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STUDY OF POTENTIAL IMPACTS OF RADIOACTIVE CONTAMINATION ON DRINKING WATER QUALITY IN TWO COLLINEAR RESERVOIRS USING CCHE2D MODEL

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ABSTRACT

There is interest in mining and milling of a large uranium ore reserve in Southern Virginia. The milling operation is expected to produce large quantities of tailings containing radioactive contaminants. The area where the uranium reserves are located is prone to extreme rainfall events. Failure of a tailings dam may flush large quantities of tailings into tributaries of the Banister River downstream of the reserves, and further into Kerr Reservoir and Lake Gaston where the drinking water sources may be polluted. This impact assessment was performed using the CCHE2D model package. Simulations of unsteady flow and non-uniform suspended sediment and contaminant transport were conducted for wet years and dry years. This paper discusses the details of the two-dimensional modeling of flow, sediment transport and contaminant transport and fate in two cascading reservoirs using CCHE2D. The results of the simulations concerning the spatiotemporal variation of dissolved and particulate contaminants concentrations in the water column, and contaminant accumulation in the bed are presented. The paper presents conclusions regarding the residence time of contaminants in both reservoirs.

1. INTRODUCTION

There is interest in mining and milling of a large uranium ore reserve in Southern Virginia. The milling operation is expected to produce large quantities of tailings that could be stored in multiple above-grade tailings dams close to the mining and milling operations. The tailings retain about 85% of the original radioactivity for hundreds of thousands of years because of the presence of radium and thorium, which are not extracted during the process. In addition, tailings still contain uranium

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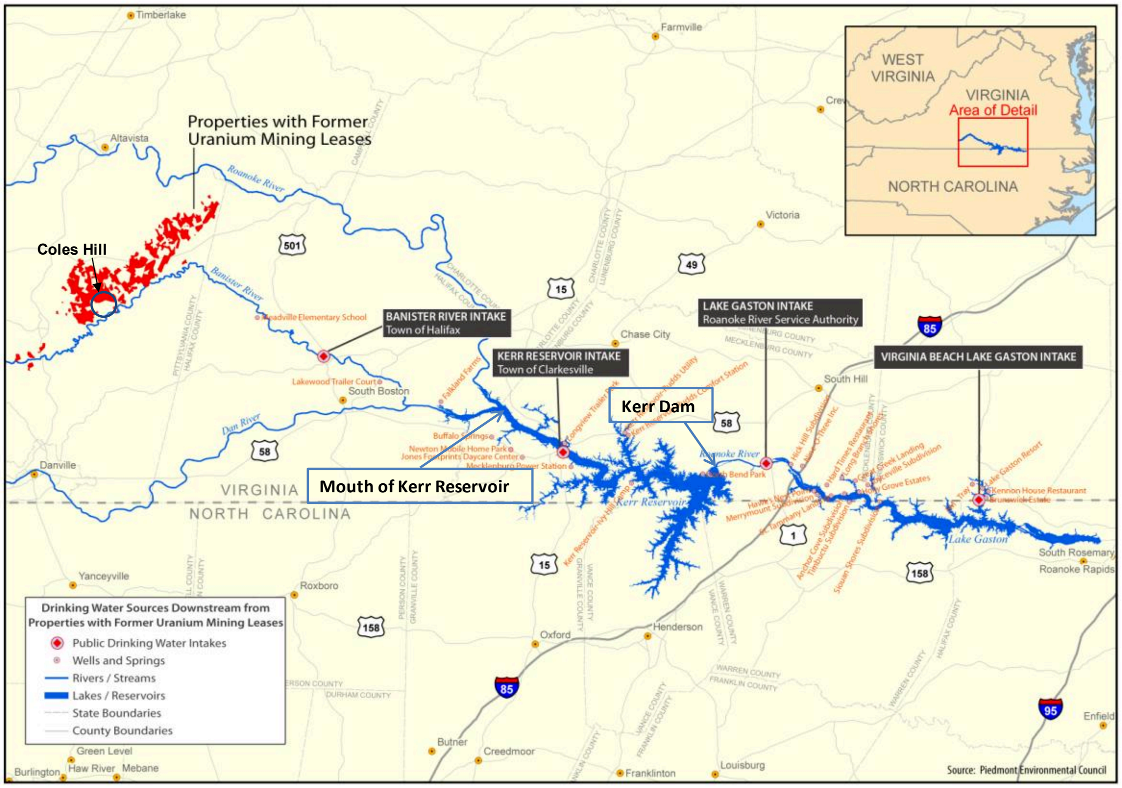
and various other potentially hazardous substances. The area where the uranium reserves are located is prone to extreme rainfall events, including tropical storms and hurricanes, some of which have generated substantial flooding and erosion in the past. Failure of a tailings dam may flush large quantities of tailings into tributaries of the Banister River downstream of the reserves. There is concern that the contaminated river water may reach Kerr Reservoir which is operated by U.S. Army Corps of Engineers for flood control and hydropower. The water from Kerr Reservoir flows into Lake Gaston which serves as a water source for numerous utilities. The site map is shown in Figure 1.



