{C}$  in the  $\text{TR1}_{\text{C14}}$   
229 simulation was passed as the initial conditions for the post-clearance to present day simulation of  
230  $^{14}\text{C}$  ( $\text{TR2}_{\text{C14}}$ ). Inflow from recharge was assigned as 100 PMC in both  $^{14}\text{C}$  simulations. The  
231 Campaspe river flows and SW-GW exchange fluxes simulated at each stream reach in the period  
232 of interest from the transient flow solution (TR) (June 2016-May 2017) were passed to the 1D  
233 transport model for simulation of  $^{222}\text{Rn}$  ( $\text{SS}_{\text{Rn}}$ ) and EC ( $\text{SS}_{\text{EC}}$ ) at each of the months within this  
234 period of interest. Groundwater concentrations for  $^{222}\text{Rn}$  and EC were assigned as static.

235

236 **Figure 3. a) The series of flow and transport models employed and the associated data**  
237 **types simulated by each, b) a 3D model schematic, including spatial grid and boundary**  
238 **conditions: drains (DRN), Campaspe River (SFR), general head (GHB), Murray River**  
239 **(RIV), pumping (WEL), and recharge (RCH), which is depicted in the overlaid and**  
240 **elevated surface with 11 time invariant recharge zones.**

241 The numerical grid was discretised into 1 km x 1 km cells (Figure 3b) with 7 layers of  
242 variable thickness covering the 6 hydrogeological units shown in Figure 1c. The mean, minimum  
243 and maximum values of each unit are shown below in Table 1.

244 **Table 1. Summary of hydrogeological layer thicknesses including, mean, minimum,**  
245 **maximum thickness and percent volume. Hydrogeological units are abbreviated as**  
246 **Coonambidgal (co), Shepparton (sh), Calivil (ca), Renmark (re), Newer Volcanics (nv),**  
247 **Basement (ba).**

248 Variable time steps are employed that are 40 yrs (1840-1880), 84 yrs (1881-1965), 20  
249 yrs (1966-2005), 10 yrs (2006-2015) and then monthly from January 2015 to March 2018. SW-  
250 GW exchange flux predictions of interest considered herein for the purposes of the current data  
251 worth analysis are made over a one year period of simulation between the start of June 2016 and  
252 the end of May 2017. The exchange fluxes are considered along the entire river from Lake  
253 Eppalock to the Murray River (141 km), and for reaches between river gauges along this length  
254 of river (11 reaches ranging from 0.8 to 40.4 km in length). The outputs of SW-GW exchange  
255 flux from the transient flow model at each reach were considered at the monthly (important for  
256 river operations and ecological assessment) and yearly resolution (important for water  
257 allocations). Also considered was the spatial sum of the SW-GW exchange flux along the whole  
258 river at monthly and annual time scales (important for groundwater use management strategies).  
259 These different spatiotemporal predictions give rise to a total of 156 predictions of interest.

260 The MODFLOW-NWT models were forced by recharge using the RCH (specified flux)  
261 package, by groundwater pumping using the WEL (specified flux) package (applied from 1966  
262 onwards), and by rivers and drains using the SFR (streamflow routing and head-dependent  
263 exchange flux, applied to the Campaspe River, which is the focal point of this study), RIV (head-  
264 dependent exchange flux applied to the Murray River) and DRN (head-dependent flux)

265 packages. Stream diversions in-to and out-of the Campaspe River are also captured using the  
266 SFR package. The locations of the boundary conditions are shown in Figure 3. There is no  
267 pumping or artificial drainage in the pre-clearance steady-state (SS) flow model. Zonal rainfall  
268 reduction parameters (11 zones) are set to 1% (i.e. assuming very low recharge at a time when  
269 the land was densely covered in vegetation) and are multiplied by the spatially varying map of  
270 temporal long-term average rainfall over this period for specifying the recharge boundary  
271 condition. As rainfall reduction parameters were used for recharge, evapotranspiration was not  
272 explicitly modelled in this study. In the post-clearance transient flow model (TR) the zonal  
273 values for each of the 11 zones are modified to reflect the land use, soil type and mean annual  
274 rainfall and multiplied by temporally varying spatial maps of rainfall to provide the temporal  
275 recharge input maps for the model. In the post-clearance transient flow model (TR) irrigation is  
276 embedded in the recharge factor for requisite zones as reflected by the land use. Temporally  
277 static aquifer and stream properties were spatially parameterised using pilot points. The locations  
278 of pilot points, which also correspond with the locations of potential observations, were  
279 automatically generated (see SI).

280 Model history matching was performed on the basis of groundwater hydraulic head,  
281 streamflow, stream stage, stream  $^{222}\text{Rn}$ , groundwater  $^{14}\text{C}$  and stream EC, at the locations shown  
282 in Figure 2. Model parameters (Table 2) for stream and aquifer properties were subject to  
283 estimation through history matching. History matching was carried out using the parameter  
284 estimation suite PEST (Doherty 2016) using Tikhonov regularisation.



285 **Table 2. Summary of model parameterization. For the aquifer property parameters, the**  
 286 **hydrogeological units are abbreviated as follows: Coonambidgal (co), Shepparton (sh),**  
 287 **Calivil (ca), Renmark (re), Newer Volcanics (nv), Basement (ba).**

288 The flow and transport models were built utilising FloPy (Bakker et al. 2016). The in-  
 289 stream transport model for  $^{222}\text{Rn}$  and EC was implemented in Python (see SI).

### 290 3.2 Assessment of predictive uncertainty in SW-GW exchange flux

291 The worth of data is considered herein as the reduction or lack thereof of the uncertainty  
 292 of the prediction of interest (SW-GW exchange) with the addition of various acquired or  
 293 potential observation data. A brief overview of the key theoretical aspects underlying the  
 294 approach adopted for the quantification of predictive uncertainty and data worth is now provided.

295 The posterior (i.e., post-history matching) parameter covariance matrix ( $\bar{\Sigma}_{\theta}$ ) can be  
 296 estimated with Schur's complement as (Christensen and Doherty 2008; Doherty 2015; Tarantola  
 297 2005; White et al. 2016):

$$298 \quad \bar{\Sigma}_{\theta} = \Sigma_{\theta} - \Sigma_{\theta} \mathbf{J}^T [\mathbf{J} \Sigma_{\theta} \mathbf{J}^T + \Sigma_{\epsilon}]^{-1} \mathbf{J} \Sigma_{\theta} \quad (1)$$

299 Where,  $\Sigma_{\theta}$  is the prior parameter covariance matrix,  $\Sigma_{\epsilon}$  is the epistemic noise covariance  
 300 matrix (i.e. accounting for both measurement and model error), and  $\mathbf{J}$  is the Jacobian matrix of  
 301 partial first derivatives of model outputs (for which there are corresponding observations) with  
 302 respect to parameters  $\theta$ . The second term on the RHS of (1) expresses the reduction in  
 303 uncertainty surrounding parameters as a result of conditioning the model on the information  
 304 contained in the observations.

305 The prior and posterior uncertainty variance for a prediction  $s$ ,  $\bar{\sigma}_s^2$ , respectively can be  
 306 estimated via uncertainty propagation:

$$307 \quad \sigma_s^2 = \mathbf{y}^T \boldsymbol{\Sigma}_\theta \mathbf{y} \quad (2)$$

308 And

$$309 \quad \bar{\sigma}_s^2 = \mathbf{y}^T \bar{\boldsymbol{\Sigma}}_\theta \mathbf{y} \quad (3)$$

310 Where  $\mathbf{y}$  is the sensitivity vector for prediction  $s$  with respect to the parameters  $\boldsymbol{\theta}$  (a row  
311 extracted from the  $\mathbf{J}$  matrix).

312 This study assumes the parameter covariance matrix ( $\boldsymbol{\Sigma}_\theta$ ) is a diagonal matrix (does not  
313 contain non-zero off-diagonal elements). This assumption means that zero correlation exists  
314 between parameters. The assumption of zero correlation between spatially distributed  
315 parameters, and in particular pilot point aquifer and river property parameters was considered  
316 appropriate given the limited spatial coverage of both aquifer and river property information as  
317 well as the large distance separating pilot points (on average, 6 km x 6 km). The lower and upper  
318 bounds of the parameter range (see Table 2) are specified based on hydrological and geological  
319 expert knowledge (in this case conservative) and are assumed to represent the 5<sup>th</sup> and 95<sup>th</sup>  
320 percentile of the (assumed Gaussian) parameter distribution.

321 The Jacobian matrix  $\mathbf{J}$  was populated using 1% two-point derivative increments. These  
322 derivatives with respect to a parameter set were obtained following a history matching  
323 undertaking that is unrelated to the implementation of the data worth analyses presented herein  
324 (see SI for details).

325 The epistemic noise covariance matrix ( $\boldsymbol{\Sigma}_\epsilon$ ) is also assumed diagonal. It is specified  
326 practically by assigning observation weights (inversely proportional to the standard deviation of  
327 noise) (Doherty 2015). Observation weights are specified on the basis of a subjective assessment  
328 of the measurement noise standard deviation (Table 3), before being adjusted in accordance with

329 model-to-measurement residuals to account for model error. Weight adjustment is undertaken in  
330 such a way that the weight of any observation cannot be increased (thereby respecting the  
331 contribution to epistemic noise from measurement noise), and that the contribution of each  
332 observation group to the model-to-measurement objective function is equal to the number of  
333 non-zero weighted observations in that group (Doherty 2016). The use of model-to-measurement  
334 residuals to approximate model error is deemed appropriate given that this quantity can never be  
335 known, and that the residuals constitute the only information available for reflecting model error  
336 with respect to different types of observation and simulated outputs. For potential observations,  
337 i.e., where no measurements exist for which to undertake the above-described weight adjustment,  
338 weights are specified based on the average (adjusted) weight assigned to existing observations of  
339 the same group/type. The observation noise variance for all but stream flow was fixed as stream  
340 flow measurement error is known to become larger at higher flows, particularly when  
341 extrapolating the rating curve (Di Baldassarre and Montanari 2009) and an assumed 40% error  
342 accounts for a worse case evaluation of this error. The posterior parameter covariance matrix and  
343 ensuing data worth analysis was calculated using the Python package pyEMU (White et al.  
344 2016).

