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USING NATURALLY OCCURRING RADON 222 AS A TRACER TO QUANTIFY GROUNDWATER FLUXES TO STREAMS

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USING NATURALLY OCCURRING RADON 222 AS A TRACER TO QUANTIFY GROUNDWATER FLUXES TO STREAMS

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Abstract

Naturally occurring radon in groundwater was used to test radon mixing models. Two different mixing models were used to quantify groundwater fluxes to streams; an analytical solution and a finite difference method. Two different bodies of waters were used in this study. The first location was Johnson Creek located in Grant-Kohrs Ranch in Deer Lodge, Montana. This is a small creek where lots of sampling points were taken. The stretch of Johnson Creek where radon samples were collected was about 0.34 km long with a flowrate between 0.01 m^3/s and 0.017 m^3/s. The second location was Merced River located in Yosemite Valley (Yosemite National Park) in the state of California. This is a much larger river compared to Johnson Creek, and also had fewer sampling points. The reach looked at in this study is from Happy Isles to Pohono Bridge, a 17.3 km distance with a flowrate that ranges between 0.20 m^3/s and ~120 m^3/s at Happy Isles depending on the time of the year. To test the models, both bodies of water were known to have groundwater gains meaning that back calculations for gas exchange values could be derived. The finite difference method was found to have errors that are still undetermined. The average gas exchange values for radon in the analytical model tested were between 154.6 day^{-1} to 195.6 day^{-1} for Johnson Creek and 2.7 day^{-1} to 3.5 day^{-1} for Merced River. Johnson Creek's gas exchange values for radon compare well to published sites. Merced River gas exchange values for radon are low in comparison to past studies on gas exchange; this could be due to the long reach with few sampling points.

1.0 Introduction

Naturally occurring radon-222 (^{222}Rn) has the potential to be used as a tracer to help locate and quantify groundwater discharge to streams, rivers, and lakes (Burnett & Dulaiova, 2003; Cook et al., 2003; Cook et al., 2006; Shaw et al., 2013; Wanninkof et al., 1990). Radon is a useful for characterizing groundwater exchange with surface water due to its inert chemical properties as a noble gas and the large activity difference between groundwater and surface water (Brooklin, 1991; Cecil & Green, 2000; Szabo & Zapecza, 1993). Radon is produced from the uranium-thorium (^{238}U – ^{234}Th) decay sequence, where several daughter products are produced through alpha and beta decay. ^{222}Rn, specifically, is produced from alpha decay of ^{226}Ra. The energy resulting from alpha decay produces a phenomenon called direct recoil, where ^{222}Rn produced moves through the mineral grain and sometimes can exit the grain into the pore spaces (Figure 1). Once ^{222}Rn enters aquifer pore spaces, it is then able to transport conservatively through the aquifer and build up. Keeping in mind that radon has a half-life of 3.8 days, after a few months of accumulation in the aquifer, aquifer radon activity reaches an equilibrium concentration as long as the aquifer is relatively homogenous and U-Th concentrations in the aquifer skeleton remains relatively constant (Schubert et al., 2005).

Surface water bodies (e.g. lakes and streams) generally have little to no radon activity because of gas exchange with the atmosphere, which has negligible ^{222}Rn in comparison to groundwater and other subsurface water (Isam et al, 2002; S. Frei and B. S. Gilfedder, 2015). When groundwater mixes with surface water, the radon activity in surface water increases, but rapid gas exchange results in low ^{222}Rn activity downstream of inflowing groundwater. This short residence time makes radon sampling a powerful method for quantifying locations of groundwater discharge (Shaw et al., 2013).

If aquifer radon activity and surface water ^{222}Rn are known, mixing models and related software have been developed to determine groundwater fluxes (Cook et al., 2006). Radon models often have sparse sample locations and gas exchange can be difficult to quantify. When using each model, discrete locations of groundwater discharge may be missed in modeling and confuse quantification of groundwater discharge flow rates to rivers if these locations are not sampled. Comparison between radon

mixing models and radon software models is valuable analysis tool to see how the results may vary depending on each model. In areas where radon may be coming in in pulses or discrete locations, radon as tracer may not be a useful tool. In streams or lakes where there is continuous groundwater, radon as a tracer may be a valuable tool.
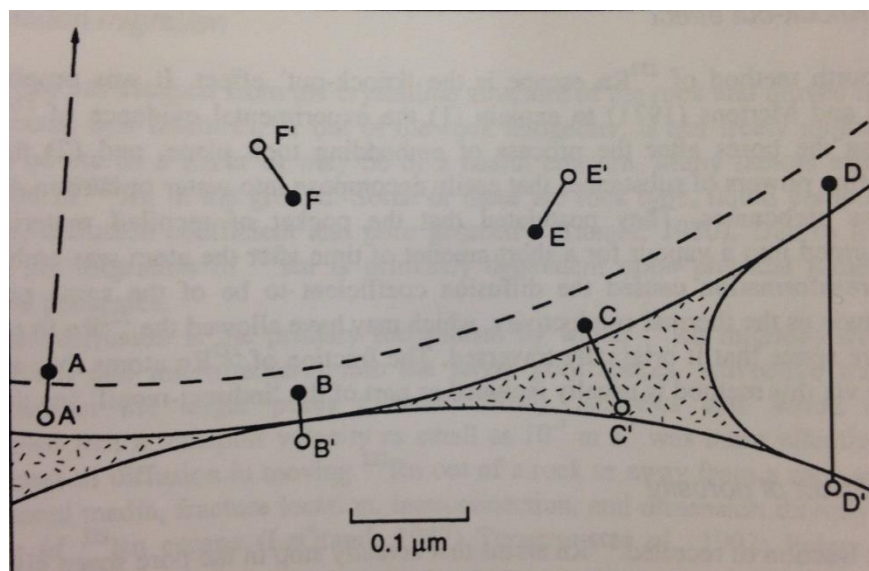

Figure 1. Schematic illustrating the direct recoil paths resulting from several alpha decays occurring in aquifer sediments. C-C' shows how some of the radon produced may become incorporated in aquifer pore spaces (figure taken from Cecil and Green, 2000)

The objective of this research project was to test the utility of radon mixing models for quantifying groundwater discharge rates by using radon as a tracer. The idea was to test the models in order to compare and determine a reasonable radon gas exchange coefficient. Groundwater influxes for the sites used in this project were fairly well known and equations were adjusted to determine the radon degassing coefficient. In this project, two models were used, an analytical mixing model, as well as a finite difference numerical model, FINIFLUX (S. Frei and B. S. Gilfedder, 2015). Also referred to as box model, the analytical model used was equation four from Cook's paper (Cook et al., 2003). The second model tested was FINIFLUX (S. Frei and B. S. Gilfedder, 2015). FINIFLUX is a software defined as a finite element method for quantifying groundwater fluxes to streams using Radon (FINIFLUX-Rn). There were two study areas where radon data was looked at and plugged into both the box models and FINIFLUX. The first study area where radon data was collected was at Johnson Creek, located at Grant-

Kohrs Ranch, a National Historic Site in Deerlodge, Montana. The second study area was the Merced

River, located in Yosemite Valley in the state of California. With both the simple box model and

FINIFLUX, there are uncertainties when measuring and determining the parameters.

2.0 Site Description

2.1 GKR—Johnson Creek

Johnson Creek is located in Grant-Kohrs Ranch, a National Historic Site in Deerlodge, Montana (figure

2). The stretch of Johnson Creek where radon samples were collected was about 0.34 km long with a

flowrate between 0.01 m^3/s to 0.017 m^3/s (Winter, 2014). Johnson Creek starts at the confluence of the

North Fork and South Fork, then continues through a culvert and eventually flows into the Clark Fork

River. Johnson Creek is small in comparison to the other study area looked at, and several locations were

sampled. The other important characteristic to note about Johnson Creek is that it is a strong groundwater

fed creek. There are no surface water inflows along the study reach and flows increase significantly
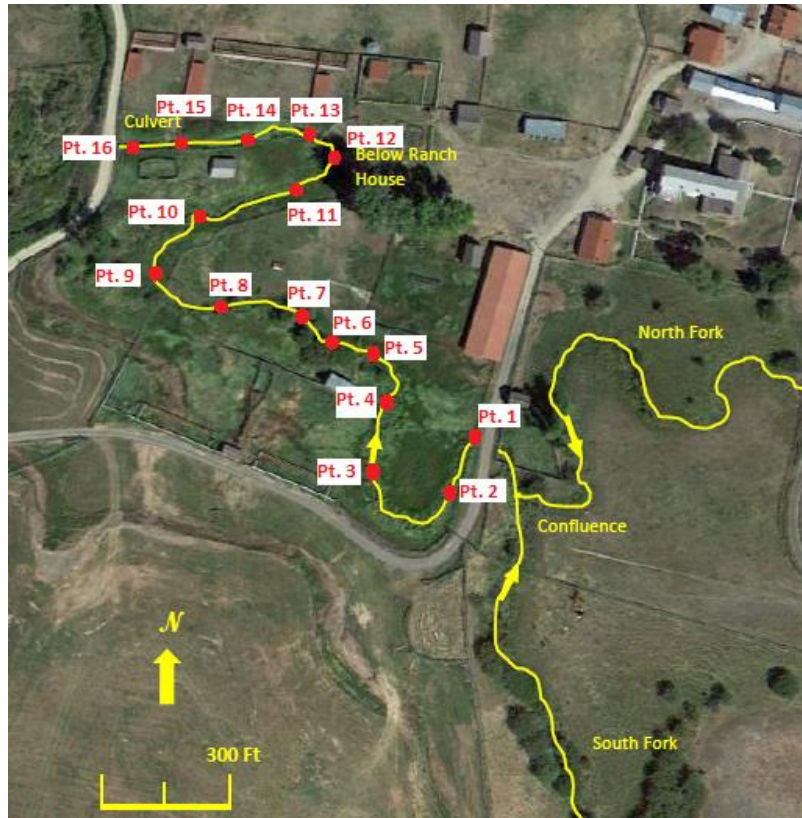
(Shirley, 2014; Winter, 2014).