Source: Piedmont Environmental Council

Figure **Error! No text of specified style in document.** Area of interest for the second phase study.

A study was initiated by the City of Virginia Beach, which has a drinking water intake in Lake Gaston on the Pea Hill Creek tributary, to assess potential impacts of a catastrophic tailings release on the quality of surface waters in Kerr Reservoir and Lake Gaston. The study was carried out in two phases. Based on one-dimensional (1D) numerical simulations of the Banister and Roanoke Rivers and the Kerr Reservoir, the Phase I investigated the potential impacts of uranium mining by simulating various scenarios of released quantity of tailings, tailing properties, initial radioactivity concentration and uranium content, pulp density of tailings and different hydrological conditions.

The second phase of this project focuses on the likely failure scenarios based on more refined data obtained from reports prepared for the uranium mining (Coles Hill) site and other sources that have data applicable to uranium tailings disposal and storage. In addition, this Phase II study is extended to include Lake Gaston, which is immediately downstream of Kerr Reservoir and directly receives the water released from Kerr Reservoir.

A two-dimensional (2D) modeling approach was used in the Phase II taking into account possible interaction of the flow in the main channel with side branches. In addition, the lateral mixing processes and water volume change in the reservoir are better represented with 2D modeling resulting in more accurate estimation of residence time of the contaminants in the reservoirs. This assessment was performed using the CCHE2D model (Jia and Wang, 1999; Zhu et al., 2009), which is a fully validated two-dimensional model developed at the National Center for Computational Hydroscience and Engineering, The University of Mississippi. Simulations of unsteady flow and non-uniform suspended sediment and contaminant transport were conducted for two two-year periods representing the wettest (9/1/1996-8/31/1998) and driest (6/1/2001-5/31/2003) hydrologic conditions for the area.

Topographic data was obtained by digitizing contour lines from paper maps. The 10m-resolution DEMs for Kerr Reservoir and Lake Gaston were used to add the topography of the area between the crest elevation of the dam and the normal pool level. For Kerr Reservoir inflow and outflow discharges and water surface elevations for wet period and dry period scenarios were obtained from measurements. For Lake Gaston inflow discharge is the outflow discharge of the Kerr Reservoir, which is available as measured data for both wet and dry period scenarios. Outflow discharge and water surface elevations for wet period and dry period scenarios were obtained from measurements. The sediment rating curves established in the Phase 1 study are used as is for the Phase 2 study.

The contaminants that were simulated included radium, thorium and uranium. Radium and thorium contributed to alpha radioactivity, which is regulated under the National Primary Drinking Water Regulations at a level of 15 picocuries per liter (pCi/L). Radium by itself cannot exceed 5 pCi/L. Uranium, due to its renal toxicity, has a maximum contaminant level (MCL) of 30 micrograms per liter.

2. NUMERICAL MODELS

2.1 Model Descriptions

In this study, two-dimensional depth-averaged model package, CCHE2D models were used for simulating unsteady flow, non-uniform sediment transport, and chemical fate and transport.). The CCHE2D models use an efficient finite element numerical scheme and staggered quadrilateral meshes developed for simulating free surface flows, sediment and pollutant transport, and channel morphological changes. The hydrodynamic model has gone through extensive verification and validation using analytical solutions, physical model data, and field data (Jia and Wang, 1999; Jia *et al.*, 2002) with demonstrated robustness in natural channels with complex flow conditions, topography and hydraulic structures. The model can handle wetting and drying of water edge, which enables users to simulate flows with complex topography with ease. Three turbulence closure schemes are available, depth-averaged parabolic, mixing length eddy viscosity models and k-ε model. The numerical scheme can handle subcritical, supercritical flows and their transition. The source terms of kinetic processes and external loads are treated explicitly. Initial conditions and boundary conditions are specified by users.