345 **Table 3. Assumed observation noise (used together with model-to-measurement residual**  
346 **information to populate  $\Sigma_\epsilon$ ).**

347 The worth of different observation data is evaluated in different ways in this study.  
348 Firstly, we consider the worth with observation data groups by themselves, i.e. the ability of an  
349 individual observation data group to reduce uncertainty on a prediction of SW-GW exchange. To  
350 do this, predictive uncertainty with that particular observation data group is estimated by  
351 evaluating equation 1 and 3 twice, once where the particular observation data does not appear in

352  $\Sigma_{\epsilon}$ , which we term the ‘base’ uncertainty ( $\bar{\sigma}_{s\ base}$ ), and again where  $\Sigma_{\epsilon}$  contains the particular  
 353 observation data group, which gives the ‘group’ predictive uncertainty ( $\bar{\sigma}_{s\ group}$ ). The  
 354 calculation of reduction in uncertainty through adding the observation data type group ( $DW_{add}\%$ )  
 355 is calculated as:

$$356 \quad DW_{add}\% = \left(1 - \frac{\bar{\sigma}_{s\ group}}{\bar{\sigma}_{s\ base}}\right) \times 100\% \quad (4)$$

357 Secondly, to evaluate the mutually exclusive information that exists in each observation  
 358 data group we consider the difference between predictive uncertainty reduction using all  
 359 observation data groups and omitting an observation data group from all groups. To do this, we  
 360 again evaluate equation 1 and 3 twice, once where in  $\Sigma_{\epsilon}$  all observation data groups are  
 361 considered together ( $\bar{\sigma}_{s\ all}$ ), and again with all observation data groups except for the one of  
 362 interest considered ( $\bar{\sigma}_{s\ all-group}$ ). Then we compare the two against the ‘base’ uncertainty:

$$363 \quad DW_{remove}\% = \left(\frac{\bar{\sigma}_{s\ all-group} - \bar{\sigma}_{s\ all}}{\bar{\sigma}_{s\ base}}\right) \times 100\% \quad (5)$$

364 Finally, in the context of the potential observations, we evaluate the next most important  
 365 observations (using built in functions in pyEMU; White et al. (2016)) by iterating over each of  
 366 the potential observations alone (for select predictions) and in groups (for all predictions within a  
 367 group) to find the best reduction in uncertainty, then we add that observation or group of  
 368 observations to the list of existing observations and repeat the process. The addition of the  
 369 previously identified best observation or observation group accounts for any correlation between  
 370 observations or groups of observations.

371 In order to answer the first question posed (**Q1**) regarding the degree to which water  
 372 chemistry data and hydraulic data reduces the uncertainty surrounding the 156 predictions of  
 373 SW-GW exchange, each of the observation data types (or “groups”) were first considered

374 individually for existing observation data with the “base” containing no observation data (Table  
375 4). Then the potential data (Q2) were evaluated with the “base” consisting of all existing  
376 observation data. The individual contribution of each potential observation to the whole of river  
377 exchange at three different times covering low, regular and high streamflow conditions was  
378 examined to determine the worth of particular potential data types and quantities of value.

379 **Table 4. Data worth assessments employed for the range of SW-GW exchange predictions**  
380 **from the Campaspe transient flow model (TR).**

## 381 **4 Results and Discussion**

### 382 *4.1 Simulated SW-GW exchange behaviour*

383 The behaviour of SW-GW exchange flux is first examined at each of the TR model’s 122  
384 stream segments on a monthly basis as a means of establishing an understanding of dynamics  
385 and spatiotemporal variability of the exchanges before considering the data worth analysis.

386 Throughout the results section we adopt the convention of denoting gaining conditions in  
387 a stream by negative values and losing conditions by positive values. The monthly flows are  
388 herein subjectively categorised as either low (<35<sup>th</sup> percentile), regular (between 35<sup>th</sup> and 80<sup>th</sup>  
389 percentile), or high (>80<sup>th</sup> percentile). Each of the flow categorisations is also associated with  
390 clearly differing SW-GW exchange patterns.

391 The post-clearance transient flow simulation generally showed that SW-GW exchanges  
392 along the length of the river exhibit gaining behaviour (Figure 4). The exception to this being  
393 during high flow events, when the river transitions to a largely losing river (0.23 m<sup>2</sup>/d) as  
394 significant inflows from Lake Eppalock raise the stream stage and reverse the hydraulic gradient  
395 along the majority of the river. The exchange fluxes per unit length of stream at any point along

396 the stream during the simulation period range from losing by  $9 \text{ m}^2/\text{d}$  during the October 2016  
397 high flow event to gaining at  $-9 \text{ m}^2/\text{d}$  as the system recovers in the following month. The  
398 spatially and temporally averaged SW-GW exchange along the entire river is gaining at  
399 approximately  $-1.1 \text{ m}^2/\text{d}$ . Reach r3 shows the strongest variance in exchange flux along its length  
400 through differing inflow conditions followed by r5, r6 and r8, while r10 and r11 show the least  
401 variance and are always gaining.

402

403 **Figure 4. Simulated SW-GW exchange fluxes per unit length of stream at each reach along**  
404 **the Campaspe River. Coloured lines depict exchange fluxes under differing low, regular or**  
405 **high flow conditions for each month. The black line depicts the temporally averaged**  
406 **exchange flux. The dotted grey vertical lines indicate gauge locations with the 11 between-**  
407 **gauges-reaches annotated at the top of the graph.**

408 The simulated SW-GW exchange fluxes for the whole river and for each of the 11 river  
409 reaches for annual average and monthly average time scales (i.e. 156 predictions) range from -  
410  $3.08$  to  $2.23 \text{ m}^2/\text{d}$  (shown in Figure 5). The strongest losing flux appears along reach 3 during the  
411 high flow event in October 2016. The simulated SW-GW exchange flux was highest along reach  
412 3. Reach 6 (r6) just upstream of the Campaspe weir exhibits losing conditions, while all other  
413 reaches show gaining conditions. For the examined year, there is a clear link between the inflow  
414 from Lake Eppalock and the pattern of exchange fluxes (Figure 5).

415

416 **Figure 5. Heatmap of simulated SW-GW exchange per unit length along the whole of the**  
417 **river and along each of the 11 reaches at annual and monthly time scales, which comprises**

418 **the 156 predictions of interest. Red cells in the heatmap indicate losing conditions and blue**  
419 **cells indicate gaining conditions. The left panel shows the location and length of each of the**  
420 **reaches for reference. The bottom panel indicates the annual average (mean) inflow from**  
421 **Lake Eppalock to the system as well as the monthly inflow with the colours of the bars**  
422 **indicating whether the flow is low, regular or high.**

#### 423 4.2 Worth of existing hydraulic and water chemistry data types (Q1)

424 Assessment of the worth of individual observational data types alone (i.e.,  $DW_{add}\%$ ) for  
425 the spatial and temporally aggregated whole of river annual exchange showed that hydraulic  
426 head followed by EC,  $^{222}\text{Rn}$  and flow observation groups had sizeable worth of  $> 40\%$  (the green  
427 dots in Figure 6a). Similar relative trends across data types were seen for the uncertainty  
428 increases *without* individual data groups when compared to all data groups ( $DW_{remove}\%$ ). The  
429 lower values in  $DW_{remove}\%$  as compared to  $DW_{add}\%$  arise because the former yields the unique  
430 information contained in an individual data group; this allows for assessment of the extent of  
431 correlation and redundancy of individual data groups. It was evident from the analysis of  
432  $DW_{remove}\%$  for the spatially and temporally averaged SW-GW exchange prediction, that the head,  
433 streamflow,  $^{222}\text{Rn}$  and EC data contain unique information.

434 Across all 156 predictions for SW-GW exchange flux predictions along the Campaspe  
435 River, the median worth obtained from both  $DW_{add}\%$  and  $DW_{remove}\%$  showed that head data were  
436 significant whereas the streamflow data were less informative. Furthermore, there appears to be  
437 redundancy in the flow data. Also, the median worth of  $^{222}\text{Rn}$  was significant whereas the EC  
438 data was much lower (Figure 6a). Stream stage and  $^{14}\text{C}$  were both poor, with the distribution of  
439  $DW_{add}\%$  for stream stage data close to zero. The large range in worth of head, flow,  $^{222}\text{Rn}$  and  
440 EC data types and the degree of information redundancy across the 156 predictions highlights the

441 nature of the local information content that particular data types have for specific predictions.  
442 The local information content is highlighted by the outliers in  $DW_{remove}\%$  showing unique  
443 information in head,  $^{14}\text{C}$  and  $^{222}\text{Rn}$  for some predictions of SW-GW exchange.

444 **Figure 6. Analysis of worth for the whole of river annual exchange (green dots) shown by a)**  
445 **% reduction in predictive uncertainty for SW-GW exchange associated with each**  
446 **particular observation group ( $DW_{add}\%$ ), and b) difference in reduction between using all**  
447 **observation data types and using all except for a particular group from the combination**  
448 **( $DW_{remove}\%$ ). Furthermore, boxplots are shown for the distributions across all 156 SW-**  
449 **GW exchange predictions.**

450 The worth for the 156 SW-GW exchange predictions shows distinct patterns that are  
451 associated with inflow to the Campaspe River from Lake Eppalock (Figure 7). During the large  
452 flow event during October 2016, across all reaches and the whole river there was consistently  
453 poorer worth for predictions within that month. The relative lack of information resident in the  
454 data types continues in the following months associated predictions, while the system recovers.  
455 The whole of river predictions show an expected dampened variability and higher average worth  
456 due to its spatially integrated nature. At the end of the river system in reaches r10 and r11 all data  
457 types are seen to have quite low worth, except  $^{222}\text{Rn}$  which appears to be the only data-type to  
458 show value in reach r10. The poor performance at the end of system could be due to a “boundary  
459 effect”, related to the fact that both the Murray River boundary condition and underlying  
460 groundwater general head boundary conditions possibly influence the model to such an extent  
461 that they overpower the information content of any existing observational data. Potential  
462 boundary effects could be avoided by extending the northern boundary of the model past the



463 Murray River and converting the Murray River to a flow routing representation rather than the  
464 fixed head representation that was implemented.

465 **Figure 7. Heatmaps of percentage reduction in SW-GW exchange uncertainty obtained**  
466 **with all data (a), and with each of the observation data types alone (b-g). The reduction is**  
467 **shown for each SW-GW exchange flux considered, i.e. for each of the stream reaches (r1-**  
468 **r11) and whole of river (nrf), and at each of the temporal scales of annual and monthly**  
469 **between the start of June 2016 and end of May 2017. The inflow to the system is shown**  
470 **under the first heatmap (a) from which the high flow event in October can be seen. The**  
471 **locations and lengths of reaches (r1-r11) are shown to the left of the first heatmap for**  
472 **reference.**

473 The analysis of existing observation data types, firstly, identified that the temporal  
474 integration in annual predictions (both whole of river and reach scale) generally led to better  
475 reductions in uncertainty than in the monthly predictions. These are plausible given that the  
476 annual signal is smoothed. For hydraulic head,  $^{14}\text{C}$  and  $^{222}\text{Rn}$ , there were not data available in  
477 every month of the year, but particular data were at least present enough in the seemingly  
478 dependent months (during large exchanges) required to inform the annual SW-GW exchange  
479 prediction.

#### 480 4.3 *Worth of individual potential future hydraulic and water chemistry data points (Q2)*

481 We analysed the worth from individual potential in-stream observations to explore the  
482 extent to which the whole of river SW-GW exchange prediction reliability could be improved  
483 through data acquisition at new sampling locations. The worth of individual potential  
484 observations of stage, flow,  $^{222}\text{Rn}$  and EC at select times when flow conditions were low (July

485 2016), high (October 2016) and regular (November 2016) are shown in Figure 8; the  
486 corresponding SW-GW exchange along the stream at each of these times is also shown. The  
487 value of both stage and EC potential observations are shown to be poor across these flow  
488 conditions, with only  $^{222}\text{Rn}$  (low and regular flow conditions) and flow (high and regular flow  
489 conditions) showing considerable value. Under low flow conditions,  $^{222}\text{Rn}$  data displayed the  
490 highest utility where existing data were not present and where the stream exhibits strong gaining  
491 conditions in the first 40 km of the stream. Also,  $^{222}\text{Rn}$  showed considerable value in the slightly  
492 gaining areas at around 130 km downstream, likely due to the paucity in local existing data for  
493 all data types. However,  $^{222}\text{Rn}$  data were seen to be of low utility when high flow conditions  
494 prevail with a corresponding reversal of hydraulic gradient resulting in a mostly losing river, as  
495 simulated during the high flow event in October 2016. In the high flow event instance, there is a  
496 trend of increasing flow data worth with distance downstream.