Figure 2. Google Earth image showing the location of the North Fork, the South Fork, and the confluence of Johnson Creek. Grant-Kohrs Ranch. Deerlodge, Montana. Image from Google Earth, November 16, 2014. (Modified from Winter, 2014)

2.2 Yosemite Valley—Merced River

The Merced River, located in Yosemite Valley (Yosemite National Park) in the state of California. The Merced River is in the central part of the state of California and is a 145 mile long tributary of the San Joaquin River. Merced River flows from the Sierra Nevada into the San Joaquin Valley. The reach looked at in this study is from Happy Isles to Pohono Bridge, a 17.3 km distance with a flowrate that ranges between 0.20 m^3/s and ~120 m^3/s at Happy Isles depending on the time of the year (Shaw et al., 2014). Sampling events took place during low-flow periods when the majority of tributaries were dry. Along this reach, there are three tributaries with low flows; Yosemite Creek, Bridalveil Creek, and Teneya Creek, as seen in figure 2 below. All of which are majority groundwater fed and have flows negligible compared to the entire Merced River (Shaw, 2009). During the late summer, fall and winter months, the tributary flows are extremely low.
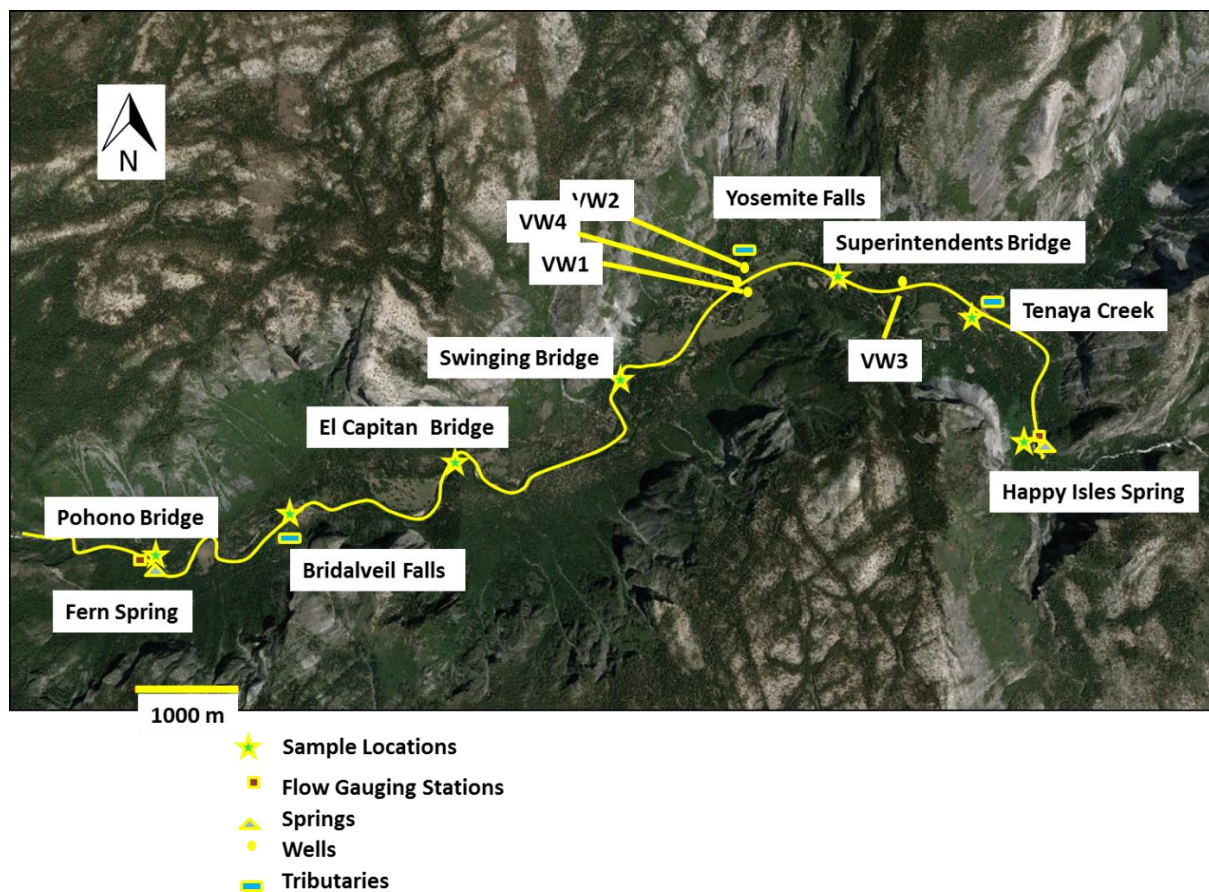
Figure 2. *Image of Merced River sampling, flow gauging, spring, wells, and the three tributaries; Yosemite Falls, Bridalveil Falls, and Teneya Creek. (Shaw, 2009)*

3.0 Methodology
3.1 Field Methods
    1.) Collecting Field Samples

In order to determine background aquifer ^{222}Rn activity, 12 shallow monitoring wells were sampled on November 13th and December 17th of 2014. Figure 3 below shows the groundwater wells sampled. The last sampling event occurred mid-morning on September 30th of 2015 where samples were collected at 16 different points along Johnson Creek (figure 1), as well as three nearby groundwater wells to ensure a similar radon level from the previous sampling event. A Magellan GPS was used to determine the sampling point location for each of the sixteen surface water samples along Johnson Creek. Times and dates were recorded in the field notebook at the time of each surface water and groundwater well sample.

Velocities and depths were recorded at each of the surface water samples and measured by a Marsh McBirney Flo-mate Model 2000 Portable Flowmeter. Temperature and specific conductivity were measured by a Hydrolab DS5 and recorded in the field notebook. Salt slug injections were mixed and calibrated according to Ryan Winter's past non-thesis project (Winter, 2014). Widths were estimated using Google Earth as well as estimated linearly. Widths were estimated to increase linearly due to the increase in groundwater fluxes. Groundwater inflow rates were estimated by examining Johnson Creek through salt slug injections and past projects (Winter, 2014). After all samples and parameters were collected for each sampling event, the water samples collected were sent to the lab.

Figure 3. Image of all groundwater wells in the Grant-Kohrs Ranch area. All wells on the figure were sampled except MTGK05, MTGK06, Cottonwood Creek Well, Ranch House Well, and Warren House Well. .

2.) Analyzing Rn Samples

The lab which received the water samples collected on the dates above was the Montana Bureau of Mines & Geology (MBMG) Analytical Lab, located at 1301 W. Park St., Butte, MT 59701. The radon samples were analyzed within two days of sampling. The MBMG Analytical Lab used a Liquid Scintillation Counter (Beckman LS 6000 SC) to analyze the water samples. The EPA method used was 913.0 Modified.

Merced River samples were collected in a previous project. Refer to Shaw (2009) for field methods of sampling and assumptions made. Sample parameters and results from Shaw (2009) were used for sampling dates October 10th, 2007 and November 11th, 2005. Parameters used from Shaw (2009) include: sampling locations, distances, radon concentrations, groundwater radon concentrations, and groundwater inflow rate estimates. Parameters estimated during this study include; depths, widths (Google Earth), and discharge values (USGS website). Samples were collected at; Happy Isles, Tenaya Creek MR, Superintendents Bridge, Swinging Bridge (Figure 2), El Capitan Bridge, Bridalveil MR, Fern Spring MR, and Pohono Bridge. Discharges used in this study were taken at Happy Isles and Pohono Bridge gauging stations from the U.S. Geological Survey (USGS) website. Widths were estimated using Google Earth and they were estimated to have a constant width. Groundwater inflows were also estimated from examining the river and surroundings.

3.2 Modeling

3.2.1 Box Models

The first model used in this research project was a box model from Cook et al. (2003) which is:

$$Q\frac{dc}{dx} = I(c_i - c) + wEc + kw(Sc_a - c) + k'w\rho c_a - dw\lambda c \qquad \textbf{Eqn. (1)}$$

where c is the concentration within the stream, c_i is the concentration in groundwater inflow, c_a is the atmospheric gas concentration, S is the tracer solubility, Q is the stream flow rate (m³/day), I is the groundwater inflow rate per unit of stream length (m³/m/day), k is the gas transfer velocity across the water surface (m/day) (zero for tracers that do not exchange with the gas phase), λ is the radioactive decay constant based on radon's half-life of 3.8 day), E is the evaporation rate (m/day), k' is the air entrapment coefficient (cm³/cm²/day), w is the width of the river surface (m), d is the mean stream depth (m), and x is the distance in the direction of flow. Sc_a is the concentration of the tracer that would occur in equilibrium with the atmosphere. The units for S will be determined by the choice of units for c. Because the atmospheric ^{222}Rn activity is assumed to be zero, the product Sc_a is assumed to be zero in this model. (Surface water inflows can also be considered with this same equation, with I and c_i becoming surface water inflows and concentrations, respectively).