CCHE2D sediment model is capable of simulating non-equilibrium non-uniform sediment transport including suspended load, bed load, and total load. The details of the sediment transport features were described by Wu and Wang, (1999 and 2001). The simulation of non-uniform sediment transport is based upon multiple size classes, taking into account of hiding and exposure among different size groups. The variation of bed material gradation in the mixing layer is determined by Wu and Li (1992). There are several options available for calculating the sediment transport capacity, non-equilibrium adaptation length and movable bed roughness as there is no formula applicable universally.

The chemical fate and transport simulation can be decoupled with the flow and sediment transport simulations. For unsteady cases, a time series of velocity, flow depth, eddy viscosity, suspended sediment concentration, and bed change will be input to the chemical simulation.

2.2 Related Chemical Fate Processes

In general, chemicals exist in four phases in the surface water system, dissolved in the water column, dissolved in porous water, adsorbed to suspended sediment and adsorbed to bed sediment. In addition to chemical decay processes, chemicals can have phase transformation between dissolved phase and particulate phase in the same medium through processes of sorption and desorption. The two dissolved phases can be exchanged through the diffusion between the pore water and the water column. The particulate phases sorbed on sediments also can be exchanged in the deposition and erosion processes of sediment entrainment.

For this study, three radioactive materials all have long half-lives and the radioactive decay rate was negligible. The radioactivity distribution in the water and bed is dominated by the sorption and desorption process. Previous study found out large variation in the partition coefficients for radium, thorium and uranium. Hence two sets of partition coefficients, representing upper and lower estimates, were used in the simulations. Linear equilibrium partition was assumed for this study. Fraction of dissolved and particulate chemical can be found using partition coefficient, K_d .

2.3 Governing Equations for Chemical Fate and Transport Model

The general governing equation of chemical fate and transport for the water column is written as:

$$\frac{\partial c_T}{\partial t} + u\frac{\partial c_T}{\partial x} + v\frac{\partial c_T}{\partial y} - \frac{\partial}{\partial x}(E_x \frac{\partial c_T}{\partial x}) - \frac{\partial}{\partial y}(E_y \frac{\partial c_T}{\partial y}) = S_{load} + S_{sed} + S_{v-diff} + S_{decay} \qquad (1)$$

in which x, y are horizontal Cartesian coordinates; t is time; $c_T(x,y,t)$ is depth-averaged concentration; $u(x,y,t), v(x,y,t)$ are depth-averaged velocities in x and y directions; $E_x(x,y,t), E_y(x,y,t)$, are components of dispersion tensor E. S_{load} is the external load source term, which is directly input to the model; S_{decay} is the kinetic decay source term, which is neglected in this case; S_{v-diff} is the vertical diffusion flux at the water-sediment interface; and S_{sed} is the chemical source/sink term due to sediment entrainment.

S_{v-diff} is determined by Fick's Law as in Eq. 2.

$$S_{v-diff} = \frac{k_f}{D}(s_{d,1} - c_d) = \frac{k_f}{D}(f_{d,s1}s_{T,1} - f_{d,w}c_T) \qquad (2)$$

in which k_f is the overall mass diffusion coefficient (in m/s), $f_{d,s}$ is the dissolved chemical fraction in surface sediment layer (dimensionless), s_T is the total chemical concentration in surface sediment layer (M/L_{w+s}).

The chemical source/sink term associated with the net settling or net eroded sediment flux is formulated as Wu (2006) based on mass balance. Wu's formula takes into account both dissolved and particulate phases. In case of net erosion, not only chemical sorbed on sediment bed was released into the water column, but also that in the porous water. Similarly, in case of net deposition, chemicals sorbed on suspended sediments settle on the bed surface layer and the dissolved chemical fills the porous volume as well.

It is assumed that the convection and dispersion in sediment layer are negligible. The governing equation for the sediment layer in conservative form is:

$$\frac{\partial(s_T \times D_{sed})}{\partial t} = S_{load} - S_{sed} + S_{v-diff,1} + S_{decay,s} \tag{3}$$

$$\begin{aligned} S_{v-diff,1} &= -k_f(s_{d,1} - c_d) + k_{f,s}(s_{d,2} - s_{d,1}) \\ &= k_f(f_{d,s1}s_{T,1} - f_{d,w}c_T) + k_{f,s}(f_{d,s2}s_{T,2} - f_{d,s1}s_{T,1}) \end{aligned}$$

in which D_{sed} is the depth of surface sediment layer.