497

498 **Figure 8. Further reduction in uncertainty for net SW-GW exchange in October 2016,**  
499 **November 2016 and May 2017 obtained through potential observations of stream stage,**  
500 **flow,  $^{222}\text{Rn}$  and EC at 80 locations along the stream. Each potential observation is**  
501 **considered alone but added to the existing observations across all observation data types.**  
502 **Underlying each uncertainty reduction plot is the pattern of exchange along the river**  
503 **during each of the months with the scatter showing the exchange rate ( $\text{m}^2/\text{d}$ ) and the**  
504 **colours representing the exchange flux along the reach at that location; reds indicate losing**  
505 **and blues indicate gaining conditions. The mean exchange rate is shown in light grey on**  
506 **each of these plots to give context to the exchange conditions relative to the mean.**

507 To explore the extent of reduction in uncertainty obtained through potential addition of  
508 subsurface data to the existing dataset, we analysed the whole of river SW-GW exchange flux  
509 during low, high and regular flow conditions through both head and  $^{14}\text{C}$  in the shallow and deep  
510 aquifers at the potential sampling locations (Figure 9). The SW-GW exchange along the  
511 Campaspe River in the highest (southern) parts of the model domain is very sensitive to the GW  
512 level which is strongly connected at the top of the catchment to the heads in the narrow alluvial  
513 channels and hence it is observational data located here that appears to inform the whole of river  
514 SW-GW exchanges the most, although the reductions in predictive uncertainty are only  
515 marginal. This generally highlights opportunity for more value from targeted observations in the  
516 southern part of the catchment in the narrow alluvial valleys. The deep heads are seen to hold the  
517 least value of the potential observations across flow conditions. As expected, due to the lesser  
518 variance of subsurface data as compared to stream data, spatial patterns of worth are more  
519 consistent across the low, regular and high flow conditions. Furthermore, there is clear crossover  
520 of high utility potential sampling locations for shallow and deep  $^{14}\text{C}$  and shallow head too in the  
521 southern part of the catchment, although shallow head also appears of some value along the  
522 entire length of the stream.

523

524 **Figure 9. Percent reduction in uncertainty for annual whole of river SW-GW exchange**  
525 **fluxes of the Campaspe River obtained through hydraulic head and  $^{14}\text{C}$  at potential**  
526 **sampling locations (identical to pilot points) in the shallow and deep aquifers.**

527 *4.4 Worth of potential future hydraulic and water chemistry data types (Q2)*

528 For all of the potential data and also each of the data type groups, we examined the  
529 benefit of using all potential data (Figure 10), which highlights the extent to which particular

530 predictions can be improved (as compared to existing data) under comprehensive sampling of all  
531 data types and individual data types. The potential hydraulic head data showed improvement in  
532 terms of SW-GW prediction reliability in the middle section of the river prior to the largest of the  
533 high-flow events and a few months after the recovery of this event (Figure 10b). The stage data  
534 again shows little value, no matter the location or time of sampling (Figure 10c). The ubiquitous  
535 poor worth of stage data was surprising as it could be assumed that the intrinsic link between  
536 hydraulic head and stage in the calculation of the exchange flux would result in stage data  
537 containing prediction-relevant information. We posit a potential reason for this is the stream  
538 stage as simulated by the numerical model showed less variance (minimum and maximum of  
539  $1.21\text{E-}4$  and  $1.11\text{E-}2$ ) than the observed data owing to the representation of a rectangular channel  
540 and associated parameterisation. For example, the effective stream width may have been  
541 overestimated in the model and hence the associated error with the simulated stage was  
542 potentially overrated. This led to a poor rating in stage data but is likely more linked to the  
543 modelling assumptions, e.g. a perfectly known riverbed elevation, and structure for the  
544 Campaspe River, rather than the “true” worth of the data itself.

545 Further reductions in predictive uncertainty up to around 25% are seen with the addition  
546 of the flow, head and EC data. The addition of potential  $^{222}\text{Rn}$  data (Figure 10f) shows clear  
547 improvements for reaches r2–r9. Especially of interest are those improvements in worth at the  
548 time prior to the high flow in October 2016 and just after. Assessment of potential  $^{14}\text{C}$  data  
549 showed significant improvement of a further 40% reduction in most predictions along reaches  
550 r1–r5 (Figure 10e), suggesting that the existing spatiotemporal  $^{14}\text{C}$  data locations were  
551 suboptimal in this context of SW-GW exchange. However, the comprehensive sampling of both

552  $^{222}\text{Rn}$  and  $^{14}\text{C}$  through space and time is likely impractical due to the costs, especially for  $^{14}\text{C}$   
553 which would incur drilling costs.

554 **Figure 10. Difference in uncertainty reductions between existing and potential observation**  
555 **data for all data (a) and for each of the individual observation groups (b-g).**

556 The analysis of the ten “next best” most important observations to collect on top of all  
557 existing data during low, high and regular streamflow conditions showed that the optimal  
558 location set is different under differing flow conditions.  $^{222}\text{Rn}$  was the most beneficial data type  
559 to collect next with head,  $^{14}\text{C}$ , and flow also in the top ten (Figure 11). Interestingly, during low  
560 and high streamflow conditions, within-stream observations of  $^{222}\text{Rn}$  and flow were distributed  
561 in the upper, middle and lower reaches of the stream, whereas for regular flow conditions, the  
562 observation data were in the middle and lower reaches only. The role of  $^{14}\text{C}$  observations in the  
563 top left of the maps (Figure 11a-c) are at first perhaps counter-intuitive, however, this location  
564 represents the longest flow path through the aquifers before exiting through the northern  
565 boundary, informing the velocity of flow and its variation and hence the hydraulic conductivity  
566 of the aquifers and its effective porosity, the former of which in turn informs the SW-GW  
567 exchange along the river.

568 **Figure 11. Locations and rank of 10 next most important potential observations to add to**  
569 **the existing observations for whole of river exchange during months of low, high and**  
570 **regular streamflow conditions (a-c). Further reduction in uncertainty (%) due to each of**  
571 **the 10 next most important potential observations (d-f).**

572 Finally, we examined the next most important observation groups for each of the 156  
573 SW-GW exchange predictions (Figure 12), i.e. using all potential data within each data type.

574 This assessment showed that potential  $^{222}\text{Rn}$  was the most important group across the majority of  
575 predictions, followed by shallow head,  $^{14}\text{C}$ , EC, flow, deep head and lastly stage, which was  
576 ranked 7<sup>th</sup> for the majority of predictions (Figure 12).

577 **Figure 12. Ranking (x-axis) of best uncertainty reduction across each of the 156 predictions**  
578 **of interest in a “next most important” type analysis. The uncertainty reduction is based on**  
579 **each observation group for potential observations when added to the existing data.**

#### 580 4.5 General observations

581 The above results have demonstrated that the worth of different hydraulic and chemical  
582 observations in the context of making SW-GW predictions is dependent on the prevailing  
583 streamflow conditions, the magnitude and direction of the SW-GW exchange and the spatial and  
584 temporal scale of the exchange considered. It has also demonstrated the large variability in worth  
585 across different SW-GW exchange predictions as a result of these dependencies. These findings  
586 are in addition to previously reported dependence of data worth on prediction specificity more  
587 generally (e.g. Dausman et al. 2010; White et al. 2016).

##### 588 4.5.1 Influence of streamflow conditions and magnitude and direction of SW-GW exchange

589 The prediction-specificity of data worth with respect to prevailing stream flow conditions  
590 can be explained by the sensitivities of the different SW-GW exchange predictions to uncertain  
591 model parameters that are conditioned on the basis of both existing and potential hydraulic and  
592 chemical observational data. During high-flow conditions, generally lower data worth is  
593 apparent. This is because SW-GW exchange predictions under high-flow conditions depend on a  
594 larger portion of uncertain model parameters (e.g., recharge and aquifer properties for the TR  
595 model); this results in lower worth given the limit on the ability of information to “spread” from

596 data in space and time. That is, there are a number of prediction-parameter sensitivities that are  
597 heightened as the Campaspe flow system is perturbed firstly by large losing SW-GW exchanges,  
598 and secondly by the presence of distributed above-average recharge which also propagates  
599 through the subsurface. Furthermore, the uncertainty in the flow observations increases with high  
600 flows. As the stream is largely losing during high flows, the  $SS_{EC}$  and  $SS_{Rn}$  transport parameters  
601 become less sensitive with respect to the corresponding SW-GW predictions. During low-flow  
602 conditions, where rainfall recharge is often relatively small and the river is generally weakly  
603 gaining along the Campaspe River, the SW-GW exchange predictions are generally less sensitive  
604 to the flow model parameters. This allows for the information contained in the  $^{222}Rn$  and EC  
605 observations to be used more effectively through the  $SS_{EC}$  and  $SS_{Rn}$  transport parameters.

606 For example, in the annual whole of river SW-GW exchange flux prediction, it was  
607 apparent (Figure 8) that in-stream sampling of  $^{222}Rn$  can lead to a further reduction in uncertainty  
608 (up to 10%) during low flows, with some value during regular flow conditions (up to 6%) but  
609 with reduced utility (<0.5%) in high streamflow conditions. This is because the predictions  
610 during lower flow show higher sensitivity to the parameters that are conditioned by the  
611 information contained in the  $^{222}Rn$  observations. It is thus necessary to target the particular time  
612 and location carefully for sampling water chemistry data due to the transient and local  
613 information content. This is further evidenced by the improvements through all potential data for  
614 each data type which showed the theoretically possible improvements when comprehensive  
615 sampling takes place in space and time. This differs in comparison to the hydraulic data, which  
616 seems to show similar patterns across sampling times in worth for groundwater hydraulic head  
617 and streamflow data points as explained above (Figure 8 and Figure 9). Despite the similar

618 patterns, the “flow of information” from hydraulic observation data appears to be larger under  
619 regular and high flow conditions.

620 As was explained at the start of the results (4.1), the general patterns between flow  
621 conditions and SW-GW exchange are clear. The apparent information content in all observation  
622 data appears linked to the magnitude and direction of the SW-GW exchange flux in many  
623 predictions. It was evident that for the very weakest exchanges, the poorest worth was found, no  
624 matter the data type; however, the opposite was not true for the strongest SW-GW exchanges  
625 which exhibit more complex worth patterns across data type.

#### 626 4.5.2 Influence of spatial and temporal scale of SW-GW exchange

627 The simulated variability in monthly reach-scale SW-GW exchange in the Campaspe  
628 River was clear, and so were the corresponding reductions in predictive uncertainty due to data  
629 collection. When averaging the SW-GW exchange over the whole of the river, the worth of data  
630 was reasonably consistent on a monthly basis for each data type alone and for all data types, with  
631 a clear trend in variability being linked to the flow conditions (discussed above). Furthermore,  
632 the consistent data worth across months was also consistently close to the best uncertainty  
633 reductions from the reaches, i.e. the reductions were not a simple average of the individual reach  
634 uncertainty reductions, but more closely linked to the best reductions. This is expected due to the  
635 spatial integration of information contained in the hydraulic and chemical data. A similar pattern  
636 with respect to temporal integration of information is present in comparing monthly to annual  
637 SW-GW exchanges.