Equation one listed above was used for both research sites, Johnson Creek and Merced River. The parameters plugged into equation four for Johnson Creek were the data collected on December 17th, 2015 for the sixteen different points along the creek. The groundwater radon concentrations used for the Johnson Creek mixing models were taken from the two previous visits (November and December of 2014) and the median was used as a representative of the concentrations of radon in the groundwater feeding into Johnson Creek. Three of the twelve groundwater wells were re-sampled the same day surface water samples were collected to verify that groundwater samples remain ~constant. There were two box models ran for the Johnson Creek data. The first box model ran used all parameters listed in table 2 in the results section with a width calculated from Width = Flowrate / (velocity*depth). The second box model ran used all parameters listed in table 2 as well, but with an estimated linearly increasing width. Each of the datasets for Johnson Creek were plugged into an excel sheet and equation four was manipulated to solve for a k value. A description of how each parameter was measured and estimated is provided in Section 3.1 and 3.2.2. Because flows were not estimated at sampling locations between the most upstream and downstream sites, flow rates were assumed to increase linearly.

For the Merced River, two datasets were also used in the mixing model (eq. 1). The first dataset used parameters from the data collection date October 10th, 2007. The second dataset used parameters from the data collection date November 11th, 2005. The parameters for each dataset used can be found in tables 3 and 4. Each of the two datasets for Merced River were solved for using an excel sheet and equation one was manipulated to solve for a *k* value. A description of how parameters were measured and estimated is provided in Section 3.1 and can be seen in Shaw (2009). Width of the Merced River remains relatively constant throughout the ~17 km stretch, so it was assumed constant. Stream depth and flow rates were assumed to increase linearly from stages recorded at Happy Isles and Pohono Bridge.

3.2.2 FINIFLUX

Model Description

FINIFLUX is an implicit finite element model that numerically solves the steady state mass balance equation for radon. FINIFLUX differs from popular previous models as in it offers the possibility to work with user specified degassing coefficients. FINIFLUX is intended to estimate groundwater fluxes into rivers based on measured radon concentrations. The model is coupled to the optimization software package PARALLEL PEST for inverse parameter estimation. PARALLEL PEST systematically varies variables such as the groundwater fluxes to reduce the residual mean square between measured and modelled data. The software package is intended to help scientists and authorities that use the radon technique to estimate surface-groundwater exchange for rivers systems at the reach scale. The intended purpose of FINIFLUX in this research project was to test different k values in order to find a reasonable k value for each site and dataset, since the groundwater influxes were fairly well known previous to this research project. An overview for running FINIFLUX is listed below. More detailed steps and instructions used to run FINIFLUX can be found in the User Manual for FINIFLUX-Rn in the appendix (Gilfedder & Frei, 2015).

1. ***Download the Software Package***

FINIFLUX is an open source software and is freely available.

2. *Fill in Data for the Input Files*

After FINIFLUX is downloaded there are 13 different files (open with Notepad++) that all are in the exec folder (seen in figure 4 below). Below is a description of nine of the parameters input before running the software (other file inputs can be seen in the user manual in Appendix B):

a. *Discharge file* – This should contain discharge values for each reach (Element). The data for Johnson Creek was calculated based on Winter's (2014) salt injection tests on Johnson Creek. Salt slug injections were conducted upstream, about 2/3rds downstream of the reach, as well as downstream. Discharge values were estimated linearly and compared with calculated values from sampling September 30th, 2015. Discharge values used for the Merced River were from the USGS gauging sites.

b. *n_observation file* is the number of observations (Rn measurements), just one number. There were 16 sampling locations along Johnson Creek where radon measurements were taken. For the Merced River, in the first dataset there were seven sampling and for the second dataset there were six.

c. *observation_points file* is the distance in meters from the upstream sampling point at which each sample was taken. The first sample location is given a value of zero. The number of entries should be the same as the number of Rn sample points. When collecting radon samples for Johnson Creek, a gps point was collected while out in the field and noted. Later the gps points were mapped on Google Earth and set as pins (figure 1). Distances were roughly estimated from Google Earth and values can be seen in table 2 above. For the Merced River datasets, distances were found from the USGS gauging stations.

d. *River_depth file* and *river_width files* are as the name implies. All values are in meters and need one value for each reach. This should be the average value for the reach. When collecting parameters for Johnson Creek, the river depth was measured using a Marsh

McBirney instrument. Some problems with using the Marsh McBirney metal rod was that it sunk into the bed of the creek, which could slightly skew some of the data collected from using the instrument. Two width values were calculated and estimated. The calculated widths were based on using the equation w = Q/(v*d). The estimated widths were estimated by using linearly increasing widths based on an increase in groundwater fluxes. Width values can also be seen in table 2 above. For Merced River, depths and widths were roughly estimated using Google Earth.

e. *obs_concentrations* is the file for the observed radon values. This should be in the SI unit Bq m^{-3}. These radon values for Johnson Creek were collected on September 30th, 2015 using glass radon sampling bottles provided by the Bureau of Mines and Geology. The samples were collected in the mid-morning and transported to the Bureau of Mines and Geology, where they were then analyzed and radon concentration results were produced. For Merced River radon data, samples were collected according to Shaw (2009) on October 10th, 2007 and November 11th, 2005 and sent to a lab for analysis.

f. *C_initial* is the first measured value. Just one number in Bq m^{-3}. This is the furthest upstream radon sample concentration. For Johnson Creek, this was the first sampling point at the confluence of the North Fork and South Fork. For the Merced River, both datasets initial radon sample concentration was taken at Happy Isles.

g. *gw_concentration* is the Rn concentration in the groundwater system. Give a value for each reach in Bq m^{-3}. Samples of radon concentrations at Grant-Kohrs Ranch in nearby wells of Johnson Creek (figure 3) were sampled in November 2014, December 2014 and September 2015. A median was taken from the November/December 2014 data, which the radon concentrations were comparable to the three groundwater wells sampled in September 2015. For the Merced River, groundwater concentrations were estimated.

h. *k_degas* is the file where you choose which empirical degassing equation that FINIFLUX will use, or if you will use your own measured k values (i.e. user defined k). You have an

option of two different equations, which have been taken from Unland et al. (2013) or, as just mentioned, your own k values. '1' has been used as the default and can be left so or changed to '2'.

$$k = 9.301 * 10^{-3}(\frac{v^{0.5}}{d^{1.5}})$$ **Eqn. (2)**

$$k = 4.87 * 10^{-4}(\frac{v}{d})^{0.85}$$ **Eqn. (3)**

Where d is river depth (m) and v is stream velocity (m day^{-1}) calculated from discharge, depth and width data.

If you plan on providing your own k values (e.g. from gas tracer experiments) you need to enter these into the file ***k_values***, and you need to give a k value for each reach. Units are per second i.e. s^{-1}. In this research project, for Johnson Creek there were six runs that were input into FINIFLUX. The different runs for Johnson Creek can be seen below:

- **Run 1:** Linearly increased widths and default k value
- **Run 2:** Width calculated (w=Q/vd) and default k value
- **Run 3:** Linearly increased widths and k value of 120/d
- **Run 4:** Linearly increased widths and k value of 110/d
- **Run 5:** Linearly increased widths and k value varied based on modeled vs. measured Rn
- **Run 6:** Linearly increased widths and k of 300/d

For the Merced River, there were six runs input into FINIFLUX, three for each of the two datasets. The different runs for the Merced River data can be seen below:

- Dataset 1: October 10th, 2007
  - **Run 1**—Default k value
  - **Run 2**—k value of 120
  - **Run 3**—k value of 1

- Dataset 2: November 11th, 2005

    o **Run 1**—Default k value

    o **Run 2**—k value of 120

    o **Run 3**—k value of 1

K values were estimated based on Genereux and Hemond (1992), where propane

displayed a k value around 100/day and ethane displayed a k value around 117/day

(Genereux & Hemond, Naturally Occurring Radon 222 as a Tracer for Streamflow

Generation: Steady State Methodology and Field Example, 1990).

i. *hz_on_off* is to turn the hyporheic zone function on or off. A value of '1' means that it is

turned on and a value of '0' means off. For this research project, the hyporheic zone for

Johnson Creek and the Merced River was assumed negligible, so a value of '0' was

inputted. With assuming a negligible hyporheic zone, porosity and depth of the hyporheic

zone does not need to be entered.

Figure 4. Input parameter files for FINIFLUX.