3. NUMERICAL SIMULATIONS

Based on 10m DEMs, quadrilateral meshes were generated for Kerr Reservoir (122,470 elements) and Lake Gaston (113,724 elements). The 2D simulations of the hydrodynamics, sediment transport and contaminant transport and fate for three species (radium radioactivity, thorium radioactivity, and uranium) were carried out for dry years and wet years considering low limit and high limit of partition. First, the time varying flow fields in both reservoirs were computed for wet and dry year scenarios by taking into account the failure of the tailings dam upstream of Banister River. Then, the sediment transport, including erosion/deposition processes and the modification of the bed, were computed using the previously computed flow fields. Finally, the chemical fate and transport simulations were carried out for different partition coefficient sets (scenarios 1 and 2) using the flow field and sediment transport results computed for wet- and dry-year hydrographs.

Flow discharge, sediment discharge by size classes and contaminant concentrations computed from one-dimensional simulations of Roanoke River and Banister River using CCHE1D model were imposed as the upstream boundary conditions for the two dimensional model of the Kerr Reservoir. At the downstream boundary, Kerr Dam, a known outflow discharge time series was imposed as the downstream boundary condition, which allowed the water surface elevation in the dam to vary as a function of incoming and outgoing discharges.

The time series of flow discharges and total sediment discharges entering Kerr Reservoir, as computed by the CCHE1D model, are plotted in Figure 2 wet years. During the dry-year, the sediment discharge is quite small for the first 500 days due to low flow discharges. During this period the sediment is mostly transported as suspended load in both Banister and Roanoke Rivers and the bed load is quite negligible. After the 500th day, the sediment discharge increases in parallel with the increasing flow discharges.

Considering the computational efficiency, the two-dimensional sediment transport simulations in Kerr Reservoir were performed using four sediment size classes: (1) Size Class 1: 2.0×10^{-6} m; (2) Size Class 2: 8.0×10^{-6} m; (3) Size Class 3: 4.5×10^{-5} m; and (4) Size Class 4: 6.9×10^{-4} m. The amount of material in each size class entering the Kerr Reservoir was obtained from the sediment discharges by size class computed by the CCHE1D model.

Most of the sediment load entering into Kerr Reservoir is deposited in the reservoir. Only the finest sediment sizes can be found in the discharge released from the Kerr Dam. Therefore, the two-dimensional sediment transport simulations in Lake Gaston were performed using only three sediment size classes, which are given as (1) Size Class 1: 2.0×10^{-6} m; (2) Size Class 2: 8.0×10^{-6} m; and (3) Size Class 3: 4.5×10^{-5} m.

The amount of material in each size class entering Lake Gaston was obtained from the sediment discharges by size class computed by the CCHE2D model of Kerr Reservoir.

The radium and thorium radioactivity concentrations and the uranium concentration entering the Kerr Reservoir with the flow and sediment discharge from the Banister River were obtained from the one-dimensional model simulations of the Banister River. Partition coefficients for variou scenarios are listed in Table 1.

Table 1 Partition Coefficients for Simulation Scenarios

Scenario	**Contaminant**	**Partition Coefficient (mL/g)**
1	Radium	10
	Thorium	2,000
	Uranium	50
2	Radium	3,000
	Thorium	10,000
	Uranium	1,000