638 There was no clear relationship between the length of the reach and annual reductions in  
639 predictive uncertainty. However, the lowest uncertainty reductions were apparent in the shortest



640 reach r10 (0.8 km). The lack of a clear relationship is likely due to a combination of the above-  
641 mentioned factors of prevailing flow conditions and magnitude of the SW-GW exchange fluxes.

#### 642 4.5.3 Model simplifications and assumptions

643 Interestingly, even though the water chemistry data provide more indirect means to  
644 calculate SW-GW exchange flux than the hydraulic data (i.e., chemistry data serve as proxy for  
645 flux), these data types alone showed greater worth in many predictions. For the cases in which  
646 the river is not experiencing low-flow conditions and gaining, we would posit that this is partly a  
647 result of the simplified 1D transport models ( $SS_{Rn}$  and  $SS_{EC}$ ) used to map the  $^{222}Rn$  and EC  
648 observations to SW-GW exchange predictions through the  $SS_{Rn}$  and  $SS_{EC}$  transport parameters.  
649 The parameterisation, spatial scale of river segments, and process assumptions that were applied  
650 to the simplified 1D transport model (e.g., the uniform fixed groundwater concentrations of  $^{222}Rn$   
651 and EC, and the monthly steady-state assumption) likely inflates their sensitivity for these data  
652 types and hence their worth to SW-GW exchange predictions (Fiene et al. 2010). Future  
653 modelling of in-stream  $^{222}Rn$  and EC transport would benefit from testing this by further  
654 evaluating the worth of these data types in a transient transport model with spatiotemporally  
655 varying parameters, including the inputs of both  $^{222}Rn$  and EC. With appropriate data collection  
656 of times series data of near-stream GW  $^{222}Rn$  and EC, future modelling of the Campaspe system  
657 may benefit from explicit modelling of groundwater transport of  $^{222}Rn$  and EC to help  
658 demonstrate that current the boundary simplification of  $^{222}Rn$  and EC to static GW conditions  
659 does not introduce large impacts to the data worth analysis.

660 The simulation of SW-GW exchange is of course subject to some simplifying  
661 assumptions that were employed to develop a tractable regional-scale model of the Campaspe  
662 system for the data worth analysis. Such simplifications include, but are not limited to, that of

663 ignoring unsaturated zone flow processes, ignoring representation of overland flow during  
664 flooding and mostly non-contributing small tributaries, and the exclusion of a hyper-resolution  
665 model grid for solving the governing equations. For example, in the case of ignoring unsaturated  
666 flow, it has been shown previously by Brunner et al. (2010) that the violation of the assumption  
667 of a hydraulically connected losing-gaining system will lead to underestimation of infiltration of  
668 GW. More generally, model simplifications (e.g., 1D steady-state transport, surface flow  
669 representation, ignoring unsaturated flow processes, numerical discretization errors, etc.) are  
670 likely to lead to uncertainty variance under-estimation (e.g., Knowling et al. 2019b; White et al.  
671 2014); however, our relativistic (i.e., concerning changes in second moments) analysis of worth  
672 is expected to be somewhat immune to the impact of such model simplifications. As the  
673 Campaspe system becomes better characterised in the future and the model employed herein is  
674 refined, exploration of such simplifications could potentially benefit the interpretation of worth.

#### 675 4.5.4 Choice of data types

676 This study focused on the worth of particular observational data in the context of SW-  
677 GW exchange. It was not exhaustive of all possible data types, and didn't include, e.g. other  
678 stream chemistry data, such as stream  $^{14}\text{C}$ , dissolved organic carbon (DOC) or total inorganic  
679 carbon (TIC), due to the complexity of additional carbon processes required to model these. It is  
680 recognised that, e.g., hydrometeorological data such as evapotranspiration and precipitation data,  
681 physical stream property measurements, aquifer property measurements and data informing the  
682 3D hydrostratigraphic model including its geometry and internal facies distribution may also be  
683 of worth and warrant investigation in future studies.

#### 684 4.5.5 Choice of FOSM

685 Our use of FOSM techniques involves consideration of only relative quantities (i.e.,  
686 changes in uncertainty following parameter conditioning). A number of works have  
687 demonstrated its particular robustness in this context (e.g., Dausman et al. 2010; Herckenrath et  
688 al. 2011). The computational efficiency of FOSM ultimately allowed for a detailed exploration  
689 of a number of different predictions in this study; far more than would have been possible within  
690 reasonable time constraints on the basis of a less approximate but more computationally  
691 demanding non-linear uncertainty quantification method (Nowak et al. 2012; Wöhling et al.  
692 2018; Wu et al. 2014). However, in highly non-linear models (Herckenrath et al. 2011;  
693 Kunstmann et al. 2002), FOSM has been shown to yield similar results to the Monte Carlo type  
694 methods. It would nevertheless be of benefit in the future to quantify the impact of the linearity  
695 assumption in this case study through a Monte Carlo sampling-type approach.

## 696 5 Conclusions

697 As water resource management and the understanding of river ecosystem functioning  
698 both rely on estimation of SW-GW exchange fluxes, meaningful estimation of the exchange flux  
699 at appropriate scales must be accompanied by a corresponding quantitative assessment of the  
700 exchange flux uncertainty, which, ideally is minimised through smart data collection. The FOSM  
701 analysis of spatiotemporally varying SW-GW exchange flux predictions presented in this study  
702 provides useful insight into the worth of various hydraulic and water chemistry observation data  
703 types in isolation, in various combinations and under individual and comprehensive sampling  
704 strategies during low, regular and high streamflow conditions.

705 The worth of particular data types is dependent on streamflow conditions, the magnitude  
706 and direction of the SW-GW exchange flux and the spatiotemporal resolution of the SW-GW

707 exchange prediction of interest. The unique information in different data types is evidenced by  
708 the significant spread of uncertainty reductions across the different predictions. For the  
709 spatiotemporal averaging of whole of river annual SW-GW exchange flux predictions,  
710 reductions in predictive uncertainty were generally higher than for the finer scale reach and  
711 monthly predictions. For the finer scale, the necessity of local scale (time and space)  
712 observations is more pertinent for obtaining considerable uncertainty reductions.

713         With the large variability in worth of varying data types for different specific predictions  
714 of SW-GW exchange, we have shown where and when particular data might be of most worth.  
715 Hydraulic groundwater head and stream flow were found to inform SW-GW exchange flux best  
716 under high- and regular- streamflow conditions. <sup>222</sup>Rn and EC were of highest value for low- and  
717 regular- streamflow conditions where the stream is gaining.

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722 running and post-processing scripts along with key data outputs are provided at  
723 [https://github.com/daniel-](https://github.com/daniel-partington/CampaspeModel/tree/amal_speed/CampaspeModel/models/Campaspe_Cascade)  
724 [partington/CampaspeModel/tree/amal\\_speed/CampaspeModel/models/Campaspe\\_Cascade](https://github.com/daniel-partington/CampaspeModel/tree/amal_speed/CampaspeModel/models/Campaspe_Cascade).  
725 Links for all data used in this study are detailed in the supplementary material, except for surface  
726 water extractions and private bore extractions data due to privacy constraints.

727

728

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## Appendix A: 1D steady-state transport model for $^{222}\text{Rn}$ and EC

The 1D steady-state model presented in Cook et al. (2006) for determining SW-GW flows with  $^{222}\text{Rn}$  observation data, used a mass balance of streamflow and radon similar to the following, but here we have added in inflows from tributaries and precipitation:

$$\frac{\partial Q(x)}{\partial x} = I_{GW}(x) - O_{GW}(x) + I_{TR}(x) - L(x) + (P(x) - E(x))w(x) \quad (\text{A.1})$$

$$\frac{\partial Q(x).c_S}{\partial x} = I_{GW}(x).c_{GW} - O_{GW}(x).c_S + I_{TR}(x).c_{TR} - L(x).c_S + P(x).w(x).c_R - k.w(x).c_S - \lambda.d.w(x).c_S + F \quad (\text{A.2})$$

Where  $Q$  is the rate of streamflow [ $\text{L}^3/\text{T}$ ],  $x$  is the distance along the stream [ $\text{L}$ ]. Varying along the  $x$ -axis,  $I_{GW}(x)$ ,  $O_{GW}(x)$ ,  $I_{TR}(x)$  and  $L(x)$  are the groundwater inflow rates, stream losing rates, tributary and diversion inflows, and losses through direct pumping [ $\text{L}^3/\text{L}/\text{T}$ ].  $E(x)$  is the evaporation rate [ $\text{L}/\text{T}$ ]  $P(x)$  is the precipitation rate [ $\text{L}/\text{T}$ ], and  $w(x)$  is the width of the river [ $\text{L}$ ] along  $x$ .  $c_S$ ,  $c_{GW}$ ,  $c_{TR}$ , and  $c_R$  are the concentrations [ $\text{M}/\text{L}^3$ ] of the stream, groundwater, tributaries and rainfall respectively.  $k$  is the gas transfer velocity across the water surface [ $\text{L}/\text{T}$ ],  $\lambda$  is the radioactive decay constant [ $\text{T}^{-1}$ ],  $d$  is the mean stream depth [ $\text{L}$ ] and  $F$  is the flux of radon through the hyporheic zone [ $\text{M}/\text{L}/\text{T}$ ].

$$F = \frac{\gamma h w \theta}{1 + \lambda t_h} - \frac{\lambda h w \theta}{1 + \lambda t_h} c_S \quad (\text{A.3})$$

Where  $\gamma$  is the production rate within the hyporheic zone [ $\text{M}/\text{L}^3/\text{T}$ ],  $h$  is the mean depth of the hyporheic zone [ $\text{L}$ ], and  $\theta$  is its porosity [-].  $t_h$  is the mean residence time of water within the hyporheic zone. Expanding the partial derivative in (2) and substituting in (1) with the chain rule and rearranging yields:

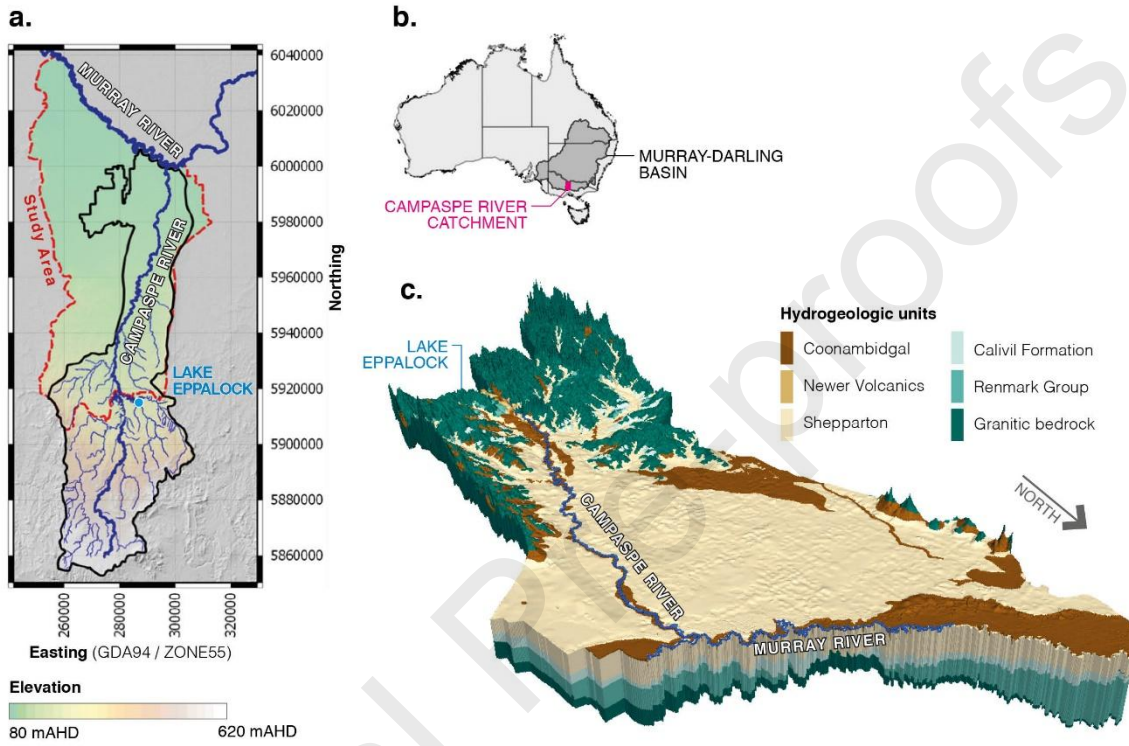
$$Q(x) \frac{\partial c_S}{\partial x} = I_{GW}(x).(c_{GW} - c_S) + I_{TR}(x).(c_{TR} - c_S) + P(x).w(x).(c_R - c_S) + E(x).w(x).c_S - k.w(x).c_S - \lambda.d.w(x).c_S + F \quad (\text{A.4})$$

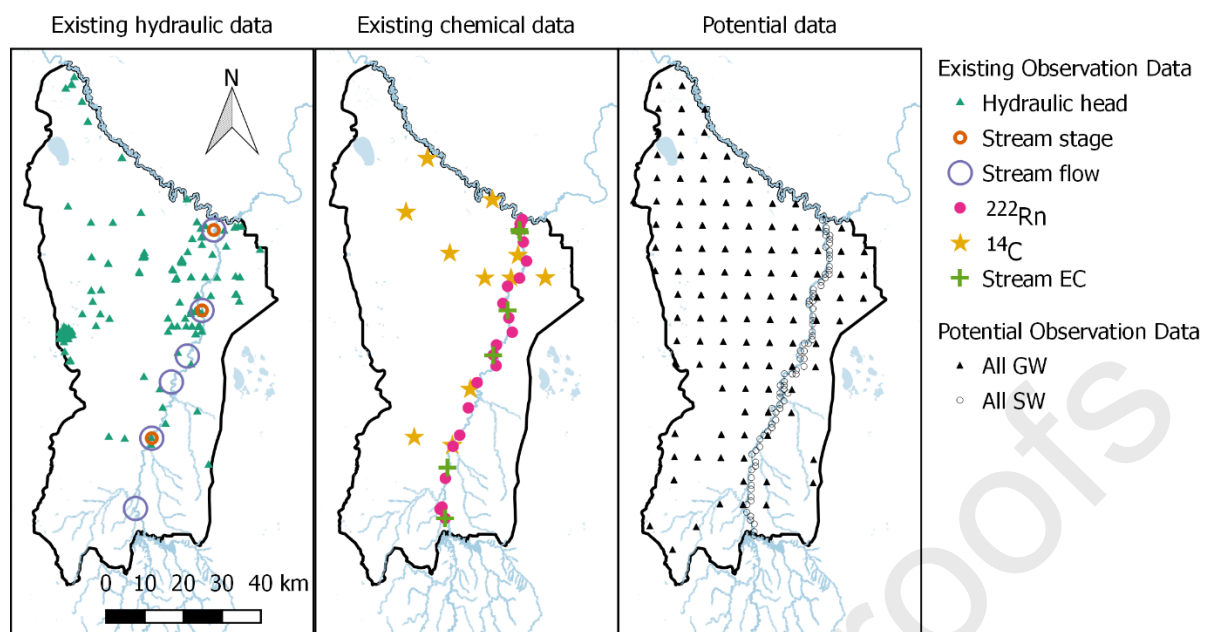
For a given stream length  $dx$  with a boundary upstream concentration of  $c_S$  we can solve for the downstream concentration  $c_{S/DS}$  with:

$$^{222}\mathbf{Rn}: c_{S/DS} = c_S - \frac{dx}{Q(x)} (I_{GW}(x) \cdot (c_{GW} - c_S) + I_{TR}(x) \cdot (c_{TR} - c_S) + P(x) \cdot w(x) \cdot (c_R - c_S) + E(x) \cdot w(x) \cdot c_S - k \cdot w(x) \cdot c_S - \lambda \cdot d \cdot w(x) \cdot c_S + F) \quad (\text{A.5})$$

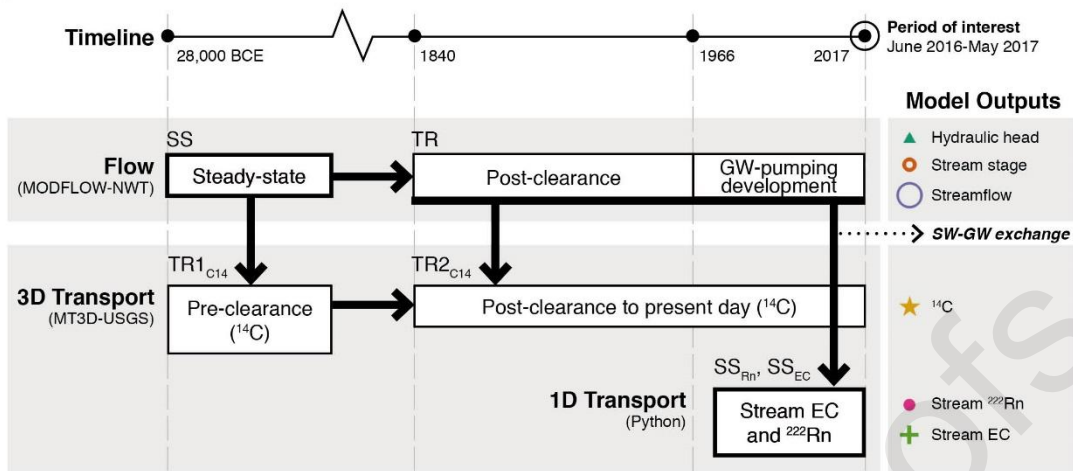
Noting the conservative nature of EC (we have no degassing, decay or production in the hyporheic zone) we can write a similar expression for EC as:

$$\mathbf{EC}: c_{S/DS} = c_S - \frac{dx}{Q(x)} (I_{GW}(x) \cdot (c_{GW} - c_S) + I_{TR}(x) \cdot (c_{TR} - c_S) + P(x) \cdot w(x) \cdot (c_R - c_S) + E(x) \cdot w(x) \cdot c_S) \quad (\text{A.6})$$