3. Run FINIFLUX

The next step after entering in all the parameters into each of the folders was to actually start running the

software. You first start by running PEST. This can be done by holding shift and right-clicking on the

folder containing all your files you had just input from above step 2, once clicked on, select 'Open

Command Window Here.' Type 'write_pest.exe' into the command window and press enter. This builds

PEST infput files and creates three slave folders in the main folder. Next, double click on the main folder

and check to see if the three slaves have been populated. Start the slaves by holding shift and right-click

on one of the slaves. Select 'Open Command Window Here' and type 'pslave' at the prompt and press

enter. Then type 'run' at the next prompt and press enter again. Repeat this for each slave. Once the slaves have been started, it's time to run the main PEST program. Go to the main folder again, and hold shift and right-click on the main folder, select 'Open Command Window Here.' Type PPEST followed by the name of the model e.g. >PPEST FINIFLUX. PEST will start and look for the slaves. This may take up to an hour (some cases even longer), but depends on the number of measurement points. More detailed steps and images can be found in the user manual for FINIFLUX (Gilfedder & Frei, 2015).

4. ***Find FINIFLUX Results in Folder***

After FINIFLUX has completed each run, it outputs two results which include a plot of measured and modelled data, as well as calculated groundwater fluxes for each section of the reach. FINIFLUX has written a small graphing program to plot the graphs and can be found in the main folder under the name 'Plot-Output.exe.' This program plotted two graphs: (1) measured and modeled Rn vs. Distance (2) modeled Rn vs. measured Rn. The calculated groundwater fluxes can be found in slave 1 in the file 'gw_inflow.dat.' Units for groundwater fluxes are in $m^3/m/d$.

4.0 Results
4.1 Field Sampling

Field parameters and radon data were collected for the Johnson Creek study site based on the field methods section above. The parameters collected for the two sampling events can be seen in tables 1 and 2 below. Parameters collected were a gps location, depth, velocity, temperature, and specific conductivity. Widths, distances and discharges were calculated and estimated based on the methods section above. Also radon results from the lab can be seen in both tables 1 and 2 below.

^{222}Rn in groundwater ranged from 17,753 Bq/m^3 to 32,653 Bq/m^3 with average an average and median groundwater concentration of 24,739 Bq/m^3 and 24,402 Bq/m^3 respectively. The standard deviation of all samples is 3,815 Bq/m^3, which suggests that aquifer radon activity shows little variation and median concentrations are justified for incoming groundwater radon activity in the model.

Sampling Date: November and December 2014	
Sample	**Conc (Bq/m3)**
MTGK01	32,652.5
MTGK02	23,853.9
MTGK-03	26,155.3
MTGK04	21,382.3
MTGK-07	17,752.6
MTGK08	21,711.6
MTGK09	26,943.4
MTGK10	22,584.8
MTGK-11	23,587.5
MTGK-12	29,973.7
MTGK-13	24,949.1
MTGK14	25,319.1
Sampling Date: September 2015	
Sample	**Conc (Bq/m3)**
MTGK 2	23,446.9
MTGK 04	19,772.8
MTGK 13	25,311.7
2014 Statistics	
Average	24,738.8
Median	24,401.5
Standard Deviation	3,814.8

Table 1. *Radon samples collected at groundwater wells surrounding Johnson Creek in November and December 2014 and September 2015.*

Sampling Date: September 2015										
Sampling Points (upstream-downstream)	Rn Concentration (Bq/m3)	Latitude	Longitude	Depth (m)	Width (m) Estimated	Width (m) from w=Q/vd	Velocity (m/s)	Temp (Celsius)	SC (uS)	Distance	Discharge (m3/s)
1	6545.3	46.4084	-112.7413	0.12192	0.610	0.834	0.030	8.32	423.0	0.0	0.0031
2	6593.4	46.4085	-112.7411	0.18288	0.648	0.371	0.061	8.54	422.0	17.5	0.0041
3	5557.4	46.4085	-112.7408	0.16764	0.686	0.241	0.128	8.37	422.4	53.5	0.0052
4	5006.1	46.4085	-112.7405	0.15240	0.724	0.742	0.055	8.42	426.3	75.5	0.0062
5	4758.2	46.4083	-112.7405	0.12192	0.762	0.885	0.067	8.63	426.6	91.0	0.0072
6	5257.7	46.4083	-112.7406	0.13716	0.800	0.430	0.140	8.55	427.0	123.0	0.0083
7	4388.2	46.4082	-112.7410	0.09144	0.838	0.596	0.171	8.61	426.5	133.5	0.0093
8	4251.3			0.12192	0.876	0.897	0.094	8.61	428.4	164.5	0.0103
9	4047.8	46.4078	-112.7410	0.13716	0.914	0.618	0.134	8.91	428.9	187.5	0.0114
10	3881.3	46.4079	-112.7406	0.15240	0.953	2.427	0.034	8.92	429.1	212.0	0.0124
11	3770.3	46.4079	-112.7405	0.18288	0.991	2.410	0.030	8.96	425.5	245.0	0.0134
12	3204.6	46.4077	-112.7402	0.24384	1.029	1.497	0.040	8.94	436.8	258.5	0.0145
13	4229.1	46.4076	-112.7401	0.24384	1.067	0.521	0.122	9.36	425.4	275.0	0.0155
14	3855.4	46.4074	-112.7402	0.24384	1.105	0.618	0.110	9.87	427.0	299.0	0.0165
15	3542.8	46.4074	-112.7399	0.18288	1.143	0.618	0.155	10.09	427.0	323.0	0.0176
16	3150.1	46.4075	-112.7398	0.16002	1.181	1.031	0.113	10.43	427.4	340.5	0.0186

Table 2. Parameters collected along Johnson Creek in September 2015.

The Merced River radon data and parameters can be seen below in tables 3. All field sampling data and

parameters were collected based on the methods section above and a description in Shaw (Shaw, 2009).

Flow rates were gathered from published USGS gauging station discharges.

Merced River Samples								
Location	Distance (m)	Rn Concentration (Bq/m3)	Groundwater Rn Concentration (bq/m3)	Depth (m)	Width (m)	Discharge (m3/s)	GW Inflow Rate (m3/m/d)	Decay Constant (/day)
Sampling October 2007								
Happy Isles	0	33561.1	282000	0.276	28	0.195	1.1455	0.1797
Tenaya Creek MR	1300	13400.7	282000	0.276	28	0.234	1.1455	0.1797
Superintendents Bridge	3500	36224.8	282000	0.276	28	0.272	1.1455	0.1797
Swinging Bridge	6500	33412.7	282000	0.276	28	0.310	1.1455	0.1797
El Capitan Bridge	9500	14279.6	282000	0.276	28	0.348	1.1455	0.1797
Bridalveil MR	13800	14857.9	282000	0.276	28	0.387	1.1455	0.1797
Pohono Bridge	17300	36139.6	282000	0.276	28	0.425	1.1455	0.1797
Sampling November 2005								
Happy Isles	0	6459.9	282000	0.276	28	0.880	1.1455	0.1797
Superintendents Bridge	3500	12445.9	282000	0.276	28	1.004	1.1455	0.1797
Swinging Bridge	6500	14299.1	282000	0.276	28	1.128	1.1455	0.1797
El Capitan Bridge	9520	14350.6	282000	0.276	28	1.252	1.1455	0.1797
Bridalveil MR	13800	6925.9	282000	0.276	28	1.376	1.1455	0.1797
Fern Spring MR	17300	10639.7	282000	0.276	28	1.500	1.1455	0.1797

Table 3. Parameters collected for Merced River in October 2007 and November 2005.

4.1 Box Models

4.1.1 GKR Results

Based on   the field results from tables 1 and 2 above, the parameter and data were plugged into a box

model using equation four from up above in the methods section. The equation was rearranged in order to

produce gas transfer velocities and values. Mixing models were used on runs two and three for Johnson

Creek. Run two for Johnson Creek was based on width calculated (w=Q/vd) and default k value. Run

three for Johnson Creek was based on linearly increased widths and k value of 120/d. Results from the

box model can be seen below in table 4.

GKR Run 2			GKR Run 3		
GKR Sampling Locations	Gas Transfer Velocities	Reach Gas Transfer Values	GKR Sampling Locations	Gas Transfer Velocities	Reach Gas Transfer Values
1	m/day	/day	1	m/day	/day
2	36.8	230.1	2	32.1	200.8
3	46.5	254.1	3	25.1	137.3
4	43.2	177.2	4	24.1	99.0
5	-1.8	-7.3	5	-0.9	-3.6
6	28.2	115.8	6	41.1	168.7
7	9.3	51.0	7	22.7	124.3
8	9.3	61.1	8	23.8	156.0
9	35.5	258.5	9	24.0	174.6
10	21.8	178.8	10	22.3	183.0
11	55.5	607.3	11	39.5	431.7
12	28.4	206.7	12	15.2	111.0
13	20.7	169.8	13	24.0	197.2
14	24.1	158.4	14	24.7	162.2
15	65.0	387.5	15	22.8	135.9
16	28.2	154.3	16	16.1	88.2
Averages	32.3	195.6	Averages	25.5	154.6

Table 4. *Box model results for Johnson Creek Run 2 and Run 3.*

4.1.2 Merced River Results

Based on   the field results from table 3 above, the parameter and data were input into a box model using

equation one. The equation was rearranged in order to produce gas transfer velocities and values. Box

models were used on two datasets for the Merced River. The two different datasets were from October 2007 and October 2005. Results from the box model can be seen below in table 5.