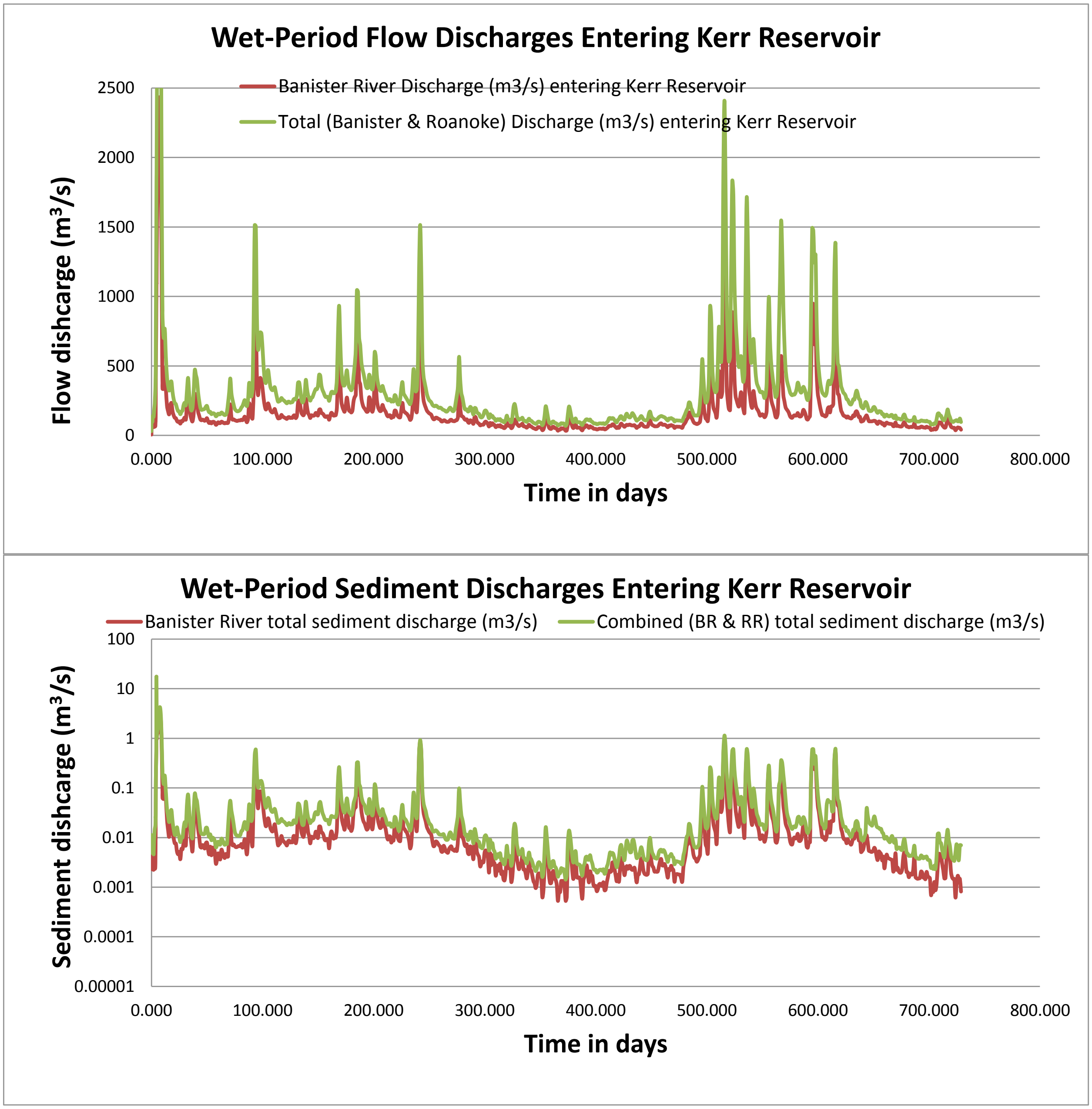


Figure 2 Wet-year (wet-period) flow and sediment discharges entering Kerr Reservoir at the upstream boundary, as computed with the CCHE1D model.

The models produced contaminant concentration distribution in space and time. Figure 3 shows the flow field and contaminant concentration contour lines when the plume reaches the furthest downstream tributary in Kerr Reservoir at a selected time. In this case, the mixing between the main channel and branches was quite strong resulting in a uniform distribution. At the branch end where the current was weak, there was higher level of radium concentration in the water column.