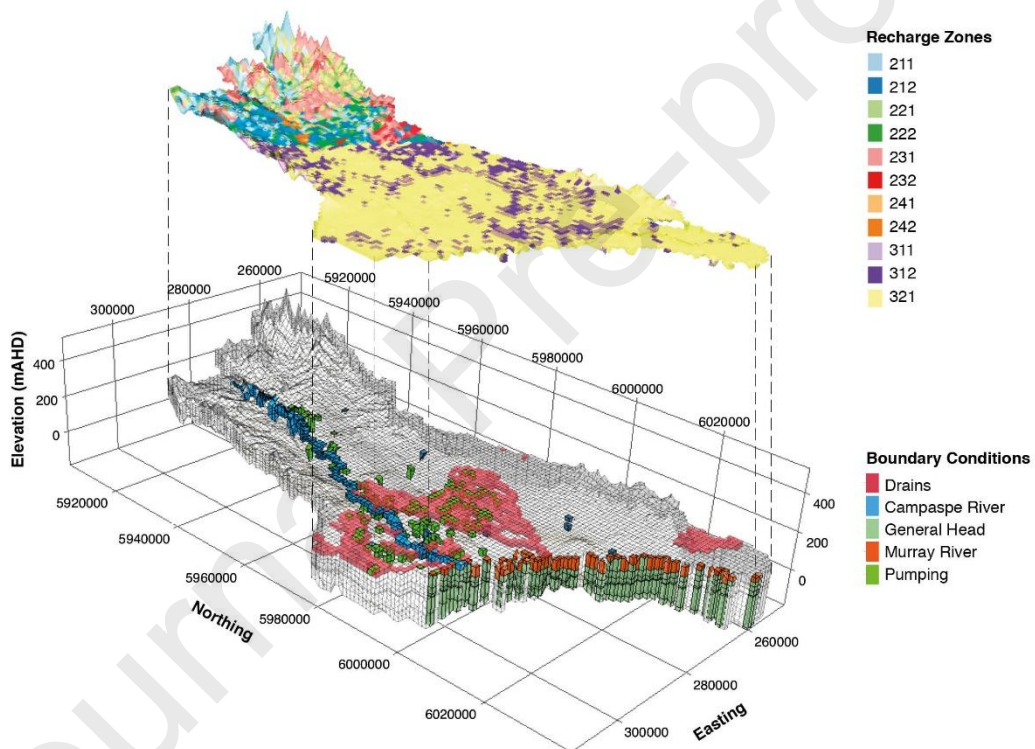


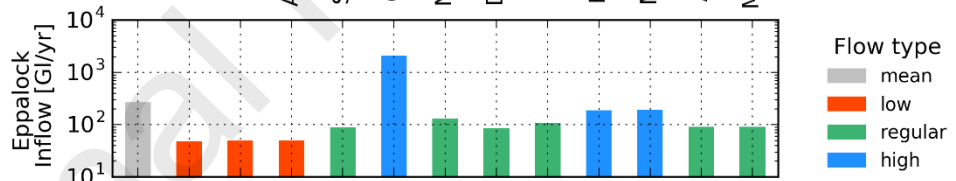
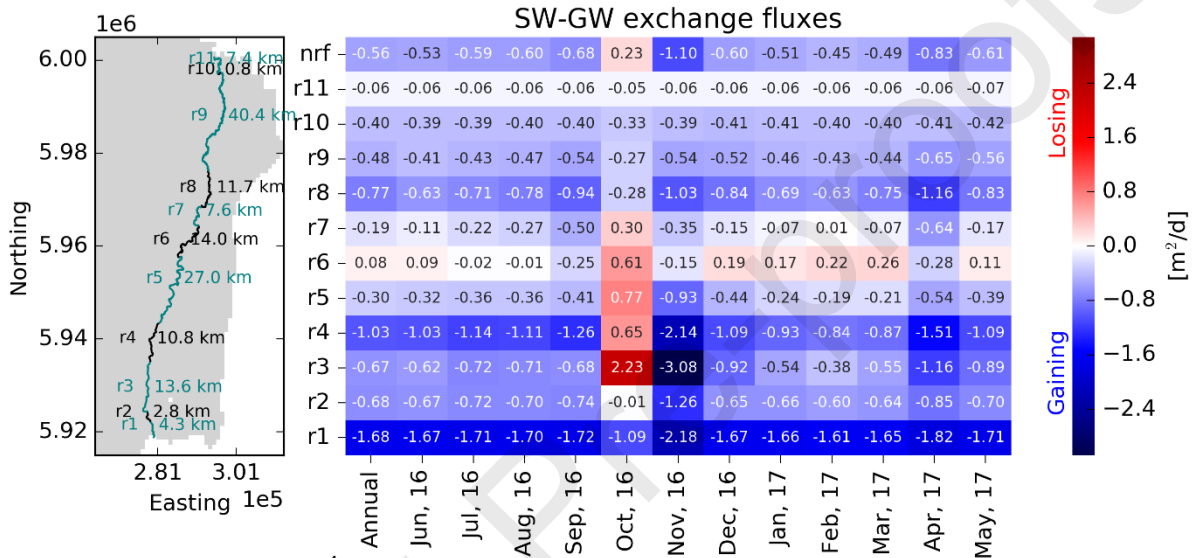
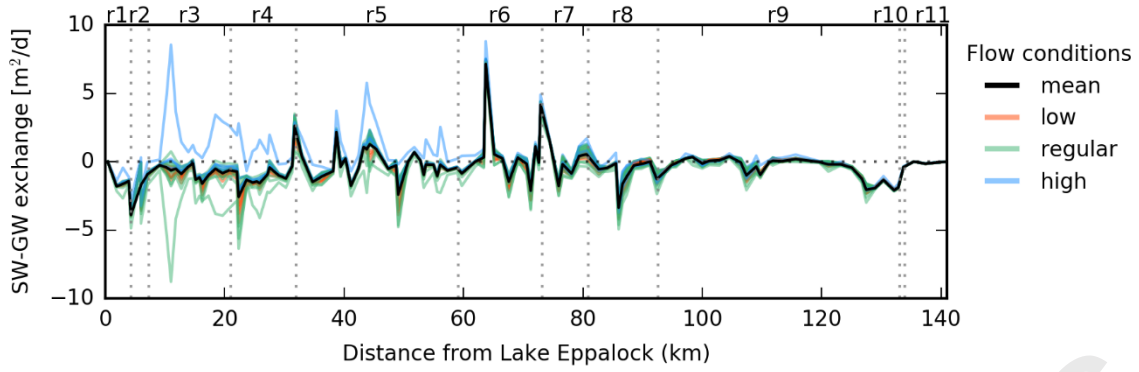


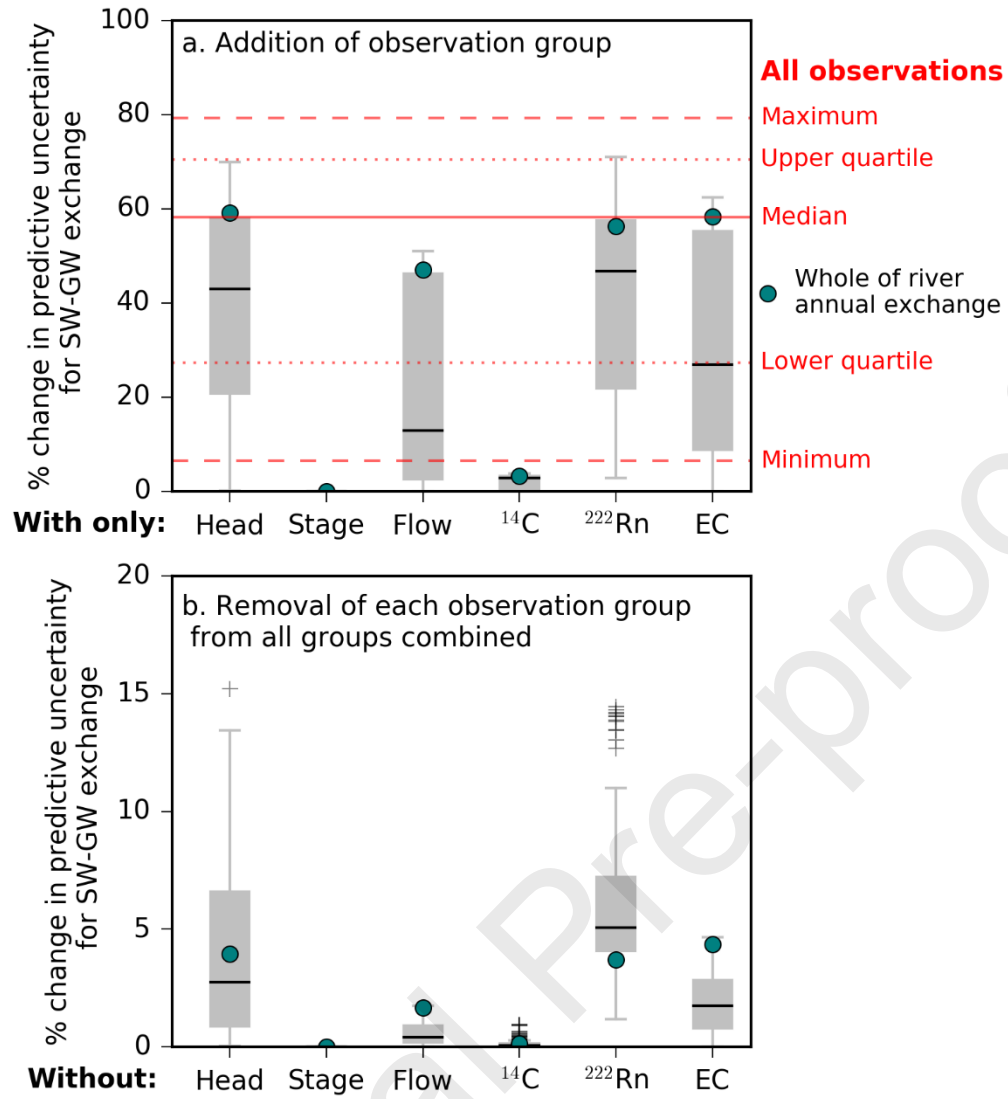
a.

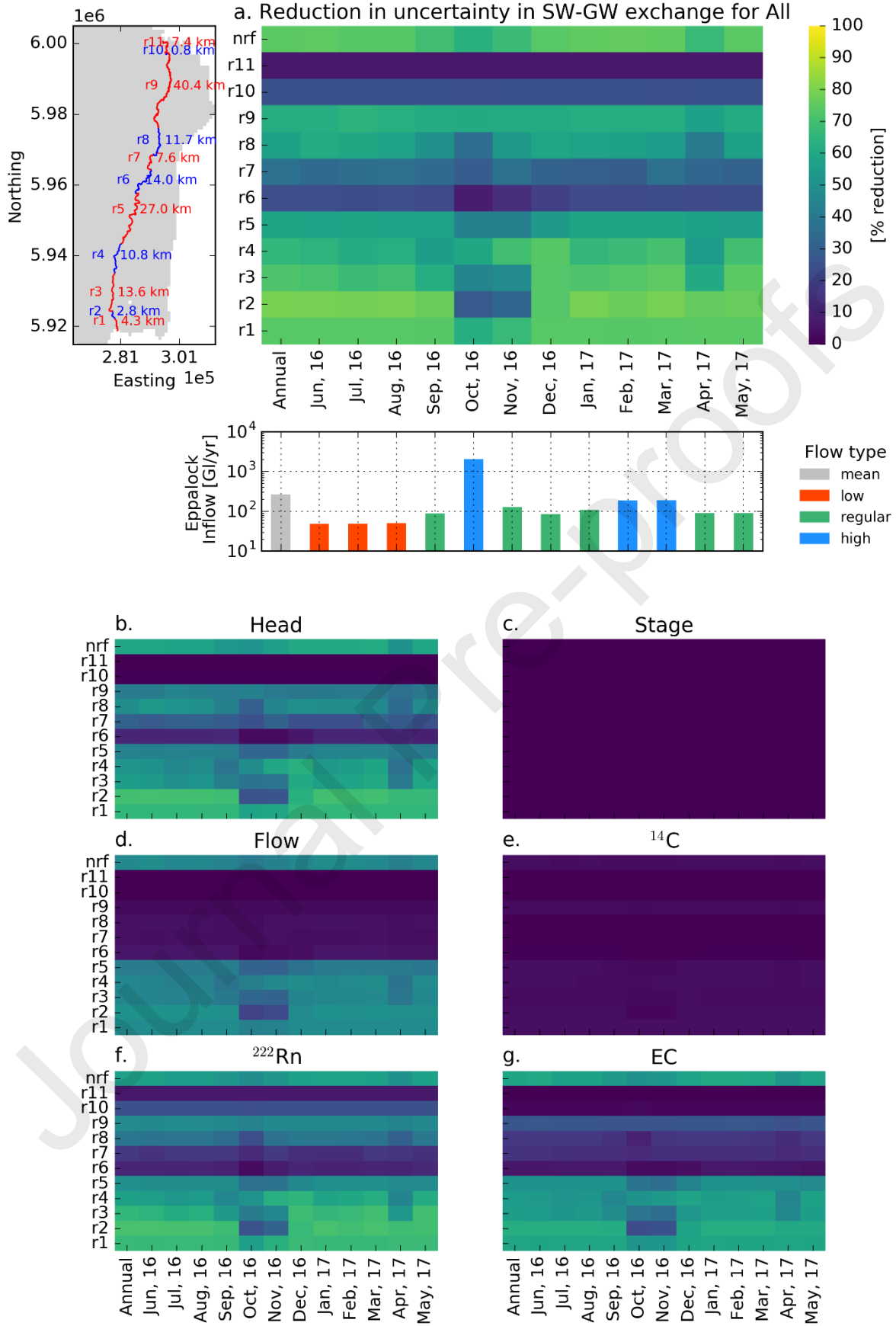


b.