	Dataset 1		Dataset 2	
Merced River Samples	**Gas Transfer Velocities**	**Reach Gas Transfer Coefficient**	**Gas Transfer Velocities**	**Reach Gas Transfer Coefficient**
Happy Isles	**m/day**	**/day**	**m/day**	**/day**
Tenaya Creek MR	1.6046	5.8139	N/A	N/A
Superintendents Bridge	-0.0123	-0.0444	0.4107	1.4881
Swinging Bridge	0.2816	1.0203	0.5659	2.0505
El Capitan Bridge	1.1974	4.3385	0.7088	2.5682
Bridalveil MR	0.6752	2.4463	2.6388	9.5607
Pohono Bridge	0.0082	0.0297	0.5322	1.9283
Average	**0.7534**	**2.7297**	**0.9713**	**3.5192**

Table 5. *Box model results for Merced River datasets 1 and 2.*

4.2 FINIFLUX

FINIFLUX results included modeled radon concentration data, as well as modeled discharge data. The output graphs FINIFLUX produced can be seen below in figures five through fourteen. Figure five through fourteen show two graphs for each run. The top graph shows measured radon data and modeled radon data plotted against distance in meters. The bottom graph shows modeled radon data plotted against measured radon data. In table 6 below, mean absolute errors (MAE) and root mean squares (RMS) were calculated for radon concentrations and discharges for each study site and run. MAE is defined as a quantity used to measure how close concentrations of radon or discharge values are to the actual results. RMS is the square root of the average of the squares of a set of numbers. Equations 4 and 5 below were used to determine MAE and RMS values. A percentage was also calculated to give an idea of how well the MAE and RMS values compared to the average concentrations and average discharges.
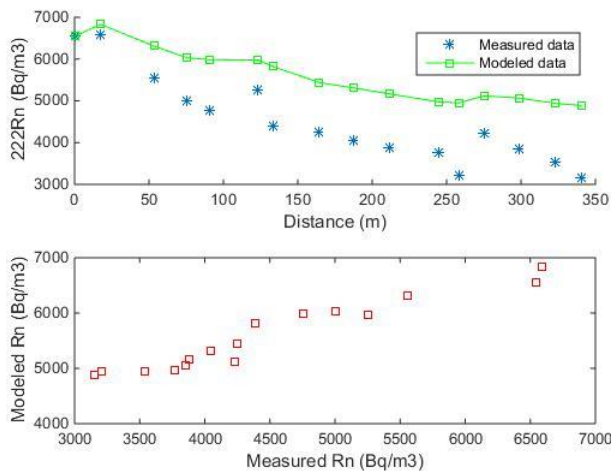
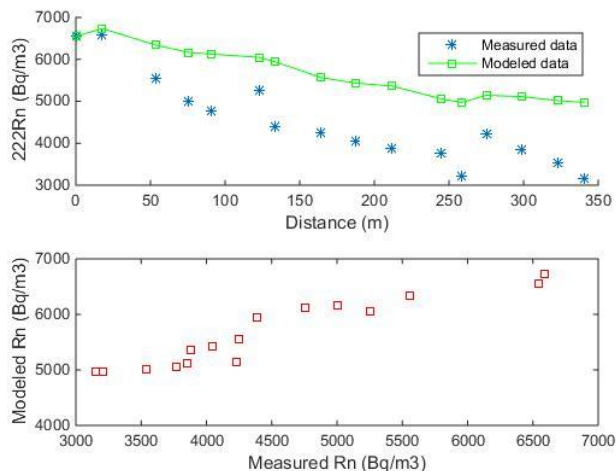*Figure 5. Run 1:* *Linearly increased widths and default k value*

Figure 7. Run 2: *Width calculated (w=Q/vd) and default k value*
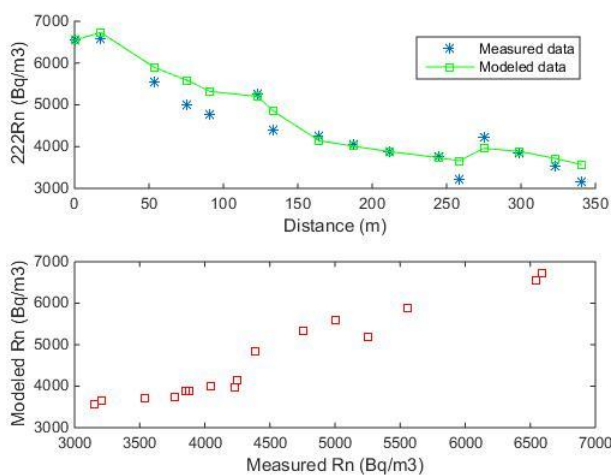

Figure 6. Run 3: *Linearly increased widths and k value of 120/d*
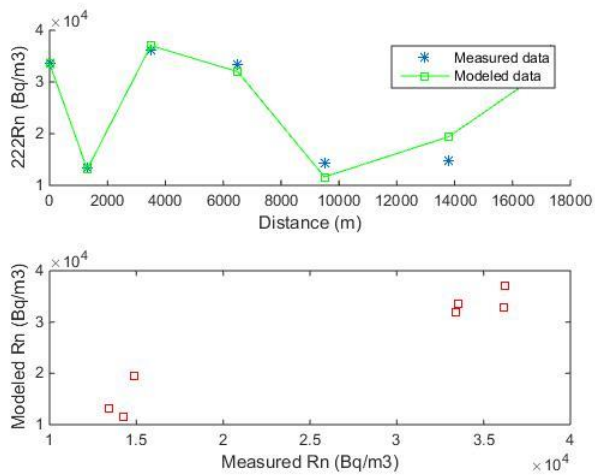

Figure 9. *MR Dataset 1* *Run 1*—*Default k value*

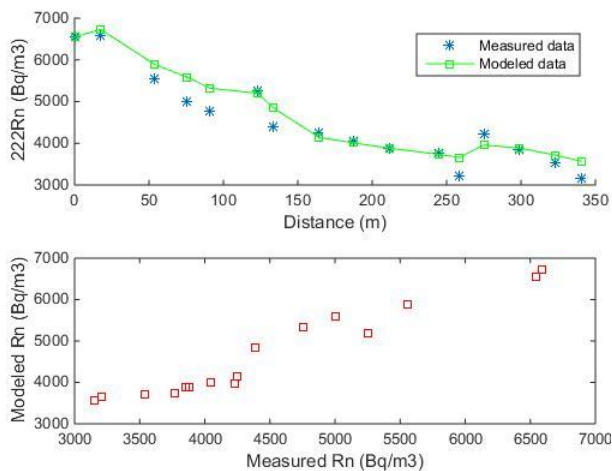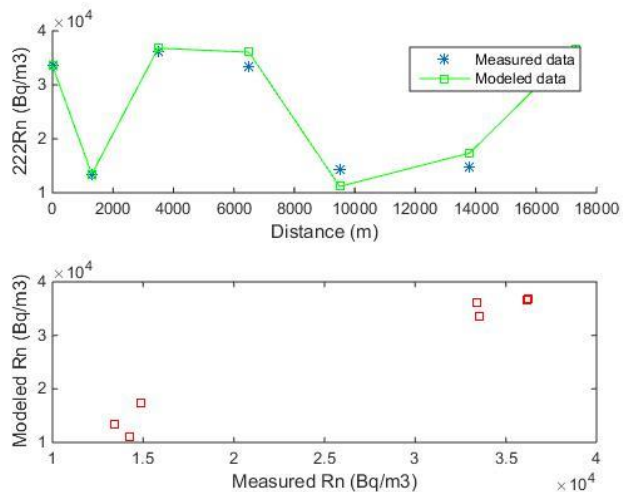**Figure 8. Run 4:** *Linearly increased widths and k value of 110/d*
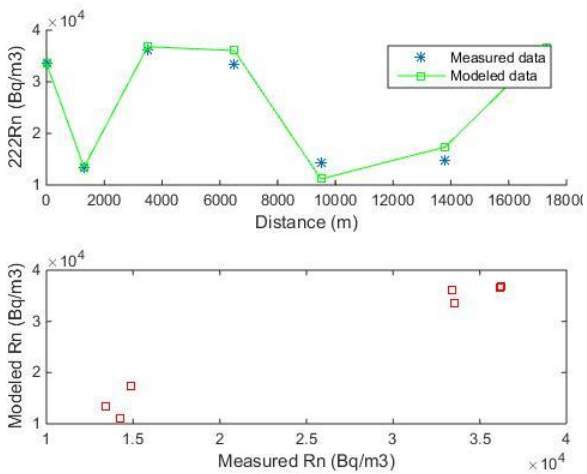

Figure 11. *MR Dataset 1* **Run 2**—*k value of 120*
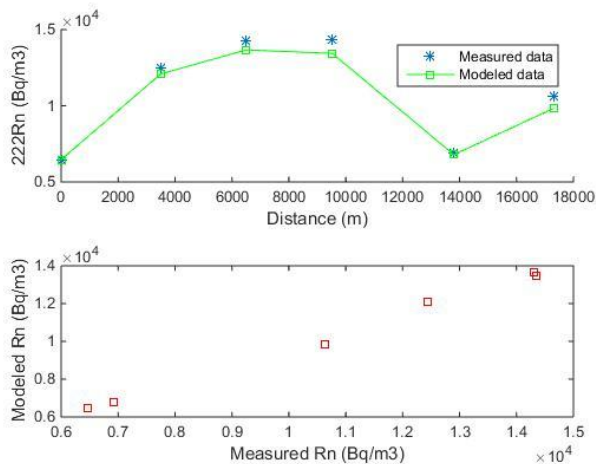