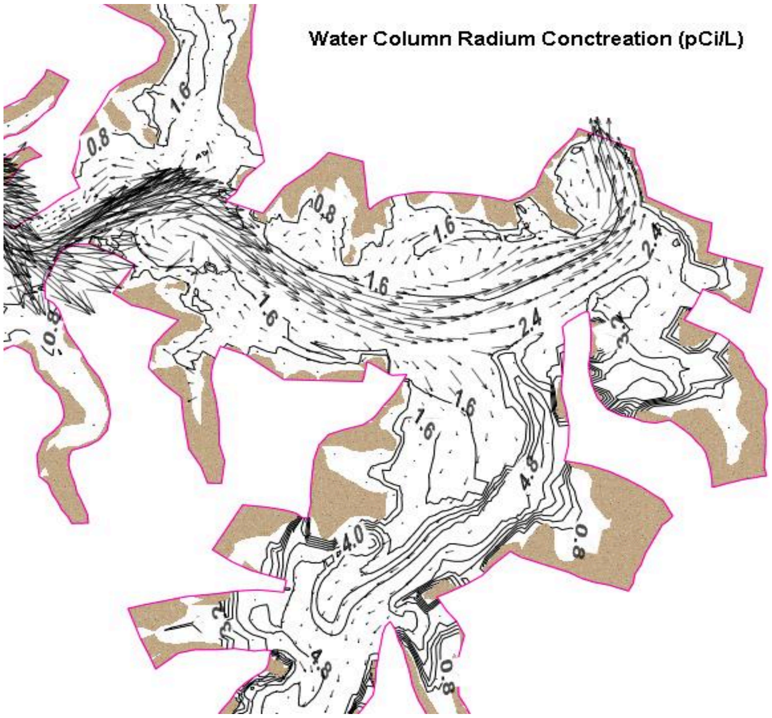


Figure 3 Flow field and contaminant plume in Kerr Reservoir

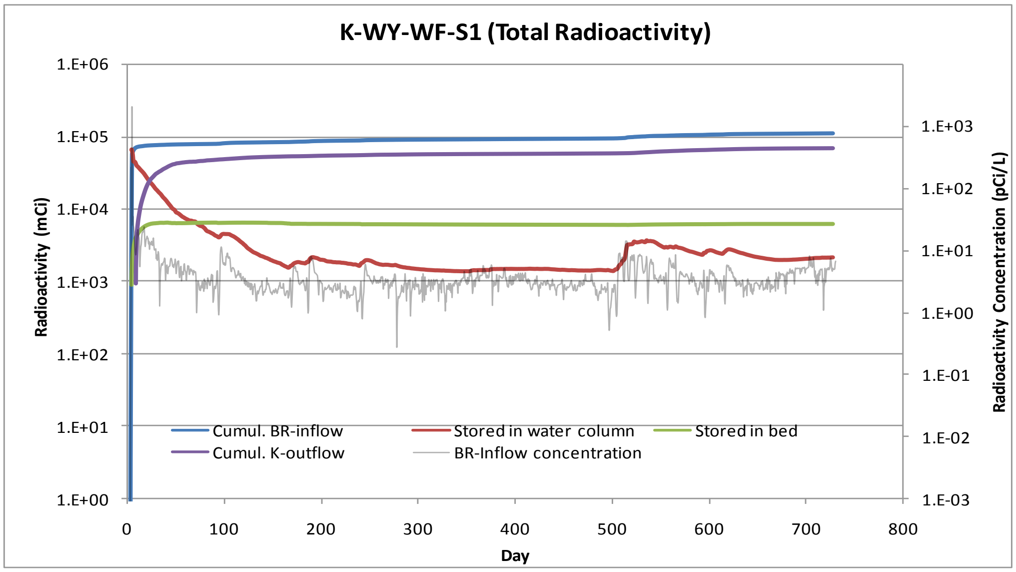


Figure 4 Total radioactivity concentration in the water column during wet years in Kerr Reservoir (Scenario 1)

There were more radioactive contaminants entering Kerr Reservoir during the wet years but with shorter detention time. A bigger fraction of contaminants stayed in the water column due to the smaller partition coefficient used in Scenario 1, and thus higher solubility. Figure 4 shows that the cumulative total radioactivity inflow (blue line) rises quickly within few days following the failure of the tailings dam and later continues to increase with a much milder slope. The cumulative total radioactivity outflow (purple line) follows a similar pattern but with a slight lag due to the time needed for the contaminant to travel from the upstream end of the reservoir to the Kerr Dam where it is released to downstream. The lag is quite short in case of wet-hydrograph due to higher travel speed. In case of dry-year scenario the flow is much slower and the lag between the inflow and outflow curve is more than 40 days. The difference between cumulative radium radioactivity inflow and outflow curves correspond to the amount of contaminant stored in the water column (volume of the reservoir) and the bed sediments of the reservoir. The red line is the time series of contaminant stored in the water column and the green line is the time series of contaminant stored in the bed.