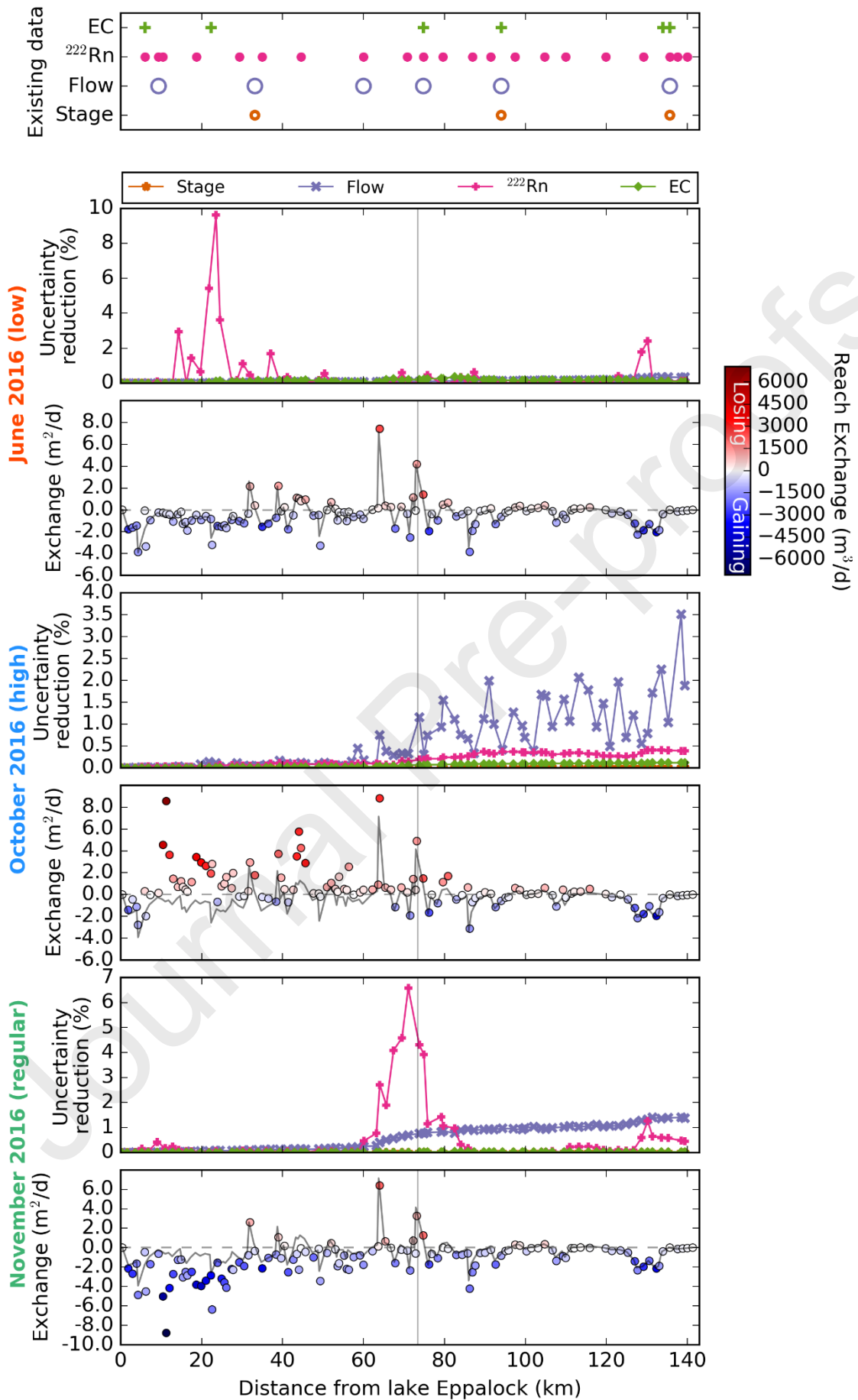


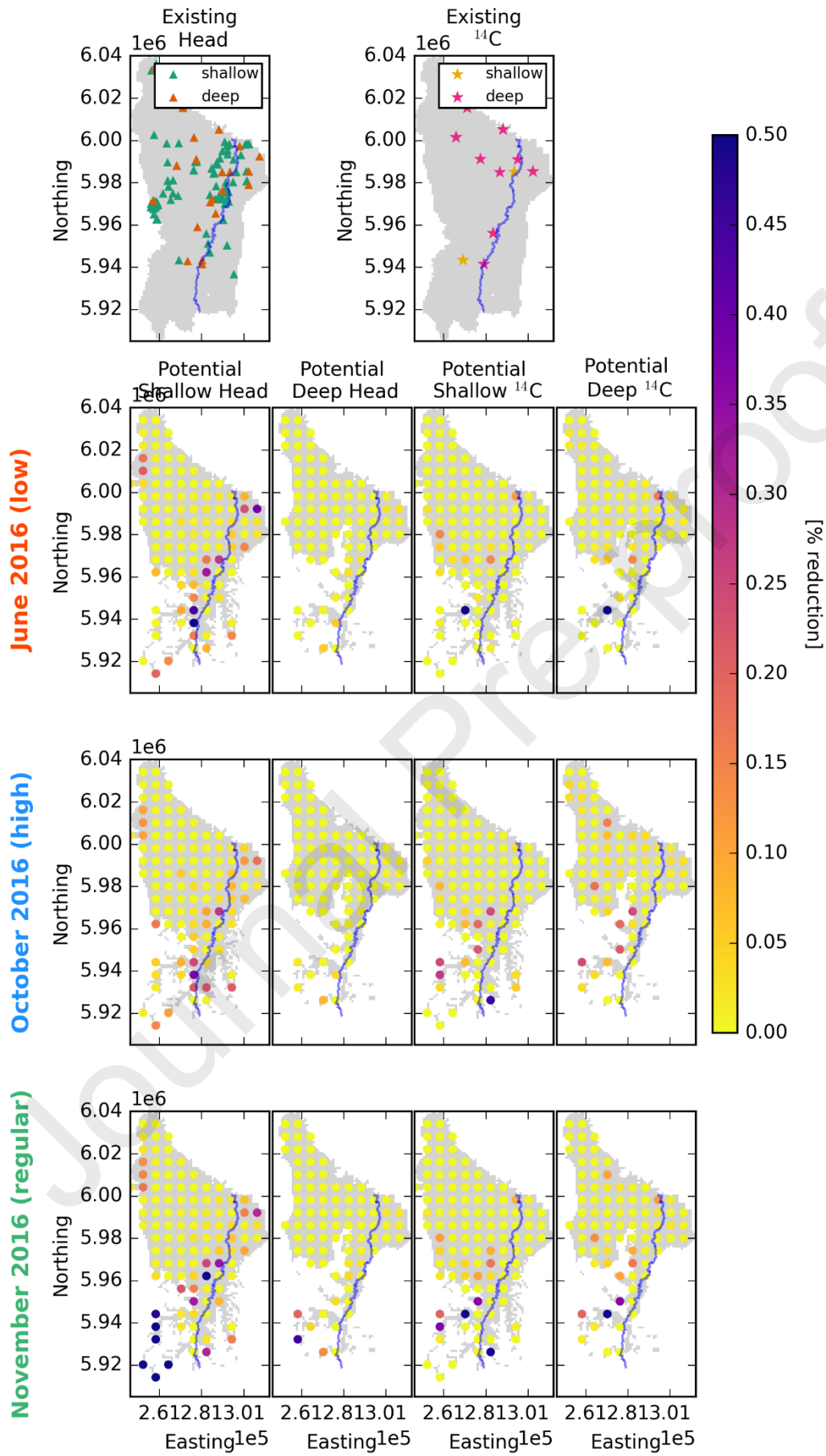


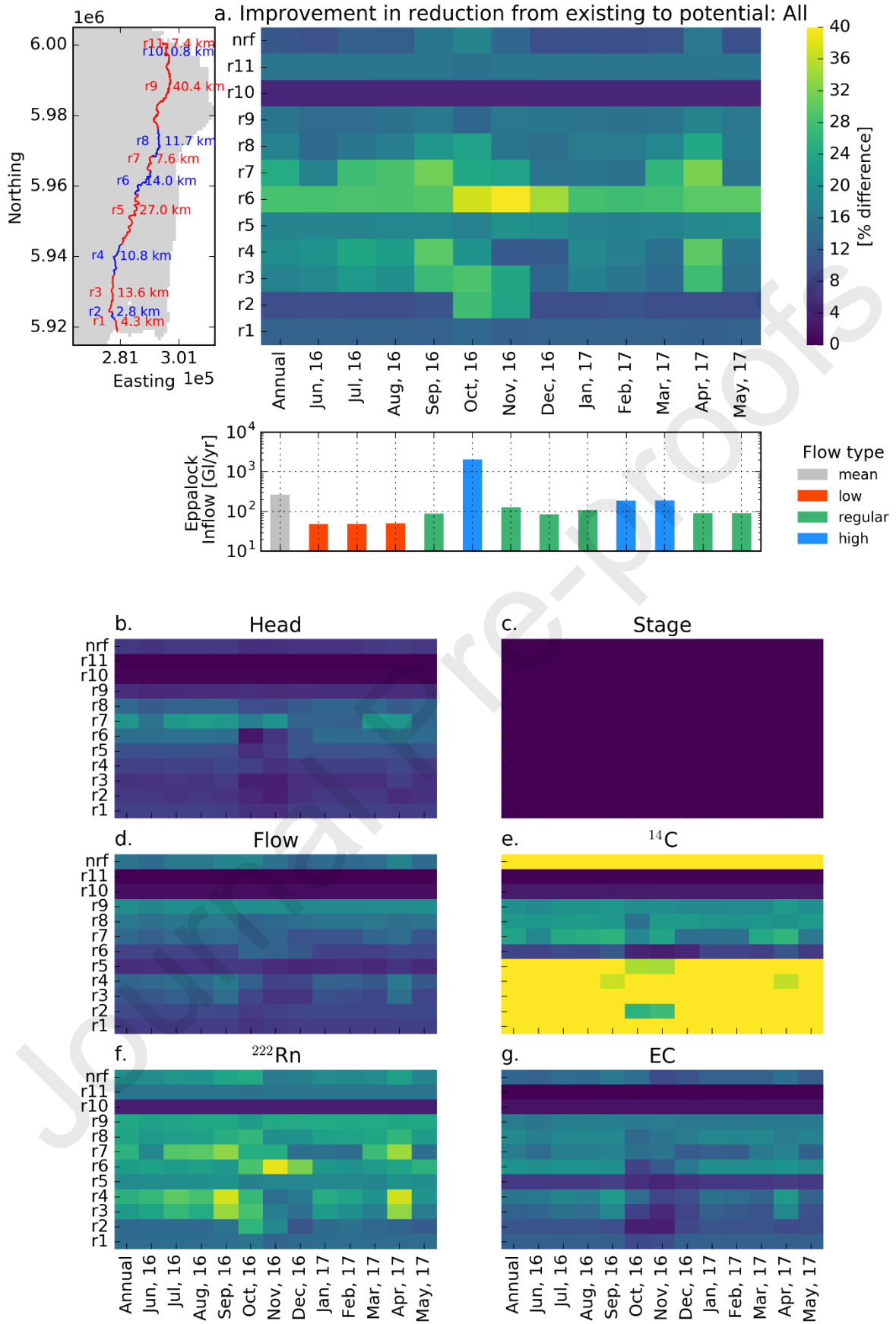


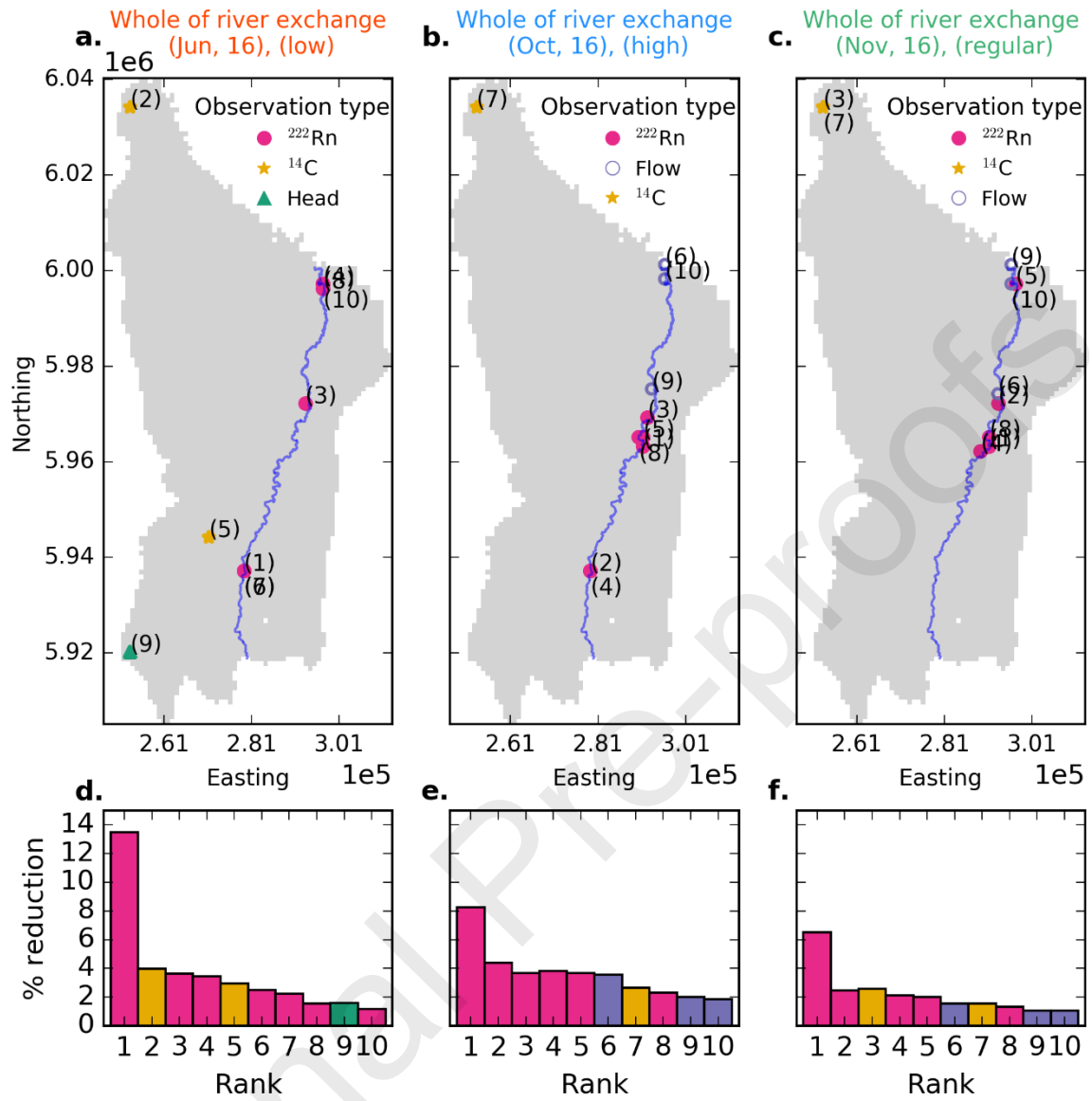


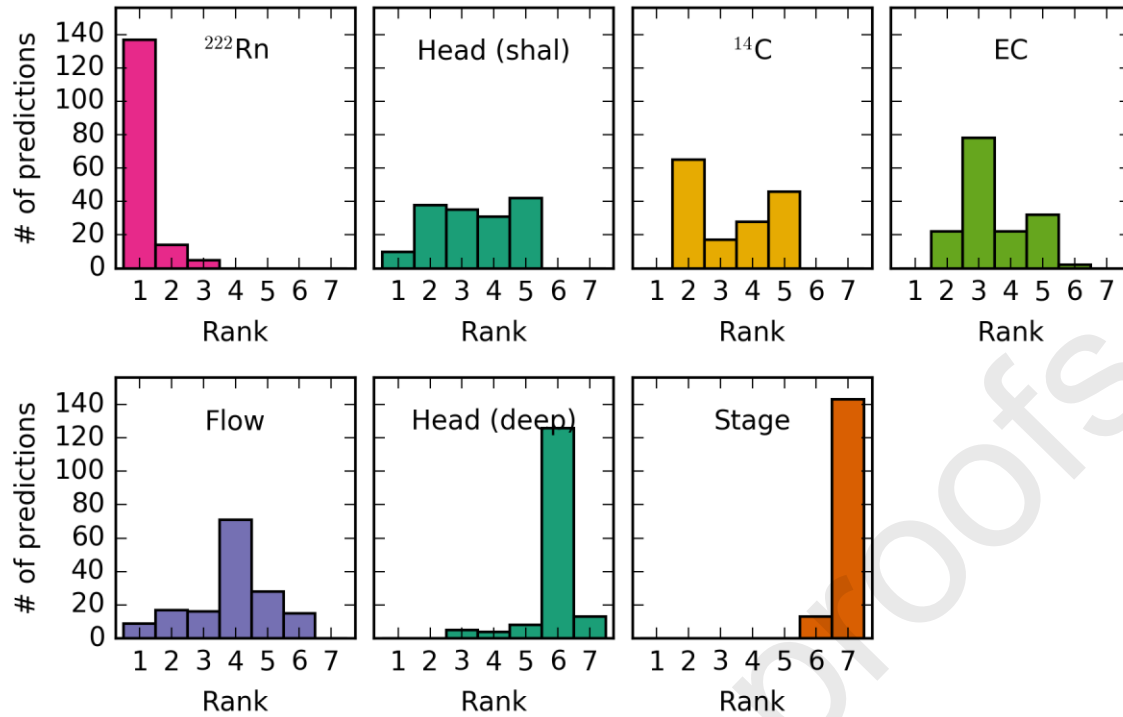












**Table 1. Summary of hydrogeological layer thicknesses including, mean, minimum, maximum thickness and percent volume. Hydrogeological units are abbreviated as Coonambidgal (co), Shepparton (sh), Calivil (ca), Renmark (re), Newer Volcanics (nv), Basement (ba).**

Hydrogeological Unit	Thickness			Percentage of active model volume (%)
	Mean (m)	Minimum (m)	Maximum (m)	
Coonambidgal	5.9	1.0	31.8	0.67
Shepparton	52.3	0.3	122.3	26.58
Calivil	26.1	1.0	82.7	9.76
Renmark	40.4	0.4	163.4	11.90
Newer Volcanics	4.6	0.1	14.3	0.05
Basement	74.4	9.7	109.5	50.93

**Table 2. Summary of model parameterization. For the aquifer property parameters, the hydrogeological units are abbreviated as follows: Coonambidgal (co), Shepparton (sh), Calivil (ca), Renmark (re), Newer Volcanics (nv), Basement (ba).**

Parameter set	Model	Type	Number	Initial Range	Log Variance ( $\sigma_\theta^2$ )
<b>Aquifer properties (7 HGUs)</b>					
Horizontal hydraulic conductivity ( $K_h$ )	SS, TR	Pilot points (PP) (416)	co: 31 sh: 107 ca: 77 re: 58 nv: 4 ba: 137	co: 4.44 – 444 m/d sh: 0.1 – 10 m/d ca: 4.25 – 425 m/d re: 6.75 – 675 m/d nv: 5 – 500 m/d ba: 0.1 – 10 m/d	0.25 (m/d) <sup>2</sup> 0.25 (m/d) <sup>2</sup> 0.25 (m/d) <sup>2</sup> 0.25 (m/d) <sup>2</sup> 0.25 (m/d) <sup>2</sup> 0.25 (m/d) <sup>2</sup>
Vertical hydraulic conductivity	SS, TR	-	1	-	-
Specific storage	SS, TR	PP (416)	see $K_h$	1E-6 – 1E-4 (-)	0.25 (-)
Specific yield	SS, TR	PP (416)	see $K_h$	1E-2 – 0.44 (-)	0.53 (-)
Porosity (7 HGUs)	TR1 <sub>C14</sub> , TR2 <sub>C14</sub>	Zonal	7	0.05 - 0.4 (-)	5.1E-2 (-)
Dispersivity (7 HGUs)	TR1 <sub>C14</sub> , TR2 <sub>C14</sub>	Zonal	7	1E-5 – 100 m	3.06 m <sup>2</sup>
<b>Recharge</b>					
Pre-clearance rainfall Proportion for recharge	TR	Zonal	16	1E-3 – 0.5 (-)	0.46 (-)
Rainfall proportion for recharge	SS	Zonal	16	1E-4 – 0.9 (-)	2E-3 - 0.55(-)
<b>GW boundary under Murray</b>					
GHB level adjuster	SS, TR	-	1	0.01 – 70.0 m	9.9E-3 m <sup>2</sup>
GHB conductivity	SS, TR	-	1	1E-8 – 50.0 m/d	5.88 (m/d) <sup>2</sup>
<b>Murray River properties</b>					
Murray River streambed K	SS, TR	-	1	1E-8 – 20.0 m/d	5.41(m/d) <sup>2</sup>
<b>Drain properties</b>					
Drain bed K	TR	-	1	1E-8 – 20.0 m/d	5.41(m/d) <sup>2</sup>
Drain bed adjust	TR	-	1	0.001 – 0.1 m	0.25 m <sup>2</sup>