Figure 10. *MR Dataset 1* **Run 3**—*k value of 1*

Figure 13. *MR Dataset 2* **Run 2**—*k value of 120*

*Figure 14. MR Dataset 2 **Run 3**—k value of 1*

*Figure 12. MR Dataset 2 **Run 1**—Default k value*

Location/Run	MAE Rn Concentration	MAE / Average Rn Conc.	RMS Rn Concentration	RMS / Average Rn Conc.	MAE Discharge	MAE Discharge / Average Discharge	RMS Discharge	RMS Discharge / Average Discharge
GKR Run 1	1081.5	24.0%	1175.5	26.1%	0.0010	9.2%	0.0010	9.3%
GKR Run 2	1156.4	25.7%	1260.6	28.0%	0.0010	9.2%	0.0010	9.2%
GKR Run 3	230.2	5.1%	307.3	6.8%	0.0009	8.6%	0.0009	8.7%
GKR Run 4	230.2	5.1%	307.3	6.8%	0.0009	8.6%	0.0009	8.7%
Merced River Dataset 1 Run 1	1848.7	7.1%	2415.7	9.3%	0.0382	13.1%	0.0382	13.1%
Merced River Dataset 1 Run 2	1339.3	5.2%	1830.7	7.0%	0.0382	13.1%	0.0382	13.1%
Merced River Dataset 2 Run 1	321.5	3.0%	443.8	4.1%	0.1566	11.1%	0.2368	16.8%
Merced River Dataset 2 Run 2	473.5	4.4%	581.4	5.4%	0.4854	27.9%	0.5895	33.9%

Table 6. Mean average error (MAE) and root mean square (RMS).

$$MAE = \frac{1}{n}\sum_{i=n}^{n}|h_m - h_s|_i \qquad\qquad \textbf{Eqn. (4)}$$

$$RMS = [\frac{1}{n}\sum_{i=n}^{n}(h_m - h_s)^2]^{0.5} \qquad\qquad \textbf{Eqn. (5)}$$

Where n is the number of sampling locations, h_m is the modeled Rn or discharge value,

and h_s is the measured Rn or discharge value.

5.0 Discussion

5.1 Mixing Models

As mentioned previously, in streams and lakes where groundwater enters in pulses or discrete locations, radon may not be as useful of tracer for quantifying groundwater inflows. However in streams or lakes where there is continuous groundwater inflow, radon as a tracer may be a valuable tool. When using radon as a tracer, radon sampling needs to be collected along short enough reaches so that accurate quantification can be measured. This is due to unknown groundwater inflows along a long reach, which could have an increase on radon values and effect radon modeling. The differences between sampling at Johnson Creek and the Merced River may illustrate this point. Johnson Creek consisted of a very short reach with nearly three times the sampling sites. Whereas, the Merced River study area was a much larger stretch with fewer radon sampling points compared to Johnson Creek which was a short stretch of water with much more sampling points. Using two different study areas with large magnitudes of difference (flows, lengths and sampling points) produced some valuable results for each of the models used in the study. For the Grant-Kohrs Ranch box model on Johnson Creek, there were a couple sampling points which produced negative gas transfer values, but overall the box models seemed to be giving realistic values (note: negative values were ignored in calculation for average gas exchange value). Negative gas transfer velocities are a possible result from calculating gas exchange at reaches where the river goes from a strongly groundwater influenced stream to a section where groundwater is not mixing with stream water, or where stream turbulence and gas exchange actually increase. For the Merced River mixing model, there was one sampling point which had a negative gas transfer value. The Merced River box model seemed to be giving invalid gas transfer values and therefore, box models would not seem to be a good fit for all or some of the Merced River that was sampled. The Merced River study area is significantly longer than the Grant Kohrs Ranch site, with much fewer sampling locations. We suspect that the negative gas transfer velocities are a result of calculating gas exchange at reaches where the river goes from a strongly groundwater influenced stream to a section where groundwater is not mixing with stream water, or where stream turbulence and gas exchange actually increase. Sampling a more spatially

frequent location where the gas transfer velocity was estimated at negative values may very well help improve the box model, but this would require multiple site visits and data analysis to help identify proper sampling locations.

When looking at the box model gas exchange coefficients in tables 4, Grant-Kohrs Ranch values match fairly well with published gas exchange values (Genereux et al., 1992). When looking at the box model gas exchange coefficients in tables 5, Merced River values are fairly low when compared with published gas exchange values (Genereux et al., 1992). The gas exchange coefficient values calculated in the box models for Grant-Kohr Ranch runs 2 and 3 were 196/day and 155/day. The gas exchange coefficient values calculated in the box models for Merced River Datasets 1 and 2 were 2.7/day and 3.5/day. Genereux's paper used propane and ethane as volatile gas tracers, which should have a fairly similar degassing rate to radon gas. The gas exchange coefficient values for propane and ethane were found to be about 100/day and 117/day.

5.2 FINIFLUX

The results from FINIFLUX for Johnson Creek and the Merced River seemed to be fairly valid and a useful modeling tool for each of the bodies of water. However, there were a few problems encountered when using FINIFLUX, the first was with gas exchange values. Gas exchange values in FINIFLUX can be set as a default in which FINIFLUX calculates values for you, or they can be set manually. The problem was when gas exchange values were set manually and varied (Johnson Creek: run 2 to run 3), no output values changed. Values of magnitudes were tested and nothing seemed to change when gas exchange values were input manually. We never determined the cause of model insensitivity to gas exchange velocities, but this is physically impossible. We ranged gas exchange velocities two orders of magnitude which would certainly show significant variations in the model. Equations 2 and 3 that FINIFLUX refers to for the default equations used to calculate gas exchange values were also tested. For both equations 2 and 3, an unrealistic gas exchange velocity was calculated. When gas exchange values were increased by one order of magnitude for equation 2, the velocity increased by two orders of

magnitude. When gas exchange values were increased by more than two orders of magnitude, the velocity increased by four orders of magnitude. When gas exchange values were increased by one order of magnitude for equation 3, velocity increased by just more than one. When gas exchange values were increased by more than two orders of magnitude, the velocity increases by more than one. Another problem encountered was that the hyporheic component of FINIFLUX would not work when turned on. Johnson Creek is a small low flowing creek in a flood plain and it's possible that there could be strong hyporheic interactions occurring. Incorporating hyporheic exchange in this problem could help construct a more realistic model, but not enough to account for the model insensitivity. The last problem faced was with the Merced River data. Since the Merced River data was a long reach with few sampling points, it seemed that FINIFLUX was insensitive to this aspect, such as forcing the amount of groundwater inflow to match the total streamflow change. Groundwater inflows and graphs of FINIFLUX results for the Merced River show where the model is forcing data results. The Merced River graphs produced from FINIFLUX appear to be more ridged than the ones for Johnson Creek (as seen above in figures 9-14). Parts of FINIFLUX that seem to not produce valid results are the gas exchange values, hyporheic zone and areas where FINIFLUX would partially force results for areas unknown.

In table 6, the MAE and RMS values for radon concentration and discharge are presented for each of the runs, along with the MAE and RMS values compared to the average radon concentration and average discharge, providing percentages. For Grant-Kohrs Ranch runs 3 and 4 had percentages at 5.1% for the MAE for radon concentration. Grant-Kohrs Ranch runs 1, 2, 3, and 4 had percentages between 8.6% and 9.3% for discharge values. For Grant-Kohrs Ranch, runs 3 and 4 produced the most valid results based on MAE and RMS. For Merced River dataset 1 run 2 and Merced River dataset 2 runs 1 and 2, the MAE and RMS for radon concentration compared to the average radon concentration had good percentages ranging from 3.0% to 5.4%. For both Merced River datasets the MAE and RMS percentages for discharge were off greatly. However, for the Merced River dataset 1 run 1, the most valid results were produced based on MAE and RMS values.

As mentioned above, problems with FINIFLUX occurred relating to gas exchange values. When gas exchange values were inputted and varied by small to large magnitudes, the outputs from FINIFLUX had no variation. These problems relating to FINIFLUX seem to be user error while trying to figure out the software and need to be further investigated.

6.0 Conclusions and Recommendations

This study has shown that using radon as a tracer for groundwater can be a valuable tool for bodies of water where groundwater is entering continuously along reaches, as long as sampling points are within a short enough distance to account for possible radon spikes or sudden decreases. Future work should include looking into the hyporheic zone aspect of FINIFLUX, as well as investigating how to vary k values in FINIFLUX. Further study could possibly look into degassing experiments in order to determine degassing values of radon. One recommendation when gathering field parameters is to gather more rather than less. This will eliminate having to make estimation of parameters. Also, when gathering field parameters, make sure to use caution in waters, as well as in extreme temperatures. Gas exchange can vary widely, and direct measurements will more conclusively illustrate the validity of these models.