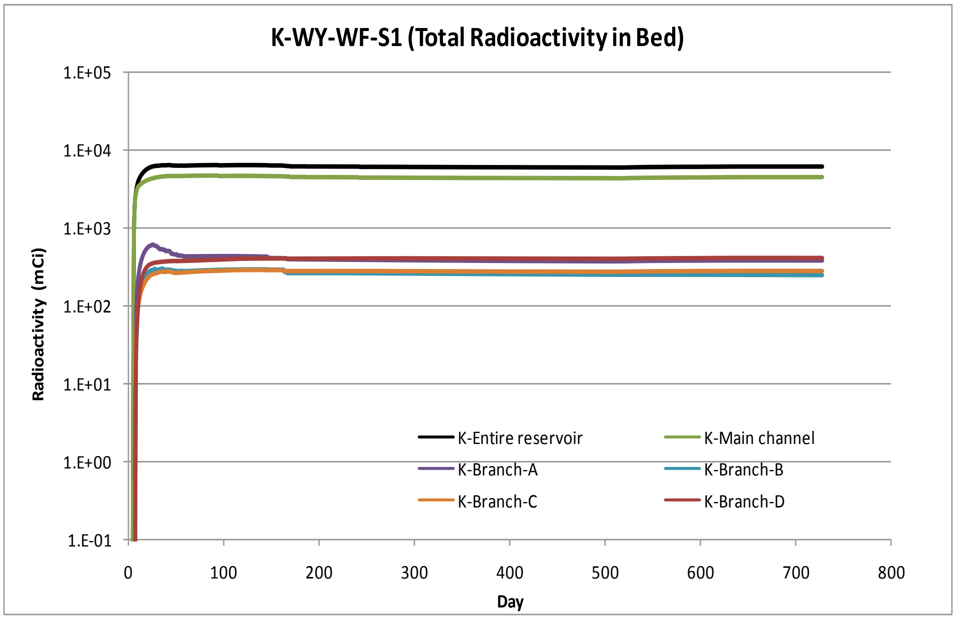


Figure 5 Total radioactivity concentration in bed (main channels and branches) during wet years in Kerr Reservoir (Scenario 1)

Figure 5 shows that cumulative total radioactivity content in the entire reservoir (black line) rises quickly within few days following the failure of the tailings dam. For Scenario 1, the black line has a negative slope (total radioactivity in the bed decreasing with time). Most of deposited radioactive contaminants stays in the main channel while about 1/10 stays in the bed of the branches.

In Lake Gaston, during the dry year scenario the total radioactivity contributed by radium and thorium exceeded the regulatory standard for a longer period of time. Figure 6 shows the simulated total radioactivity concentrations during the 2-year dry period at several cross-sections along the main channel of Lake Gaston assuming low partition coefficients (Scenario 1). The MCL , is exceeded for up to 1.5 years in the main channel, which represented the worst-case scenario regarding the drinking water quality in Lake Gaston. The concentrations decline much slower during dry years than in wet years when the travel time was much faster.

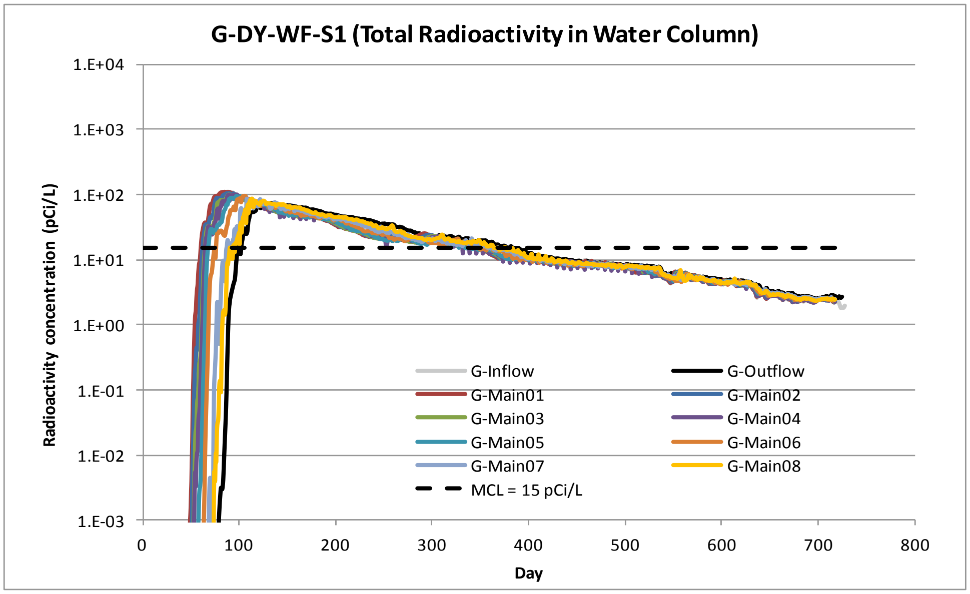


Figure 6 Water Column Total Radioactivity Concentrations at different locations in the Main Channel of Lake Gaston during Dry Years (Scenario 1)