<b>Campaspe River properties</b>					
Stream dispersivity	TR1 <sub>C14</sub> , TR2 <sub>C14</sub>	-	1	1E-5 – 1000.0 m	4.0 m <sup>2</sup>
Riverbed hydraulic cond.	SS, TR	PP	80	1E-4 – 10.0 m/d	1.56 (m/d) <sup>2</sup>
River width	SS, TR	PP	80	4.0 – 40.0 m	6.25E-2 m <sup>2</sup>
Riverbed roughness	SS, TR	PP	80	0.001 – 0.1 d/m <sup>1/3</sup>	0.25 (d/m <sup>1/3</sup> ) <sup>2</sup>
GW EC concentration	SS <sub>EC</sub>	-	1	1E3 – 5E3 $\mu$ S/cm	0.03 ( $\mu$ S/cm) <sup>2</sup>
GW <sup>222</sup> Rn concentration	SS <sub>Rn</sub>	-	1	1E4 – 5E4 mBq/l	0.03 (mBq/l) <sup>2</sup>
Gas transfer velocity	SS <sub>Rn</sub>	-	1	0.6 – 1.4 m/s	8.46E-3 (m/s) <sup>2</sup>
Hyporheic zone porosity	SS <sub>Rn</sub>	-	1	0.1 – 0.4 (-)	2.27E-2 (-)
Hyporheic zone production	SS <sub>Rn</sub>	-	1	1E3– 1E4 mBq/l/d	0.0625 (mBq/l/d) <sup>2</sup>
Hyporheic zone residence time	SS <sub>Rn</sub>	-	1	0.05 – 5.0 d	0.25 d <sup>2</sup>
Hyporheic zone depth	SS <sub>Rn</sub>	-	1	0.0 - 1.0 m	0.26 m <sup>2</sup>
<b>TOTAL</b>			<b>1546</b>		

**Table 3. Assumed observation noise (used together with model-to-measurement residual information to populate  $\Sigma_\epsilon$ ).**

Observation data type	Observation noise ( $\sigma_\epsilon$ )
Hydraulic head	1 m
Stream stage	1 m
Streamflow	40% of observation value [ $\text{m}^3/\text{d}$ ]
$^{222}\text{Rn}$	50 mBq/l
$^{14}\text{C}$	10 PMC
Electrical conductivity	100 $\mu\text{S}/\text{cm}$

**Table 4. Data worth assessments employed for the range of SW-GW exchange predictions from the Campaspe transient flow model (TR).**

	$\bar{\sigma}_s$	Combinations	Predictions
Q1	Adding individual data types with existing data	6	All (156)
	Removing individual data types with existing data	6	All (156)
Q2	Added benefit of each potential observation for annual whole river exchange: SW observations	316	Whole river exchange (4)
	Added benefit of each potential observation for annual whole river exchange: GW observations	376	Whole river exchange (4)
	Next best observation group (potential observations)	7	All (156)
	Next best observation (potential observations) for low, regular and high streamflow conditions	10	Whole river exchange (4)

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### **Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

### **Highlights**

- Worth of data depend on spatiotemporal scale, flow and exchange conditions
- Hydraulic data informs SW-GW exchange flux best under high/regular flow conditions
- Radon-222 and EC data hold value for low/regular flow conditions where gaining