7.0 Acknowledgements

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Appendices

Appendix A

FINIFLUX Results

GKR Run 1									
Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
1	6545	6545.3	0.3	0.09	0.0031				
2	6830	6593.4	236.6	55979.56	0.0041	0.0032225	0.000878	7.7E-07	0.000007
3	6309	5557.4	751.6	564902.6	0.0052	0.0041072	0.001093	1.19E-06	2E-07
4	6031	5006.1	1024.9	1050420	0.0062	0.0052	0.001	1E-06	1E-09
5	5986	4758.2	1227.8	1507493	0.0072	0.006262	0.000938	8.8E-07	0.000004
6	5975	5257.7	717.3	514519.3	0.0083	0.007392	0.000908	8.24E-07	0.000006
7	5820	4388.2	1431.8	2050051	0.0093	0.0083	0.001	1E-06	4E-09
8	5437	4251.3	1185.7	1405884	0.0103	0.009393	0.000907	8.23E-07	0.000003
9	5309	4047.8	1261.2	1590625	0.0114	0.010392	0.001008	1.02E-06	0.000004
10	5164	3881.3	1282.7	1645319	0.0124	0.0114735	0.000926	8.58E-07	0.000003
11	4973	3770.3	1202.7	1446487	0.0134	0.0124759	0.000924	8.54E-07	2.3E-06
12	4950	3204.57	1745.43	3046526	0.0145	0.0134527	0.001047	1.1E-06	3.9E-06
13	5120	4229.1	890.9	793702.8	0.0155	0.014698	0.000802	6.43E-07	0.000012
14	5065	3855.4	1209.6	1463132	0.0165	0.0155648	0.000935	8.75E-07	2.7E-06
15	4940	3542.75	1397.25	1952308	0.0176	0.0165074	0.001093	1.19E-06	3.1E-07
16	4888	3150.18	1737.82	3020018	0.0186	0.017663	0.000937	8.78E-07	3.6E-06
		Sums	1081.475	1175.462		Sums	0.00096	0.000963	

GKR Run 2									
Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
1	6545	6545.3	0.3	0.09	0.0031				
2	6737	6593.4	143.6	20620.96	0.0041	0.0032225	0.000878	7.7E-07	0.000007
3	6341	5557.4	783.6	614029	0.0052	0.0041	0.0011	1.21E-06	1E-09
4	6165	5006.1	1158.9	1343049	0.0062	0.0052	0.001	1E-06	1E-09
5	6125	4758.2	1366.8	1868142	0.0072	0.006262	0.000938	8.8E-07	0.000004
6	6048	5257.7	790.3	624574.1	0.0083	0.007392	0.000908	8.24E-07	0.000006
7	5943	4388.2	1554.8	2417403	0.0093	0.0083	0.001	1E-06	1E-09
8	5565	4251.3	1313.7	1725808	0.0103	0.009362	0.000938	8.8E-07	0.000002
9	5434	4047.8	1386.2	1921550	0.0114	0.010392	0.001008	1.02E-06	0.000004
10	5363	3881.3	1481.7	2195435	0.0124	0.011498	0.000902	8.14E-07	0.000004
11	5059	3770.3	1288.7	1660748	0.0134	0.012532	0.000868	7.53E-07	0.000004
12	4972	3204.57	1767.43	3123809	0.0145	0.01345	0.00105	1.1E-06	3.7E-06
13	5143	4229.1	913.9	835213.2	0.0155	0.0147145	0.000786	6.17E-07	0.000013
14	5111	3855.4	1255.6	1576531	0.0165	0.0155504	0.00095	9.02E-07	2.1E-06
15	5015	3542.75	1472.25	2167520	0.0176	0.0165029	0.001097	1.2E-06	1.2E-07
16	4975	3150.18	1824.82	3329968	0.0186	0.0176455	0.000954	9.11E-07	2.6E-06
		Sums	1156.413	1260.565		Sums	0.000958	0.000962	

GKR Run 3									
Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
1	6545	6545.3	0.3	0.09	0.0031				
2	6733	6593.4	139.6	19488.16	0.0041	0.00324	0.00086	7.4E-07	0.000008
3	5897	5557.4	339.6	115328.2	0.0052	0.0041288	0.001071	1.15E-06	8E-07
4	5588	5006.1	581.9	338607.6	0.0062	0.0052088	0.000991	9.82E-07	4E-07
5	5322	4758.2	563.8	317870.4	0.0072	0.0062775	0.000923	8.51E-07	0.000005
6	5201	5257.7	56.7	3214.89	0.0083	0.00752	0.00078	6.08E-07	0.00001
7	4850	4388.2	461.8	213259.2	0.0093	0.0083053	0.000995	9.9E-07	5E-07
8	4140	4251.3	111.3	12387.69	0.0103	0.00961	0.00069	4.76E-07	0.00001
9	4009	4047.8	38.8	1505.44	0.0114	0.01053	0.00087	7.57E-07	0.00001
10	3879	3881.3	2.3	5.29	0.0124	0.011596	0.000804	6.46E-07	0.000008
11	3732	3770.3	38.3	1466.89	0.0134	0.012631	0.000769	5.91E-07	0.000007
12	3658	3204.57	453.43	205598.8	0.0145	0.0134459	0.001054	1.11E-06	3.4E-06
13	3958	4229.1	271.1	73495.21	0.0155	0.014797	0.000703	4.94E-07	0.000018
14	3887	3855.4	31.6	998.56	0.0165	0.0155792	0.000921	8.48E-07	3.3E-06
15	3714	3542.75	171.25	29326.56	0.0176	0.0165	0.0011	1.21E-06	1E-09
16	3572	3150.18	421.82	177932.1	0.0186	0.0176403	0.00096	9.21E-07	2.3E-06
		Sums	230.225	307.2545		Sums	0.000899	0.000908	

GKR Run 4

Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
1	6545	6545.3	0.3	0.09	0.0031				
2	6733	6593.4	139.6	19488.16	0.0041	0.00324	0.00086	7.4E-07	0.000008
3	5897	5557.4	339.6	115328.2	0.0052	0.0041288	0.001071	1.15E-06	8E-07
4	5588	5006.1	581.9	338607.6	0.0062	0.0052088	0.000991	9.82E-07	4E-07
5	5322	4758.2	563.8	317870.4	0.0072	0.0062775	0.000923	8.51E-07	0.000005
6	5201	5257.7	56.7	3214.89	0.0083	0.00752	0.00078	6.08E-07	0.00001
7	4850	4388.2	461.8	213259.2	0.0093	0.0083053	0.000995	9.9E-07	5E-07
8	4140	4251.3	111.3	12387.69	0.0103	0.00961	0.00069	4.76E-07	0.00001
9	4009	4047.8	38.8	1505.44	0.0114	0.01053	0.00087	7.57E-07	0.00001
10	3879	3881.3	2.3	5.29	0.0124	0.011596	0.000804	6.46E-07	0.000008
11	3732	3770.3	38.3	1466.89	0.0134	0.012631	0.000769	5.91E-07	0.000007
12	3658	3204.57	453.43	205598.8	0.0145	0.0134459	0.001054	1.11E-06	3.4E-06
13	3958	4229.1	271.1	73495.21	0.0155	0.014797	0.000703	4.94E-07	0.000018
14	3887	3855.4	31.6	998.56	0.0165	0.0155792	0.000921	8.48E-07	3.3E-06
15	3714	3542.75	171.25	29326.56	0.0176	0.0165	0.0011	1.21E-06	1E-09
16	3572	3150.18	421.82	177932.1	0.0186	0.0176403	0.00096	9.21E-07	2.3E-06
			Sums						
			230.225	**307.2545**		**Sums**	**0.000899**	**0.000908**	

Merced River Dataset 1 Run 1

Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
Happy Isles	33560	33561.1	1.1327	1.283009	0.19538592				
Tenaya Creek MR	13100	13400.7	300.735	90441.52	0.2336136	0.1953859	0.038228	0.001461	0.000001
Superintendents Bridge	37040	36224.8	815.1725	664506.3	0.27184128	0.2336136	0.038228	0.001461	0.00004
Swinging Bridge	32000	33412.7	1412.741	1995838	0.31006896	0.2718413	0.038228	0.001461	0.00005
El Capitan Bridge	11630	14279.6	2649.65	7020643	0.34829664	0.310069	0.038228	0.001461	0.00002
Bridalveil MR	19430	14857.9	4572.075	20903871	0.38652432	0.3482966	0.038228	0.001461	0.00002
Pohono Bridge	32950	36139.6	3189.58	10173419	0.424752	0.3865243	0.038228	0.001461	0.00005
			Sums						
			1848.727	**2415.684**		**Sums**	**0.038228**	**0.038228**	

Merced River Dataset 1 Run 2

Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
Happy Isles	33560	33561.1327	1.1327	1.283009	0.19538592				
Tenaya Creek MR	13460	13400.73496	59.26504	3512.344	0.2336136	0.1953859	0.038228	0.001461	6.00E-07
Superintendents Bridge	36800	36224.82746	575.1725	330823.5	0.27184128	0.2336136	0.038228	0.001461	5.00E-05
Swinging Bridge	36050	33412.74114	2637.259	6955134	0.31006896	0.2718413	0.038228	0.001461	7.00E-05
El Capitan Bridge	11170	14279.64964	3109.65	9669921	0.34829664	0.310069	0.038228	0.001461	4.00E-05
Bridalveil MR	17360	14857.92485	2502.075	6260380	0.38652432	0.3482966	0.038228	0.001461	2.00E-05
Pohono Bridge	36630	36139.57974	490.4203	240512	0.424752	0.3865243	0.038228	0.001461	8.00E-05
			Sums						
			1339.282	**1830.702**		**Sums**	**0.038228**	**0.038228**	