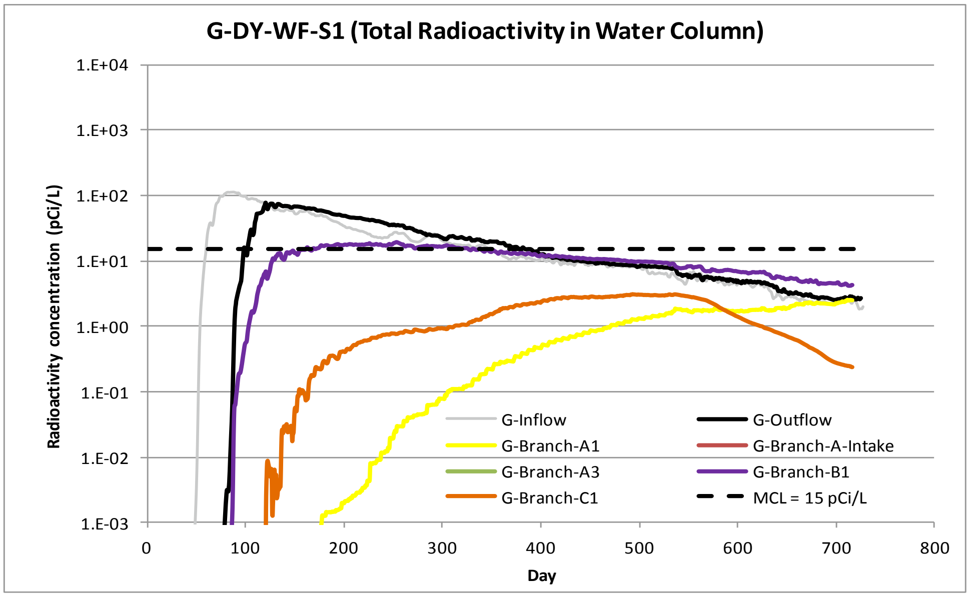


Figure 7 Water Column Total Radioactivity Concentrations at different locations in the Branches of Lake Gaston during Dry Years (Scenario 1)

Figure 7 shows the total radioactivity concentration at various locations in the branches of Lake Gaston during dry years. It can be seen the concentration is lower in the branches than in the main channel. For the dry-year scenario the contaminants enter the branches later due to low discharges and lower water surface levels. During wet-year simulations the concentrations are generally below the MCL.

Due to the small loading of uranium into the reservoirs, the uranium concentration in the water column in either Kerr Reservoir or Lake Gaston would not exceed the regulatory level for drinking water for most scenarios. More detailed simulation results for each scenarios can be found in the project report (Virginia Beach Uranium Mining Impact Study, 2012).

4. CONCLUSIONS

The results of the simulations concerning the spatiotemporal variation of dissolved and particulate contaminants concentrations in the water column, and contaminant accumulation in the bed are presented. Conclusions were drawn based on the simulation results (Virginia Beach Uranium Mining Impact Study Phase II Report, 2012): 1) Unlike Lake Gaston, contaminants will enter tributaries of Kerr Reservoir (Figure 3) due to varying water levels. 2) During dry periods, total radioactivity (thorium and radium) levels in the water column may exceed the allowable levels for various periods in Kerr Reservoir and Lake Gaston (Figures 6 & 7). 3) The peak levels of total radioactivity in Kerr Reservoir and Lake Gaston could exceed the MCLs by up to an order of magnitude. And 4) uranium concentrations would remain below the MCL in Lake Gaston.

The 2D simulations for this phase did not take into account the discharges from the tributaries into the Kerr Reservoir or Gaston Reservoir. It was also assumed that, following the failure of the tailings dam the water intakes were shut down. Therefore, the discharges extracted by the water intakes were not modeled in the 2D study. In a subsequent phase, if needed, more realistic operational characteristics of the two lakes can be taken into account.

The effect of the wind shear stress was not taken into account in the model. Past experience with modeling studies performed for various other reservoir studies shows that, the wind field over the lake may sometimes play an important role in mixing and transport of contaminants. In the present study the flow velocities in the reservoir, especially during dry periods can be as small as a few centimeters per second. Therefore additional advection and mixing provided by the wind shear stress may be significantly more important than the advection and mixing due to flow alone. Although wind shear stress can be defined in a two-dimensional model, this is generally used only for studying storm surge or seiche effects. In order to study the contaminant transport and fate due to the effect of wind, which leads to vertical structures in the form of vertical rotational cells and flow reversal in the water column, it is necessary to use a three dimensional model.

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