Merced River Dataset 2 Run 1

Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
Happy Isles	6460	6460	0.086	0.007	0.88				
Superintendents Bridge	12710	12446	264	69745	1.004	1.02	0.016	0.000256	0.00004
Swinging Bridge	14590	14299	291	84608	1.128	1.134	0.006	3.6E-05	0.00002
El Capitan Bridge	14230	14351	121	14550	1.252	1.604	0.352	0.123904	0.00005
Bridalveil MR	5962	6926	964	929014	1.376	1.39	0.014	0.000196	0.00001
Fern Spring MR	10350	10640	290	83906	1.5	1.895	0.395	0.156025	0.00003
		Sums	321.5	443.8		Sums	0.1566	0.2368	

Merced River Dataset 2 Run 2

Sampling Locations	Modeled Rn	Measured Rn	MAE	RMS	Measured Discharge	Modeled Discharge	MAE	RMS	GW Inflows
	Bq/m3	Bq/m3			m3/s	m3/s			m3/m/s
Happy Isles	6460	6459.9144	0.0856	0.007327	0.88				
Superintendents Bridge	12090	12445.90662	355.9066	126669.5	1.004	1.125	0.121	0.014641	7.00E-05
Swinging Bridge	13670	14299.12463	629.1246	395797.8	1.128	1.264	0.136	0.018496	4.00E-05
El Capitan Bridge	13440	14350.6227	910.6227	829233.7	1.252	2.08	0.828	0.685584	1.00E-04
Bridalveil MR	6792	6925.853573	133.8536	17916.78	1.376	1.804	0.428	0.183184	4.00E-05
Fern Spring MR	9828	10639.6656	811.6656	658801	1.5	2.414	0.914	0.835396	6.00E-05
		Sums	473.5431	581.4377		Sums	0.4854	0.589458	

Appendix B

FINIFLUX User Manual

User manual for Finiflux-Rn (Finite element method for quantifying groundwater fluxes to streams using Radon)

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Please also see the paper: Technical Note: FINIFLUX an implicit Finite Element model for quantification of groundwater fluxes and hyporheic exchange in streams and rivers using Radon, in Water Resources Research 2015.

This model is intended to make groundwater fluxes estimated using Rn more mathematically robust and also provide information on how important the different variables in the model are for determining the measured Rn activities. It is based on an implicit solution to the governing mass-balance differential equations using a finite element code. This model is fitted to measured data using the parameter optimisation model PARALLEL PEST (Doherty, 2010), which systematically varies variables such as the groundwater flux and hyporheic exchange residence times to reduce the residual mean square between measured and modelled data. Below are the basic steps to run the model in streams. For the background mathematics and case studies please see the associated paper. The description below is for a model including hyporheic exchange. All the following steps are **based on the files found in the downloaded folded exec**.

1. There are a number of files (15 to be exact) for which data are needed. Before getting into this it is important to understand two important differences in the data structure. On one hand, we have **'Nodes'** or **measured data points**, while on the other hand we have '**Elements'** or **reaches**, which is the lengths between measured points. By definition, the number of Elements is one less than the number of Nodes, since there is always a measurement point at one of the boundaries (up-stream or downstream).

2. The first program generates the PEST input files and sets up the directory structure. It works by first reading in the input files, from which it extracts the important data for PEST. The program will do this, as well as create three new folders for the PEST slaves. We have mostly used default settings for the PEST input file, but the interested user is direct to the very comprehensive PEST manual for more information on these settings, as well as more generally how PEST works. Moreover, the PEST input files can still be changed after the initial set-up, but before the model run, by a more experienced user (e.g. parameters in the

Singular Value Decomposition (SVD) routine can be edited). The main file that drives PEST is the **finiflux.pst** file.

3. Ok so let's look at the files that need to be completed. Note that for all files we have given example files that can, and probably should, be simply over-written by copy-and-paste of your data.

   a. path_definition is the file that shows the program where you have your input files, where slave will be created and where you want to run your model. It is easiest to copy it from window header e.g. D:\Programs\finiflux

   b. processor_nodes is the number of slaves that you want to run. Number of slaves = number given minus one, since one of the nodes is also the Master. We have found that 3 slaves works well on quad core machines and also allows you to work on other things while the model is running. In this case we recommend entering '4' in this file. This is also given as default and does not necessarily need to be changed.

   c. Discharge file – This should contain discharge values for each **reach (Element)**. It is unlikely that you have so much discharge data, and in the past is has been useful to extrapolate discharge for unknown reaches from known gauging stations. The data is arranged in a single vertical column in the units m^3/s.

   d. n_observation file is the number of observations (Rn measurements), just one number.

   e. observation_points file is the distance in meters from the upstream sampling point at which each sample was taken. The first sample location is given a value of zero. The number of entries should be the same as the number of Rn sample points (nodes).

   f. River_depth file and river_width files are as the name implies. All values are in meters and need one value for each **reach**. This should be the average value for the reach.

   g. obs_concentrations is the file for the observed Rn values. This should be in the SI unit Bq m^{-3}.

   h. C_initial is the first measured value. Just one number in Bq m^{-3}.

   i. gw_concentration is the Rn concentration in the groundwater system. Give a value for each reach in Bq m^{-3}.

   j. k_degas is the file where you choose which empirical degassing equation that finiflux will use, or if you will use your own measured k values (i.e. user defined k). You have an option of two different equations, which have been taken from Eq. 5 and 6 in Unland et al. (2013) or, as just mentioned, your own k values. We have used '1' as the default and can be left so or changed to '2'. If you plan on providing your own k values (e.g. from gas tracer experiments) you need to enter these into the file **k_values**, and you need to give a k value for each reach. Units are **per second i.e. s^{-1}**.

   k. hz_on_off is to turn the hyporheic zone function on or off. A value of '1' means that it is turned on and a value of '0' means off.

   l. porosity_hz is the porosity of the hyporheic zone for each reach (default = 0.4)

   m. depth_hz is the approximate depth of the hyporheic zone in meters. This will be optimised by PEST but needs an initial value for each **reach**. We have given a default of 1m which should be an adequate starting value for many streams.

4. Ok now it is time to run the PEST set-up program (write PEST input files). Hold shift and right-click on the folder containing all your files and the downloaded PEST.exe program. Select 'Open Command Window Here' from the menu that appears. Type 'write_pest.exe' into the command window at the prompt and press enter. This should build your PEST input files and create three salve folders in your main folder. Check that the slaves have been populated, if not you have probably forgotten to add the correct path for the slaves – see point 'a' above.

5. Start the slaves. Hold shift and right-click on a slave. Again select 'Open Command Window Here' and type 'pslave' at the prompt. Then type 'run' at the next prompt 'enter command to run model:'Do this for each of the three slaves. The saves will then wait for instructions from the Master.

6. Run the main PEST program. Open the command window as above, but in the main folder, rather than in the slaves. Type PPEST followed by the name of the model e.g. >PPEST finiflux. PEST will start, and look for the slaves. Once it has found them it will start the optimisation process and look like this:

7. The optimisation will take some time (1-24h usually, but depends on the number of measurement points). When the optimisation is finished the Master will look like this:

8. First thing is to have a look at how well the data fits the measured values. We have written a small graphing program to do this - 'Plot_Output.exe'. The actual values of measured and modelled data can be found in the Radon.seo file. This is a text document and can be opened in any text editor (we find Notepad++ convenient).
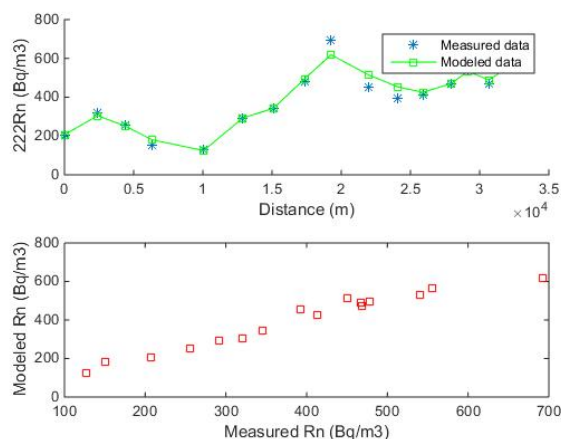
9. The calculated groundwater fluxes can be found in slave 1 in the file **'gw_inflow.dat'**. The groundwater flux units are in $m^3/m/s$ (sticking with SI units), but should probably be scaled to $m^3/m/d$ for better representation. This is of course for the user to decide. Also a text file.

10. The goodness of fit (correlation coefficient as well as other indicators) calculated by PEST can be found in the **finiflux.rec** file. It is often located at the bottom of the file, but not always, and sometimes one needs to scroll around a bit to find it. It looks like this:

11. Optimised Hyporheic residence time can be found in slave1 in the file **'rtimes_hz'**, with the units 'seconds'.

12. The importance of hyporheic exchange for the goodness of fit can be found in the file **Radon.sen** (text). Look at the last column (Sensitivity) of the last run (bottom of the file). The higher the number the more important is the parameter for determining the fit. Of course one can also run the model with and without hyporheic exchange (see file **hz_on_off**) and compare e.g. groundwater fluxes and goodness-of-fit to determine the importance of the hyporheic exchange.

Please let us know if you have any comments, requests or problems.

Ben Gilfedder and Sven Frei

References

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